ANALYSIS OF EVAPORATIVE WATER LOSS IN THE SKYLAB ASTRONAUTS

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ABSTRACT

Daily evaporative water losses (EWL) during the three Skylab missions were measured using the indirect mass and water balance techniques. A mean inflight EWL of 860 ml/day-m^2 was obtained for nine men who averaged one hour of daily exercise. Although it was expected the EWL would increase in the hypobaric environment of Skylab (1/3 atm), an average decrease from preflight sea level conditions of 11% was measured. The results suggest that weightlessness may have been a factor in modifying EWL primarily by decreasing sweat losses during exercise and possibly by reducing insensible skin losses as well. The weightless environment apparently promotes the formation of a sweat film on the skin surface both directly, by reducing heat and mass convective flow and sweat drippage, and perhaps indirectly by inducing measurable biochemical changes resulting in high initial sweating rates. It is proposed that these high levels of skin wettedness favor sweat suppression by a previously described mechanism.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

Throughout NASA, manned space flight program environmental pressures in the habitable portion of spacecrafts have been approximately one-third atmosphere. It was expected, therefore, that insensible water loss would be increased due to a greater cutaneous diffusion in this hypobaric environment (Taylor & Buettner, 1953; Hale, et al, 1958). Subsequent studies in space cabin simulation chambers confirmed an increase of insensible water loss of more than 30% in oxygen enriched-reduced pressure surroundings (Carleton & Welch, 1971a; Gee, et al, 1968).

Loss of body water has been an invariable result of spaceflight irrespective of mission duration. Preliminary reports of several manned missions have indicated the possibility that an uncompensated increased evaporative water loss (EWL) might partly explain this negative water balance (Berry, et al, 1962; Dietlein, 1974). Although it has been noted that any increase in EWL should be replaced by drinking (Webb, 1967), this has not yet been confirmed. There have been no previous attempts to estimate evaporative loss during weightless space flight.

It is possible that thermal stress and high rates of sweating contributed to body water loss in certain of the early Mercury short-duration spaceflights when full-pressure suits were worn and during short periods of extravehicular activity in the Gemini series. In the longer Apollo missions, however, the crewmen were primarily in a shirt sleeve environment in which elevated cabin temperatures were rarely, if ever, experienced and sweating in space suits was minimized by an efficient liquid-cooled garment system (Johnston, et al, 1975). The Skylab workshop provided a shirt-sleeve environment of unrestricted mobility for visits of up to three months and with provisions for daily personal exercise on several training devices. Insensible water loss would, therefore, be expected to be comparable to those found in hypobaric space cabin simulators. These terrestrial studies, however, restricted the activity of subjects to sedentary tasks, and there is no information from other sources regarding exercise sweating during exposure to normoxic, hypobaric environments. Therefore, it is unclear whether sweat losses would also be expected to increase.

The Skylab program represents the first opportunity to study the dynamics of EWL during extended periods of weightlessness in subjects engaged in an activity schedule not unlike that routinely found on earth. Although the limited timelines for flight preparation did not allow experiments to be included for measuring evaporative loss directly, a rather complete metabolic balance program provided the information necessary to compute this quantity indirectly and continuously throughout the mission. In addition to providing previously unavailable data for preparing complete water balances of the Skylab crew, the results of this study will be useful for space cabin environmental control system design. In addition, it will provide baseline information for validating predictive simulation models that are currently employed by NASA to study human thermoregulatory processes in weightlessness (Stolwijk, 1971).

PROCEDURE

The Skylab flight program consisted of three manned missions with three crewmen on each mission (Table I). Skylab II (SL-2), the first flight, lasted 28 days (SL-1 was the launch of the Skylab workshop itself) and was followed by a 59-day flight (SL-3) on an 84-day flight (SL-4).

Detailed descriptions of the extensive Skylab metabolic and biochemical investigation have been previously reported (Johnston & Dietlein, 1974; Leach & Rambaut, 1975). Only a portion of the data concerned with those experiments have been utilized for the calculation of EWL. In brief, the study consisted of measuring dietary constituents, excreta, and body weight (mass) on a daily basis beginning at least 21 days prior to each flight and continuing throughout the flight until the crews returned to earth. Complete urine and fecal collections were accomplished and samples of these were analyzed for urinary specific gravity and fecal water and calories. While water intake varied according to thirst, all water ingested was recorded. Throughout the program the crewmen ate assigned food and fluctuations in diet were controlled within narrow limits. Samples of all foods were analyzed for calories, nutrients and water prior to the flight.

Body weight was determined daily prior to and following the spaceflights. Inflight body mass was measured daily using a special mass measurement device with repeatability of $\pm$ 45 gms (Thornton & Ord, 1974). Measurements of total body water (TBW) were conducted at least once preflight and immediately post-flight on each crewman utilizing isotopic dilution of tritiated water.

Caloric intake was increased with each mission as was the amount of time allotted for daily personal exercise. Exercise increased from 30 minutes on SL-2 to 60 minutes on SL-3 and 90 minutes on SL-4. Otherwise, the astronaut activities in each mission were quite similar.

The atmospheric composition in the Skylab workshop consisted of approximately 30% N_2:70% O_2 at a nominal pressure of 1/3 atmosphere. Air velocity

Table 1. Physical Characteristics of Skylab Crew

FLIGHT	CREW	AGE (Yrs)	HGT (cm)	WGT* (Kg)	SURFACE** AREA (m^2)
SL2	CDR	43	170	62.2	1.65
	SPT	41	183	77.9	1.96
	PLT	41	178	80.2	1.93
SL3	CDR	41	175	68.6	1.74
	SPT	42	175	61.8	1.66
	PLT	37	183	88.0	2.02
SL4	CDR	41	175	67.8	1.75
	SPT	37	175	71.5	1.78
	PLT	43	175	69.6	1.77
	MEAN±SD		177	71.7	1.81
			±4	±8.7	±0.13

* Average Preflight Weight

** Sterophotometrically Measured (Avg. of 3 Preflight Measurements) varied from 0.08 to 0.2 m/s and averaged 0.15 m/s. The crewmen wore clothing with a clo value varying from 0.1 for exercise to 1.0 during sleep and 0.35 for their most frequently used flight garment (Jim Waligora, private communication). Other pertinent characteristics of the Skylab environment are presented in Table II.

Table 2. Skylab Environmental Parameters

FLIGHT	TEMP. °C	PRESSURE mm Hg	pH_2O mm Hg	pO_2 mm Hg
SL2	24.3±2.2	252±0.04	8.9±1.4	194±0.5
SL3	23.1±1.1	263±0.12	9.7±0.7	185±1.0
SL4	24.1±1.6	259±0.11	9.8±1.5	189±0.5

Values are Mean±SE

METHOD OF COMPUTATION

Two standard balance equations were used to estimate EWL from the input and output of fluids and solids for each crewman (Consolazio, et al, 1963; Bernauer, et al, 1967; Gee, et al, 1968):

Water Balance Equation

EWL = total water ingested from food and liquids + metabolic water
- water in urine and feces - gain in total body water

Mass Balance Equation

EWL = dry weight of food + total water ingested from food and liquids
- urine volume x urine sp gr - wet weight of feces - weight of
CO_2 expired + weight of O_2 used - gain in body weight

EWL estimated by these balance methods include insensible water losses from the respiratory tract and dermis as well as sensible sweat losses. Metabolic water, CO_2 expired and O_2 used were determined indirectly from the daily measured amounts of protein, fat, and carbohydrate in the ingested diet according to the general relationship:

$$\hat{X} = (EFF) \left[(A)\ (\text{diet carbohydrate}) + (B)\ (\text{diet fat}) + (C)\ (\text{diet protein}) \right]$$

where X represents metabolic water, CO_2 or O_2; A, B, and C are well-accepted stoichiometric values for metabolic reduction of food to CO_2, water and urinary nitrogen (Consolazio, et al, 1963; McHattie, 1960;Calloway & Pace, 1972)., and EFF is an efficiency factor to allow for incomplete digestion. A value of EFF equal to $0.954 \pm .005$ (sd) was obtained from calorimetry of the food and feces of all nine crewmen. Individual urinary specific gravity values (mean = $1.021 \pm .006$ (sd)) were used in the computations. Average measured and derived values for the terms in these balances are presented for each mission in Table 3. *

* A similar table of values for each crewmember appears in the Appendix.

Table 3. Measured and derived metabolic data for preflight and inflight phases; average daily values for each mission.

		SL2	SL3	SL4	SKYLAB MEAN
NO. OF DAYS OBSERVED	PRE	30	20	26	
	INF	23	54	79	
TOTAL WATER INGESTED	PRE	2941±536	2678±295	3293±225	2971±208
	INF	2911±591	2670±325	2953±245	2845±212
FOOD (DRY)	PRE	594.9±19.8	641.5±89.0	611.0±5.5	615.8±27.2
	INF	598.5±10.6	686.4±85.6	638.2±8.3	641.0±28.1
URINE	PRE	1610±535	1333±116	1660±161	1535±172
	INF	1824±474	1386±111	1681±113	1630±158
FECAL WATER	PRE	78.4±7.9	90.0±25.5	77.2±25.8	81.8±10.9
	INF	69.5±3.9	78.7±20.5	60.9±7.5	69.7±6.9
FECAL SOLIDS	PRE	23.5±2.9	25.2±4.5	26.0±2.6	24.9±1.8
	INF	21.0±1.1	26.6±4.5	24.3±2.4	24.0±1.7
CHANGE IN BODY WEIGHT	PRE	-44.5±7.8	16.7±33.7	0.0±17.8	-9.3±14.5
	INF	-55.1±31.4	-25.9±1.8	3.8±5.7	-25.7±12.5
DIET PROTEIN	PRE	107.4±1.5	123.4±20.2	120.0±4.2	116.9±6.5
	INF	102.3±2.0	117.9±19.8	120.0±5.4	113.4±6.6
DIET FAT	PRE	105.0±2.3	113.3±9.9	110.5±2.7	109.6±3.3
	INF	79.1±2.6	75.3±3.8	101.1±5.4	85.2±4.5
DIET CARBOHYDRATE	PRE	355.1±19.0	378.8±55.7	356.4±4.3	363.4±17.5
	INF	394.4±9.0	468.3±62.4	393.5±3.8	418.7±22.1
METABOLIC WATER	PRE	352±11	381±49	363±3	365±15
	INF	346±6	391±44	375±6	371±15
INSENSIBLE GAS LOSS (CO_2-O_2)	PRE	164.4±8.5	176.7±26.6	166.6±1.7	169.2±8.3
	INF	182.2±4.1	217.0±29.6	183.3±1.2	194.1±10.4

All liquid quantities are expressed in ml/day, all other quantities are in gms/day

Values are means ± SE; N=3 for mission means, N=9 for Skylab means

The EWL results used in this study (except for Table 5) were obtained from the mass balance equation since all terms in that relationship were measured either directly or indirectly on a continuous daily basis. Since TBW was measured only several times for each subject, EWL as computed from the water balance equation, represents an average value for the period between TBW measurements. Comparison of these two methods served as a check on the accuracy of the experimental procedures. Certain factors such as blood draws, sweat solids, etc. were estimated to be only 12-20 gm/day (Roth, 1968;Webb, 1964), and, therefore, were not considered in the analysis.

The first few days of each flight were accompanied by motion sickness, anorexia, ambient temperature excursions, and activities not typical of the remainder of the mission. Major readjustments in fluid and electrolytes also occurred during this period. In addition, atypical, but appropriate changes in EWL were demonstrated (see Figure 2). For this reason, with the exception of Tables 2 and 5, and Figures 1 and 2, the first five days of the inflight phase were not considered in the analysis. The experimental design provided that each subject serve as his own control; his inflight data were compared to his preflight control phase. Statistical analysis of the data included the paired t-test, correlation analysis, and analysis of variance with consideration for the unbalanced number of daily observations in each flight phase (Roy, et al, 1966; Snedecor, 1956).

RESULTS

Daily EWL for a typical crewman (SL-4/PLT) is plotted in Figure 1 as a function of mission time. Calculated EWL was less on days when no planned exercise occurred and during periods when the workshop was at its lowest temperatures. During the flight EWL increased during the work periods of extra-vehicular activity and when environmental temperatures were the highest. Otherwise, evaporative loss showed no tendency to return to preflight levels. Similar correlations existed for other crewmen, but there was no formal attempt to explain all the variations in the data. While postflight values are also shown in this figure, they have not been included in the remainder of the analysis. No physical activity program was scheduled during this period making it unlike that of the preflight and inflight phases.

