Response of Subjects to Some Conditions of a Simulated Orbital Flight Pattern

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UPON the request of the National Aeronautics and Space Administration, the Air Crew Equipment Laboratory conducted a series of tests on certain aspects of orbital flight patterns. These tests served two primary purposes: they were used to indoctrinate the NASA astronauts in the use of the full pressure suit and they provided indications of human reactions to a range of relatively severe thermal loads and some other related conditions anticipated as rather extreme possibilities in orbital flight. (Orbital flight, as used in this paper, refers to all operational phases from pre-launch to postlanding recovery of an astronaut.) In all, twenty tests were conducted, and these form the basis of the present report. The results of these tests indicate that, for the conditions investigated, thermal stress alone posed no serious physiological problem during all phases of simulated capsule flight until touchdown. The duration and magnitude of the heat load in the postlanding period, however, were critical in determining the physiological status of the capsule inhabitant.

MATERIALS AND METHODS

Chamber.—Tests were conducted in two adjoining chambers. The smaller of these was used for all tests in which the subject assumed an upright, seated position. The larger chamber was used whenever it was necessary for the subject to assume a supine position. The arrangement of components of the smaller chamber is shown in Figure 1. Wall temperature of this chamber was controlled by circulating brine of appropriate temperature within the walls and by adjusting the intensity of quartz heating lamps located on the walls. The ambient air temperature and pressure within the smaller chamber were also regulated. Tests conducted in the larger chamber involved no dynamic changes in temperature, consequently the temperature of the walls and air were maintained at some predetermined level throughout the exposure period, and all tests were made at sea level pressure. Both chambers are provided with glass windows through which the subjects could directly be observed.

Clothing.—The full pressure suit (Fig. 1) adopted for use in Project Mercury was worn by all subjects in the tests reported here. In essence, it consists of an aluminized, impermeable covering which encloses the entire body with the exception of the head. The latter is protected by means of a helmet-visor combination which is sealed around the neck to the suit proper. Ventilating gas entering the suit at the left side of the torso is directed by perforated tubes over the body and limbs to the hands and feet. The ventilating gas leaves the interior of the suit by passing through the space between the suit and the body surface to an exhaust port located on the lower right portion of the helmet. In this manner, some of the ventilating gas is breathed by the wearer.

A layer of polyurethane insulation was incorporated on the inner aspect of the suit for the indoctrination tests. Suits having this insulation are designated here as "insulated suits." Beneath the pressure suit proper, the subjects also wore long, open-weave underwear, socks and a "trilok" spacer. The latter is a garment designed to maintain the patency of the space

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between the pressure suit and underwear, thus enhancing the distribution and ease of flow of ventilating gas. For later tests, the spacer material was sewn in patches to the underwear, the resulting combination was then designated as an "integrated spacer."

