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REPORT NO. NADC-88017-60

AD-A213 047

COLD WATER EVALUATION OF NASA LAUNCH ENTRY SUIT (LES)

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1 JULY 1988

FINAL REPORT
Period Covering January 1988 to March 1988
Task No. WX30403
Work Unit No. 107679
Program Element No. NIF

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Prepared for
NATIONAL AERONAUTICS & SPACE ADMINISTRATION (Code SP)
Johnson Space Center
Houston, TX 77058

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19 ABSTRACT (Continued)

capable of protecting individuals for up to 3 hours. As subjective tolerance was the limiting factor in these runs, it is certain that the actual survival times would be greater. While trial durations were less than the maximum desired, LES/r proved capable of providing Space Shuttle crews with effective thermal protection for periods exceeding 13 hours. With the longest LES/r runs terminated due to subjective intolerance, survival times greater than 13.5 hours could be expected for some individuals in the LES/r.

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INTRODUCTION

NASA has identified the need to provide expanded Space Shuttle crew protection within the last year. The Launch Entry Suit (LES) has been developed which provides both a counter pressure system for protection against extreme hypobaria, as well as anti-exposure protection. Based on an expanded polytetrafluoroethylene (PTFE) membrane, the anti-exposure protection inherent in the LES is intended to provide thermal protection in 4.4°C (40°F) water for up to six hours when used with only a personal flotation device and 24 hours if used with a raft.

The present study was intended to evaluate the thermal protection afforded by the LES when used under the most demanding ocean conditions which might be encountered by downed Shuttle crews. A Navy CWU-27/P flight coverall was used for comparison since it is representative of the garment used on the operational Space Shuttle flights to date (27/P). As NASA had an interest in determining the thermal protection provided by the addition of a raft, both the LES and 27/P were tested alone and in combination with a raft. The raft used in this study was a variant of the Navy LRU-18/U, modified by the inclusion of a canopy.

MATERIALS AND METHODS

Subjects: Four healthy males and one female (Table 1) 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 for each subject calculated. Body surface area (BSA) was calculated (2) from the mean weight and height of each subject. Percent body fat was determined from estimates of body density (1), which were computed from skinfold measurements obtained with Lange Skinfold Calipers (Cambridge Scientific Inc., Cambridge, MD) and the equations of Lohman (10), for the male subjects, and Jackson and Pollock (10), for the female subject.

Materials: The clothing ensembles used in this study were the LES and 27/P (Table 2). The LES (Figures 1 & 2) consists of a laminated PTFE membrane shell, which allows for the passage of water vapor but not of liquid, coupled with pressure bladders and controllers designed to provide protection against loss of cabin pressure. Integrated flight gloves were designed for use in low pressure environments, but provided minimal thermal protection. A number of survival mittens were evaluated in this study, with a neoprene/PTFE type ultimately selected.

The raft used was a variant of the Navy LPU-18/U one-man raft, modified by the inclusion of a canopy. The canopy consisted of a fabric cover, running the length of the raft, that was designed to come over the head with a drawstring for sealing the facial opening. To permit raft entry, the fabric was split, from the drawstrings to the foot of the raft, into two flaps of material. These flaps were designed to be secured over

Table 1. Physical Characteristics of Subjects.

Subject	Age (yrs)	Height (m)	Weight (kg)	%Body Fat	Surface Area (m^2)
A	36	1.82	75.4	9.3	1.96
B	44	1.73	71.5	12.6	1.85
C	31	1.83	87.4	14.4	2.10
D	34	1.88	90.3	18.9	2.17
E	32	1.65	69.8	29.5	1.77
mean	35	1.78	78.9	16.9	1.97
SEM	2	0.04	4.2	3.5	0.07

TABLE 2. Clothing configurations worn during tests.

Table 2. Clothing Configurations Worn During Tests.

Configuration	Protective Garment & ancillary equipment
1	Launch Entry Suit (LES) a. Parachute harness b. Life vest c. Parachute pack d. Life raft pack e. LES helmet f. LES gloves g. Various survival mittens h. Capilene underwear i. Polypropylene sox j. Urine collection device/ Disposable Absorption Collection Device (DACT) k. Flyer's Boots l. Flotation device
2	Standard Navy Flight Ensemble (27/P) a. PRK-37/P flight helmet b. Navy flight gloves c. Survival mittens d. SV-2 survival vest e. CWU-43/P and -44/P Nomex underwear f. Flyer's Boots g. Flotation device

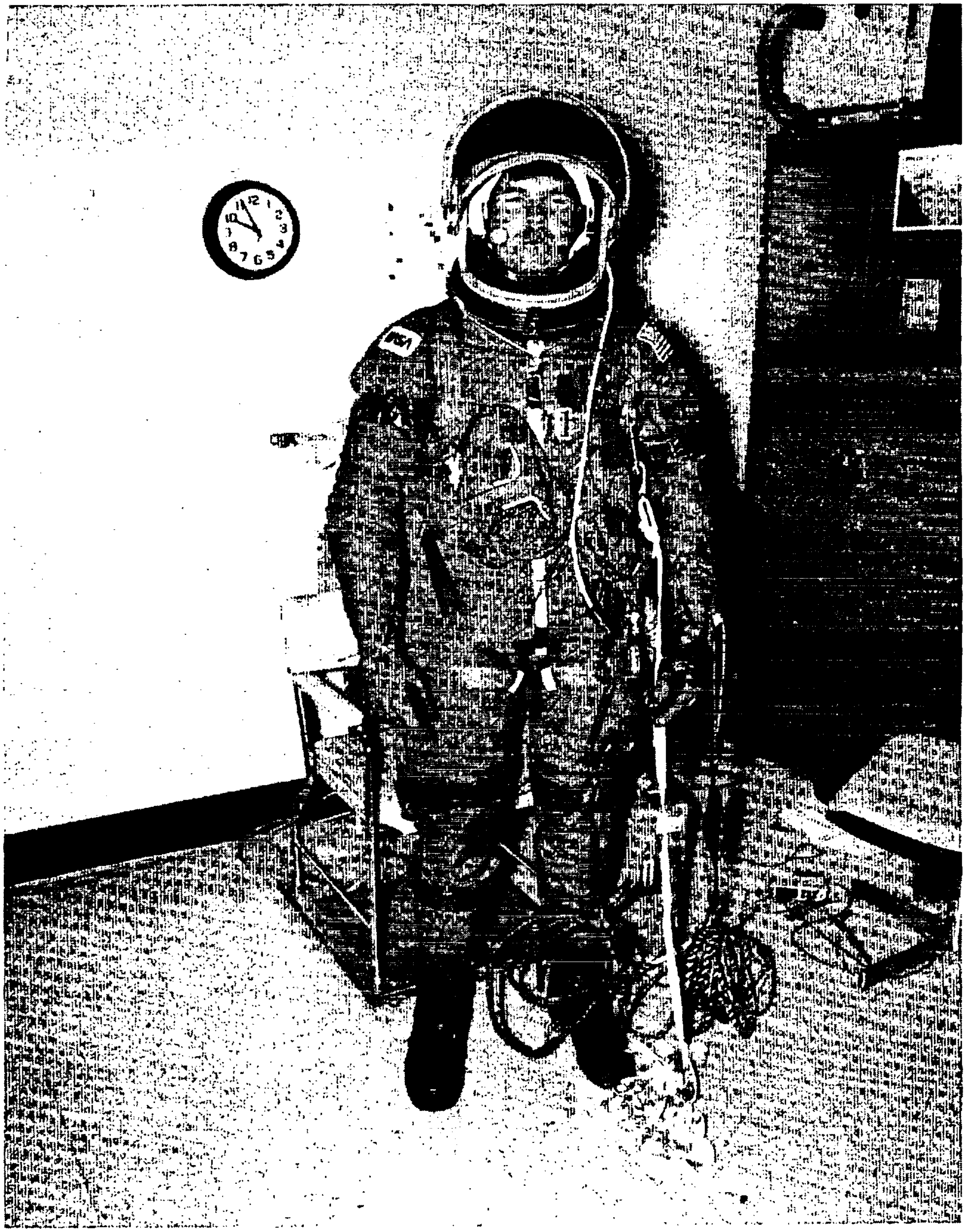

Figure 1. Front view of the NASA Launch Entry Suit.

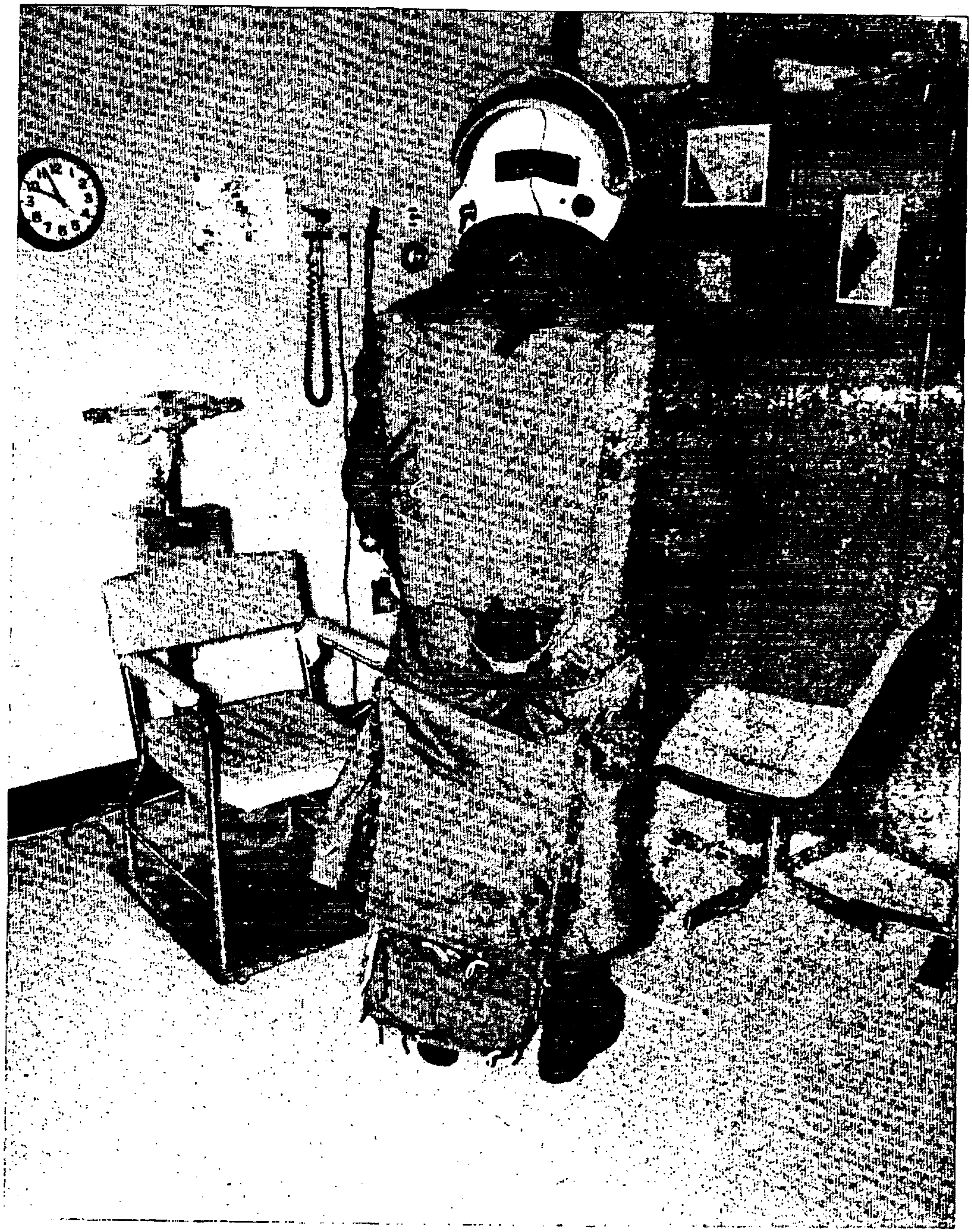

Figure 2. Rear view of the NASA Launch Entry Suit.

the raft mid-line by means of a two inch wide Velcro strip. Subsequent to the first LES/r trial, subjects were instructed to sit on the water packets supplied as part of the LES in an attempt to increase the insulation between themselves and the raft bottom.

The flotation system employed with the LES was changed as the study progressed to eliminate design weaknesses which were evidenced by the attitude assumed by subjects in the water. Initially, the system employed was an Air Force model currently in use by T-38 aircrews. When used in this study, subjects assumed a horizontal position in the water. Unfortunately, this position permits the aspiration of water through the anti-suffocation valve located on the back of the LES helmet; this both exacerbated thermal stress and increased the risk of drowning. Subsequently, a modified Navy flotation system was then adopted, which worked reasonably well, but used a makeshift interface with the LES. Water inflow through the anti-suffocation valve continued to be a problem, despite the approximate 45° angle relative to the water surface assumed by floating subjects, until the valve was closed off with a waterproof plug. Finally, the Air Force flotation system used by SR-71 crews was adopted and was found to be acceptable. This system placed subjects in a relatively upright position (i.e., approximately perpendicular to the water surface).

The raft bailing system was similarly refined as the testing progressed. Initially, the sea anchor supplied with the raft was to be used for bailing. This proved to be totally unacceptable due to its inefficiency and the magnitude of physical exertion required for successfully bailing. A number of bailers modeled after a British design were subsequently evaluated until a single design was found to be acceptable to all subjects. The type finally selected was a small wedge-shaped scoop with a relatively square opening and fitted with a strap designed to slide over a survival mitten. To accomplish nearly complete bailing of a raft, a small hand pump was also provided, which consisted of a squeeze bulb connected to pieces of tubing. The addition of the hand pump facilitated bailing when the raft canopy was closed and allowed for more complete removal of water from the raft while retaining metabolic heat trapped under the canopy.

Methods: Subjects employed each configuration at least once for a minimum of four total exposures per subject. Repeated trials resulted from equipment problems; the additional runs provided more representative data for analysis. One run in which equipment difficulties were encountered could not be repeated; least squares estimates for the missing values were used in the statistical analyses (16). The minimum time interval between tests for a given subject was two days, to minimize acclimatization effects.

Subjects reported to the laboratory on the morning of a test and were given physical examinations by the attending flight surgeon. A urine specimen was collected and a urinalysis performed as part of the flight surgeon's examination of the subject. Each subject's baseline weight was obtained on a scale accurate to ± 10g (Scale-Tronix, Wheaton, IL, model 6006SP) and ECG electrodes (3M, Minneapolis, MN, Red Dot) were 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 ten body sites: (A) forehead; (B) left upper chest; (C) left distal upper arm; (D) dorsum of left hand; (E) right anterior thigh; (F) left posterior thigh; (G) right shin; (H) dorsum of right foot; (J) right proximal 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). A rectal thermocouple (Sensortek, Clifton, NJ, model RET-1) was inserted at least 8-10 cm anterior to the anal sphincter (later runs employed a redundant thermocouple).