The average EWL for the first 10 days of each mission is presented in Figure 2 as compared to preflight controls. The significant increase during the first week of SL-2 is related to the unusually high temperatures (about 32°C) in the Skylab workshop during this period. This was the result of the accidental damage during launch of SL-1 of a heat shield surrounding the orbiting workshop. The first crew was able to deploy a new sunshade and after five days the temperatures returned to near normal (27°). The crew remained primarily in the environmentally protected command module during the first two days of that period. Figure 2 also indicates a significant decrement in EWL during the first few inflight days of the longer missions when the crew was relatively inactive due to motion sickness symptoms. As was mentioned earlier, the data during this atypical period of flight was not included in the analysis.

Mean daily EWL results for all crewmen are shown in Table 4. Contrary to expectations, EWL decreased inflight in six subjects and in all three missions. There was an average decrease of 10.8% ($p < .01$) for all subjects. The effect of spaceflight on EWL was different in magnitude for each mission and was not related to any single variable such as mission length or exercise levels.

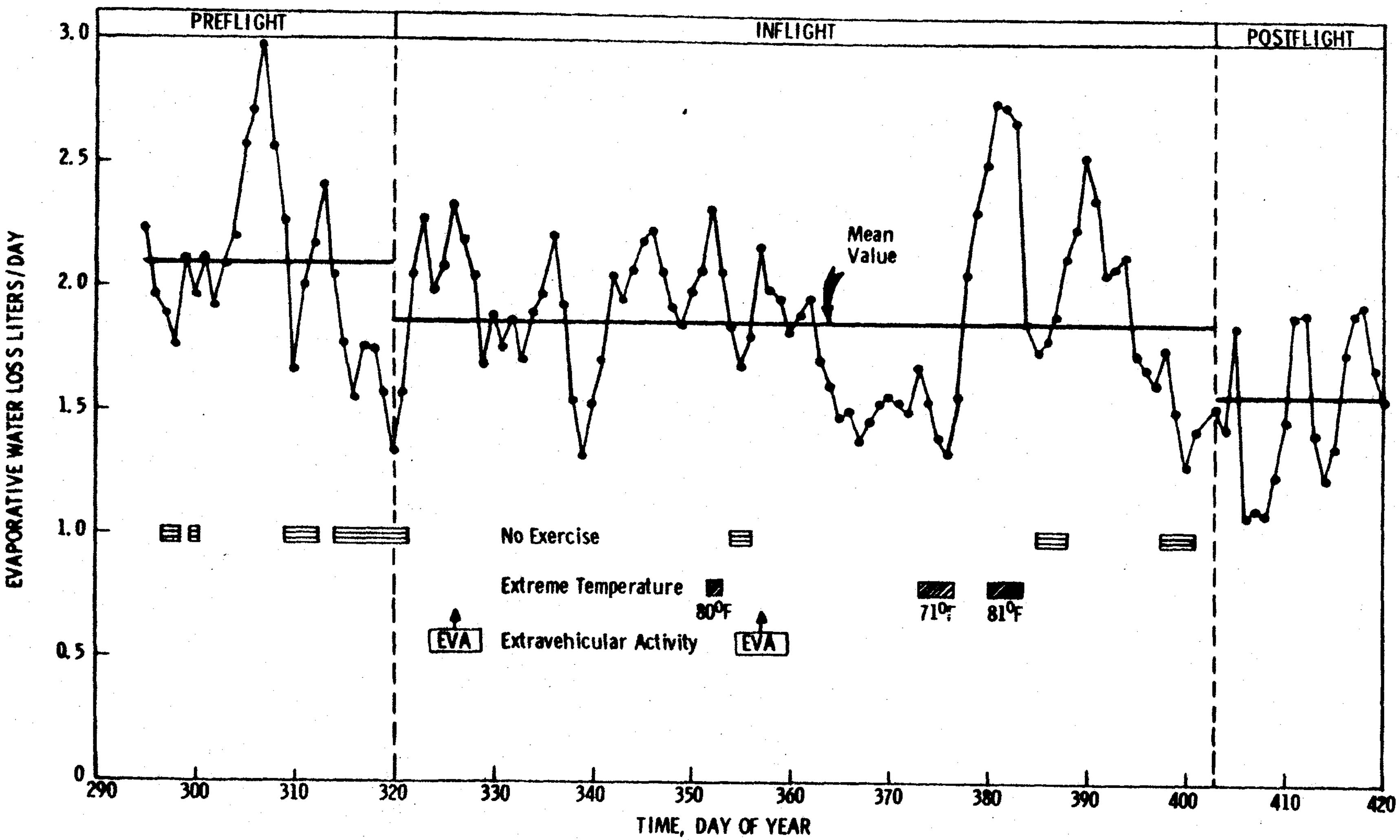

FIGURE 1. **EVAPORATIVE WATER LOSS OF A TYPICAL CREWMEMBER (SL4/PLT)**
(3-Day Sliding Average)

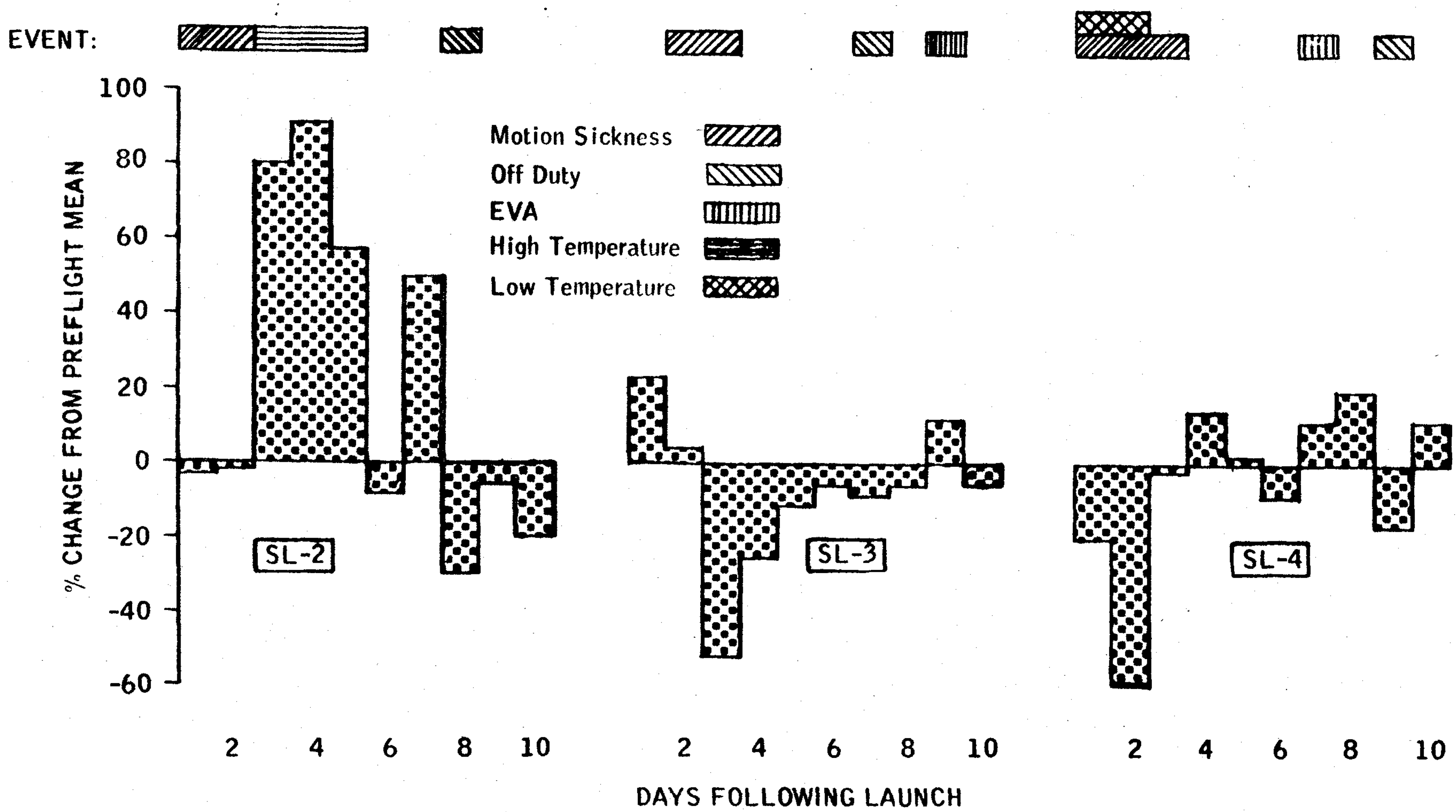

FIGURE 2. **EVAPORATIVE WATER LOSS DURING THE FIRST TEN DAYS OF EACH MISSION (N=3)**

Table 4. Average Daily Evaporative Water Loss of three Skylab missions

FLIGHT	NO. OF DAYS OBSERVED PRE	NO. OF DAYS OBSERVED INF	SUBJECT	PREFLIGHT ml/day	PREFLIGHT ml/day-m^2	INFLIGHT ml/day	INFLIGHT ml/day-m^2
SL2	30	23	1	1472	892	1206	731
			2	1814	926	1372	700
			3	1664	862	1725	894
	MEAN±SE			1650±99	893±18	1434±153	775±60
SL3	20	54	1	1124	646	1351	776
			2	1794	1081	1410	849
			3	2036	1008	2170	1074
	MEAN±SE			1651±273	912±134	1644±264	900±90
SL4	26	79	1	1378	787	1303	745
			2	2333	1311	1625	913
			3	2104	1189	1862	1052
	MEAN±SE			1938±288	1096±158	1597±162	903±89
	SKYLAB MEAN±SE			1747±127	967±68	1558±105	859±46

Values are means ± SE

There were significant changes from preflight values on the shortest (-13%, $p < .05$) and longest (-18%, $p < .01$) missions while the SL-3 crew showed a negligible decrease. Two of the three Skylab astronauts who increased their EWL were on this latter flight.

Normalizing the data by body surface area permits more meaningful comparison between crews. During both the preflight and inflight periods the mean EWL of each successive crew increased. This was qualitatively related to the amount of exercise performed, but proportional increases in EWL were not consistent with those of exercise. For example, while the differences of preflight EWL were greater between SL-3 and SL-4 than between SL-2 and SL-3 ($p < .05$), during inflight the last two crews showed nearly identical responses compared to the first two crews ($p < .05$). Thus, if the amount of exercise performed was truly the main factor separating these different crews, as is believed, these results indicate that the EWL response to greater levels of exercise is different on earth than it is in space, at least for these nine men.

Although the results in Table 4 show a large variation in the different crewmen's EWL response to spaceflight (range: 70% to 120% of preflight value), these changes were significantly correlated with their preflight EWL values ($r = -0.71$, $p < .05$). This first-order relationship, illustrated in Figure 3, shows that the largest decrements of EWL during each mission occurred in those crewmen having the highest preflight EWL. Furthermore, it suggests a common influence on EWL due to spaceflight, affecting both those subjects that increased or decreased their inflight EWL.

The possibility of acclimation during the longer missions was considered. Monthly averages of EWL for each crew indicated no apparent time-varying trends (see Figure 4(a)).