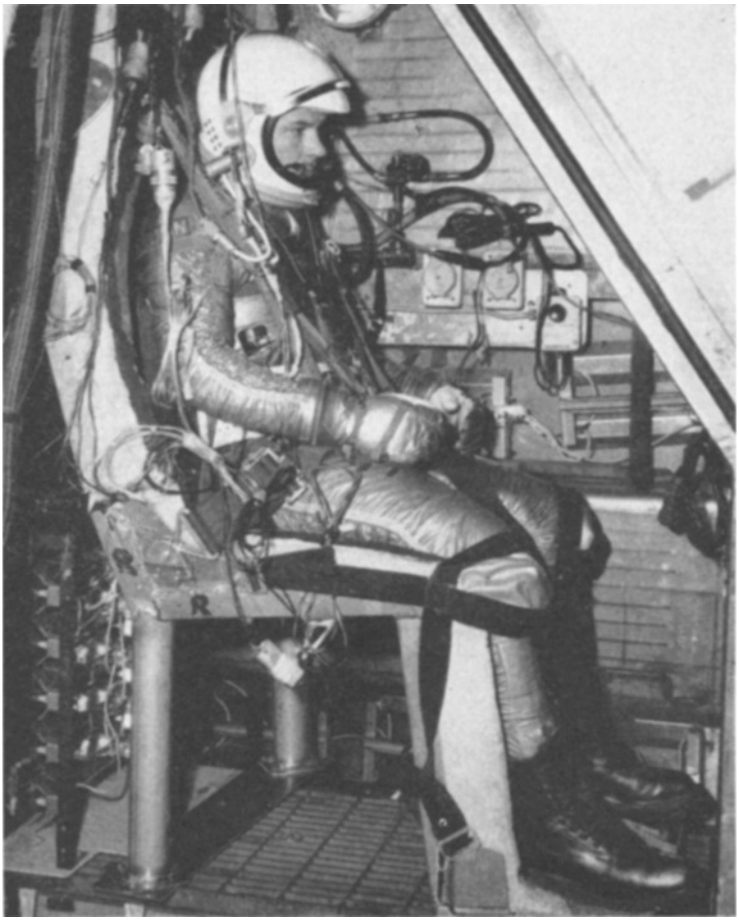

Fig. 1. Subject wearing full pressure suit while seated in thermal test chamber.

Instrumentation.—Plastic-coated copper-constantan wire thermocouples were used in all cases to measure environmental, suit, couch, skin, and rectal temperatures. Readings obtained were corrected by maintaining a group of thermocouples, identical in all respects to those used for the measurements just mentioned, in a water bath of accurately known temperature. Thermocouple output was read directly in millivolts from a self-balancing, indicating potentiometer. The "hot" junctions of the thermocouples were fixed to the surfaces being measured with tape, while the "cold" junctions were kept in an insulated bath containing an ice-water mixture at 0°C.

Electrodes used to obtain electrocardiograms were of various experimental types. An example of those proving the most suitable and reliable is shown diagrammatically in Figure 2. This electrode[4] consists essentially of a monel wire screen, electrically connected to the body surface through a layer of electrode paste. After adhesing the rubber screen support to a shaved and cleaned area of the torso, the electrode and paste were covered with a piece of adhesive-

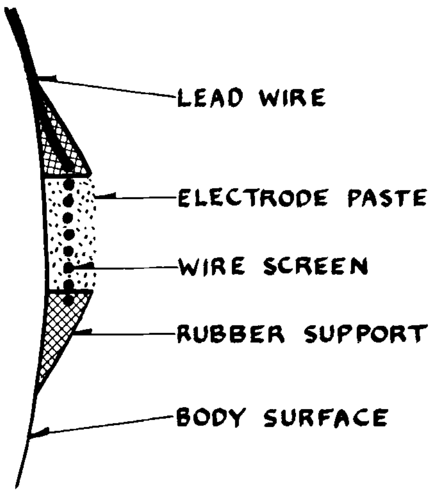

Fig. 2. Diagram of electrode used for obtaining electrocardiograms.

backed cloth. ECG electrodes were located on the torso in all cases; two active electrodes being fixed over the pectoral muscles and an inactive electrode located on the lumbar region of the back. Wire leads from thermocouples and ECG electrodes were arranged to exit from the interior of the suit through the exhaust port located in the helmet. From connecting plugs located in the test chambers, wire leads ran directly to recording and indicating instruments. ECG recordings were obtained using a Sanborn ECG amplifier and recorder. Measurements of relative humidity of the ventilating air were made using electric hygrometer sensing elements.

The subjects participating in these tests were NASA astronauts, test pilots, and Navy enlisted personnel. All were in good health and were instructed in the use of the full pressure suit before tests were begun. Before dressing, each subject was accurately weighed, electrocardiographic (ECG) electrodes were fixed to the torso, copper-constantan thermocouples were located on the skin surface, and, in the majority of tests, a rectal thermocouple was inserted. The subject then donned the clothing described above and was weighed again. In some cases, when Naval personnel served as subjects, blood and urine samples were obtained both before and after the heat exposure. Following removal from the test chamber, the subject was weighed, undressed, patted dry with a towel, and weighed again. Difference in dressed weights was taken as evaporative weight loss; difference in nude weights was designated total weight loss.

During all experiments in which subjects were required to remain in an upright seated position, they were strapped in place using a seat belt, shoulder harness, and leg restraints. Continuous voice communication was maintained at all times. The subjects were encouraged to report their feelings, and assured that they could immediately terminate a test upon request.

Modified Thermal Profile.—Eleven tests were conducted using 10 different subjects in which the entire thermal and pressure profile of a typical capsular flight was compressed into a total duration of 115 minutes. It was in this series of indoctrination tests that the NASA personnel were exposed for training purposes to the test conditions while wearing the full pressure suit. A typical modified thermal profile is graphically shown in Figure 3. In addition to thermocouples fixed to the skin surface, thermocouples were also placed on the couch surface upon which the subject was to sit, and on the outer surface of the suit. Couch and suit thermocouples were located in corresponding positions, i.e., at places where the thickness of the body and its coverings separated each pair of thermocouples.