Subjects were then dressed in the appropriate clothing configuration for that scheduled trial (i.e., the CWU-27/p or LES)(Table 2). On the external suit surface of both garments, type T thermocouples were placed on the locations corresponding to the skin surface sites upon which the heat flux/thermistors transducers were placed. Thermocouple outputs, including the rectal probe, were measured with optically isolated signal conditioners (Ben-Dec, Santa Ana, CA, model TC.4). Upon completion of dressing, subjects were weighed, followed by a rest period of 20 minutes which enabled subjects' temperature and heart rate to return to a resting condition before commencing that day's trial. The LES was cooled with a ventilator during this 20 minute rest period. Laboratory temperature was maintained at approximately 20°C (68°F) to minimize thermal stress during dressing.

Following the conclusion of the rest period, subjects entered the pool. Testing was performed in chamber conditions of water temperature (T_{water}) = 4.4 ± 0.2°C, air temperature (T_{air}) = 5.6 ± 0.1°C, wind velocities of 6.7 - 11.7 km hr^{-1}, overhead spray, and approximately 1 foot choppy waves. Raft tests required subjects to remain in the water for 2 minutes (a trial in which the raft sank had the subject initially in the water for 10 minutes), after which they were handed a raft with its primary air chambers inflated. Subjects then boarded the raft and inflated the secondary air chambers. Bailing the raft was then initiated, first by use of the canopy, which served to remove large quantities quickly, then by means of hand-held bailers, and continued until the subject decided sufficient water had been removed to justify closing the raft canopy. After closure of the raft canopy, bailing was accomplished by means of the small hand pump. Type T thermocouples were passed through the opening of the raft canopy located at the feet (which was used for all leads) to measure changes in the air and water temperatures within the raft.

Subjects were instructed to remain in the raft for 24 hours or until the trial was terminated. Trials using only a personal flotation device consisted of subjects entering the water and attempting to remain floating while immersed up to the neck for up to 6 hours. Runs were terminated early due to: a rectal temperature (T_{re}) = 35°C; hand temperature (T_{hand}) = 10°C; foot temperature (T_{foot}) = 4.4°C (i.e., equal to T_{water}); heart rate (HR) exceeding 90% of the maximum predicted for age; or the subject, flight surgeon, or principal investigator requesting termination. Potable water was available to subjects in packets carried in the LES, but was not available in 27/P trials. No food was provided to subjects.

Measurements of respiratory function and metabolism were obtained for 15 minutes of every 30 minutes during the 27/P immersion trials. Initially, attempts were made to obtain measurements in the other configurations, but the opening of the helmet visor (in the case of the LES immersion trials) or the raft canopy (during raft trials) caused artifactual heat losses. As a result, respiratory and metabolic measurements were not obtained during these runs. Respiratory function was measured with a pneumotachometer (Hans Rudolph, Kansas City, Mo., model 3813) and expiratory gases were analyzed for determination of metabolic rate using a 5 liter mixing box and gas analyzers (Ametek, Pittsburgh, PA, models S-3A oxygen analyzer and CD-3A carbon dioxide analyzer).

Subjective sensations were evaluated by means of scales for fatigue, shivering, temperature, and comfort. Subjects were instructed to indicate their subjective sensation for each criterion on a 1 - 7 scale. Fatigue, shivering and comfort used a 1 to indicate the most pleasant situation and 7 to indicate the greatest unpleasantness. Temperature used 1 to indicate extreme warmth, 3 indicated thermal neutrality, and 7 indicated extreme cold. Final data from all four scales was summed and divided by the time at which the final data was obtained (QSST), in order to obtain an overall measure of final subjective state for each run.

Mean weighted skin temperature (Tsk) was calculated using the equation:

(1) $$Tsk = 0.1(T_A) + 0.125(T_B+T_K) + 0.07(T_J+T_C) + 0.06(T_D) + 0.125(T_E) + 0.15(T_G) + 0.125(T_E+T_F)/2 + 0.05(T_H)$$

where T_i are the measured skin temperatures at locations i = A - K (9). Mean weighted skin surface heat flux (HF) was calculated from the equation:

(2) $$HF = 0.1(HF_A) + 0.125(HF_B+HF_K) + 0.07(HF_J+HF_C) + 0.06(HF_D) + 0.125(HF_E) + 0.15(HF_G) + 0.125(HF_E+HF_F)/2 + 0.05(HF_H)$$

where HF_i are the measured heat fluxes at locations i = A - K (6,7,9). Cumulative energy losses from the body were calculated by:

(3) $$Q = \Sigma(HF \times SA) \qquad \text{(Joules)}$$

where Q is the total heat energy and SA is the body surface area.

Statistical Analysis: Initial and final T_{re} and exposure duration data was analyzed using an analysis of variance (ANOVA). Paired-t tests were used to compare variations over time, and for comparing pooled data when applicable. Heart rate data was used only for subject safety during testing and not for analysis due to difficulty with the noise resulting from shivering. Differences were considered significant at the level of $p<0.05$.

RESULTS

The results of this study demonstrated that differences between configurations, i.e., a combination of garments (LES or 27/P) and environment (personal flotation or use of a raft), were significant in terms of physiological effect.

Exposure Duration: Examining the data for trial duration (Table 3), the factors responsible for significant differences were: 1) subject differences ($p < 0.001$); 2) garment ($p < 0.001$); 3) personal flotation versus raft ($p < 0.02$); and 4) a second order interaction between garment and personal flotation versus raft ($p < 0.02$). Subject differences could not be correlated with either percent body fat or weight due to the small sample size.

Exposure durations for the LES trials were approximately 3 times greater than for the 27/P trials among subjects (Table 3). All LES run terminations were for subjective reasons (i.e., pain and discomfort), while all but one of the 27/P runs were terminated for $T_{re} = 35.0°C$. The durations observed in the LES/r trials fell into two groups: 1) trials terminated due to $T_{re} = 35.0°C$ (n = 3, all durations < 240 minutes); and 2) trials terminated due to pain and discomfort (n=2, durations of 587 and 801 minutes). Termination of the 27/P/r trials occured for both $T_{re} = 35.0°C$ (n = 3) and for subjective reasons (i.e., pain and discomfort)(n = 2). In these trials, exposure duration did not correspond to the reason for test termination, with subjective terminations occuring in both the shortest and longest runs.

Rectal Temperature: Tre was analyzed by comparing initial versus final temperatures (T_{re},i/f), and examining the temperature data as a function of time (cf., Table 3, Figures 3-7). Significant differences with regard to T_{re},i/f resulted from three factors: 1) subject differences ($p < 0.01$); 2) initial versus final values ($p < 0.0003$); and 3) a third order interaction between garment, immersion versus raft usage, and initial versus final values ($p<0.05$). These values include an estimated value for the missing data resulting from the trial in which a subject's raft sank.

Significant differences in T_{re} between configurations, as a function of time during a trial, were observed only during the later stages of runs ($p < 0.05$). No significant differences were found between the LES and LES/r runs for the available 122 minutes of complete common data, i.e., the time period for which data is available for all runs in both configurations. Though not significant, mean T_{re} for the LES runs, while initially less than that observed in the LES/r runs, had a smaller decline over time. A higher mean T_{re} (36.7°C vs. 36.2°C) was observed at the end of 122 minutes for the LES versus LES/r.

No significant differences were observed for T_{re} between the 27/P and 27/P/r trials for the available 29 minutes of complete data (similar to the LES versus LES/r comparison). Significant differences among the other configuration comparisons became evident only after at least 17 minutes had elapsed. A comparison of the changes in T_{re} by configuration showed that the mean difference between initial and final values for the LES runs was 0.9°C, while for the LES/r, 27/P, and 27/P/r, the means were

Table 3. Mean Values, Duration & Temperatures, by Configuration.

Configuration		Exposure Duration (minutes)	Rectal Temperature (°C)			Mean Weighted Skin Temperature (°C)		
			i	f	change	i	f	change
LES	mean	150	37.3	36.5	-0.8	32.7	22.2	-10.5
	SEM	9	0.2	0.3	0.3	0.5	1.7	1.6
27/P	mean	46	37.6	35.2	-2.4	32.4	10.7	-21.7
	SEM	4	0.1	0.3	0.2	0.4	0.5	0.2
LES/r	mean	398	37.5	35.6	-1.9	33.3	27.6	- 5.7
	SEM	126	0.2	0.4	0.3	0.7	1.2	1.2
27/P/r	mean	124	37.6	35.6	-2.0	30.1	20.9	- 9.2
	SEM	58	0.1	0.4	0.4	2.0	2.6	3.6

Mean values of exposure duration, rectal temperature, and mean weighted skin temperature by configuration, resulting from exposure to experimental conditions. The configurations denoted below are: LES – NASA Launch Entry Suit ensemble; 27/P – standard Navy flight suit ensemble, with /r signifying use with a raft.

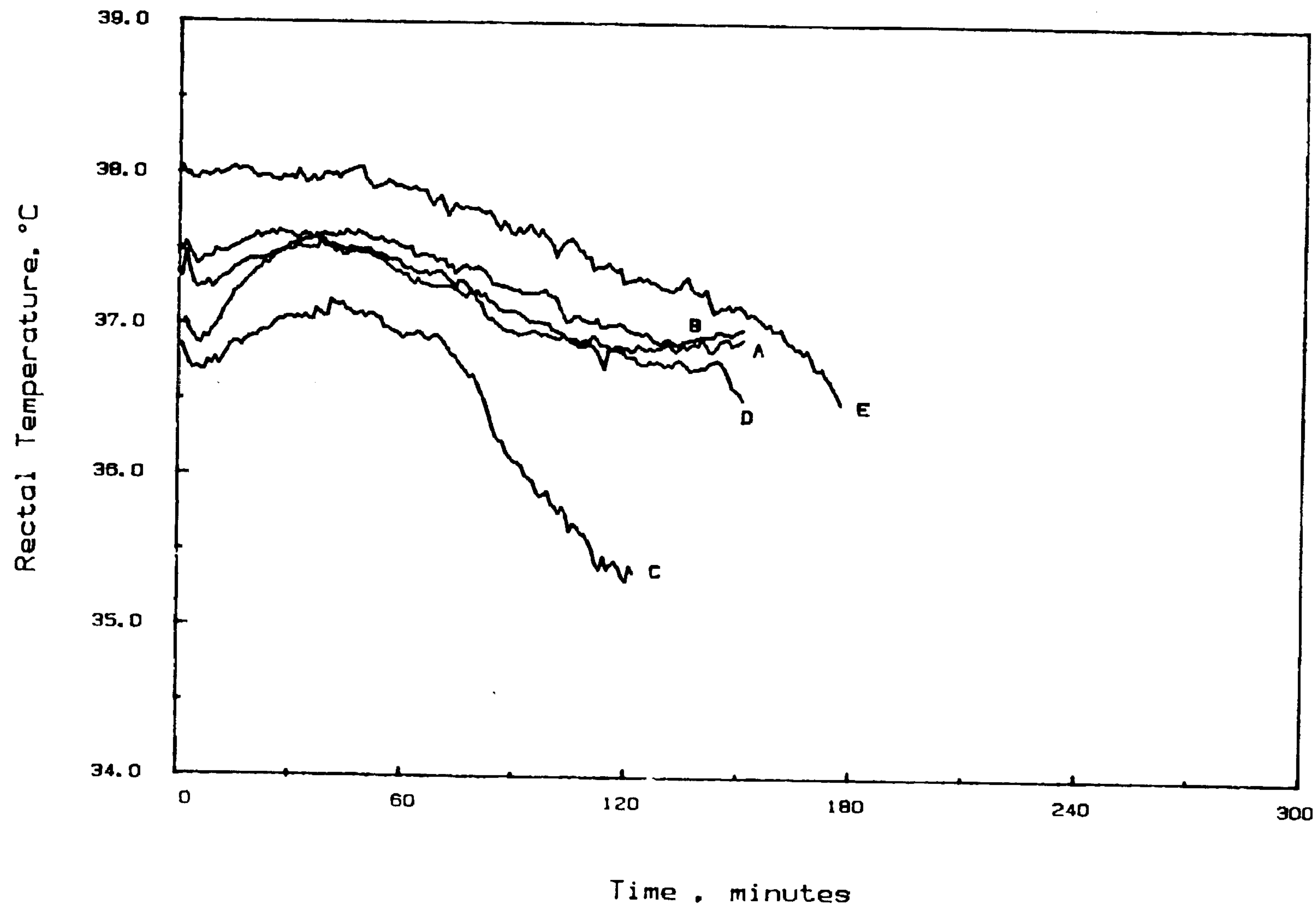

Figure 3. T_{re} versus time for the Launch Entry Suit (LES) using only personal flotation, by subject. All trials terminated due to discomfort.

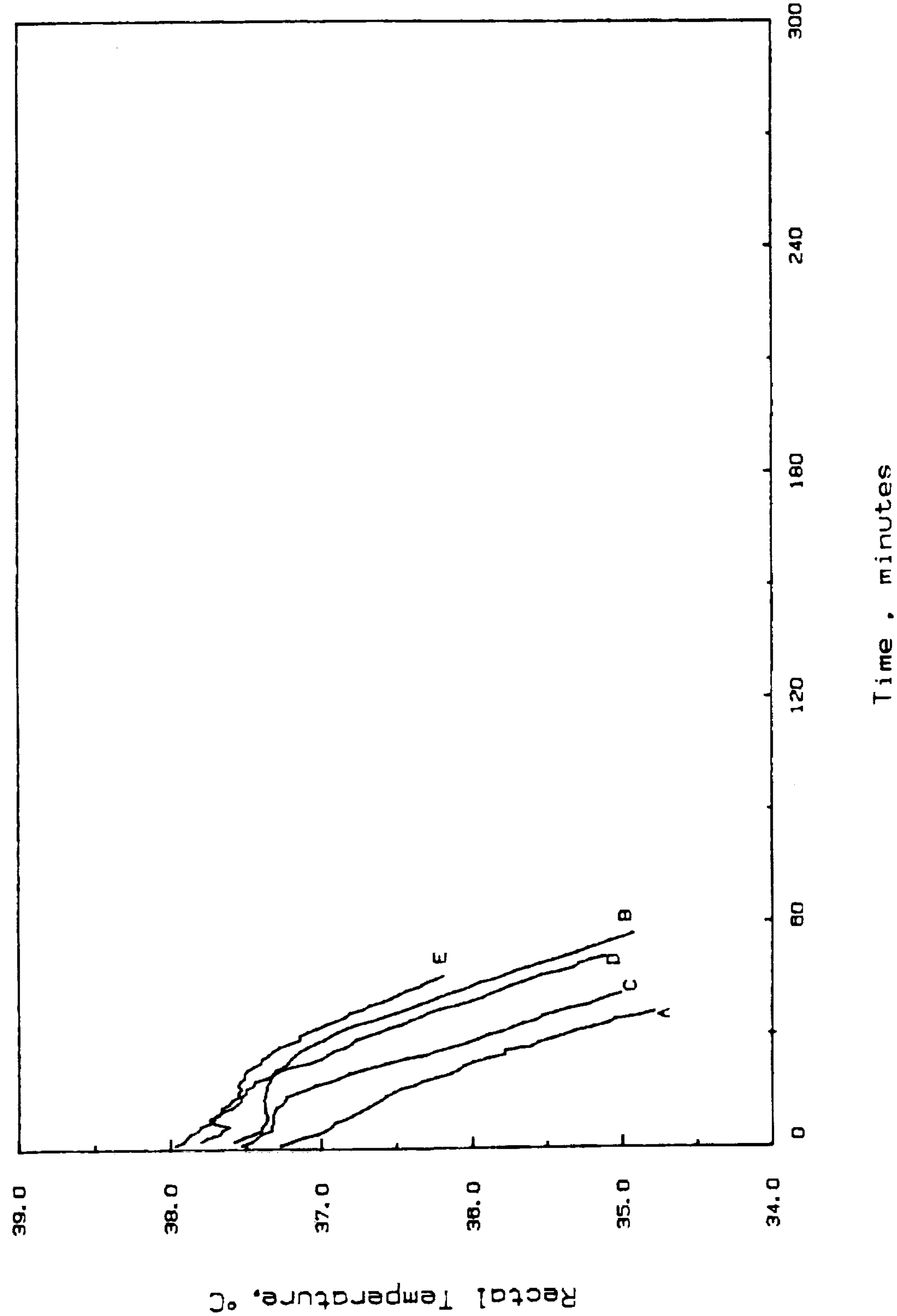

Figure 4. T_{re} versus time for the flight suit (27/P) using only personal flotation, by subject. Trial terminations for subjects A, B, C, and D were for T_{re} =35.0°C. Subject E terminated trial due to discomfort.