A comparison of the two methods used in estimating EWL - the mass balance and water balance – is shown in Table 5. Since TBW was measured at the beginning and end of preflight and inflight periods in six crewmen, results

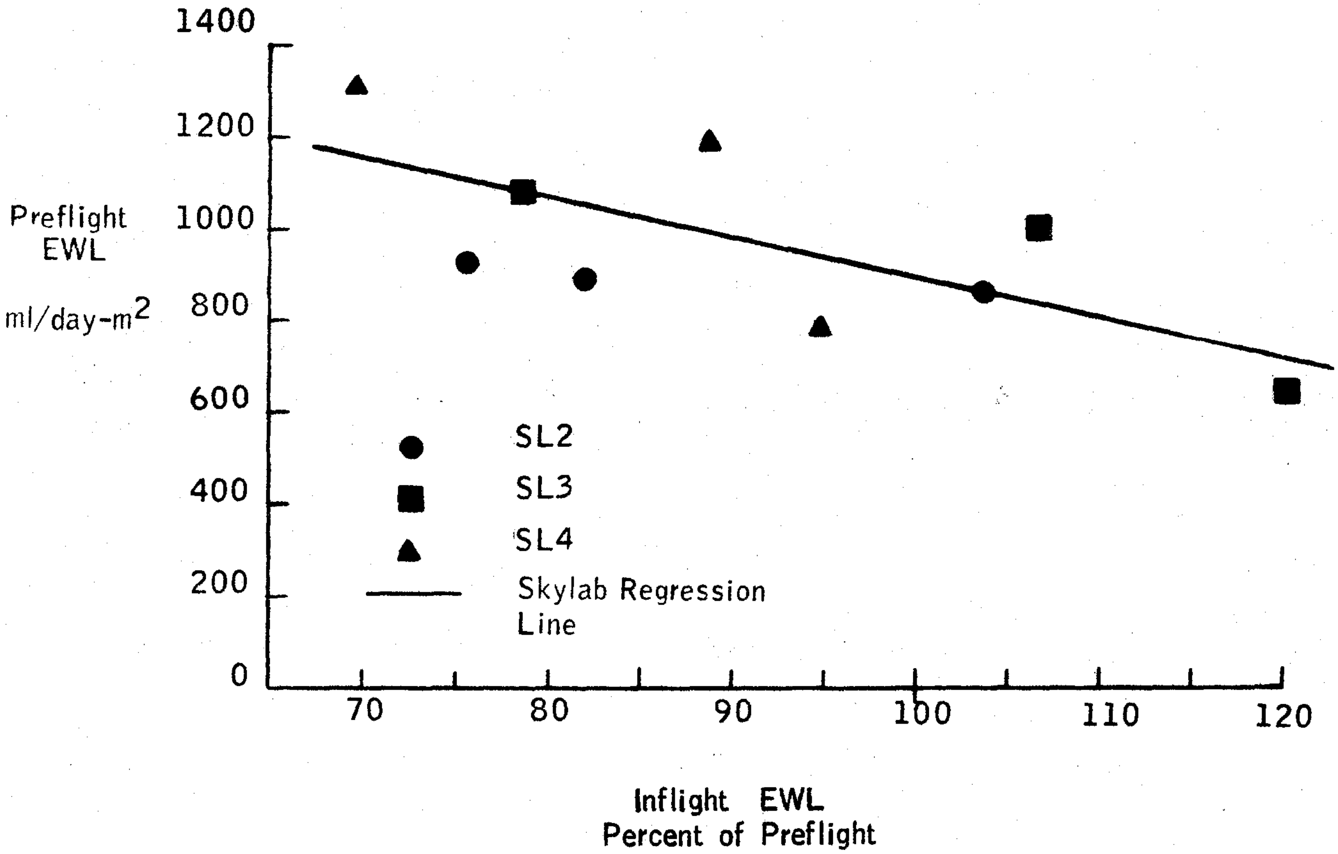

FIGURE 3. EVAPORATIVE WATER LOSS RESPONSE OF SKYLAB CREW (n=9) TO SPACEFLIGHT VS. PREFLIGHT VALUES

Correlation of the nine crewmen's evaporative water loss (EWL) response to zero-g spaceflight (% of preflight) with their preflight values ($r = -0.71$, $p < .05$).

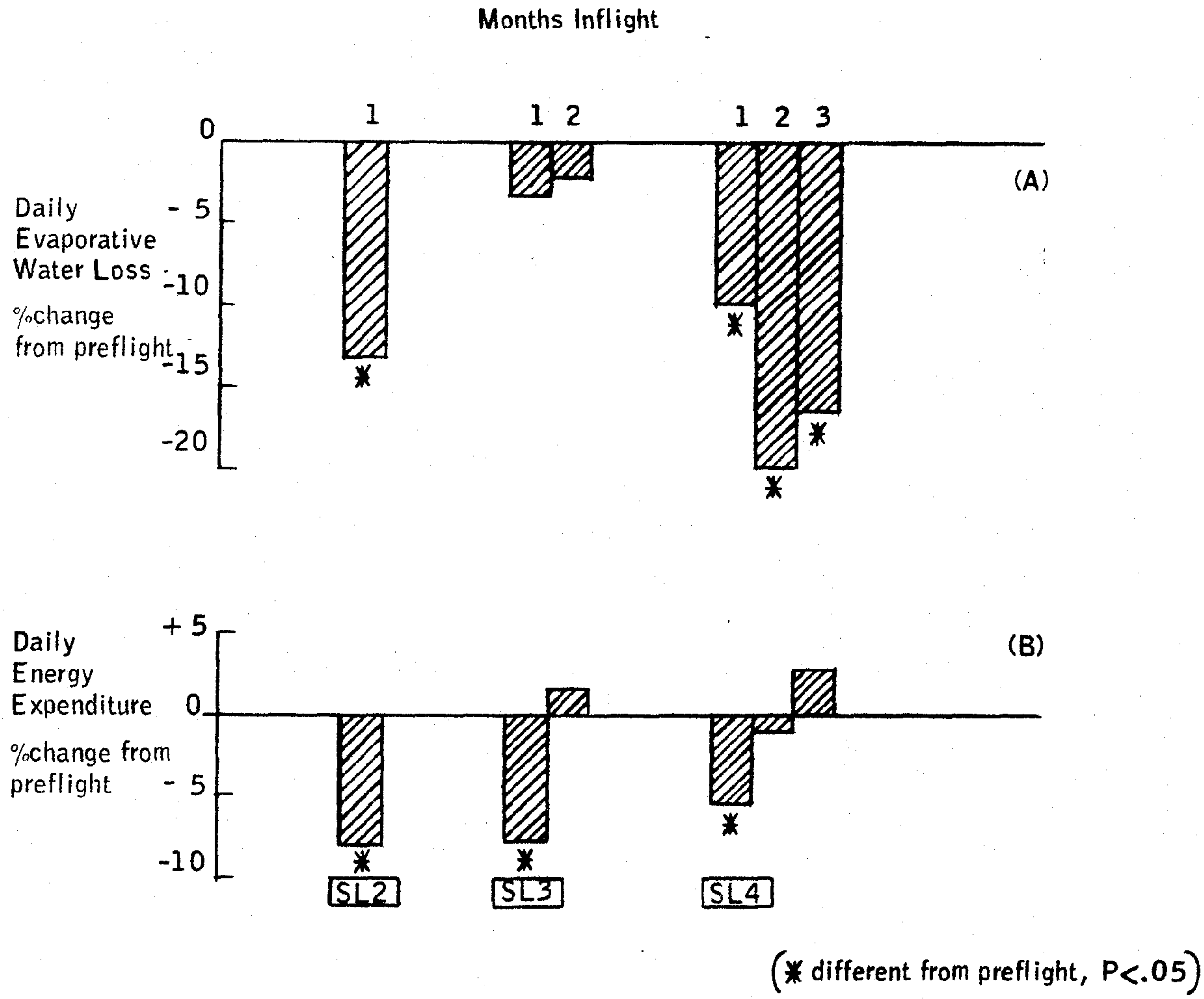

Figure 4. MONTHLY EVAPORATIVE WATER LOSS AND ENERGY EXPENDITURE CHANGES DUE TO SPACEFLIGHT FOR EACH SKYLAB MISSION

Monthly inflight changes (percent from preflight) of: (A) mean daily evaporative water loss and (B) mean daily energy expenditure (* different from preflight, $p < .05$). Comparison shows poor correlation between the two quantities especially after first month.

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Table 5. Comparison of Two Methods for Determining Evaporative Water Loss

Subject	Preflight Δt* days	Preflight TBW ml/day	Preflight W ml/day	Preflight M ml/day	Preflight Δ	Inflight Δt days	Inflight TBW ml/day	Inflight W ml/day	Inflight M ml/day	Inflight Δ
SL2/CDR	20	-25.0	1307	1316	-9	29	-17.2	1344	1390	-46
SL2/SPT	20	+40.0	1726	1790	-64	30	-40.0	1515	1620	-105
SL2/PLT	20	-15.0	1656	1702	-46	29	-69.0	1770	1824	-54
SL4/CDR	20	+5.0	1390	1398	-8	85	-10.6	1318	1326	-7
SL4/SPT	20	+10.0	2253	2299	-46	85	-7.1	1604	1637	-33
SL4/PLT	20	+35.0	2050	2132	-82	85	-10.6	1859	1858	+1
MEAN ± SD			1730 368	1773 390	-43 -30			1568 220	1609 218	-40 -37

*Δt = time between TBW Measurements; TBW = ΔTBW (Measured)/Δt; W = Evaporative water loss from water balance = Total fluid intake + Met. H_2O - Total fluid excretion - TBW; M = Evaporative water loss from mass balance; Δ = W - M

from only those subjects are presented. Values for the mass balance were averaged over the time span (indicated in Table 5) coinciding with the interval between TBW measurements. This period did not include exactly the same number of days as the analysis shown in Table 4 and, therefore, these two tables are not expected to be in complete agreement. The results indicate a small but significant systematic difference ($< 3\%, p < .05$) between the two methods.

DISCUSSION

EWL is affected by a complex of factors including environment, metabolism, physical activity, clothing, psychological stress, hydration, degree of heat acclimatization as well as interactions in the physiological systems that participate directly and indirectly in thermoregulation (Hardy, 1963;Hardy, et al, 1970). Weightlessness, as this study suggests, could be an additional environmental factor which influences EWL. In order to demonstrate an environmental effect on EWL it is desirable to control as many as these parameters as possible.

The Skylab medical experiments were designed to closely monitor and/or control the physical activity, diet, physiological condition and environment of the crewmen before, during, and following the flights. There were no significant changes between the environment of the Skylab workshop and that of the buildings and trainers used by the crewmen preflight except for that of total pressure, gas composition*, and the gravity (g) effect. The Skylab workshop's environment was rather stable for all missions during the time span considered in this study. The level of routine daily activity was also thought to be rather similar for the three crews throughout preflight and inflight phases. However, the nature of the entire Skylab project obviously precluded the type of control normally desired in such experiments. These considerations suggest that mean changes in EWL may be related to a number of important factors which were either purposefully different between mission phases or not controlled: ambient pressure, g-effect, metabolic activity levels during exercise periods, and the outdoor preflight environment in which the crew performed a portion of their exercise.

The significant finding that inflight EWL did not increase as expected suggests: a) the balance method used in these studies was not sufficiently accurate or sensitive to detect the expected changes, b) certain environmental and metabolic activity factors, which could not be precisely controlled, favored a preflight

*different O_2-N_2 mixtures have little effect on thermoregulatory processes (Berensen & Robertson, 1973)

EWL even higher than the expected inflight changes, or c) there is an effect of weightless spaceflight that tends, directly or indirectly, to decrease one or more components of EWL. These will be discussed below.

Sensitivity of Indirect Method to Measure EWL

It has been previously shown that EWL measurements obtained indirectly from mass and water balances are not always in agreement with more direct measurements and that the influence of environmental variables on the rates of EWL are not as easily discerned with the indirect method (Carleton & Welsh, 1971a). While in the present study direct measurements were not performed, there is evidence to indicate that the method produces reasonably accurate results and can detect reasonably small changes in EWL.

It was demonstrated that the indirect technique was sufficiently sensitive to reveal dramatic changes in daily EWL that were appropriately correlated with ambient temperature excursions and various levels of metabolic activity (Figure 1). The wide variation in day-to-day EWL shown in Figure 2 may appear surprising, but it primarily reflects similar variation in water intake, urine losses, and daily changes in body mass which were measured directly and from which EWL was in part computed. Significant, although smaller, unexplained intrasubject variation has been previously noted in studies in which activity was restricted and direct techniques of measurement were employed (Carleton & Welsh, 1971a; Hale, et al, 1958). It would be expected that variability would increase under conditions of significant thermal sweating. Variation between subjects was relatively small and similar to those previously reported (Gee, et al, 1968; Carleton & Welsh, 1971a; Hale, et al, 1958).

The ability of the indirect method to resolve differences between the two mission phases was estimated to be limited to changes greater than 8 - 12% and this was possible, in the light of the intrasubject variability, because of the large number of consecutive daily observations. The contribution of instrument error was evaluated as less than $\pm 4\%$ of EWL (Beers, 1957). Absolute levels of preflight EWL were similar to prior estimates of crewmen at normal sea level ambients having similar energy requirements (Pecoraro, 1973). A further indication of the precision of the analysis is the close agreement found between the mass and water balance estimates of EWL (Table 5).

Effect of Preflight Exercise Environment

During the two to three week isolation period preceding each flight the crew was confined to environmentally controlled areas except for the time devoted to physical training out-of-doors. The crew of the first mission did not use outside training while those on the last mission exercised more outdoors than indoors and the SL-3 crew utilized both nearly equivalently. It was estimated that the mean temperatures of the preflight physical training environments due to the seasonal temperature variations prevalent in Houston * were: SL-2: Spring, 22°C; SL-3: Summer, 25°C; SL-4: Fall, 21°C. These temperatures are not widely different from those of the Skylab workshop (Table 2) and do not appear to be correlated with the preflight EWL of the three crews. Preflight-inflight changes cannot, therefore, be explained by this temperature effect.