Post-Landing Thermal Profile.—It was found, after attempting two full thermal profile tests, that the conditions were so stressful that subjects elected to abort some time during the post-landing portion of the profile. It was therefore decided to determine the effect of a scheduled twelve-hour post-landing phase alone. Two experienced subjects were exposed in five tests of this series. For each of the tests, the subjects remained in a recumbent position, except for relatively brief intervals when the subjects stood in order to urinate. The subjects were exposed to environmental conditions maintained as constant as possible during the exposure interval. Each of the subjects wore uninsulated suits, and in the last of this series, the subject also wore the integrated spacer. All tests of this series were conducted using a ventilating air flow of 0.57 lb. per minute (7.45 cu. ft. per min.), and were conducted at an ambient air temperature of 90°-95°F.

Full Thermal Profile.—This series consisted of four tests in which three subjects wearing uninsulated suits were exposed to the full thermal profile, simulating all phases from pre-launch to a post-landing recovery period lasting twelve hours. The conditions of thermal and pressure changes, together with the durations of each phase, are shown in Figure 4. In the last test of this series, the subject wore an integrated spacer beneath his suit. During the post-landing phase, a ventilating air flow of 0.57 lb. per min. (7.45 cu. ft. per min.) was used for all tests. The temperature and relative humidity of the post-landing ventilating air were 105, 85 and 97° F and 50, 100 and 58 per cent, respectively. During this test series, subjects were permitted to drink water from a filled, 3-quart container until the re-entry phase was initiated. At the start of the post-landing phase of the last test, the subject moved from the smaller chamber to the larger and assumed a recumbent position on the couch.

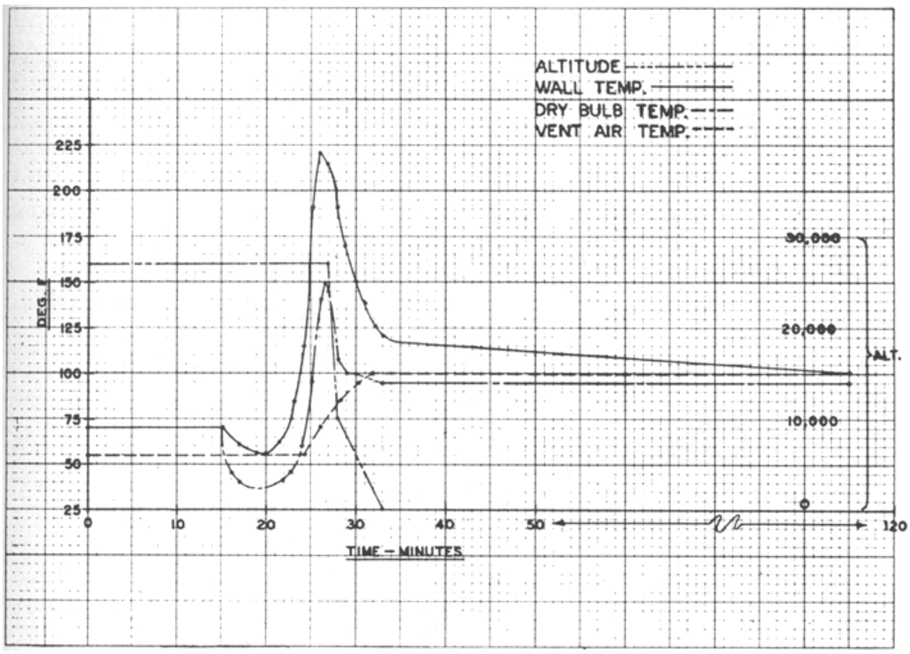

Fig. 3. Modified thermal profile.

RESULTS

Modified Thermal Profile.—As expected, skin and especially rectal temperatures showed relatively minor changes with time, while couch and outside suit temperatures tended to follow the imposed thermal profile. Thus, temperatures measured at the neck, chest, and upper leg regions of the couch generally increased from levels of about 27°C., before application of the heat pulse, to about 36°C. at, or immediately following, application of the heat pulse. Changes occurring on corresponding regions of the anterior suit surface were generally greater, increasing from a level of about 25°C to about 43°C. during the same interval. Skin temperatures rarely exceeded 38°C., although in some isolated instances skin temperature of the upper arm just exceeded 40°C. for a relatively short period. A typical record of suit, seat, skin, and rectal temperatures is shown in Figure 5.