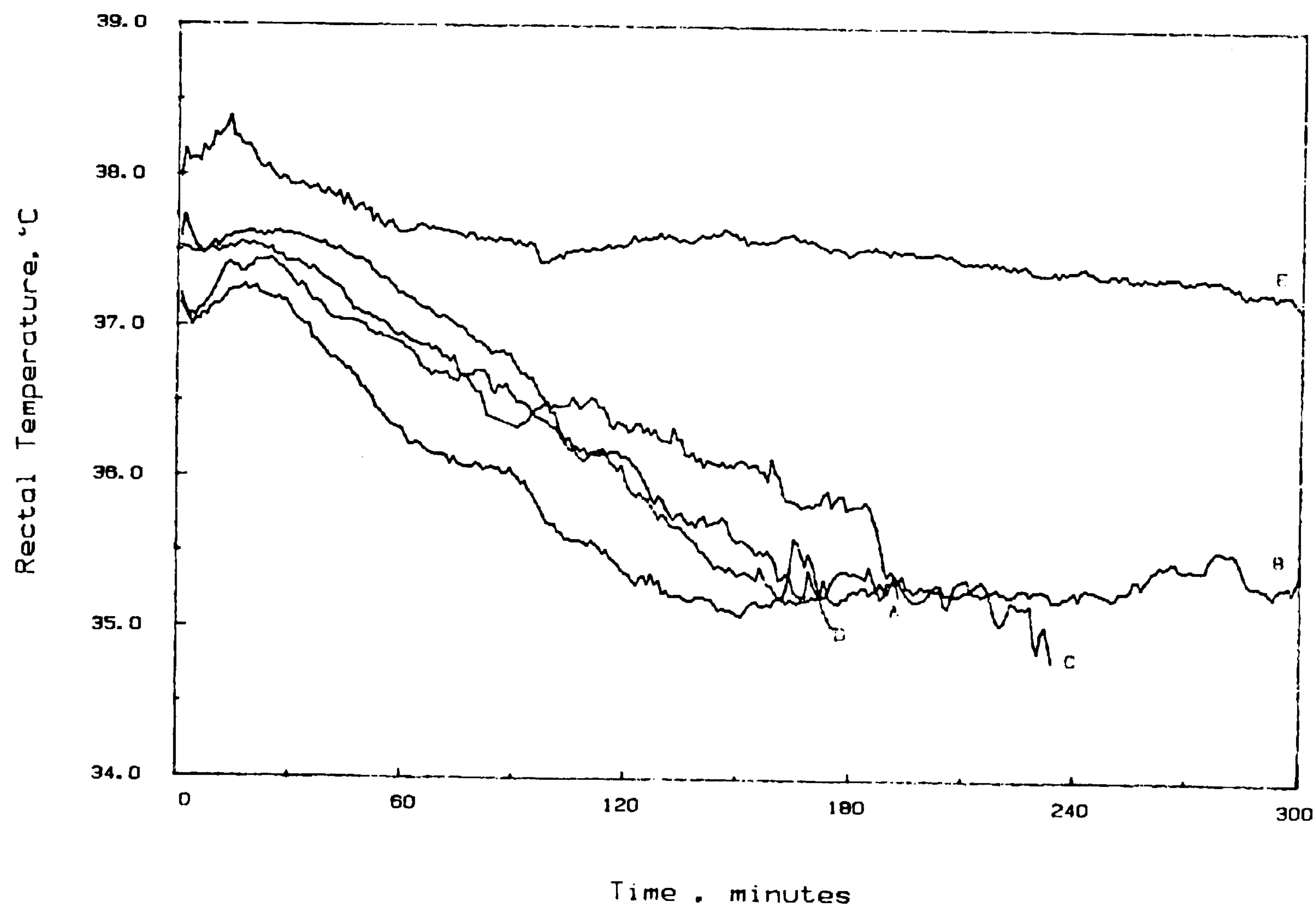

Figure 5. T_{re} versus time for the Launch/Entry Suit (LES) with the NASA raft, by subject. Trials for subjects C and D were terminated because T_{re} = 35.0°C. Sensor problems terminated subject A's trial with T_{re} approximately equal to 35.1°C. Subjects B and E had trial durations of 801 and 587 minutes, respectively, and their runs were terminated due to discomfort.

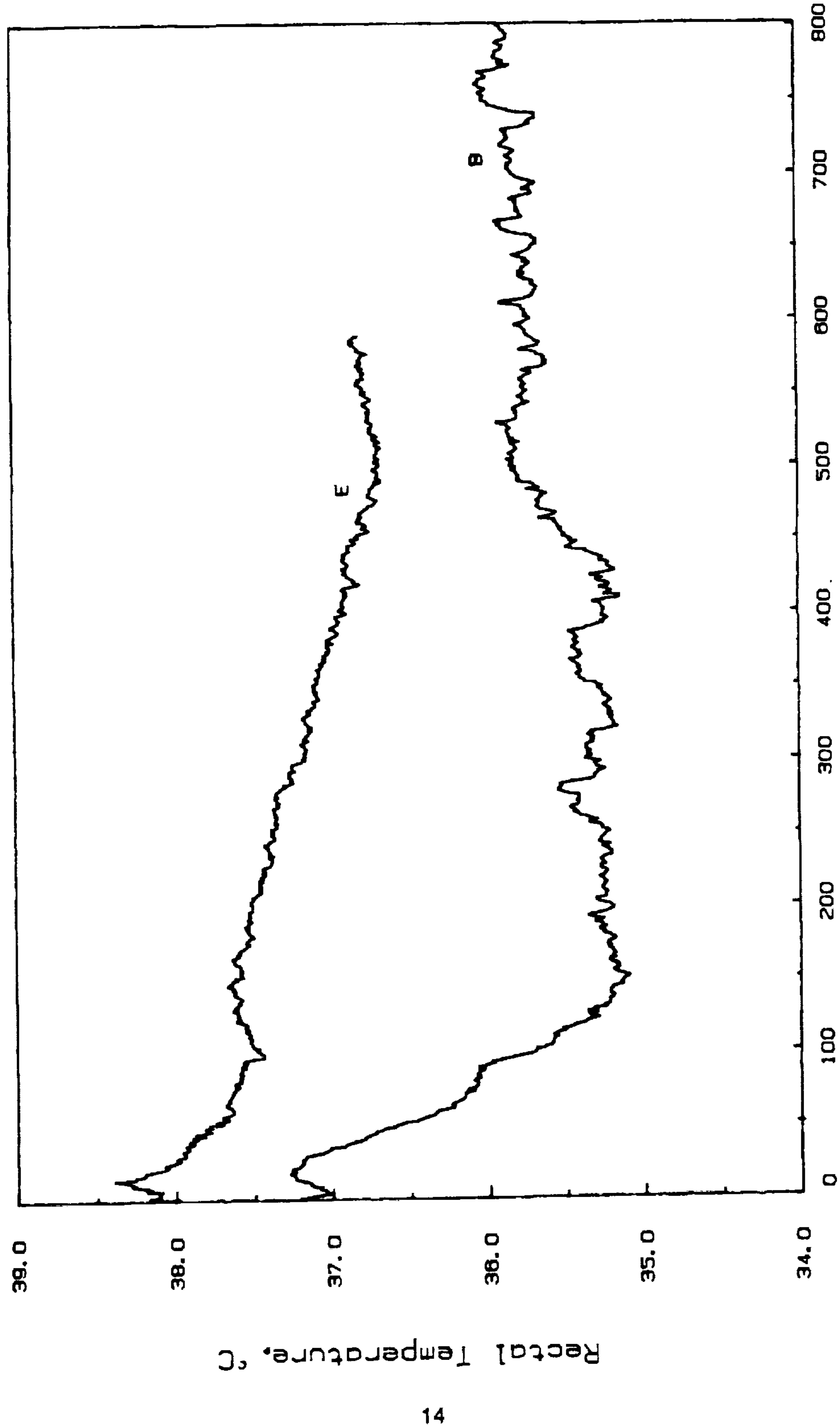

Figure 6. T_{re} versus time for the Launch Entry Suit (LES) with the NASA raft, for subjects B and E.

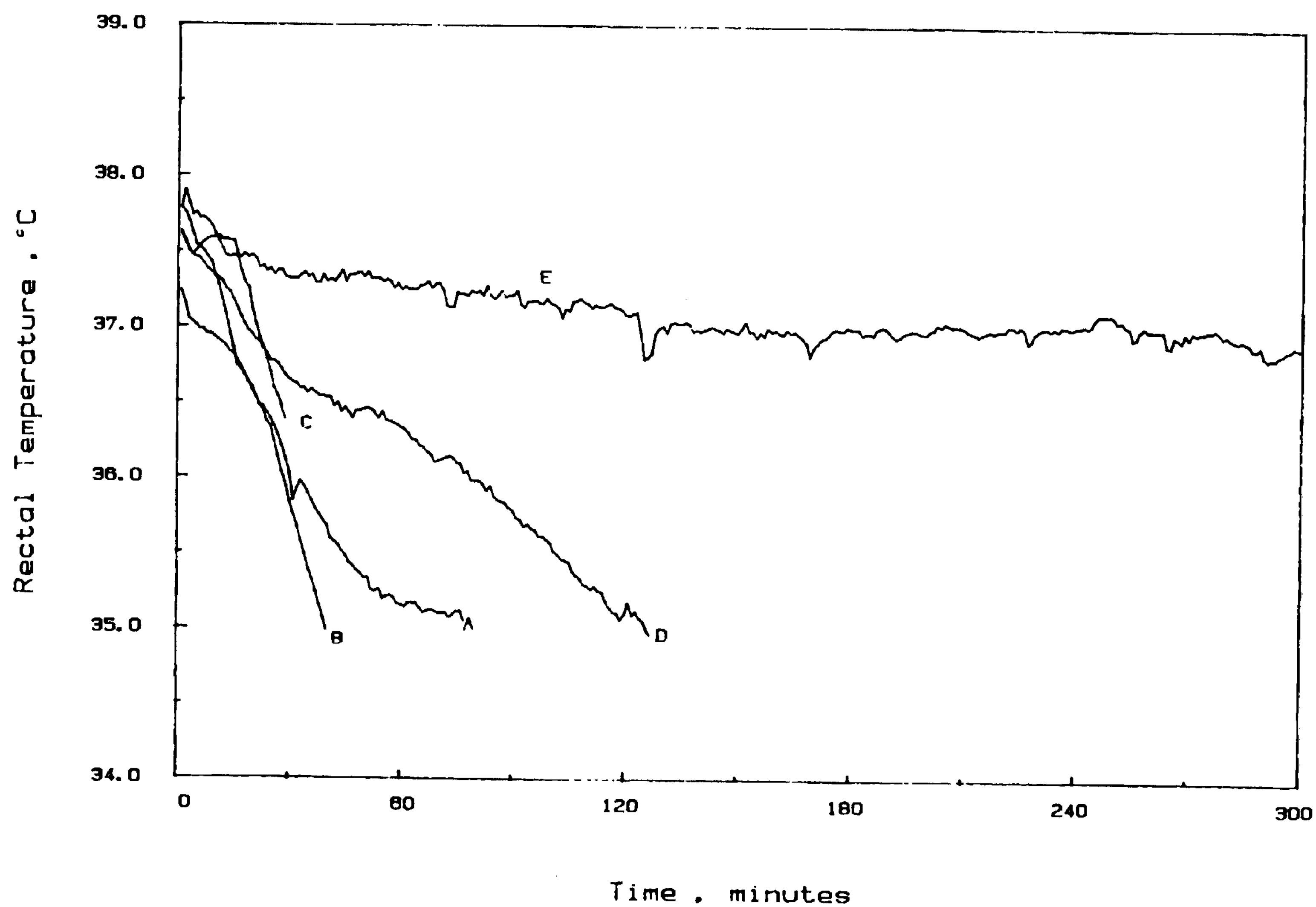

Figure 7. T_{re} versus time for the 27/p with the NASA raft, by subject. Trials terminations for subjects A, B, and D were for T_{re} = 35.0°C. The raft sank in subject C's trial. Subject E terminated the trial due to discomfort.

1.9°C, 2.0°C, and 2.2°C, respectively. Unlike the other configurations, the five subjects demonstrated substantially different trial times in the LES. Termination of LES trials were not primarily a result of T_{re}, unlike the other configurations, but rather was generally due to localized pain experienced by the subjects, as indicated by their post-run comments.

Mean Weighted Skin Temperature: T_{sk} was analyzed by comparing initial versus final temperatures (T_{sk},i/f) (Table 3), and examining the temperature data as a function of time (Figures 8-12). Significant differences were observed between T_{sk},i/f's calculated for the 27/P versus 27/P/r ($p < 0.03$), 27/P versus LES ($p < 0.002$), and 27/P versus LES/r ($p < 0.0001$). No significant differences in T_{sk},i/f were noted between the other configurations. T_{sk}'s were significantly different among all combinations of configurations as a function of time into a run ($p < 0.01$). None of the configurations, however, were significantly different at the start of a run. Comparisons of the 27/P/r runs with LES and LES/r runs show that T_{sk}'s in the earlier periods of trials were significantly different, but that in the later stages of runs no significant differences were evident. In the other comparisons, once differences became significant they remained so for the duration of the period of available complete data. The abrupt change in T_{sk} observed for subject E during the LES run corresponds to leakage into the helmet which was first noted at minute 147 (Figure 8).

Extremities Temperatures: Differences (initial-final) in foot (T_{foot},i/f), hand (T_{hand},i/f), and forehead (T_{fore},i/f) temperatures were calculated in order to determine localized effects (Table 4). Significant differences in T_{foot},i/f result from comparing 27/P runs with the 27/P/r ($p < 0.01$), LES ($p < 0.02$), and LES/r ($p < 0.001$) runs, with T_{foot},i/f obtained from the 27/P runs consistently greater. In addition, a highly significant difference was observed between T_{foot},i/f for LES versus LES/r, with the LES runs having the greater loss in foot temperature. None of the other differences in T_{foot},i/f between configurations demonstrated statistical significance. T_{hand},i/f obtained from LES runs was greater and significantly different than T_{hand},i/f from LES/r runs ($p < 0.05$), as well as from 27/P ($p < 0.001$) and 27/P/r ($p < 0.05$) runs. No other significant differences in T_{hand},i/f between configurations were observed. Only the differences in T_{fore},i/f observed between the 27/P and 27/P/r runs were significant ($p < 0.01$), with greater temperature change occurring in the 27/P runs.