Effect of Exercising Metabolic Activity on EWL

The crew of each succeeding mission were allowed an additional half-hour for inflight personal exercise starting with 30 minutes a day in the first mission. Inflight bicycle ergometry data of mechanical work performed reflect this trend: SL-2: 31 watt-min/kg; SL-3: 65; SL-4: 72 (Michel, et al, 1974). ** The preflight exercise regimen paralleled, but did not exactly duplicate the inflight program. Routine activity can be considered similar throughout the program and there have been no findings that performance of routine tasks is less difficult in weightlessness (Kubis, et al, 1974). Thus, the major differences between flights with regard to metabolic expenditure was that each successive crew exercised more frequently and vigorously both preflight and inflight. These considerations suggest

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* Outdoor temperatures obtained from U. S. Weather Service

** This was the only exercise device providing a indication of energy expenditure; other devices were used, especially by the SL-4 crew, but the bicycle was the most popular form of training.

that daily insensible water loss and low level sweating was similar for the three Skylab crews. Any significant differences in EWL between missions may, therefore, be a result of variations in the sweat component due to exercise. Indeed, the average preflight + inflight EWL rates of 834, 906, and 999 ml/day-m^2 for the SL-2, SL-3, and SL-4 crews, respectively, are consistent with these assumptions.

It was not feasible to make personal exercise a controlled variable during Skylab. While records are available on the type, duration, and frequency of personnel exercise (Rummel, et al, 1975), these data do not lend themselves to precise quantification of the differences in physical activity between preflight and inflight. The decrease in EWL could be explained if the energy expenditure for exercise was less inflight. There is indirect evidence to show that this did not occur, at least for the last two missions. Results from the exercise performance experiments have demonstrated a decrease in physical fitness for the first Skylab crew, but an increase possibly in the second, and definitely in the third Skylab crews by the end of their flights when compared to preflight levels. This was attributed to the higher level of aerobic exercise performed inflight (Rummel, et al, 1975; Sawin, et al, 1975; Buderer, et al, 1975). More compelling evidence is obtained from the caloric balance study (Rambaut, et al, in press) which showed, compared to preflight, a decrease in the inflight energy consumption of SL-2, but increases or no change in this quantity for the other missions during periods when EWL decreased (see Figure 4).

Thus, the decreased EWL of the first crew perhaps may be explained by a reduction in inflight metabolic levels. But on the average for the nine crewmen, there was only a reduction of 3% in inflight calories utilized, hardly enough to account for the significant decreases in EWL. Moreover, the crew that performed the most inflight exercise showed the largest decrement in EWL, and the individual crewman that was qualitatively considered to have had the highest exercise level of all subjects (SL-4/SPT) also showed the largest decrease in EWL (see Figure 3). This suggests that on the average the inflight exercise protocol caused a much lower EWL than did preflight exercise. In summary, it appears that the failure to find an increase in inflight EWL cannot be completely explained by uncontrolled environmental and metabolic activity factors.

Effect of Hypobaric Environments on EWL

EWL consists of three components: respiratory losses (RL), skin diffusion losses (DL), and sweating (SL). It is well known that reduced barometric pressure increases DL primarily due to enhanced vapor conductivity and, to a lesser extent, a diminished heat convective loss (Taylor & Buettner, 1953; Berenson & Robertson, 1973). Previous studies on inactive subjects in hypobaric chambers at 1/3 atm have reported increases in DL ranging from 36% to 59% above those measured at sea level, and overall increases in insensible water loss (RL + DL) from 15% to 38% (Carleton & Welsh, 1971; Gee, et al, 1968; Hale, et al, 1957). Others have found that DL is inversely proportional to the square root of the pressure (Taylor & Buettner, 1953). RL , while not measured directly on Skylab, probably also increased since resting minute volume (proportional to RL (Wortz, 1966)) increased inflight by nearly 20% (Michel, et al, 1974). There is much less information regarding the hypobaric effect on SL during high metabolic activity. In two exercise studies at altitude (460 - 490 mm Hg) evaporative losses significantly increased by 16% and 33% (Greenleaf, et al, 1969; Varene, et al, 1973). However, it is not clear whether apparent sweating responses recorded during hypoxic exercise would be similar to those expected in the hypobaric,normoxic environment of Skylab.

If one quantitatively considers the enhanced evaporation due to reduced pressures the actual inflight decreases in EWL can be shown to be much greater than the apparent decrease of 11% measured in this study. Using data from reports cited above it was estimated that inflight EWL decreased from 17% to 33% of expected values (see Appendix). Similarly, actual inflight sweat losses were estimated to range from 35% to 67% below prediction. Therefore, the failure for inflight EWL to increase appears to involve a mechanism capable of causing major changes in either insensible, or more probably, sensible water loss.

Effect of Weightlessness on EWL

In weightlessness, both evaporation and heat convection would be reduced because the natural convective (buoyant) forces are absent. At the low air velocities used in hypobaric chamber studies (and in Skylab; e.g., $v < 0.2$ m/s) natural convection may have contributed a significant proportion of total convective forces (Rapp, 1973). Therefore, superimposing the effects of the combined hypobaric and zero-g environment may lead to a large decrease in heat convection (compared to preflight control) and an evaporative effect less than would be expected in hypobaric chambers on earth. The net evaporative power of this environment (which determines maximum evaporation rates) would be determined in part by the balance between the reduced pressure-enhanced vapor conductivity effects on the one hand, and the decreased natural convection effects on the other. The absence of natural convection might become more apparent in zero-g situations where air flow over the skin is normally minimal such as in a clothed sedentary subject.

It should be emphasized that the effects of natural convection of EWL have not been directly studied in man although a theoretical treatment exists (Sibbons, 1970). The above arguments, however, would seem to apply more convincingly to sensible water loss during exercise where the skin is wet and evaporation is rate limiting. Where the skin is dry and the water-air interface is located within the skin membrane (the usual situation for insensible water loss during low level activity), water diffusion through the skin is rate limiting. It is more difficult to predict the influence of natural convective forces on mass transfer in these cases. There is no evidence that diffusion through the skin, an essentially passive process depending on the skin-air environment (Buettner, 1953), can be directly affected by g-fields. Indirect zero-g effects on the skin membrane caused by biochemical changes will be discussed below.

An additional important clue was provided by the Skylab crew. They observed that in zero-g exercise sweat does not readily drip from the body, but rather tends to become evenly distributed on the skin surface much like a film.

An important factor known to modify sweat rates is the degree of skin wettedness determined by the balance between sweat production and evaporative loss rates. It has been demonstrated that as the wetted area increases, the buildup of surface water acts to inhibit the rate of sweating by non-thermal mechanisms which are not entirely understood (Brown & Sargent, 1965; Nadel & Stolwijk, 1973; Taylor & Buettner, 1953). These studies have shown that this phenomena – skin wettedness hidromeiosis – can suppress sweat rates by up to 80%, a value more than high enough to account for the discrepancy between expected and measured inflight EWL. It has already been suggested that evaporation rates tend to be diminished in zero-g, thus favoring an even wetter skin. Therefore, it may be postulated that an increase in skin wettedness occurred in Skylab during the exercise periods associated with high thermal sweating and that the sweat rates were suppressed to an extent that they masked the effect of an increased insensible water loss that may have occurred during the remainder of the day. The net effect was a decrease in daily EWL. A skin wettedness hidromeiosis mechanism is consistent with the observation that the crewmembers associated with the greatest amount of exercise and the highest preflight EWL values also showed the largest decline in EWL from preflight. These subjects would be expected to have the highest degree of skin wettedness. Similar correlations have previously been used to suggest a sweating threshold for hidromeiosis (Brown & Sargent, 1965). In addition, since sweat does not fall off the body, the increased water residence time on the skin would provide for greater heat exchange per ml of sweat produced. This increased cooling capacity may tend to reduce the thermoregulatory sweating drive.

Fluid, Electrolyte and Hormonal Influence on Evaporative Loss Rates

There is a growing body of evidence indicating the ability of certain physiological parameters, other than those normally associated with environmental effects and metabolic activity, to influence evaporative loss rates. Factors which have been implicated in modifying thermal sweating during exercise in normal ambients include: the state of hydration (Greenleaf & Castle, 1971; Nielsen, 1971), body fluid osmolarity (Sargent, 1962), plasma sodium and calcium concentrations (Nielsen, 1974), and antidiuretic hormone levels (Fasciolo, 1969). In addition, significant changes in insensible skin water losses have been demonstrated by hypotonic volume expansion and drhydration (Carleton & Welsh, 1971b). The mechanisms for these effects are not well understood and in the case of ADH the evidence is equivocal.

Major fluid shifts both from and within the body were known to occur in the Skylab crew during their exposure to weightlessness (Berry, 1976) as well as significant adjustments in hormonal and electrolyte levels (Leach & Rambaut, 1975). However, comparison of the direction and magnitude of these changes (i.e., decreases in plasma osmolarity, sodium concentration and ADH excretion; increases in calcium concentration) with those found in the previously cited studies suggest that they would have acted to <u>increase</u> evaporative water loss.

Hypotonic overhydration has also been shown to increase sensible and insensible water loss. Whether this condition existed in the Skylab crew cannot be as easily answered. Blood and tissue fluid volume was believed to have shifted from the legs to the upper body accompanied by a 1-2 liter loss of total body fluid (Thornton, et al, 1974b). Clinical dehydration was certainly not present because electrolyte losses were more than commensurate with fluid losses. A certain decline of body fluids appears to be an appropriate adjustment to the weightless environment.

It should be emphasized that these changes observed in Skylab were all measured at rest. Whether they were reversed temporarily during the periods of high activity and thermal sweating is not known. In any case, it may be supposed that these conditions existed at the onset of exercise which may have tended to increase early sweating (Nielsen, 1974), a condition known to favor sweat suppression (Brown & Sargent, 1965).

Summary and Conclusions

Daily evaporative water losses during the three Skylab missions were computed using the indirect mass and water balance techniques. A mean inflight EWL of 860 $\pm$ 25 ml/day-m^2 (SE) was obtained for nine men who averaged one hour of daily exercise. Although it was expected that EWL would increase in the reduced barometric pressure environment of Skylab, an average decrease from preflight sea level conditions of 11% was measured. Comparison of these results with previous studies in hypobaric chambers revealed that the effective decrease was probably higher than this value. It was determined that the method of measuring EWL was sufficiently sensitive to resolve changes of this magnitude. These results could not be completely explained by various environmental and metabolic factors that were not ideally controlled. Weightlessness itself appears to have been a factor in modifying EWL.

Although the components of EWL were not measured, indirect evidence suggests that skin and respiratory insensible water losses increased. Therefore, it was proposed that the decreased EWL was primarily due to a reduction in exercising sweat rates. It appears that unique conditions existed on Skylab which promoted the formation of a sweat film on the skin surface — this being an observable effect — despite the enhanced evaporative power of the environment. Weightlessness may have been a causative factor in creating this sheeting phenomena both directly, by reducing convective flow and sweat drippage, and indirectly, by inducing measurable biochemical changes resulting in high initial sweating rates. These combination of factors are likely to favor an hidromeotic effect that could account for the discrepancy between the expected and measured EWL. Whether or not there was a reduction in sweat rates in Skylab that were sufficiently great to obscure a probable increase in insensible water loss remains to be established. The possibility cannot be ruled out that skin diffusional losses may also be diminished by the weightless environment.

These hypotheses are stated guardedly because of the indirect evidence employed, the lack of strict controls, and the complexity of factors involved. A wide variation in EWL changes were seen and the results may be peculiar to the nine astronauts involved in this study. However, it can be concluded that the reduction of body fluids found in these subjects after their return to earth cannot be attributed to an increase in EWL during their prolonged stay in zero-g. Also, it appears justified to pursue a more precise quantification of thermoregulatory behavior, especially during periods of intensive exercise, both in weightlessness and in terrestrial hypobaric chambers. Paradoxically, future space laboratories may prove to be an ideal environment in which to study the importance of natural convection on evaporative water loss.

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APPENDIX A

ESTIMATE OF EXPECTED INFLIGHT EVAPORATIVE WATER LOSS

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ESTIMATE OF EXPECTED INFLIGHT EVAPORATIVE WATER LOSS

A significant finding in this study was that the inflight EWL was not greater than preflight. It would be instructive to quantitate the degree to which EWL would have been expected to increase in the Skylab hypobaric environment based on prior studies and compare that with the EWL actually observed. In addition, it may be possible to provide an estimate of the decline in sweat loss that may have occurred and verify if it is reasonably in accord with known factors governing sweat production, skin wettedness, and sweat suppression.