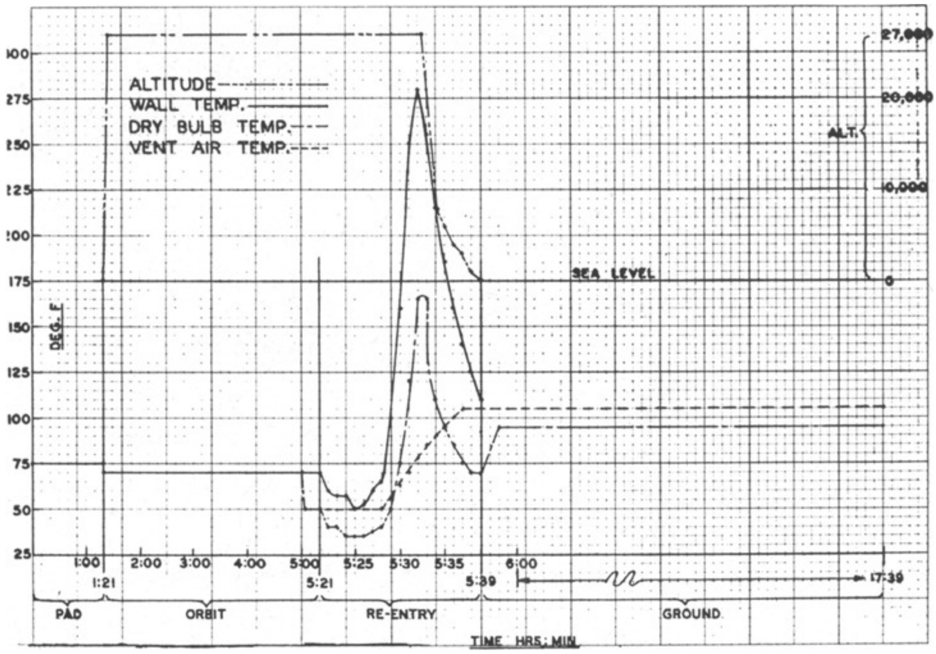

Fig. 4. Full thermal profile.

Two representative tests were analyzed for relative stability of skin temperature as measured on various regions of the body, and for the relationship of skin to rectal temperature. The results of this analysis are shown in Table I. Concurrent readings of skin temperature and rectal temperature (which did not change, in both cases, by more than 1°C.) were used to calculate ratios, and the mean ratio and its standard deviation for each region is shown in Table I. It should be noted that subject S wore an insulated suit, while Subject L wore an uninsulated suit. Examination of this table shows the relatively low skin temperature of the abdomen, and the small ratio differences between other skin regions measured. From Figure 5, the general trend of variations in surface temperatures is apparent, as is the relative stability of rectal temperature. It can be seen that in the period following application of the heat pulse, there was a tendency for the body to become isothermal.

Total weight loss averaged 468 ± 121 gm., of which an average of 165 ± 167 gm. was evaporated. The total weight loss averaged 0.63 ± 0.46 per cent of the initial nude weight. In one case, a subject lost 1048 gm. of water, of which 312 gm. were evaporated, representing a total weight loss of 1.42 per cent of the initial nude weight. Increase in heart rate between initial and final values averaged about 7 beats per minute. No abnormalities were noted in the ECG records obtained.

Based upon the response of subjects wearing uninsulated suits, it was determined that suit insulation was not effective in reducing thermal load. The data from Table I tend to confirm this conclusion, as does examination of body temperature records. It can also be seen that of the superficial regions of the body examined, least variation of surface temperature with respect to deep temperature occurred on the perineum. However, even temperatures measured on the upper leg or arm showed little more variation with respect to rectal temperature than perineal temperature. Since application of heat tended to make the body as a whole isothermal, absolute differences between temperatures of various skin regions were reduced. It would appear, therefore, that under these conditions, several sites on the skin could be used to provide a reliable index of whole body temperature.