Heat Flux: HF showed no distinct pattern in analyzing for significant differences among configurations (cf., Figures 13-17). No HF differences were significant at the start of runs between all configurations although mean HF for the 27/P was generally greater than for the other configurations. However, HF differences between 27/P and 27/P/r runs were observed be be significant from approximately 6 minutes through 23 minutes into trials ($p < 0.05$). The remaining 6 minutes were not analyzed because of the limited available data, displayed no significant differences. Comparing HF between the 27/P and LES, significant differences were evident between 3 and 35 minutes ($p < 0.01$). Minute 36 showed no significant difference in HF between 27/P and LES, being the last minute of this comparison. From minute 3 onward, HF was significantly different between 27/P and LES/r ($p < 0.01$).

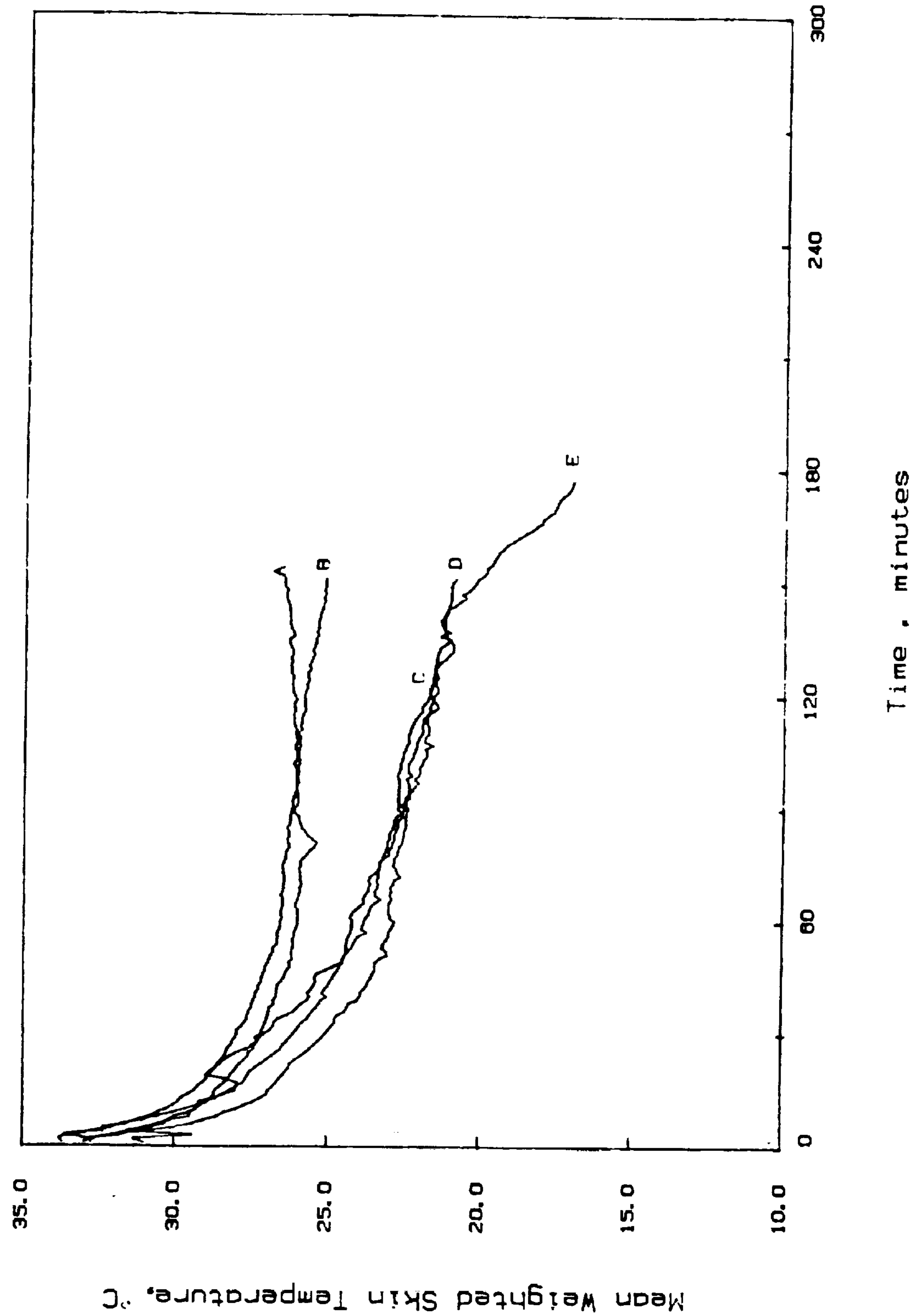

Figure 8. T_{sk} versus time for the Launch Entry Suit (LES) using only personal flotation, by subject.

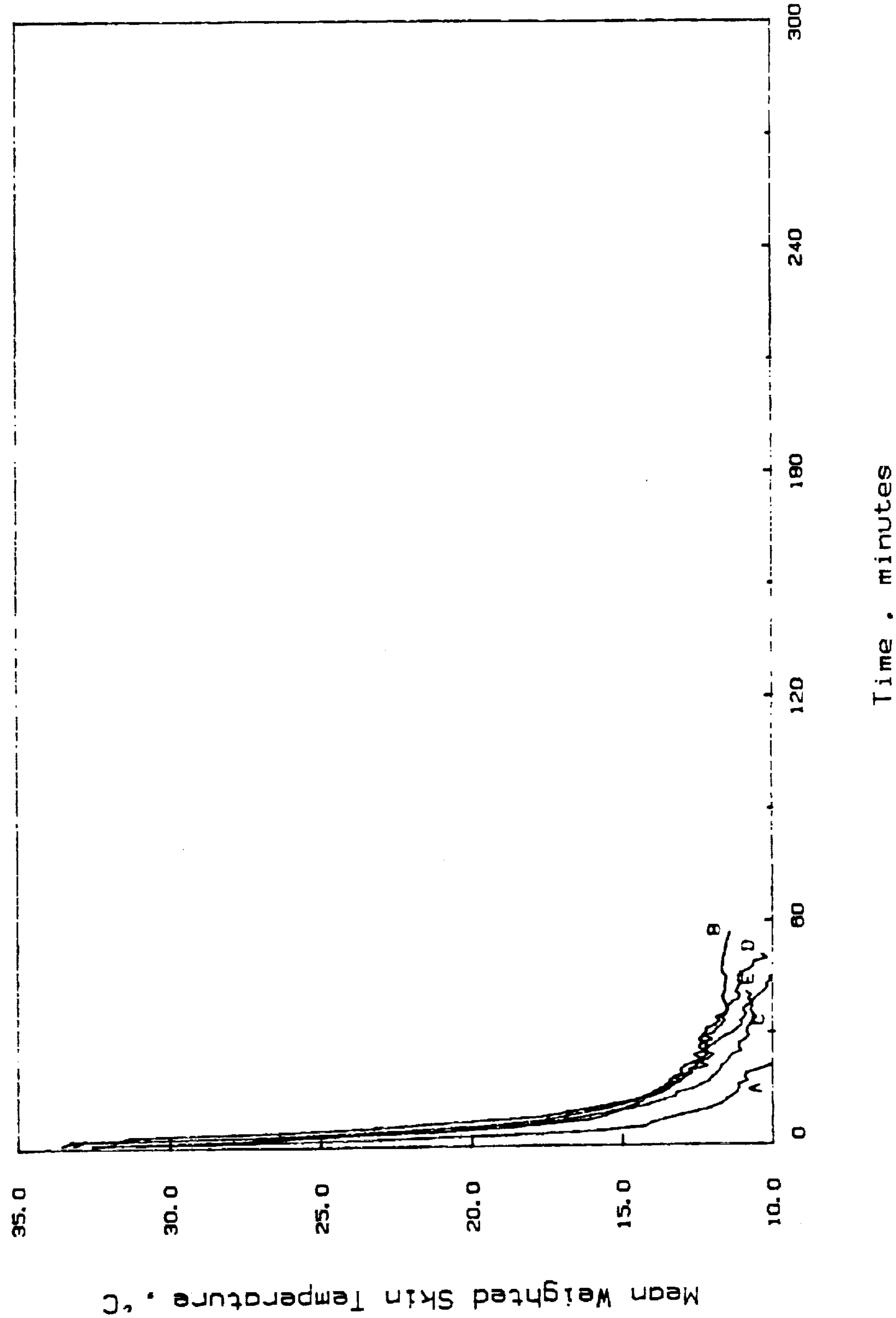

Figure 9. T_{sk} versus time for the flight suit (27/P) using only personal flotation, by subject.

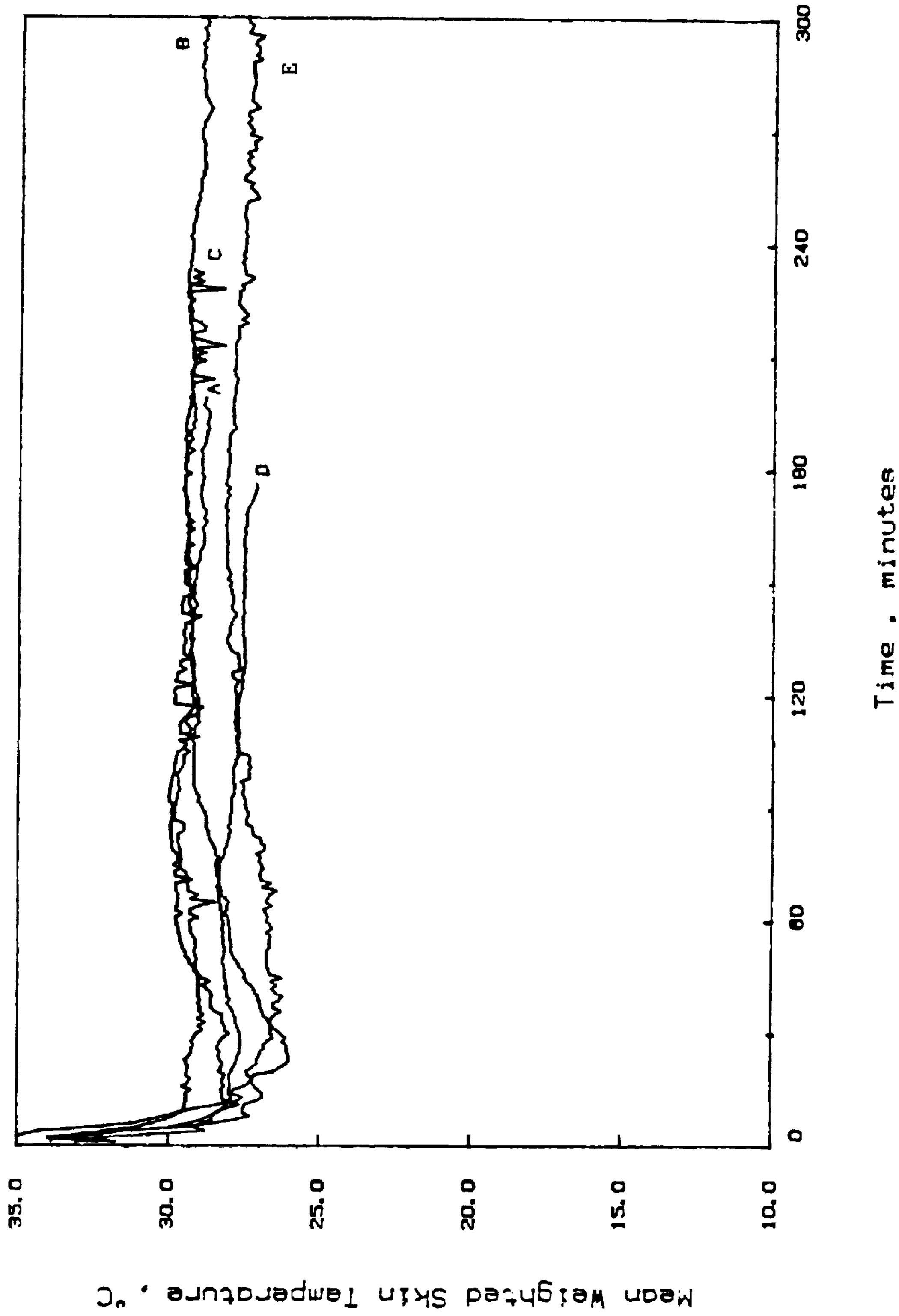

Figure 10. T_{sk} versus time for the Launch Entry Suit (LES) with the NASA raft, by subject.

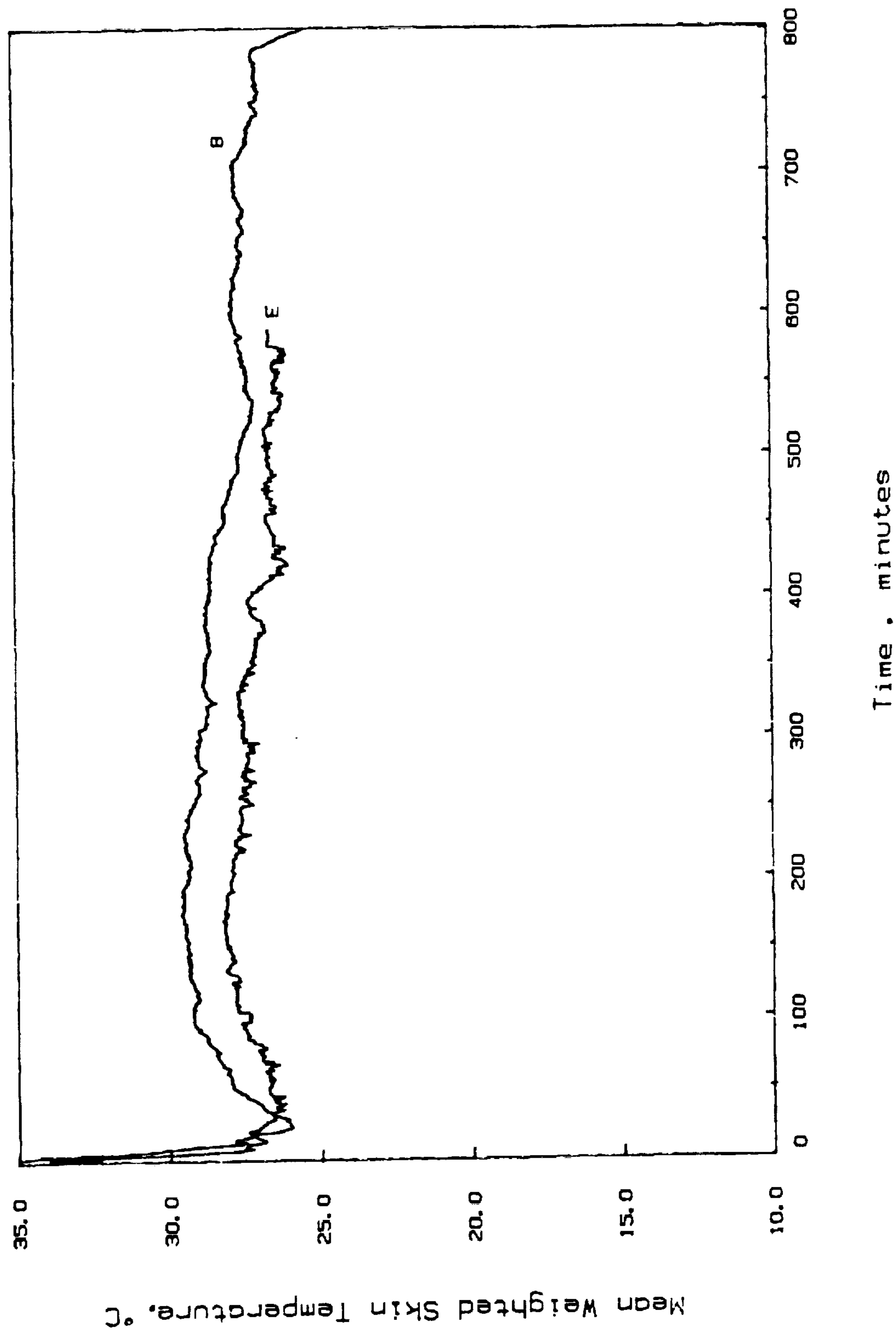

Figure 11. T_{sk} versus time for the LES with the NASA raft, for subjects B and E.