An estimate of insensible and sensible evaporative water losses will be made for the following cases: a) preflight control, b) expected inflight, based on the hypobaric environment, and c) actual inflight. The following assumptions will be made: a) preflight insensible water loss (respiratory + skin diffusion) is based on the generally accepted value for a normal ambient environment ($23^{o}C$: 760 mm Hg: 11 mm Hg pH_2O: 160 mm Hg pO_2:0.35 clo:1-g) of 35.5 ml/hr or 850 ml/day (Gee, et al, 1969; Webb, 1975), b) there is a 15% to 38% expected increase in insensible water loss at 253 mm Hg ambient pressure and 160 mm Hg pO_2 based on hypobaric normoxic chamber studies (Hale, et al, 1957; Gee, et al, 1969; Carleton & Welch, 1971), c) insensible water loss will be assumed to be unaffected by a weightless environment, d) sweat losses in the reduced pressure, normoxic environment will be expected to change from 0% to 30%. (No data is available for this particular ambient condition; the higher value was obtained during moderate exercise at 4000 m altitude (Varene, et al, 1973), d) other than differences in pressure and gravitational field the preflight and inflight environments will be considered identical. Interpretation of these results will assume an inflight metabolic rate equal to preflight. This assumption has been previously discussed (See Discussion).

Table A-1 summarizes the calculations based on the above restrictions. Preflight and estimated inflight values for total EWL were taken from the present study. Estimated sensible water losses were determined by difference between total EWL and estimated insensible losses. Nearly all sweat losses can be considered to be associated with one-hour daily exercise. Expected inflight values for total losses were 7% to 34% higher than preflight, although a decrease of 11% was actually measured. Thus, total inflight EWL ranged from 17% to 33% below expected values. Similarly, it is estimated that actual inflight sweat losses ranged from 35% to 67% below expected values. This appears to be within acceptable limits of sweat suppression previously attributed to high degrees of skin wettedness (Nadel & Stolwijk, 1973).

On the other hand, if the decrease in EWL were due to changes in insensible water loss assuming expected sweat rates were realized, it can be similarly shown that the measured data could only be explained by decreases of 33% to 67% of insensible water loss below expectation or about 20% to 55% below preflight values. There is no supportive evidence at this time to know if such an effect did occur although several possible mechanisms have been discussed (see Discussion).

It is also possible to estimate the degree of skin wettedness and the potential for dripping during exercise for these various cases. The degree of skin wettedness is usually expressed as S/E_{max}, where S is the sweating rate and E_{max} is the maximal evaporative rate possible for a given environment (Nadel & Stolwijk, 1973). An expression for E_{max} for sea level conditions as well as hypobaric, zero-g environments can be written as: $E_{max} = \phi h_e (760/P)^{0.5} (P_s - P_a)$, ml/hr-m^2 (Berenson & Robertson, 1973). P_s and P_a are the saturated water vapor pressures (mm Hg) at the skin and ambient/dewpoint temperatures, respectively. P is the ambient total pressure (mm Hg). The evaporative mass transfer coefficient, h_e, can be computed from a previous study to be 8.74 at rest and 15.2 during exercise (Saltin, et al, 1970). Assuming a body surface area of 1.8 m^2 and an ambient water vapor pressure of 10 mm Hg, the following values have been calculated for E_{max}: 405 and 820 ml/hr for rest and exercise, respectively; at 760 mm Hg and 1-g; 490 and 1300 ml/hr at rest and exercise, respectively; at 253 mm Hg and zero-g. Values of S/E_{max} have been inserted in Table A-1 in parenthesis below the sweat rate losses which were assumed to be hourly rates. According to Kerslake (1963), sweat begins dripping when the sweat rate is about 1/3 of the maximum evaporative capacity. Therefore, any value of S/E_{max} greater than 0.33 is conducive to dripping in 1-g and conducive to surface sheeting in zero-g. Because of the tenacity of any excess water to cling and spread over the skin surface in weightlessness (Owen Garriott, personal communication), it is likely that sheeting begins well before S/E_{max} reaches the values that Kerslake found for terrestrial environments. In either case, it appears that the potential for a buildup of surface water exists for all the cases considered and in spite of the hypobaric environment. The observation that surface sheeting occurred on all Skylab flights supports these estimations. The high value of S/E_{max} shown for preflight indicates a very wet skin, but does not necessarily imply that sweat suppression would have been greater than inflight because during preflight the excess water would merely drip off the body.

TABLE A-1. ESTIMATES OF INSENSIBLE AND SENSIBLE EVAPORATIVE LOSSES (ml/day)

MISSION PHASE	INSENSIBLE WATER LOSS	SENSIBLE WATER LOSS	TOTAL EWL	Δ% TOTAL FROM PREFLIGHT
Preflight (1 atm, 1-g)	850[1]	900[2] (1.10)[4]	1750[3]	—
Inflight (1/3 atm, D-g)				
a) Expected	980-1170[5]	900-1170[6] (.69 - 90)	1880-2340[2]	7% to 34%
b) Estimated	980-1170[5]	390-580[2] (.30-.45)	1560[3]	-11%
Δ% Expected vs. Estimated	0	-35% to -67%	-17% to -33%	

[1]Nominally accepted value for comfortable sea level environment, [2]Determined by difference or addition: EWL = Insensible + Sensible, [3]Data from present study, [4]Values in parenthesis are wetted area = Sensible/E_{max}, [5]Based on hypobaric chamber studies showing a 15-38% increase over sea level, [6]Based on hypoxic, hypobaric exercise studies showing up to a 39% increase over sea level.

APPENDIX B

STATISTICAL ANALYSIS OF EVAPORATIVE WATER LOSS CHANGES DURING SKYLAB

APPENDIX B

STATISTICAL ANALYSIS OF EVAPORATIVE WATER LOSS CHANGES DURING SKYLAB

Method

The grouping of evaporative loss data according to subject, flight, and flight phase is shown in Table I. Also shown are the number of daily observations for each subject and the standard deviation of these observations. Analysis of this data was accomplished by a two-way analysis of variance using all daily observations with consideration for the unbalanced number of replications in each group (Reference 1 and 2).

Results

Analysis of variance tables for all of the pooled data (pooled by flight and by subject) are shown in Table II. In the first case (Table II-A), the differences between treatments (preflight vs. inflight) and flights were investigated by pooling data from all three crewmen on each flight as though they were only one subject. The results suggest that no differences existed between the three flights and, therefore, it might be appropriate to pool all flights together. The results of pooling all subjects as though they were on one flight appear in Table II-B.

The results of these two analyses may be summarized as follows: There was a highly significant difference between the evaporative loss rates of each crewmember ($p < .001$.) However, each three-member crew was apparently homogenous with respect to the total population of crewmembers so that there was no discernable difference between average evaporative loss rates of each mission. More important to the present study, however, is the finding that the decrease in inflight evaporative loss rate was highly significant ($p < .01$).

The effect of space flight on evaporative loss rate was also investigated separately for each flight as well as for each month of flight. Table III contains the results of these analyses and also includes the results from Table II. Analysis of individual flights revealed that when all data are considered, the only significant changes in evaporative loss rates occurred on the SL-4 mission ($p < .001$). In that flight, significant changes were associated with each month of the mission. However, if the first five days of the SL-2 mission are omitted (because of unusually high ambient temperatures) the changes in that mission are also found to be significant ($p < .05$).

The observed decrease in inflight evaporative loss was large enough to assume a change actually occurred for the Skylab crew of nine men ($p < .01$). But there was sufficient variability in each of the subjects response (ranging from +20% to -31%), see Table I) to prevent extrapolation of this finding to a larger population ($p > .15$). However, if the data for the first five days of the SL-2 mission are excluded, the findings for the Skylab crew can be extended to a random population with a more reasonable degree of significance ($p < .07$), as shown in Table IV. *

Conclusions

The general conclusion from this analysis is that significant decreases in inflight evaporative loss (-9.1% excluding the first five days of SL-2) were observed on Skylab. This negates the prior expectation that inflight evaporative losses would increase in an environment of reduced ambient pressure.

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* The variability of subject response to treatment is known as the "interaction effect." Analysis of treatment means with a fixed population ANOVA model does not account for interaction effects (even though they are computed) and does not permit conclusions to be drawn for a random population. If interaction effects are large, as they were in this study, they should be included in the analysis of treatment means. This is accomplished by using a random population (i.e., components of variance) ANOVA model which does allow interpretation to be extended a larger group of subjects. Both of these models were used in the present study. However, since the Skylab crew were not altogether randomly chosen and their preflight environmental conditions were not completely controlled, there is good reason to consider them a fixed population.

The failure to find the expected changes may be attributed to weightlessness itself, but the contribution of other environmental and physiological factors cannot be ruled out. If weightlessness is a major factor, and if evaporative losses decreased despite the reduced pressure, greater decreases may occur in the Shuttle Orbiter (operating at one atmosphere) than have been demonstrated here.

The present study has demonstrated that the indirect method of measuring evaporative loss can be surprisingly sensitive to day-to-day fluctuations. However, since daily variations were so large (average s.d. = 590 ml/day), the ability of this technique to resolve differences between the two environmental conditions appears to be limited to changes greater than 8-12% and this was possible only with a large number of observations. A more precise quantification of the evaporative water loss response in a zero-g environment must await future Shuttle missions where it will be possible to separate out the different effects of weightlessness, temperature, and metabolic activity by a direct and more sensitive technique.

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TABLE B-I

SKYLAB EVAPORATIVE WATER LOSS
(ml/day)

FLIGHT	MAN	PREFLIGHT			INFLIGHT			Λ%
		n	$\bar{X}$	s	n	$\bar{X}$	s	
SL-2	CDR	30	1472	651	28	1382	670	− 6.11
	SPT	30	1814	519	28	1587	674	−12.5
	PLT	30	1664	850	28	1840	749	+10.6
SL-3	CDR	20	1124	374	59	1343	289	+19.5
	SPT	20	1794	599	59	1422	395	−20.7
	PLT	20	2036	680	59	2116	459	+ 3.9
SL-4	CDR	26	1378	372	84	1321	484	− 4.14
	SPT	26	2333	723	84	1622	792	−30.5
	PLT	26	2104	527	84	1863	567	−11.5
N:			228			513		
$\bar{\bar{X}}$:			1748			1611		- 5.72
S_p:			615			570		

TABLE B-II

Two-Way ANOVA With Unbalanced Replicated Measurements

A) Treatment vs. Flights

Source of Variation	df	Sum of Squares ($\times 10^6$)	Mean Squares ($\times 10^6$)	F
Between Flights	2	0.47	0.24	0.57
Between Treatments	1	3.01	3.01	7.21 *
Interaction	2	3.85	1.92	4.61 *
Between Groups	5	7.33	1.47	3.51 *
Within Groups (Error)	735	306.94	0.42	
TOTAL	740	314.27		

B) Treatment vs. Subjects

Source of Variation	df	Sum of Squares ($\times 10^6$)	Mean Squares ($\times 10^6$)	F
Between Subjects	8	52.81	6.60	19.4 **
Between Treatments	1	3.63	3.63	10.6 *
Interaction	8	11.81	1.48	4.3 **
Between Groups	17	67.63	3.98	11.7 **
Within Groups (Error)	723	246.64	0.34	
TOTAL	740	314.27		

* $p < .01$

** $p < .001$

TABLE B-III

ANOVA Computer Results - Fixed Population Model

Group Tested	σ^{+}	df	F Statistic: Treatments	F Statistic: Persons	F Statistic: Interactions
Individual Flights (n=3)			df = 1	df = 2	df = 2
SL-2 (all data)	692	168	0.2	3.64 *	1.26
SL-2 (exclude 1st 5 days)	617	153	4.75 *	4.32 *	2.22
SL-3 (all data)	438	231	0.13	71.42 **	7.43 **
SL-3 (1st month)	494	138	0.70	26.81 **	4.19 *
SL-3 (2nd month)	428	138	0.22	53.94 **	6.50 *
SL-4 (all data)	547	321	18.26 **	34.43 **	7.00 **
SL-4 (1st month)	531	156	5.86 *	29.04 **	2.42
SL-4 (2nd month)	525	156	22.05 **	22.39 **	6.03 *
SL-4 (3rd month)	703	156	14.34 **	14.51 **	5.61 *
Pooled Flights (n=9)				df=8	df=8
All data	584	723	10.63 *	19.35 **	4.33 **
All data (exclude 1st 5 days SL2)	563	708	19.16 **	21.77 **	4.76 **
1st month	585	462	3.95 *	13.81 **	1.90
1st month (exclude 1st 5 days SL2)	552	447	10.41 *	16.40 **	2.29 *
Compare Flights (n=9)				Flights df=2	df=2
All data	646	735	7.21 *	0.57	4.61 *

+ σ^2 = mean square error

* $p < .05$

** $p < .001$

TABLE B-IV

ANOVA Results
Test for Differences Between Preflight and Inflight Means
Fixed Population vs Random Population Models*

	Fixed Population			Random Population		
TEST GROUP	F	df	p	F	df	p
INDIV. FLIGHTS (n = 3)						
SL-2 (all data)	0.2	1/168	NS	0.2	1/2	NS
SL-2 (exclude 1st five days)	4.75	1/153	< .05	2.14	1/2	NS
SL-3 (all data)	0.13	1/231	NS	.02	1/2	NS
SL-4 (all data)	18.26	1/321	< .001	2.61	1/2	NS
POOLED SUBJECTS (n=9)						
All data	10.63	1/723	< .05	2.45	1/8	NS
Exclude 1st five days of SL2	19.16	1/708	< .001	4.20	1/8	< .08

*Fixed Model, F = mean square treatment/mean square error

Random Model, F = mean square treatment/mean square interaction

= F (treatment/F (interaction)

NS = not significant

df = degrees of freedom

p = level of significance

n = number subjects

Preliminary Statistical Analysis

Prior to performing the extensive analysis of variance using over 700 data elements, preliminary statistical analysis was accomplished by using the paired t-test. This was performed for two cases. In the first case, all the data in preflight and inflight phases were considered. In the second case, the same data was used with the exception of excluding the first five days of SL-2 because of the high temperature excursion. The results of both these analyses are shown in Table E.