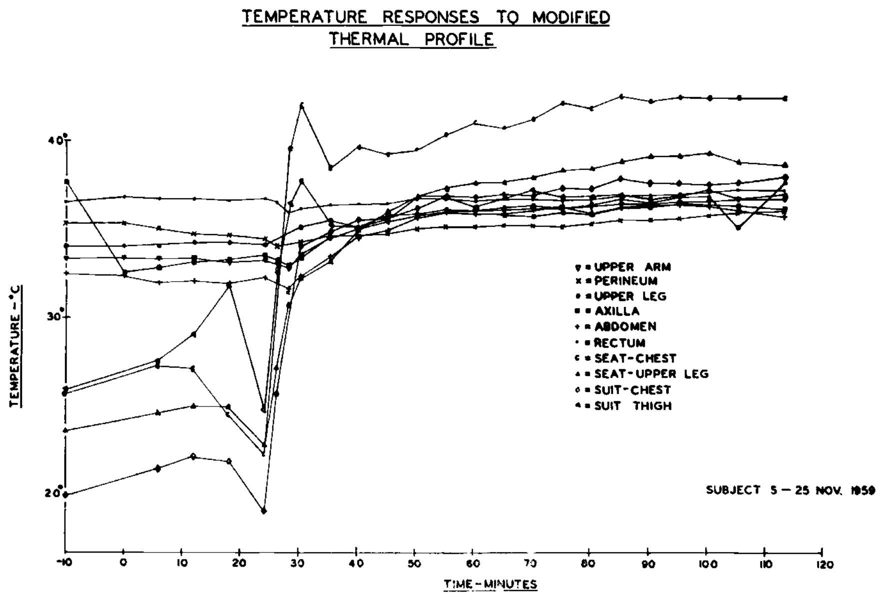

Fig. 5. Surface temperatures measured during exposure to modified thermal profile.

TABLE I. SKIN TEMPERATURE CHANGES DURING MODIFIED THERMAL PROFILE

Region	Subject S N=25		Subject L N=23	
	Mean Ratio*	Stand. Dev.	Mean Ratio*	Stand. Dev.
Upper arm	0.956	0.0357	0.957	0.0348
Upper leg	0.966	0.0293	0.944	0.0368
Abdomen	0.933	0.0815	0.932	0.0326
Perineum	0.953	0.0197	0.937	0.0148
Axilla	0.956	0.0389	0.950	0.0271

*Ratio of skin temperature to corresponding rectal temperature.

Post-Landing Thermal Profile.—The results of this series of tests is shown in Table II. During the first test, it was noted that the subject's face became very flushed, and termination followed shortly after the subject stood to urinate. The act of assuming a standing position caused a transient increase in heart rate, and was followed by complaints of dizziness and nausea. When removed from the test chamber, the subject appeared to be in a condition of borderline circulatory collapse. Recovery was uneventful, following removal of clothing and rest at usual room temperature. The subject in the second test also appeared flushed and showed a transient rise in heart rate (to 170 beats per minute) when assuming a standing position in order

TABLE II. RESPONSE TO POST-LANDING AND COMPLETE THERMAL PROFILES

Type Profile	Test No.	Subj.	Duration (Hr.-Min.)	Post-Land. Vent. Air		Rectal Temp. (°C)		Mean Weighted Skin Temp. (°C)		Heart Rate (Beats/Min.)		Weight Loss (Gm.)		
				Temp. (°F)	R.H. (%)	Initial	Final	Initial	Final	Initial	Final	Total	Evap.	% Evap.
Post-landing	1	F*	4-15	105	50	37.3	38.4	35.2	37.4	78	150	1476	—	—
	2	M†	8-23	105	50	37.6	38.9	34.8	37.8	95	109	2108	—	—
	3	F	12	85	100	36.6	37.4	35.0	36.5	72	80	1148	660	57.5
	4	M	12	85	100	37.0	37.5	35.0	36.4	85	85	1228	500	40.8
	5	F	12	97	58	37.0	38.6	34.7	38.0	74	126	1588	1140	71.8
Complete	1	F	14-30	105	0	36.8	37.6	33.5	35.2	82	102	1348	1192	88.4
	2	M	8-25	105	50	37.6	38.9	35.1	40.4	106	125	940	380	40.5
	3	D‡	8-10	105	50	37.6	38.0	34.1	36.8	110	90	1112	300	27.0
	4	F	16-55	97	58	36.8	38.9	33.9	38.2	72	115	1840	1480	80.5

*Age=26 yrs.; Wt.=153 lb.; Ht.=5′ 11″.
†Age=31 yrs.; Wt.=160 lb.; Ht.=5′ 7½″.
‡Age=21 yrs.; Wt.=174 lb.; Ht.=5′ 11″.

to urinate. Even after reassuming a recumbent attitude, the heart rate continued to remain at a level of 140 beats per min. Gradually, this rate decreased to the final level shown in Table II, rising to 120 beats per minute when the subject was removed from the test chamber because of the level and rate of rise of rectal temperature. After one hour, the rate continued to be 100 beats per min., while the subject rested at normal room temperature. A moderate degree of facial pallor was evident during this recovery period. The subject stated that he had occasionally opened his helmet visor during the course of the test.