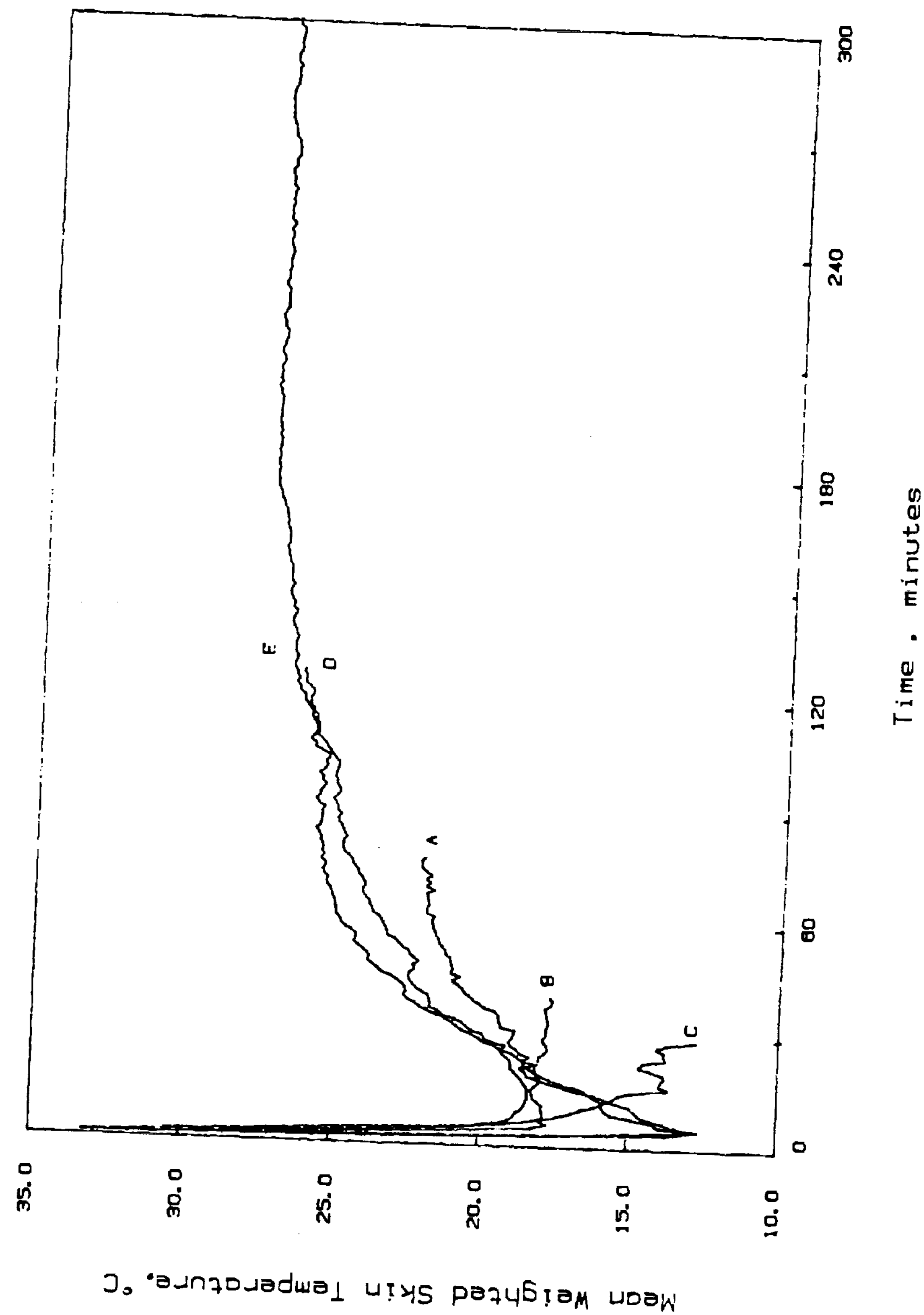

Figure 12. T_{sk} versus time for the 27/p with the NASA raft, by subject.

Table 4. Mean Values, Extremity Temperatures, by Configuration.

Configuration		Foot Temperature (°C)			Hand Temperature (°C)			Forehead Temperature (°C)		
		i	f	change	i	f	change	i	f	change
LES	mean	34.1	18.3	-15.8	33.6	17.7	-15.9	32.4	22.3	-10.1
	SEM	0.3	1.6	1.5	0.7	1.7	1.4	0.4	3.2	3.3
27/P	mean	28.6	7.3	-21.3	32.2	25.2	- 7.0	33.0	19.9	-13.1
	SEM	2.0	0.7	2.0	0.9	1.2	1.4	0.6	1.0	0.6
LES/r	mean	33.9	26.9	- 7.0	34.1	23.6	-10.5	33.9	25.7	- 8.2
	SEM	0.4	0.9	1.1	0.6	0.5	1.1	0.4	2.5	2.8
27/P/r	mean	34.1	18.3	-15.8	33.6	17.7	-15.9	30.2	26.7	- 3.5
	SEM	0.3	1.6	1.5	0.7	1.7	1.4	1.3	2.8	2.2

Mean value of foot, hand and forehead temperatures, by configuration, resulting from exposure to experimental conditions. The configurations denoted below are: LES – NASA Launch Entry Suit ensemble; 27/P – standard Navy flight suit ensemble, with /r signifying use with a raft.

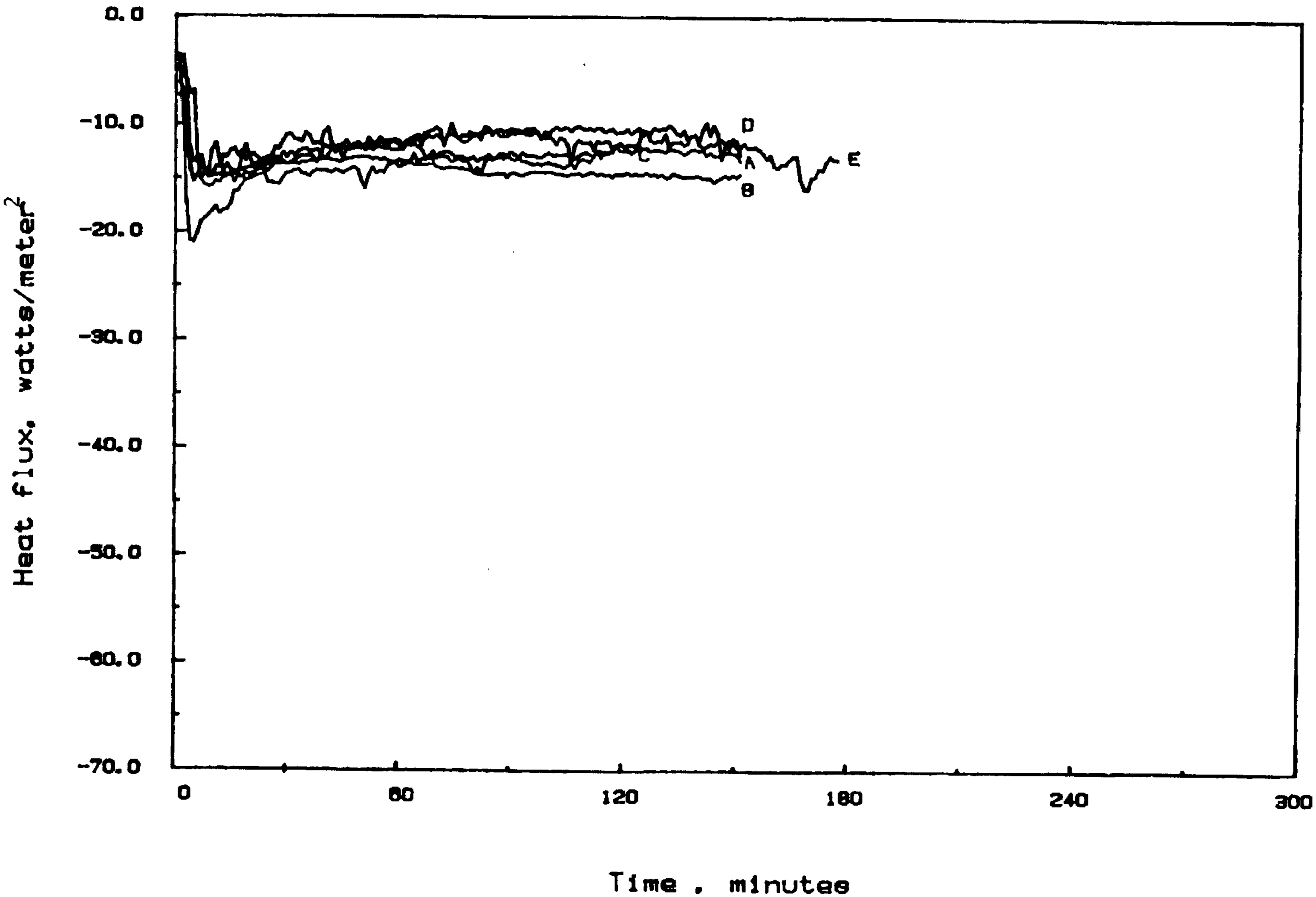

Figure 13. Heat flux versus time for the Launch Entry Suit (LES) using only personal flotation, by subject.

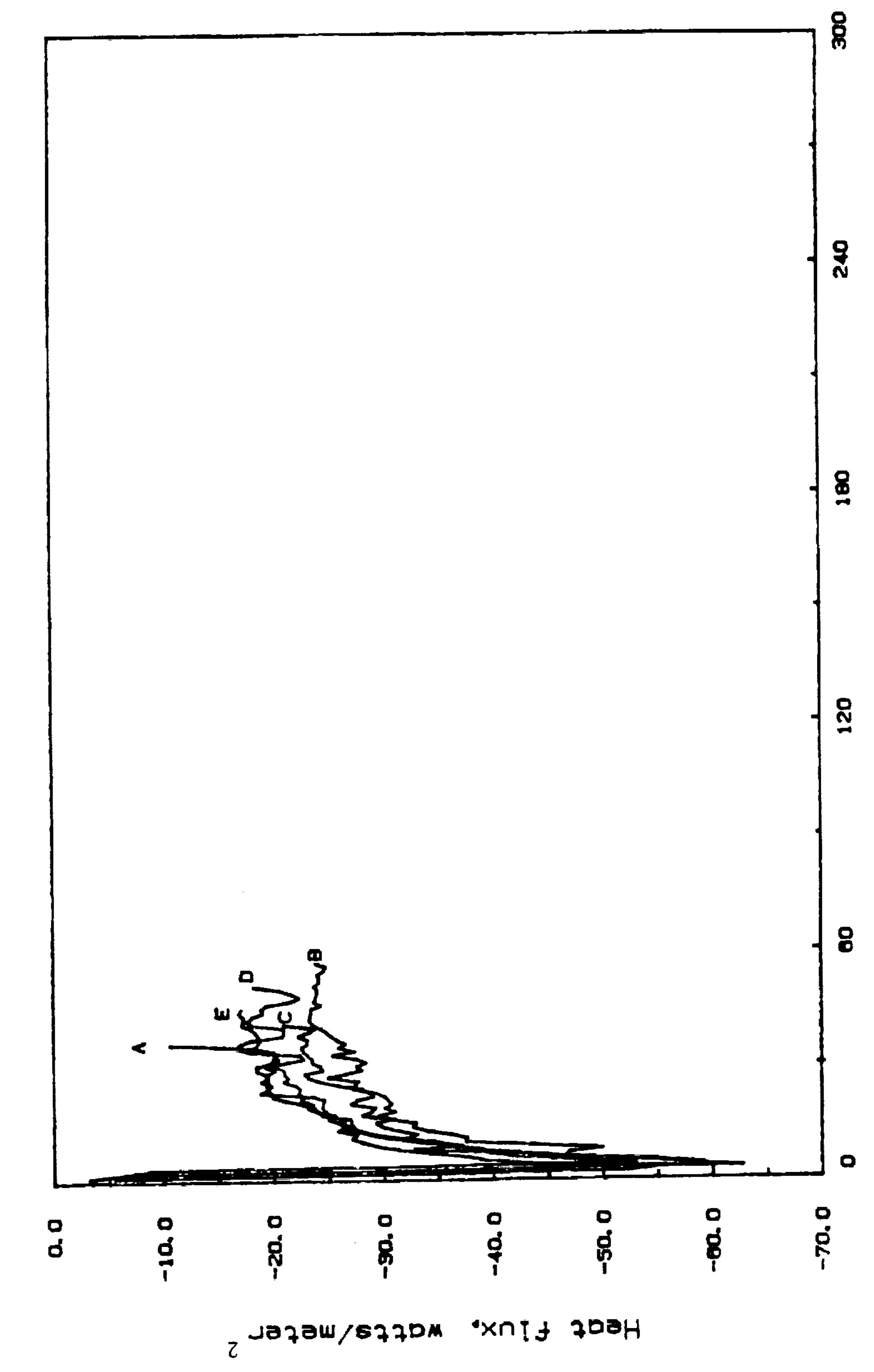

Figure 14. Heat flux versus time for the flight suit (27/p) using only personal flotation, by subject.