When all data are considered the results suggest that the observed inflight decrease in evaporative water loss is not significant ($p > .2$) but when the 15 questionable data elements are omitted the acceptability of the results as being real was enhanced ($p < 0.1$).*

Pairing observations in this manner is useful for excluding extraneous factors which can cause or can mask a significant difference in means. In the present case some of these factors might be differences in the size of the individual, number of sweat glands, skin porosity, etc. It is assumed that these factors effect the evaporative loss response in any one subject in the same way (i.e. in a constant additive manner) during preflight and inflight phases. The results of such a test may be generalized to a larger population of individuals. However, the use of paired t-test in the present situation is extremely conservative (having only 8 degrees of freedom) and results in an increase in the probability of accepting the hypothesis (i.e. preflight means = inflight means) when it is false. The fact that there is actually a large number of replicate samples for each subject suggests that a more powerful method might be used to advantage. In addition, a more appropriate analysis technique should consider the unequal sample sizes in each treatment group (ranging from n=20 to n=84). It was for this reason that a two-way analysis of variance model for unequal group sizes was eventually chosen.

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* These results are for a two-tailed interpretation. Inasmuch as the evaporative water loss was expected to be higher inflight, it is legitimate to use a one-tailed test. In this case the probabilities cited should be halved.

In spite of these theoretical arguments, it is interesting to note that the paired t-test (Table B-V)resulted in similar conclusions as the more powerful analysis of variance(Table B-IV)with regard to treatment means extended to a random population. The analysis of variance, however, generated much useful information that was impossible to obtain from a simpler analysis. For example, components of variation between subject means, treatment means and interactions were obtained as well as levels of significance for both fixed and random populations.

TABLE B-V

PAIRED T-TEST ANALYSIS OF EVAPORATIVE LOSS DATA

I. All Data Considered:

Subject	Preflight Mean	Inflight Mean	Difference	Δ%
1	1472	1382	-90	- 6.1
2	1814	1587	-227	-12.5
3	1664	1840	+176	+10.6
4	1124	1343	+219	+19.5
5	1794	1422	-372	-20.7
6	2036	2116	+80	+ 3.9
7	1378	1321	-57	- 4.1
8	2333	1622	-711	-30.5
9	2104	1863	-241	-11.5
$\overline{X}$:	1747	1611	-136	- 5.7
SD:	±381	±276	±292	±15.5

$$t = \frac{135.9}{292.2/\sqrt{9}} = 1.39 \quad (p > 0.2)$$

II. Exclude First Five Days of SL-2:

Subject	Preflight Mean	Inflight Mean	Difference	Δ %
1	1472	1206	-266	-18.1
2	1814	1372	-442	-24.4
3	1664	1725	+ 61	+ 3.7
4	1124	1343	+219	+19.5
5	1794	1422	-372	-20.7
6	2036	2116	+ 80	+ 3.9
7	1378	1321	- 57	- 4.1
8	2333	1622	-711	-30.5
9	2104	1863	-241	-11.5
$\overline{X}$:	1747	1554	-192	- 9.1
SD:	±127	±100	±295	±16.2

$$t = \frac{192}{295/\sqrt{9}} = 1.95 \quad (p < 0.1)$$

Potential Sources of Errors with ANOVA

The particular ANOVA test used in this study was originally developed for the SMEAT experiment. In that case it was sufficient to use a two-way design for different treatments (baseline, inflight, postflight) and different subjects with unequal replicate measurements in each group. Thus, this ANOVA method can easily be adapted for analyzing each Skylab mission separately. However, inasmuch as the entire Skylab experiment really consisted of three flighrs of unequal length it would be more appropriate to consider a three-way ANOVA design with unequal group size for analysis of treatment means (preflight, inflight, postflight), flight means (SL-2, SL-3, SL-4) and subject means (three crewmen per flight). Since this was not available, it was necessary to pool all subjects and flights as described earlier in this report. It is not certain if there was a loss of precision by making this adaptation, but it is not thought to be significant.

One of the assumptions in the use of the analysis of variance F test is that there is homogeneity of variances in each of the groups. This assumption was tested by Bartlett's test which indicated that homogeneity did not exist for the 18 individual subgroup variance (9 crewmen x 2 treatments = 18 cells), but did exist for the two pooled preflight and inflight groups (9 pooled variances in each group). Although the ANOVA technique is normally insensitive to mild deviations away from homogeneity, this result suggested that a log transormation of data be performed prior to analysis. This was done for several test cases and although the F-statistic changed somewhat due to the transformation, general conclusions and levels of significance were similar. Therefore, it was decided to present the analysis without the transformation.

APPENDIX C

ERROR ANALYSIS

ERROR ANALYSIS

Evaporative water loss is an indirect measurement and is subject to the random errors or variation in the directly measured components of the material balance equation. These random errors are the result mainly of two sources of variation: a) variation between daily observations and between subjects due primarily to biological variability, environmental disturbances, etc., and b) variation due to limited instrument resolution. In addition, any factors neglected in the mass balance equation (primarily losses of sweat solids) are a source of systematic error. Inasmuch as the differences in evaporative loss between flight phases were rather small it is important to estimate the magnitude of these errors and, if possible, locate their origins. This information would provide an overall estimate of precision of the material balance method for determining evaporative water loss in the present study. It would also be useful in designing new experiments with improved resolution.

Table I lists the sampling errors ($s_{\bar{x},i}$ = instrument error + biological variability) and the instrument errors (e_i) for each term in the material balance equation. Sampling errors were taken as the standard errors of the mean of each quantity for nine men during the inflight phase. (This statistic was used rather than standard deviation because of our interest in determining estimates in the error of average evaporative loss, $\bar{X}$(Evap), rather than in only a single observation of X_i(Evap)). Instrument errors were obtained by estimating the precision of each instrument from preflight and inflight studies (1,2,3). The percent contribution of the errors associated with each term towards the total variance of sampling errors and instrument errors are also shown in Table I.

Since evaporative loss is given by a linear sum of terms (see Table I, Eq. (a)) the errors in evaporative loss are found by the propagation of errors in each term (Table I, Equations (b,c)). In particular, if the errors in each term are statistically independent of one another (i.e., correlation coefficients are zero) then the average total error associated with $\bar{X}$(Evap) is given by the root sum of squares of the individual errors.

While the assumption of error independence is reasonable in computing total instrument error, this is not the case for total sampling error. For example, it might be expected that variation of water intake would be highly correlated with the variation in urine output. For the case where high correlations exist, a more accurate estimate of $S_{\bar{X}}$(Evap) is given by taking the covariances into account*. The difference between the value of $S_{\bar{X}}$(Evap) in Table I and the corresponding value in Table III (733 vs. 276) arises from the fact that in the former case the covariances were neglected. (Table II contains a more complete estimate of the propagation of errors in which covariances were computed.)

Nevertheless, the simplified analysis of errors provided by Table I is very informative by demonstrating that the errors in computing evaporative water loss are almost entirely due to the total variation associated with measuring water intake and urine. In fact, accounting only for these two variances and the covariance between water intake and urine (correlation coefficient =.946) according to the equation below (*) will produce a value of $S_{\bar{X}}$(Evap) very close to the directly computed standard deviation shown in Table III. Random sampling errors may usually be reduced by including more observations and more subjects. But because of the large contribution of water and urine to the total variability and the high correlation between these quantities the precision of evaporative loss estimated can probably be more easily increased by controlling water intake within smaller limits.

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* If X is composed of a linear sum of terms,

$$X = \sum_i a_i x_i$$

then the variance of X is given by (3):

$$\mathrm{Var}(X) = \sum_i a_i^2 \mathrm{Var}(x_i) + 2 \sum_i \sum_i a_i a_j (\mathrm{Cov}(x_i x_j)$$

On the other hand, the total instrument error can be accounted for almost entirely by the errors associated with the body mass measuring device. The fact that the total error of this term is shown to be somewhat smaller than the instrument error is nonsensical and arises due to an apparent overestimation of the instrument error. In spite of this discrepancy it can be reasonably assumed that, unlike the other terms used to compute evaporative loss, the instrument error constitutes a large fraction of the sampling error in measuring weight changes with this device. This follows from the expectation that average daily changes in body weight measured over long periods of time would be small and similar among any group of healthy individuals. Hence, the instrument error and sampling error of the body mass measurement could both be reduced by improving the precision of this instrument rather than by increasing sample size. However, this approach would not be of much consequence to the final results since the total instrument error is such a small component of total sampling error and since the mean value and total error of the weight change measurements constitutes a small fraction of the final value of evaporative loss and its total error. The instrument error analysis also illustrates that the limiting resolution of the material balance technique in measuring evaporative water loss on Skylab (in the absence of significant biological fluctuations) is ~~about~~ $\pm$ 70 gms which represents approximately a 4% error.

Systematic errors in the present technique are essentially associated with neglect of less significant terms in the material balance equation. In particular, failure to account for sweat solids, sebaceous residues and desquamated epithelium would systematically cause the calculated evaporative loss to be overestimated by about 12-22 gm/day (5,6). This is a negligible fraction of the total evaporative loss, but could account for about 50% of the discrepancy found between the mass balance and water balance techniques (see Table IV). The water balance method, of course, does not require accounting for these solid residues. However, uncertainties in other measured quantities may also account for this disagreement. Thus, it is not believed that serious systematic errors are present in the estimation of evaporative loss in the present study.

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TABLE C-I

PROPAGATION OF ERROR ANALYSIS OF MASS BALANCE EQUATION IN DETERMINING EVAPORATIVE WATER LOSS

i	Quantity	Inflight Mean $\overline{X}_i$	TOTAL ERROR: Standard Error $S_{\bar{x},i}$	TOTAL ERROR: Total Error Contribution $S^2_{\bar{x}i}/S^2_{\bar{x}} \times 100$	INSTRUMENT ERROR: Instrument Error E_i	INSTRUMENT ERROR: Instrument Error Contribution $E_i^2/E^2 \times 100$
1	Food (wet)	1063	± 150	4.2%	± 3	0.2%
2	Water (drink)	2389	± 571	60.6%	± 10	2.3%
3	Urine x ρ	1612	± 432	34.7%	± 10	2.3%
4	Feces (wet)	92	± 23	0.1%	± 3	0.2%
5	$(CO_2 - O_2)$	192	± 28	0.1%	± 10	2.3%
6	Wgt.	-53	± 38	0.3%	± 64	92.7%
		$\overline{X}$ (Evap) = 1609	$S_{\bar{x}} = \pm 733$	100.0%	$E = \pm 66$	100.0%

$$\overline{X}\,(\text{Evap}) = \overline{X}_1 + \overline{X}_2 - \overline{X}_3 - \overline{X}_4 - \overline{X}_5 - \overline{X}_6$$ (Mass Balance Equation) (a)

$$S^2_{\bar{x}}(\text{Evap}) = \sum_{i=1}^{6} S^2_{\bar{x},i}$$ (Propagation of Sampling Errors) (b)

$$E^2(\text{Evap}) = \sum_{i=1}^{6} E_i^2$$ (Propagation of Instrument Errors) (c)

* Means and Standard errors shown are pooled values for all inflight observations on all nine subjects, unless otherwise noted units are in grams.