The remaining three tests of this series were terminated when the scheduled exposure time had elapsed. After the last test, the subject appeared pale and weak, and complained of feeling nauseous. However, after 15 minutes of rest, he felt well enough to resume his normal activity.

Complete Thermal Profile.—Results of the four tests conducted in this series are summarized in Table II. No significant signs of strain were seen during the phases preceding the post-landing conditions in any of these tests. During the first test, the subject reported feeling uncomfortably warm about six hours after initiation of the test and reported aching and burning sensations in his knees. During the subsequent period, the subject appeared apprehensive and frequently shifted his position to relieve pressure points, especially around the knees. The test was terminated at the subject's request, and he appeared extremely fatigued and restless upon being taken out of the test chamber. Recovery was uneventful. The second test was terminated because of high body temperature, as indicated by the relatively high levels of skin and rectal temperatures. The third test was terminated upon request of the subject who appeared flushed and complained of severe headache, nausea, and abdominal cramps. While being undressed, the subject appeared considerably pale and later became faint and nauseated during venipuncture. Recovery was rapid after a short rest. The final test was terminated when the rectal temperature reached 38.8°C. The subject had complained of nausea during the later portion of the test, but, after being withdrawn from the test chamber, he rapidly recovered.

DISCUSSION

The findings reported here are not intended to represent a detailed study of human tolerance to heat loads. Rather, they represent an interim report, for the purpose of providing certain timely data which may prove useful to persons concerned with various aspects of manned orbital flight. The inherent limitations restricting the use of these findings to conditions similar to those described here should be obvious. It should also be mentioned that the outcome of such tests is often directly dependent upon the motivation and experience of the subjects. In tests lasting as long as some of those described here, the subject's ability to cope with boredom, discomfort, fatigue, and frequently low levels of pain often determines the total test duration.

Calculation of the Craig physiological strain index[2] for six modified thermal profile tests in which rectal temperature was measured, resulted in values ranging from 1.14 to 1.55. In three of the remaining tests of this series, skin temperature, total weight loss, increase in heart rate, and subjective comments support the view that strain indices of the same order of magnitude as those already given also apply. In the remaining test, in which the subject lost over 1 Kg. of sweat, the rectal temperature was not measured. However, this subject showed the greatest increase in perineal temperature (4.8°C.), when compared to all ten of the other subjects. Based on the relationship between rise in rectal and perineal temperatures in those cases where both were simultaneously measured, it is reasonable to assume that rectal temperature rose about 2°C. in the case being considered. Such a rise would result in a strain index of 2.36, which would be expected to indicate serious discomfort.[3] Since the subject was observed to be sweating profusely during the course of the test, he was frequently questioned regarding his feeling, but he reported no unusual discomfort.

In the post-landing tests, the beneficial effects obtained by lowering the temperature of the ventilating air, in spite of an increase in its relative humidity, is reflected in the ability of the subjects to complete the scheduled test duration. In addition, strain indices of less than one can be calculated for the two tests involving the use of 85°F., 100 per cent relative humidity ventilating air, whereas the indices rise in those cases where the ventilating air temperature is above initial mean weighted skin temperature. However, the value of the strain index does not exceed two even in those cases of post-landing and full profile tests where the subjects elected to abort, and where indications of impending circulatory collapse were present. This probably means that other factors, such as discomfort from localized pressure points, or boredom, may have contributed significantly to the physiological stresses being imposed. This is substantiated by calculations of heat storage, which also show that some tests were terminated before the theoretical physiological tolerance limit[1] was reached.

SUMMARY

Some of the physiological responses of subjects wearing ventilated full pressure suits and exposed to pressure and thermal profiles characteristic of extreme conditions of orbital flight patterns were presented. No significant physiological stress was evidenced in subjects exposed to a modified thermal profile, except for the sweating response of one subject. Exposure of experienced subjects to long duration thermal loads simulating relatively severe post-landing and full thermal profiles resulted in premature test termination when ventilating air temperature was more than a few degrees above initial mean skin temperature.

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