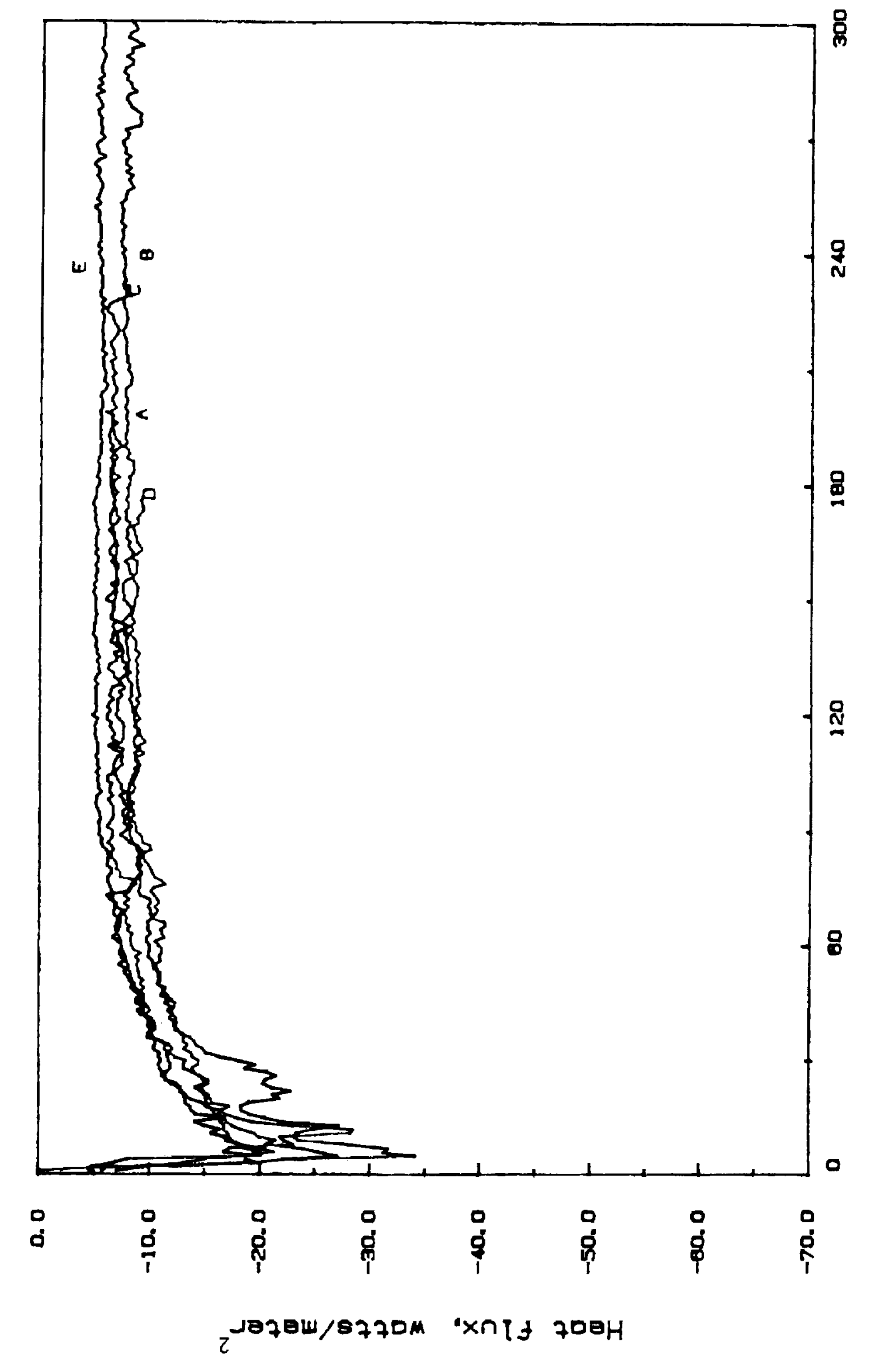

Figure 15. Heat flux versus time for the LES with the NASA raft, by subject.

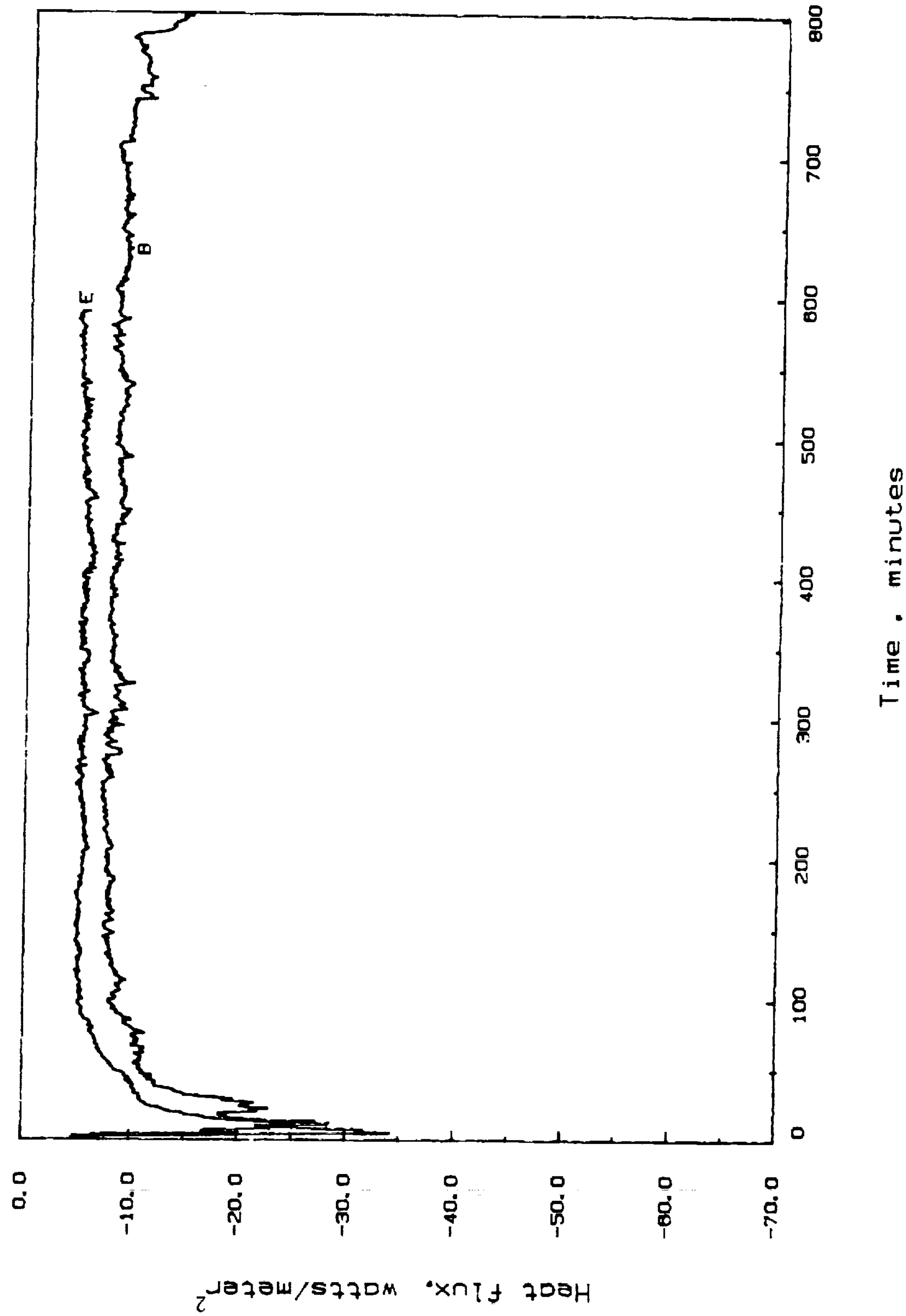

Figure 16. Heat flux versus time for the LES with the NASA raft, for subjects B and E.

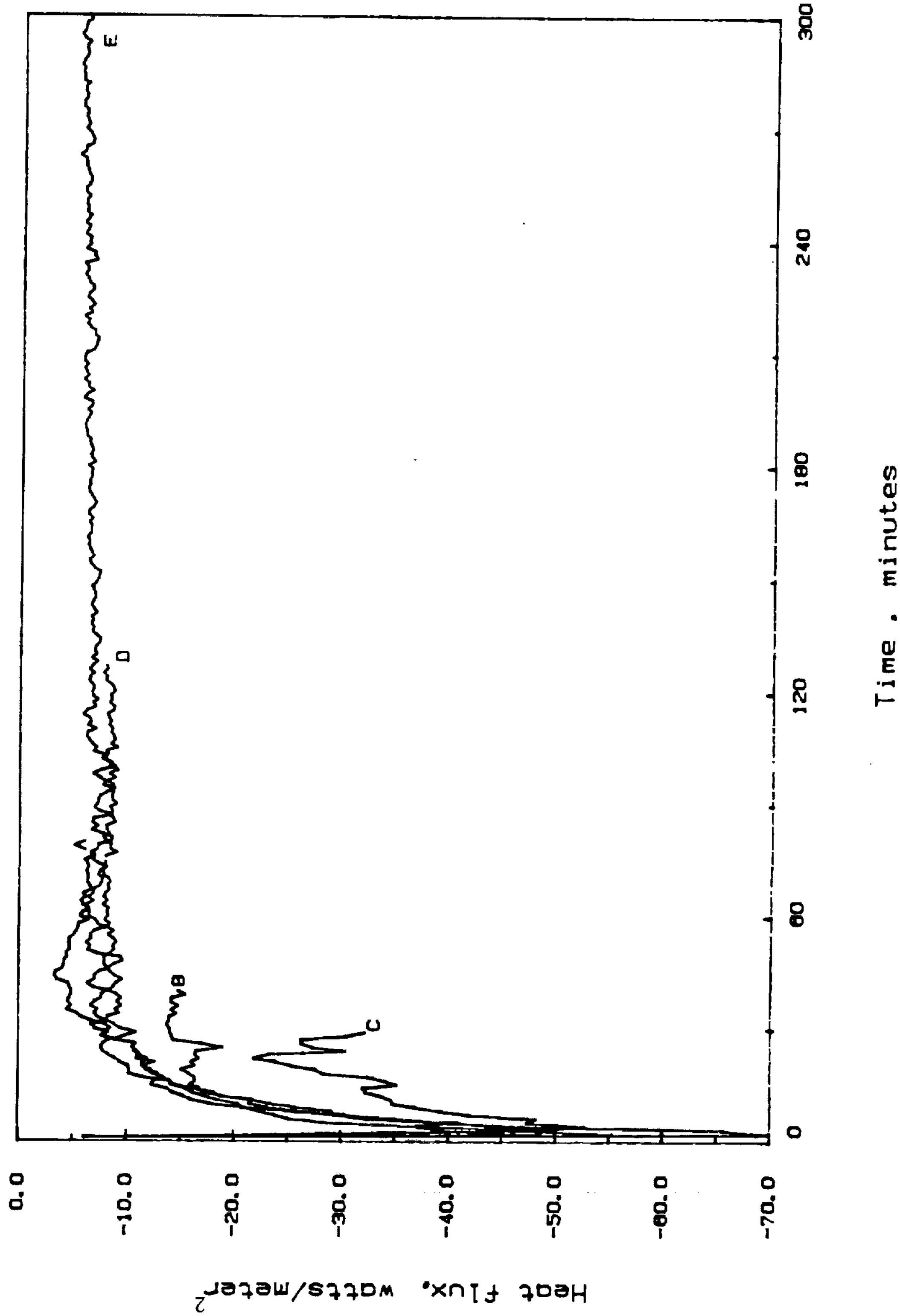

Figure 17. Heat flux versus for the 27/p with the NASA raft, by subject.

Mean HF was initially much greater in the 27/P/r than either LES or LES/r. No doubt, this reflected the initial period spent in the water with the 27/P, compared to the LES, without the raft. Over the duration of the time analyzed (i.e., 29 minutes), however, the means reach equivalence. The 27/P/r and LES runs showed significant differences in HF only between minutes 2 and 10 ($p < 0.01$). In contrast, HF in the 27/P/r and LES/r was only significantly different between minutes 2 and 6 ($p < 0.01$). The mean HF is initially greater in LES/r than the LES (statistically significant from minutes 5 through 14 ($p<0.05$)), though this relationship inverts as the runs progress and becomes statistically significant from minute 38 onward ($p<0.05$).

The cumulative energy losses, Q, were found to be initially greater in the raft versus immersion trials (cf., Figure 18-22). In the case of the 27/P versus 27/P/r trials, this relationship inverted after 7 minutes, with heat losses in the 27/P consistently greater from that point onward. Comparison of the LES with the LES/r trials shows a similar inversion, but this occurred at 62 minutes into the runs. Heat losses were consistently greater with the 27/P relative to the LES under the same conditions (27/P vs. LES, 27/P/r vs. LES/r). Mean values were statistically significant when comparing the common data of the 27/P and LES runs between minutes 4 and 17 ($p < 0.05$), for minutes 3 through 6 of the 27/P versus LES/r trials ($p < 0.05$), and for the 27/P/r versus LES data between minutes 2 and 9 ($p < 0.05$). Eliminating data from subject D who provided "outlier data" (cf., Figures 18-21) increased the extent to which significant differences were found. Significant differences were found from minute 5 onward between the 27/P and LES runs ($p < 0.01$) and the 27/P and LES/r runs ($p < 0.01$). Significant differences also appeared in the modified data between minutes 2 and 17 between the data for the 27/P/r and LES runs ($p < 0.01$) and between minutes 2 and 13 for the 27/P/r versus LES/r runs ($p < 0.05$).

Subjective Condition: While the relatively small changes in T_{re},i/f observed during the LES runs are attributable to localized pain, no significant differences in final subjective comfort, fatigue, shivering, or temperature were observed between configurations (Table 5). Significant differences were observed for the QSST (Table 5) between the 27/P and LES trials ($p < 0.0003$), the 27/P and LES/r trials ($p < 0.0007$), and between the LES and LES/r trials ($p < 0.03$). A smaller value observed for the QSST is indicative of a more gradual worsening of the subjective state during an exposure. LES/r runs consequently had the slowest onset of discomfort and 27/P runs had the fastest.

Metabolism: Maximum VO_2 uptake was only obtained for subjects during the 27/P runs. The observed maximum VO_2 values have a mean of 5.5 L/min and a standard error of the mean of 0.55. The 27/P trials were short, permitting only one or two 15 minute periods in which to obtain data and it is consequently unclear whether the reported values represent the actual maximum oxygen uptake during these trials.