TABLE C-II

A) Correlation Coefficients for Inflight Data Used in Mass Balance Equation

	Food	Water	Urine	Feces	(CO_2-O_2)	ΔWgt.
Food	1.00					
Water	0.17	1.00				
Urine	0.19	0.95*	1.00			
Feces	0.71*	0.23	0.13	1.00		
CO_2-O_2	0.97*	0.05	0.11	0.78*	1.00	
Δ Wgt.	-0.30	-0.02	0.17	-0.43	0.19	1.00

B) Variances and Covariances $(X\,10^{-3})$

*p < .05

		Food	Water	Urine	Feces	(CO_2-O_2)	ΔWgt
Variances S_i^2	Food	22.5	326	187	0.53	0.78	1.44
Covariances S_{ij}	Water	14.5	–	–	–	–	–
	Urine	12.5	233	–	–	–	–
	Feces	2.46	3.06	1.29	–	–	–
	CO_2-O_2	4.08	0.81	-1.29	0.51	–	–
	Δ Wgt.	-1.73	-3.32	-2.78	-3.76	-0.21	–

$a_1 = a_2 = +1$

$a_3 = a_4 = a_5 = a_6 = -1$

$$S^2(\text{Evap}) = \sum_{i}^{6} a_i\, S_i^2 + 2 \sum_{i}^{6} \sum_{i}^{6} a_i\, a_j\, S_{ij}$$

$$= 537289 - 479483 = 57806$$

$S(\text{Evap}) = 240$

TABLE C-III

EVAPORATIVE WATER LOSS ANALYSIS

Flight	Subject		Preflight Wgt(kg)	Preflight ml/day	Preflight ml/day-kg	Inflight Wgt(kg)	Inflight ml/day	Inflight ml/day-kg
SL2	CDR		62.21	1472	23.66	61.16	1382	22.60
	SPT		77.89	1814	23.29	75.62	1587	20.99
	PLT		80.18	1664	20.75	78.47	1840	23.45
		Mission Means*:		1650 $\pm$99	22.57 $\pm$0.91		1603 $\pm$132	22.35 $\pm$0.72
SL3	CDR		68.56	1124	16.39	66.20	1343	20.29
	SPT		61.83	1794	29.02	58.89	1422	24.15
	PLT		88.01	2036	23.13	85.67	2116	24.70
		Mission Means:		1651 $\pm$273	22.85 $\pm$3.65		1627 $\pm$246	23.05 $\pm$1.39
SL4	CDR		67.75	1378	20.34	67.51	1321	19.57
	SPT		71.51	2333	32.62	69.33	1622	23.40
	PLT		67.61	2104	31.12	65.89	1863	28.27
		Mission Means:		1938 $\pm$288	28.03 $\pm$3.87		1602 $\pm$157	23.75 $\pm$4.36
		Skylab Means: (N = 9)		1747 $\pm$127	24.48 $\pm$1.79		1611 $\pm$92	23.05 $\pm$0.88

$$\sqrt{\frac{\sum^{K}(\overline{X}_i - \overline{\overline{X}})^2}{K\,(K-1)}} \quad K = 9$$

sd = 92 x 3 = 276

= standard error of sample mean

TABLE C-IV

Comparison of Two Methods for Determining Evaporative Water Loss

SUBJECT	Preflight					Inflight				
	Δt* days	TBW ml/day	W ml/day	M ml/day	Δ	Δt days	TBW ml/day	W ml/day	M ml/day	Δ
SL2/CDR	20	-25.0	1307	1316	-9	29	-17.2	1344	1390	-46
SL2/SPT	20	+40.0	1726	1790	-64	30	-40.0	1515	1620	-105
SL2/PLT	20	-15.0	1656	1702	-46	29	-69.0	1770	1824	-54
SL4/CDR	20	+5.0	1390	1398	-8	85	-10.6	1318	1326	-7
SL4/SPT	20	+10.0	2253	2299	-46	85	-7.1	1604	1637	-33
SL4/PLT	20	+35.0	2050	2132	-82	85	-10.6	1859	1858	+1
MEAN $\pm$ SD			1730 368	1773 390	-43 -30			1568 220	1609 218	-40 -37

*Δt = time between TBW Measurements; TBW = ΔTBW (Measured)/Δt; W = Evaporative water loss from water balance = Total fluid intake + Met. H_2O - Total fluid excretion - TBW; M = Evaporative water loss from mass balance; Δ = W - M

APPENDIX D

PREDICTIONS OF EVAPORATIVE WATER LOSS FROM A SIMULATION MODEL OF THE HUMAN THERMOREGULATORY SYSTEM

APPENDIX D

PREDICTIONS OF EVAPORATIVE WATER LOSS FROM A SIMULATION MODEL OF THE HUMAN THERMOREGULATORY SYSTEM

A mathematical model of the human thermoregulatory system has been in use at the Johnson Space Center for several years. As described earlier in this paper, it has been utilized, quite effectively, for predicting the thermal loads imposed on man during various activities. This information has been useful for designing thermal comfort specifications for space suits and environmental control systems of large chambers such as the Skylab workshop. The model has undergone several phases of development and most recently it has been validated for predicting evaporative water losses in 1-g environments during simulated spacecraft activities. The results from the present study, particularly those regarding evaporative loss estimates, will be extremely useful in validating the model for weightlessness conditions. A preliminary step in this direction is presented below where the model has been used to predict evaporative loss rates for a single Skylab crewmember based on inflight records of environmental and metabolic parameters. These results are compared to observed inflight losses as calculated from the mass balance technique.

The thermoregulatory model is a deterministic model based on a total heat balance and physiological mechanisms involved in controlling body temperature. Environmental parameters such as temperature, humidity, pressure, and air velocity are considered as well as physiological parameters such as metabolic rate, tissue heat capacities and conductivities, blood flows, and central nervous system controller sensitivities. Forty-one tissue compartments are specified in the model. Heat transport equations are included to account for heat exchange by radiation, convection and evaporative losses via the respiratory tract, skin diffusion and sweating. Thermoregulation is simulated by integrating central and skin temperatures which produces the necessary drives for controlling skin blood flows, shivering and sweating. Simulation of exercise causes appropriate changes in respiration and muscle blood flow. The model is capable of being operated either in a dynamic mode in which short term transient effects may be simulated or in a steady-state mode. The model is presently programmed on the Univac 1110 computer at the Johnson Space Center and simulations may be performed in conversational fashion at remote terminals.

At present the model is validated for 1-g simulations, and has been tested successfully for various environmental situations over a large range of metabolic activities. While validation is relatively complete for sea level barometric pressure, data are still lacking for testing the model under simulated hypobaric conditions at high metabolic rates. For this reason the results presented below for the reduced pressure simulations should be considered preliminary.

Table D-I lists the input parameters to the model that were based on inflight records for the second Skylab mission. Six separate simulations were performed for each of the six basic activities shown. Metabolic rates for sleep and gymnastic activity were estimated from average values found in the literature, while bicycle ergometry and EVA rates were measured directly inflight. The metabolic rate for "routine work" (which accounts for the largest fraction of daily evaporative loss) was based on a caloric balance on the nutrients consumed during the flight. This table also indicates the capability of this model for considering a large number of input parameters, thereby describing a given environmental and metabolic situation in considerable detail.

The evaporative losses predicted by the model are shown in Table D-2 for two different ambient pressures – 760 torr and 264 torr – the latter case representing the Skylab environment. The model's output is in the form of an evaporative rate (gm/hr) which must be multiplied by the appropriate time period for each particular activity; these times are shown in the first two columns and are based on inflight records for the selected crewman. The average daily evaporative loss rate predicted by the model for the two ambient pressures is compared with the preflight and inflight values obtained from

TABLE D-I

VALUES OF INPUT PARAMETERS FOR HUMAN THERMOREGULATORY SIMULATION MODEL

(A) Activity Parameters

PARAMETER	SLEEP	ROUTINE WORK	ERGOMETRY LEG	ERGOMETRY ARM	GYM	EVA
			ACTIVITY			
*Metabolic Rate (kcal/hr)	75	109	630	405	350	230
Work Efficiency (%)	0	5	22	22	10	10
Clothing Resistance (clo)	1.0	0.35	0.2	0.2	0.2	0.6
Position: 0 = seated 1 = standing	1	0.5	0	0	1	1

*Estimated from inflight records for SL-3/CDR

(B) Environmental Parameters

Ambient Temperature	=	73°F	=	23°C
Wall Temperature	=	73°F	=	23°C
Ambient Dewpoint	=	52°F	=	11°C
Ambient Pressure	=	5.1 psia	=	264 torr
Air Velocity	=	40 ft/min	=	0.20 m/sec
Atm. Specific Heat	=	0.22 kcal/kg-C°		
Body Emissivity	=	0.95		

TABLE D-II

EVAPORATIVE WATER LOSSES PREDICTED BY HUMAN THERMOREGULATORY SIMULATION MODEL FOR SUBJECT SL-3/CDR FOR INFLIGHT ACTIVITIES AT TWO AMBIENT PRESSURES

			PREDICTED EVAPORATIVE WATER LOSS				
ACTIVITY	HRS/DAY*	DAYS*	GM/HR		GM/MISSION		
			760 torr	264 torr	760 torr	264 torr	Δ%
Sleep	8	58	17.7	20.1	8213	9326	14
Routine Work	15.3	59	32.1	48.8	28977	44052	52
Leg Ergometry	0.54	46	662	738	16444	18332	12
Arm Ergometry	0.092	6	375	431	207	238	15
Gymnastics	0.38	40	368	420	5594	6384	14
EVA	2.68	1	173	213	464	571	23
TOTAL MISSION EVAPORATIVE LOSS (59 DAYS)					59899	78903	
AVERAGE DAILY EVAPORATIVE LOSS: SIMULATION MODEL					1015	1337	32%
*DATA					Preflight	Inflight	
MASS BALANCE					1136	1344	18%
WATER BALANCE					1082	1272	18%

*Estimated from inflight records for SL-3/CDR

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experimental data using a mass and water balance. The simulated results for the low pressure situation is excellent, well within several percent of the experimental inflight values. While the simulated results at atmospheric pressure are also in good agreement with the preflight data it must be remembered that the simulation was not designed to duplicate the preflight case. Unfortunately, physical activity and environmental conditions were not controlled variables during preflight and there is insufficient data to quantify these conditions as we have done with the inflight period.

It is not apparent from this example that evaporative losses were lower than would be expected in a hypobaric environment as was suggested by the data of all Skylab crewmembers. The SL-3/CDR crewmember was one of two subjects that showed an increase in average inflight evaporative loss compared to preflight. Seven of the nine astronauts showed inflight decreases. The simulation does reveal, however, that the hypobaric effect is to increase evaporative loss by 32% for this particular set of metabolic protocol and environmental conditions. The increase actually observed between preflight and inflight was only 18%. A similar analysis for the other crewmen may reveal a clearer trend.

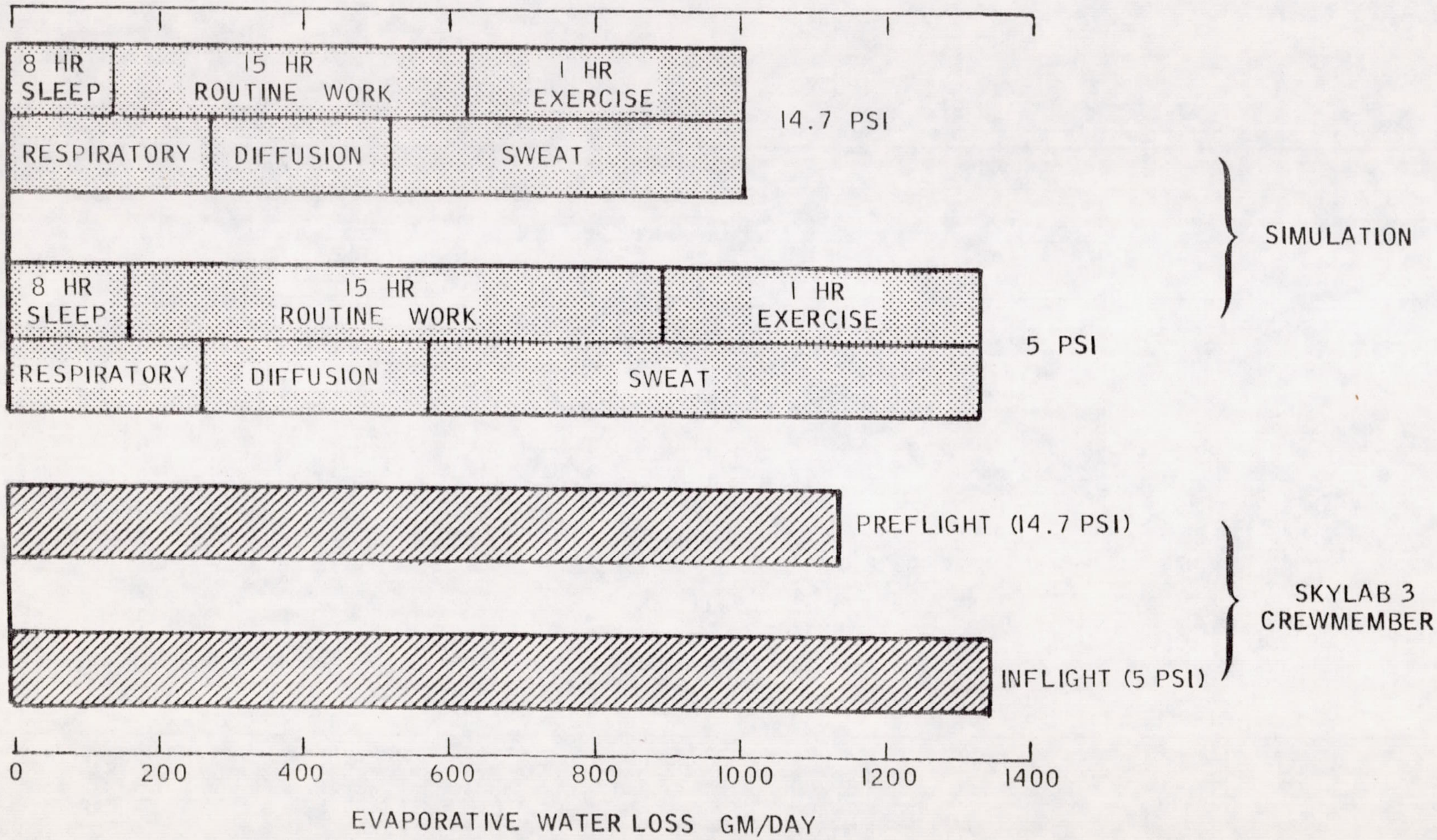
While the mass and water balance studies have provided an overall estimate of daily evaporative losses, the model used in this predictive fashion is capable of revealing the components of this total loss. Table D-3 lists the contribution to the total evaporative loss that may be assigned to each major activity and to each evaporative loss pathway. The values shown have been obtained from the simulation, previously described, at 264 torr. The model predicts that 32% of the total evaporative loss can be attributed to less than an hour/day of exercise. In addition, 57% of the total loss is derived from thermal sweating, half this amount being given off during routine work at reasonably low levels of metabolism.