Temperatures of Air and Water in Raft: Temperature data for the air and water trapped within rafts was obtained for four trials (one 27/P/r and three LES/r trials) (Table 6). Additional data was unavailable since this temperature sampling was introduced late in the study. The sample size was too small to perform meaningful statistical analyses, but does suggest

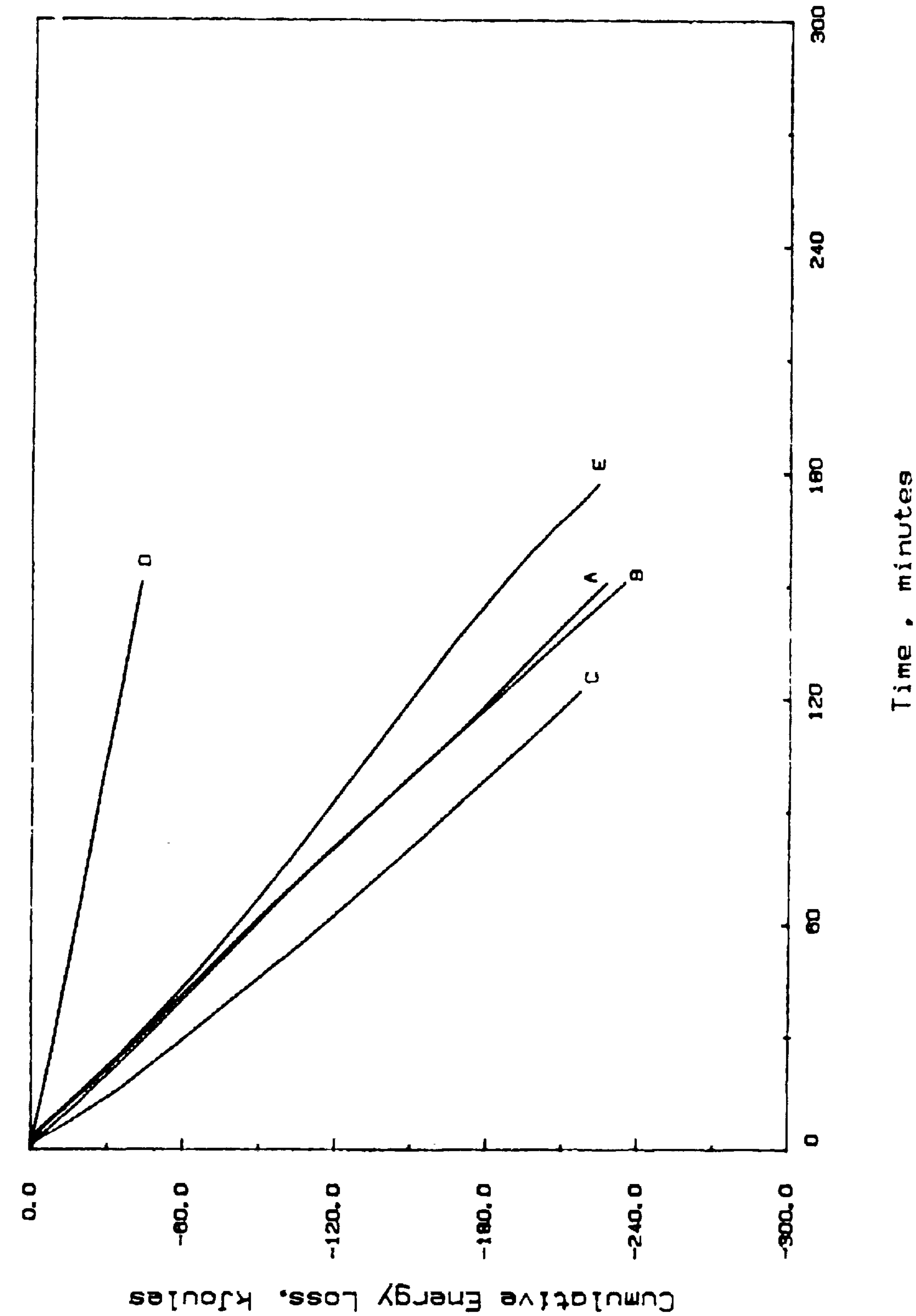

Figure 18. Cumulative energy losses versus time for the Launch Entry Suit (LES) using only personal flotation, by subject.

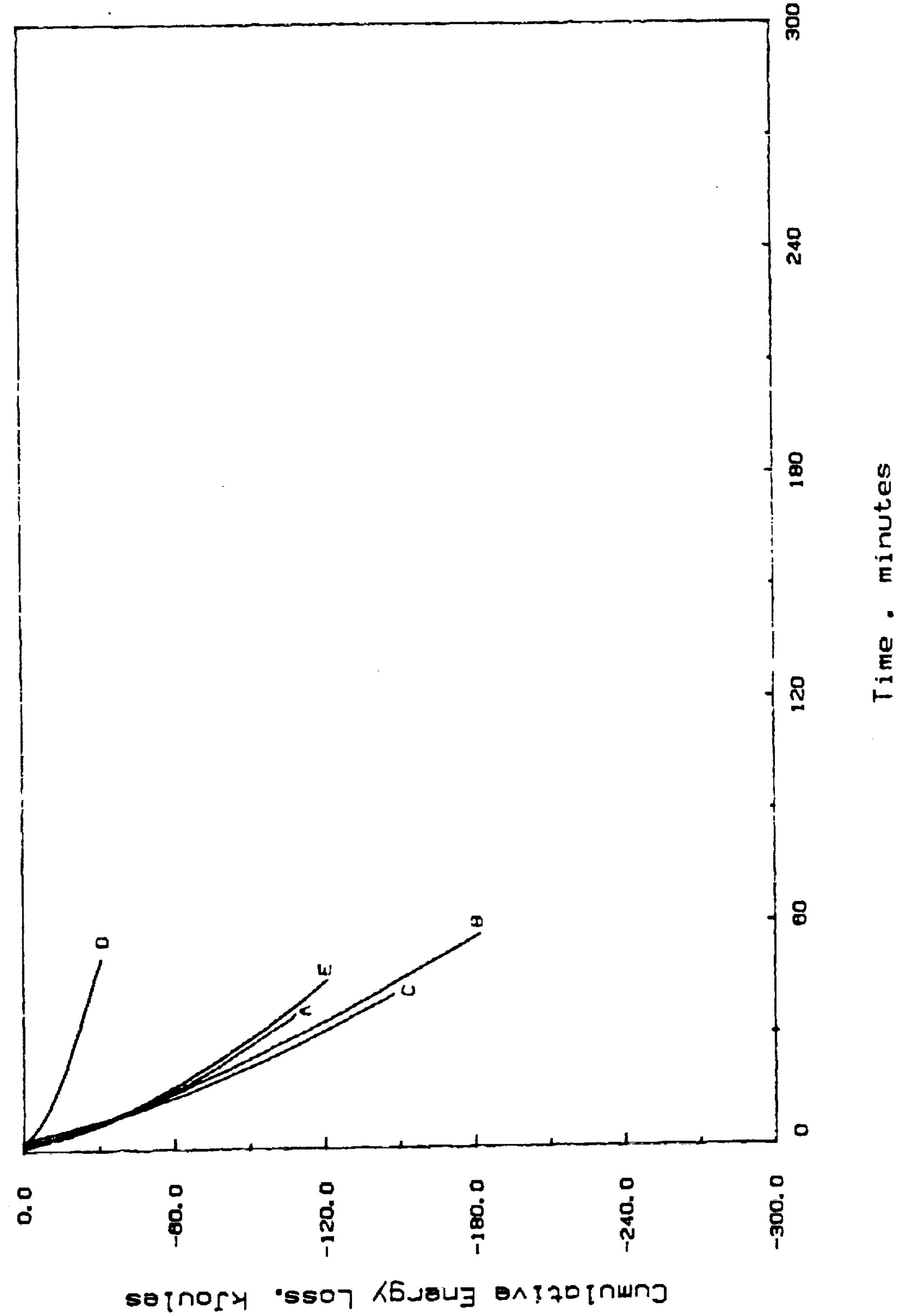

Figure 19. Cumulative energy losses versus time for the flight suit (27/p) using only personal flotation, by subject.

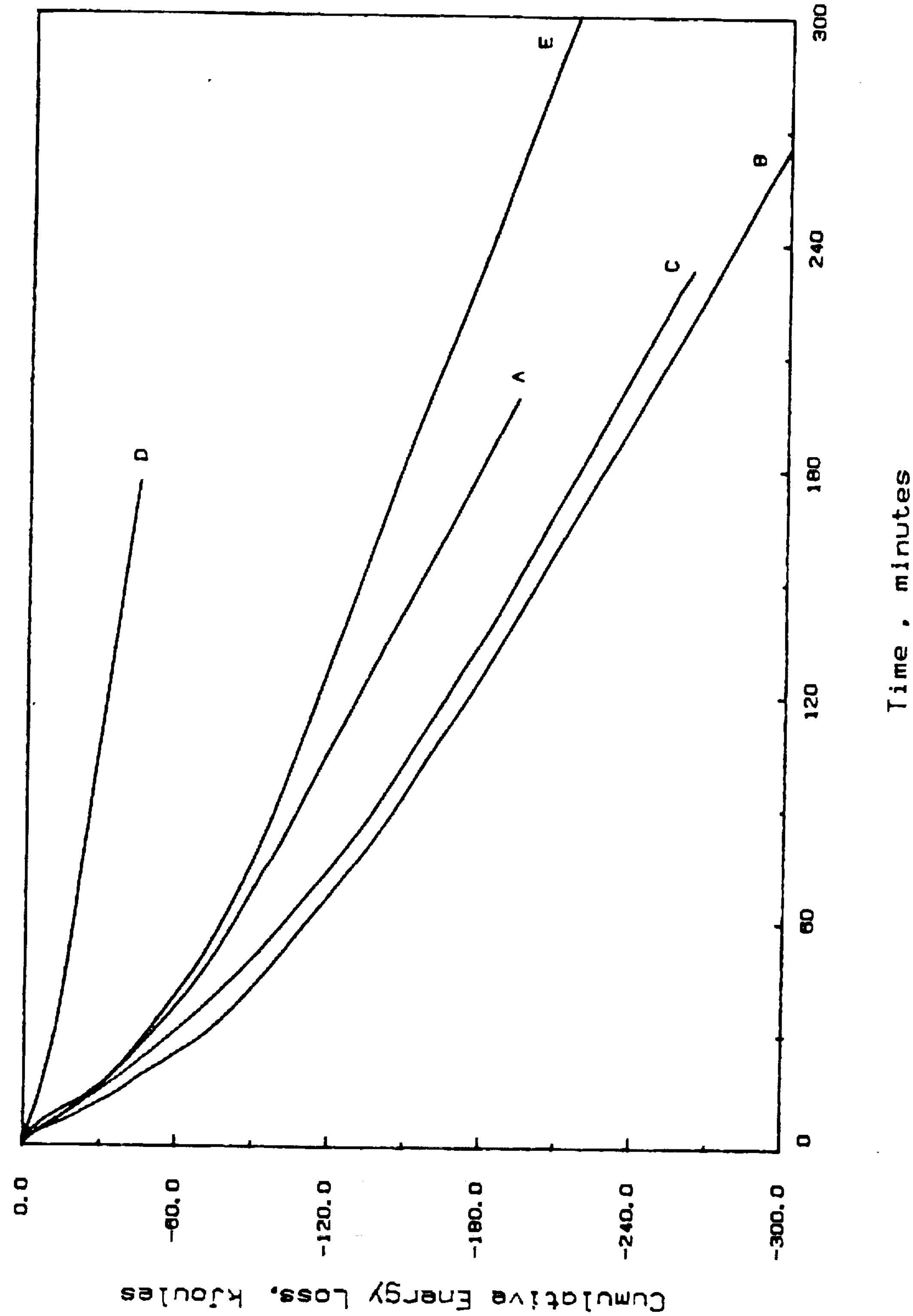

Figure 20. Cumulative energy losses versus time for the LES with the NASA raft, by subject.

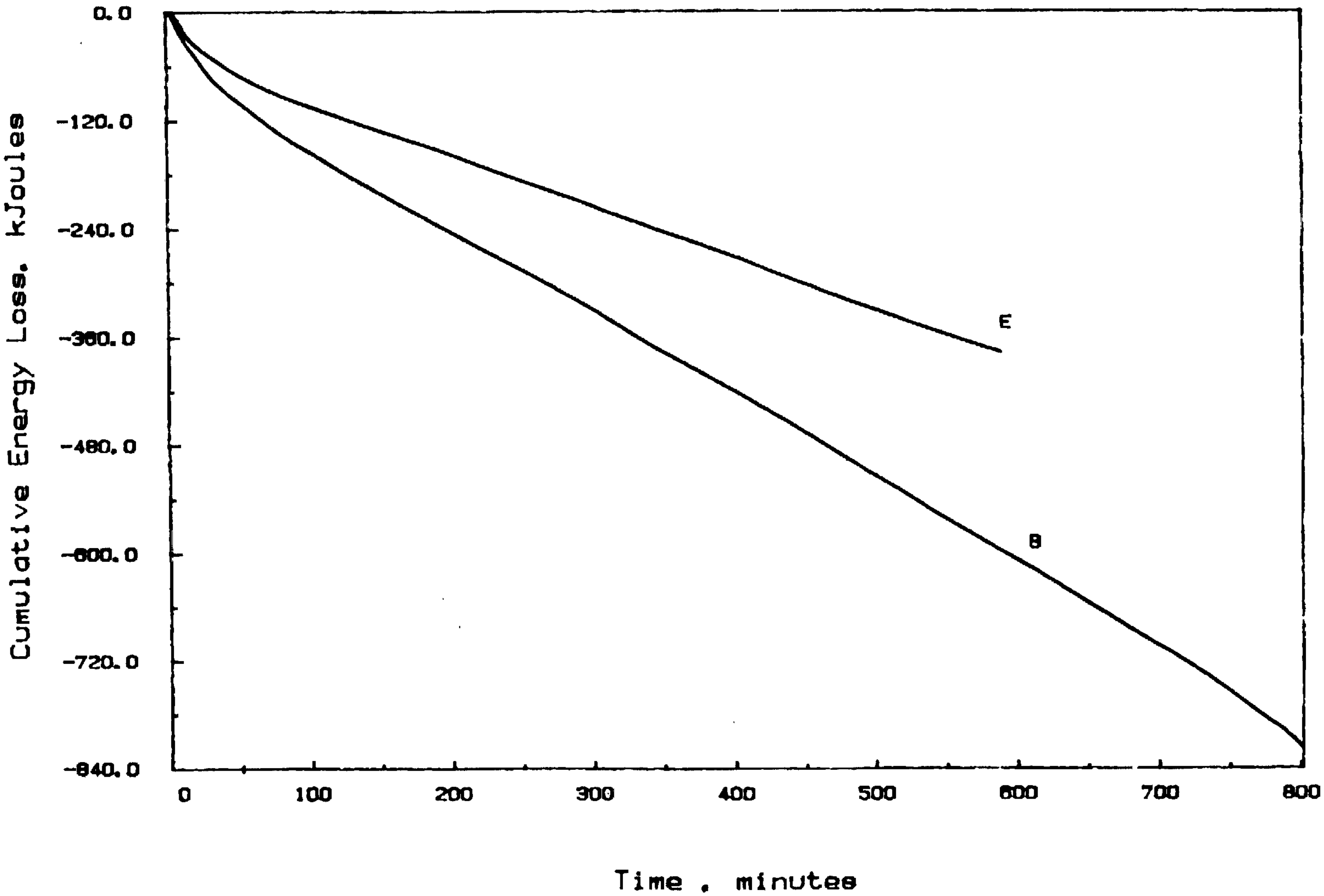

Figure 21. Cumulative energy losses verses time for the LES with the NASA raft, for subjects B and E.

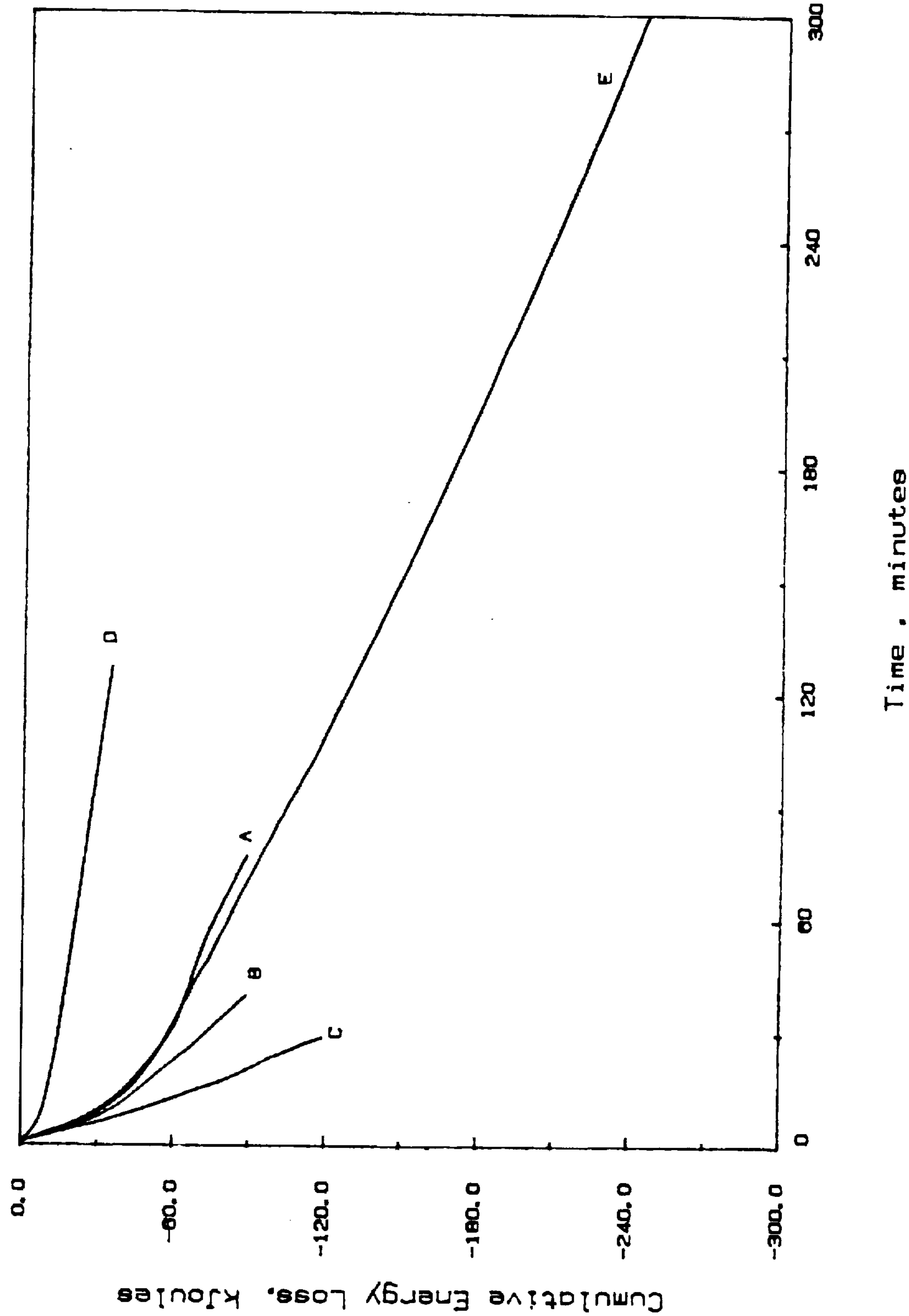

Figure 22. Cumulative energy losses versus time for the 27/p with the NASA raft, by subject.

Table 5. Mean Values, Subjective Scales, by Configuration.

Configuration		(a) Comfort	(b) Fatigue	(c) Shivering	(d) Temperature	QSST
		Final Values				
LES	mean	6.2	4.0	5.0	6.3	0.16
	SEM	0.2	0.8	0.6	0.2	0.03
27/P	mean	6.0	5.0	5.2	6.0	0.59
	SEM	0.3	0.8	0.7	0.3	0.05
LES/r	mean	4.0	3.6	3.0	4.4	0.04
	SEM	0.8	1.2	0.8	1.2	0.01
27/P/r	mean	5.2	4.2	4.6	5.4	0.38
	SEM	0.7	0.8	0.9	0.8	0.18

Mean values of final subjective state, as determined by subjects prior to trial terminations. Evaluations were based on ratings of 1-7; 1 being least unpleasant and 7 representing the most unpleasant sensation on the relevant scale. QSST represents the onset rate of subjective discomfort and is calculated from: $d(a+b+c+d)/t$ where a-d are the final values obtained from the four subjective rating scales and t is the time into the trial at which these values were obtained. The configurations denoted below are: LES – NASA Launch Entry Suit ensemble, 27/P – standard Navy flight suit ensemble, with /r signifying use with a raft.

Table 6. Air and Water Temperatures in Raft.

Configuration	Air Temperature (°C)			Water Temperature (°C)		
	i	f	change	i	f	change
27/P/r	5.2	17.5	+12.3	4.9	14.2	+ 9.3
LES/r	6.0	11.7	+ 5.7	5.5	11.2	+ 5.7
LES/r	6.4	9.1	+ 2.7	6.1	9.0	+ 2.9
LES/r	5.3	18.7	+13.4	4.7	13.3	+ 8.6

Air and water temperatures as measured within the raft. The configurations denoted below are: LES – NASA Launch Entry Suit ensemble; 27/P – standard Navy flight suit ensemble. Temperatures are mean values calculated over the length of a trial.

Table 7. Mean Values, Duration & Temperatures, by Subject.

Subject		Exposure Duration (minutes)	Rectal Temperature (°C)			Mean Weighted Skin Temperature (°C)		
			i	f	change	i	f	change
A	mean	114	37.5	35.6	-1.9	32.4	21.7	-10.7
	SEM	35	0.1	0.5	0.6	0.4	4.4	3.9
B	mean	262	37.3	35.7	-1.6	32.3	19.3	-13.5
	SEM	181	0.1	0.5	0.6	0.4	3.1	3.0
C	mean	106	37.3	35.4	-1.9	31.9	18.7	-13.2
	SEM	47	0.2	0.3	0.3	0.4	4.3	4.2
D	mean	126	37.6	35.4	-2.2	32.8	21.1	-12.8
	SEM	27	0.1	0.4	0.4	0.9	3.3	4.5
E	mean	289	38.0	36.7	-1.4	33.5	21.1	-12.4
	SEM	117	0.1	0.1	0.2	0.7	4.6	4.2

Mean values of exposure duration, rectal temperature, and mean weighted skin temperature by subject, resulting from exposure to experimental conditions.

Table 8. Mean Values, Extremity Temperatures, by Subject.

Configuration		Foot Temperature (°C)			Hand Temperature (°C)			Forehead Temperature (°C)		
		i	f	change	i	f	change	i	f	change
A	mean	31.0	17.4	-13.6	32.2	21.9	-10.3	31.4	25.6	- 5.8
	SEM	1.5	3.7	2.6	0.6	1.8	1.5	0.4	2.9	2.6
B	mean	31.9	14.8	-17.0	31.8	20.6	-11.2	34.0	25.5	- 8.5
	SEM	1.2	3.8	3.8	1.2	1.9	2.5	0.5	3.2	3.2
C	mean	28.3	17.5	-10.8	32.5	24.3	- 8.3	31.5	20.6	-10.9
	SEM	3.1	5.3	2.6	0.8	1.6	2.3	1.4	2.6	1.9
D	mean	32.7	17.4	-15.3	32.9	21.7	-11.2	32.2	22.2	-10.0
	SEM	1.1	4.4	4.1	0.7	3.0	3.4	1.1	2.0	2.9
E	mean	33.1	20.3	-12.7	34.9	23.7	-11.2	32.8	24.2	- 8.6
	SEM	1.5	4.1	3.2	0.7	1.3	1.6	1.3	4.4	5.1

Mean values of foot, hand and forehead temperatures, by subject, resulting from exposure to experimental conditions.

Table 9. Mean Values, Subjective Scales, by Subject.

Subject		Final Values (a) Comfort	(b) Fatigue	(c) Shivering	(d) Temperature	QSST
A	mean	5.3	2.3	3.5	5.5	0.24
	SEM	0.8	0.3	0.9	0.5	0.10
B	mean	5.5	4.0	4.3	5.8	0.26
	SEM	0.5	0.9	0.5	0.6	0.11
C	mean	5.8	5.0	5.3	5.5	0.52
	SEM	1.3	1.4	1.4	1.5	0.23
D	mean	4.5	3.8	4.0	4.5	0.20
	SEM	0.9	0.8	1.2	0.9	0.10
E	mean	5.8	6.0	5.3	6.4	0.25
	SEM	0.3	0.4	0.3	0.5	0.16

Mean values of final subjective state, as determined by subjects prior to trial terminations. Evaluations were based on ratings of 1-7; 1 being least unpleasant and 7 representing the most unpleasant sensation on the relevant scale. QSST represents the onset rate of subjective discomfort and is calculated from: $d(a+b+c+d)/t$ where a-d are the final values obtained from the four subjective rating scales and t is the time into the trial at which these values were obtained.

that considerable warming of both air and water occurred within rafts during trials.

DISCUSSION

This study demonstrated that some individuals' survivability will be sufficiently enhanced with the LES and LES/r to survive for greater than 3 and 13.5 hours, respectively, in 4.4°C water. A number of relatively lengthy runs in this study were terminated as a result of localized pain and discomfort rather than T_{re}. A number of subjects, when terminating their lengthier trials for subjective reasons, indicated that they would have been able to tolerate the pain longer had this been an actual survival situation. Therefore, in a true survival situation, pain would probably be subjugated with respect to the overriding need to survive. The capability to tolerate similar cold conditions within a raft for periods of up to 22 hours was shown by Veghte (12). It therefore seems possible for certain individuals to approach the survival time goal of 24 hours for the LES/r in an actual survival situation with conditions similar to those used in this study. Survival for some individuals over extended periods, however, would be problematic since the rates of cooling evident at the time of run termination for certain trials indicate that potentially hazardous T_{re}'s (i.e., 34°C or less (8)) could be attained at times sooner than those desired (cf., Figures 3, 5 and 6).

The wide variations observed for exposure durations in this study, particularly for the LES/r runs, probably resulted from subject variations in their physiological responses to cold exposure. For individuals exposed to cold, thermal protection has both a static component, i.e., body fat, and a dynamic one, i.e., shivering thermogenesis. One's response to cold and consequently total survival time is dependent on both the insulation properties of body fat and the thermogenic response. Hayward and Keatinge (4) observed that metabolic responses, and thus ultimate duration in the environment, could not be predicted by the body fat of a subject in 10°C water. It can consequently be concluded that metabolic response to cold does not necessarily correlate to an individual's percent body fat.

It is interesting to note that in this study, the subjects with the longest endurance times (B and E) had the smallest maximum VO_2 observed in the 27/P runs. These results might suggest that the observed values of maximum VO_2 do not reflect the effective utilization of the metabolic heat generated, which is possible since these two subjects were highly active individuals. These results could also suggest that other factors, e.g., vascular adjustment (13), account for their ability to withstand the cold. This could explain why, despite a lower percent body fat, the second leanest subject had the longest duration, since he may have compensated for a lack of internal insulation by an increased metabolic rate. Greater endurance fitness has been shown by Jacobs, et al. (5) to provide increased ability to conserve T_{re}, though the responsible mechanism was unclear. One possible mechanism which could account for this observation would be that greater fitness, resulting in increased muscle vascularization, would allow for similar metabolic outputs at greater efficiency and lower blood flow, resulting in a reduced thermal loss.

Another factor which should be discussed is the apparent T_{re} rebound which was observed in the longest LES/r trial (Figure 6). In this trial, the subject's T_{re} fell to within 0.1°C of trial termination after approximately 2 hours. It then stabilized and gradually increased until the run was terminated at 801 minutes due to discomfort. It is believed that the increase in T_{re} observed for this subject relates to the observed increase in air temperatures measured within the closed raft, and may be related to the oscillation in T_{re} observed by Veghte (12). One is compelled to ask whether such a phenomena would have been observed for the other subjects whose trials were terminated at 35°C if permitted to continue. Survival times are often based on a linear extrapolation of the observed core temperature decay rate for a lack of a better technique, an approach which this study demonstrates can be greatly erroneous.

As expected, the LES trials proved to be subjectively less harsh, based on QSST data. This analysis does not account, however, for the localized pain experienced by subjects, particularly in the LES runs. Pain experienced by subjects was in: the hands, thighs, feet, and penis (probably related to the urine collection device and its interaction with the LES). While T_{foot},i/f was predictably greatest among configurations in the relatively unprotected 27/P runs, T_{hand},i/f proved to be greatest in the LES runs, indicating a serious hand protection problem. This may explain the greater T_{re} observed in the LES versus LES/r runs after 122 minutes, as Van Someren, et al (11) has previously shown that changes in T_{hand} and T_{foot} correlated inversely with T_{re}. The various attempts throughout the study to find superior mittens to protect the hands of subjects attests to the problem of adequate extremity protection.

Hand protection must be provided beyond that afforded by the flight gloves. Precipitous drops in hand temperatures were observed prior to the introduction of a mitten designed for cold water use. While such mittens are bulky, they are essential if one is to maintain sufficient dexterity to perform the manual tasks required in a survival situation.

Equipment design and maintenance is of vital importance for the LES system to perform at levels predicted by this study. Analysis of the data produced by runs in which equipment was damaged showed that the damaged raft trial produced values roughly equivalent to those obtained using only personal flotation. Also, a leaking LES was only slightly better than the 27/P. The anti-suffocation valve can allow water to be aspirated through it when immersed, cooling the back of the head and neck. With the head and neck representing a significant heat loss area (3), such leakage resulted in reduced exposure times. This effect was clearly demonstrated, albeit unintentionaly, when subject E experienced leakage into the helmet at minute 147 of the LES run. The dramatic change in T_{sk} would probably have presaged a subsequent precipitous fall in T_{re} had the subject been exposed for much longer. T_{re} data obtained during the final few minutes of that run support this conjecture (Figure 3). Drowning may also become a serious threat under these conditions. Similarly, the neck seals must be properly sized to prevent an influx of cold water into the torso area should water enter the helmet.

Training was also shown to be a crucial element in extending exposure durations. Subjects trained in raft boarding in only warm water displayed considerable difficulty in entering rafts in cold water. It is likely that this is a result of both the distraction due to the intense cold sensation experienced by subjects and the loss of dexterity resulting from the cold. Untrained subjects found boarding in the test conditions nearly impossible. Bailing technique was also shown to play a critical role in extending durations. One subject attempted, during a 27/P/r run, to maintain a relatively dry raft prior to closure of the canopy. In his efforts to achieve this, his run was terminated due to T_{re} = 35.0°C without ever closing the canopy. This resulted in a considerably shortened trial compared with other trials in the same configuration. Inefficient bailing techniques were found to waste precious energy and further diminish exposure durations due to increased heat losses. The addition of a hand bailer, as distinguished from the sea anchor, and a small hand pump seemed to play a role in extending immersions by increasing the efficiency of bailing.

This study indicates that the LES and LES/r provides considerable protection for some individuals, sufficient to permit survival for greater than 3 and 13.5 hours, respectively, under the investigated test conditions. It was also shown that it is unlikely that this system will provide such protection for all individuals.

CONCLUSIONS

1. The LES has the potential for providing at least 3 hours of protection during immersion in 4.4°C water. The LES/r has the potential to provide at least 13.5 hours of protection under the same conditions.

2. Protective items, i.e., raft and/or LES, which are damaged or leaking appear to negate any positive contributions to thermal protection which they might normally provide.

3. The female subject was not atypical of the other subjects and inclusion of her data does not change the conclusions which may be drawn from this study.

4. Observed inter-subject variability leads to the conclusion that some individuals may be unable to attain 3 and 13.5 hour exposures in the respective LES and LES/r.

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