Figure D-1 shows these components of evaporative water loss predicted by the model and compares the daily water loss rate with that of a Skylab crewmember. (This is the same subject whose data were used in Table D-2). Figure

TABLE D-III

RELATIVE CONTRIBUTION OF MAJOR ACTIVITIES
AND EVAPORATIVE PATHWAYS TO TOTAL
SIMULATED EVAPORATIVE LOSS
AT 264 TORR

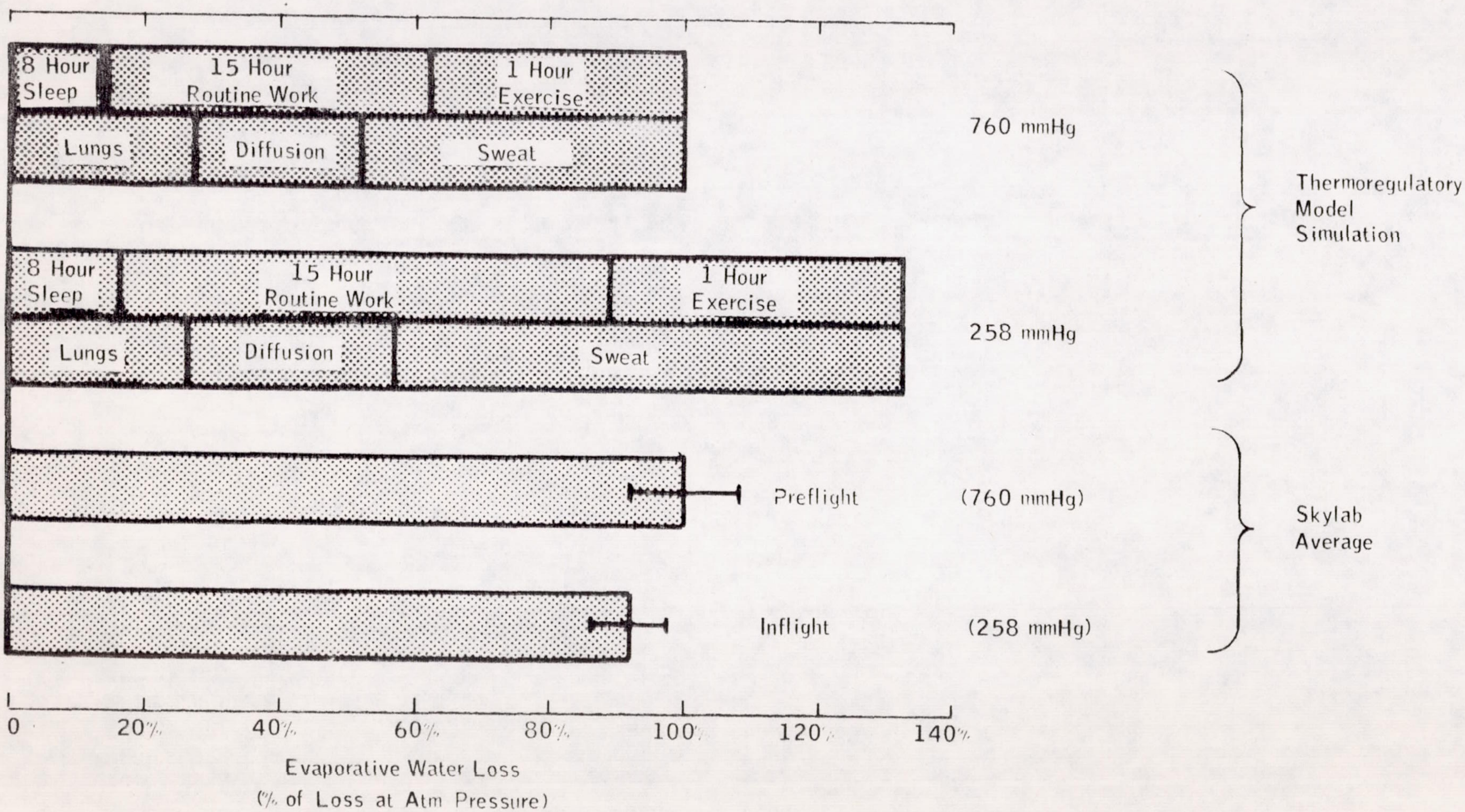
	RESPIRATION	DIFFUSION	SWEAT	TOTAL
SLEEP (8 HRS)	4.4%	7.4%	0.0%	11.8%
ROUTINE WORK (15.7 HRS)	12.5%	15.4%	27.9%	55.8%
EXERCISE (0.7 HRS)	2.8%	0.4%	29.2%	32.4%
TOTALS	19.7%	23.2%	57.1%	100.0%



EFFECT OF AMBIENT PRESSURE AND SPACE FLIGHT ON DAILY EVAPORATIVE WATER LOSS
SIMULATION VS. CREW DATA
SHOWING CAPABILITY OF SIMULATION MODEL TO PREDICT COMPONENTS
OF EVAPORATION

FIG. D-1

D-2 shows the same model prediction, this time in comparison with the average experimentally derived values for the entire nine-man Skylab crew. The predictions of the model are in agreement with the 1-g hypobaric chamber studies (see Appendix A), but do not agree with zero-g data on the average. This suggests that additional thermoregulatory mechanisms may be needed in a model validated for zero-g. These may include effects on sweat dripping, lack of natural convection, sweat suppression, etc.



PREDICTED EFFECT OF AMBIENT PRESSURE ON EVAPORATIVE WATER LOSS VS. MEASURED SKYLAB CREW AVERAGE

FIG. D-2

APPENDIX E

APPENDIX E-1

COMPONENTS OF METABOLIC BALANCE FOR EACH SKYLAB CREW MEMBER

MEASURED VARIABLES USED IN BALANCE EQUATIONS

FLIGHT	CREWMAN	TOTAL WATER INGESTED		FOOD DRY		DIET PROTEIN		DIET FAT		DIET CARBOHYDRATE		URINE		FECAL WATER		FECAL SOLIDS	
		PRE	IN	PRE	IN	PRE	IN	PRE	IN	PRE	IN	PRE	IN	PRE	IN	PRE	IN
SL2	1	2500	2405	555.6	583.8	104.6	101.9	104.9	81.3	318.5	377.8	1340	1509	81.0	66.6	18.4	19.4
	2	2316	2239	619.3	619.1	107.9	105.9	101.2	82.2	382.3	408.9	849	1207	90.6	64.6	28.4	23.0
	3	4008	4089	609.8	592.6	109.8	99.0	109.0	73.9	364.4	396.5	2642	2757	63.5	77.2	23.7	20.5
MEAN±SE		2941 ±536	2911 ±591	594.9 ±19.8	598.5 ±10.6	107.4 ±1.5	102.3 ±2.0	105.0 ±2.3	79.1 ±2.6	355.1 ±19.0	394.4 ±9.0	1610 ±535	1824 ±474	78.4 ±7.9	69.5 ±3.9	23.5 ±2.9	21.0 ±1.1
SL3	1	2214	2175	544.6	608.8	95.1	87.3	98.1	67.7	331.2	434.7	1392	1169	45.1	45.3	18.1	20.1
	2	2594	2554	560.7	593.1	112.4	111.6	110.1	78.7	315.4	381.0	1110	1453	91.5	74.8	23.8	24.6
	3	3227	3282	819.2	857.3	162.6	154.9	131.8	79.6	489.8	589.3	1498	1535	133.3	115.9	33.6	35.2
MEAN±SE		2678 ±295	2670 ±325	641.5 ±89.0	686.4 ±85.6	123.4 ±20.2	117.9 ±19.8	113.3 ±9.9	75.3 ±3.8	378.8 ±55.7	468.3 ±62.4	1333 ±116	1386 ±111	90.0 ±25.5	78.7 ±20.5	25.2 ±4.5	26.6 ±4.5
SL4	1	2888	2630	617.3	641.5	120.7	118.5	108.2	100.6	363.1	398.6	1739	1635	128.6	75.8	31.2	28.4
	2	3325	2797	600.1	622.5	112.5	111.4	107.5	92.0	357.6	395.7	1350	1513	55.7	53.2	24.1	20.1
	3	3667	3433	615.6	650.7	126.9	130.0	115.8	110.6	348.4	386.1	1892	1896	47.2	53.6	22.8	24.3
MEAN±SE		3293 ±225	2953 ±245	611.0 ±5.5	638.2 ±8.3	120.0 ±4.2	120.0 ±5.4	110.5 ±2.7	101.1 ±5.4	356.4 ±4.3	393.5 ±3.8	1660 ±161	1681 ±113	77.2 ±25.8	60.9 ±7.5	26.0 ±2.6	24.3 ±2.4
TOTAL MEAN±SE		2971 ±208	2845 ±212	615.8 ±27.2	641.0 ±28.1	116.9 ±6.5	113.4 ±6.6	109.6 ±3.3	85.2 ±4.5	363.4 ±17.5	418.7 ±22.1	1535 ±172	1630 ±158	81.8 ±10.9	69.7 ±6.9	24.9 ±1.8	24.0 ±1.7

APPENDIX E-2

DERIVED DATA USED IN BALANCE EQUATIONS

FLIGHT	CREWMAN	DAYS PRE	DAYS IN	METABOLIC WATER PRE	METABOLIC WATER IN	INSENSIBLE GAS LOSS (CO_2-O_2) PRE	INSENSIBLE GAS LOSS (CO_2-O_2) IN	CHANGE IN BODY WEIGHT PRE	CHANGE IN BODY WEIGHT IN
SL2	1	30	23	330	339	148.1	174.8	-30.0	-17.4
	2	30	23	364	359	176.5	188.9	-46.7	-30.4
	3	30	23	363	341	168.6	182.9	-56.7	-117.4
MEAN±SE				352 ±11	346 ±6	164.4 ±8.5	182.2 ±4.1	-44.5 ±7.8	-55.1 ±31.4
SL3	1	20	54	327	352	152.6	198.0	+5.0	-24.1
	2	20	54	337	342	147.7	177.9	-35.0	-24.1
	3	20	54	478	479	229.8	275.0	+80.0	-29.6
MEAN±SE				381 ±49	391 ±44	176.7 ±26.6	217.0 ±29.6	16.7 ±3.4	-25.9 ±1.8
SL4	1	26	79	365	377	169.8	185.3	+30.8	+10.1
	2	26	79	358	364	166.1	183.4	-30.8	-7.6
	3	26	79	367	385	163.9	181.1	.000	+8.9
MEAN±SE				363 ±3	375 ±6	166.6 ±1.7	183.0 ±1.2	0.0 ±17.8	3.8 ±5.7
TOTAL MEAN±SE				365 ±15	371 ±15	169.2 ±8.3	194.1 ±10.4	-9.3 ±14.5	-25.7 ±12.5