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SUBJECT Energy Balance and the Composition of Weight Loss During Prolonged Space Flight

An invariable finding in manned space flight studies is a significant loss of body weight. Interpretation of this weight loss was made easier by the biomedical investigations on Skylab. The attached study integrates all of the relevant data in a more definitive manner than has been heretofore available, and directly addresses the question "why do astronauts lose weight in space?" This study report completes an extensive analysis of space flight metabolic balance data that was begun before the last Skylab crew returned to Earth. The objective of the entire effort was to characterize the changes in body composition and biochemical balance that results from exposure to weightlessness. Thus, the approach for this integrated data analysis was based on fundamental equations of conservation for mass, water, and energy. A complete water balance study, including evaporative water loss estimations, formed the initial study of this series. Others included sodium, potassium, nitrogen, and energy balance. Not only were each of these data analysis studies useful in their own right, but an accompanying systems analysis effort sought to integrate this data as a means of rigorously defining the behavior of the fluid-electrolyte regulating system in weightlessness. A foreword to this report summarizes the scope and approach of this overall effort.

J. I. Leonard

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ENERGY BALANCE AND THE COMPOSITION OF WEIGHT LOSS DURING PROLONGED SPACE FLIGHT

Prepared for

National Aeronautics and Space Administration

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October 1982

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ABSTRACT

An invariable finding in manned space flight studies is a significant loss of body weight after only several days exposure to weightlessness. Interpretation of this weight loss was made easier by the biomedical investigations on Skylab which consisted of inflight body mass measurements, metabolic balance studies, and postflight determinations of whole-body changes in water, potassium, and density. This study integrates all of the relevant data in a more definitive manner than has been heretofore available. The approach for the analysis is based on fundamental equations of conservation for mass, water, and energy. A new technique for analyzing this metabolic balance data was developed which permits cumulative balances to be computed without incurring the large errors that are normally obtained when this is done. The result is a continuous-time profile of daily total body changes of water, protein, and fat throughout the mission and addresses the question "why do astronauts lose weight in space?" Each of the three Skylab missions is treated separately and factors that were not identical on each flight (such as exercise, diet, and mission duration) are examined for their effect on body weight loss.

The findings presented here for the Skylab crews suggest that all the major components of body composition (water, protein, and fat) undergo significant changes in space flight. The results appear consistent with the concept that there is an acute obligatory loss of body water in weightlessness (a response to headward fluid shifts) and a more gradual degradation of certain postural muscles (a response to disuse of weight-bearing and locomotion functions). Changes in body fat appear to depend on the gradual cumulative effects of a positive or negative energy balance; in most Skylab crewmen fat loss was significantly high at the end of one month of flight, suggesting an inadequate diet. Those crewmen who exhibited the space motion sickness syndrome demonstrated higher losses of body water and fat, presumably because of temporary eating and drinking restrictions. Energy requirements in Skylab did not appear to be less than required to maintain body weight on the ground for similar levels of physical activity, contrary to former expectations. Also, exercise did not seemingly abate the loss of body protein. Although this analysis provides only indirect estimates of inflight tissue and fluid losses, it is being reported because it is unlikely that direct inflight measurements of body composition changes will be accomplished in the near future.

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FOREWORD

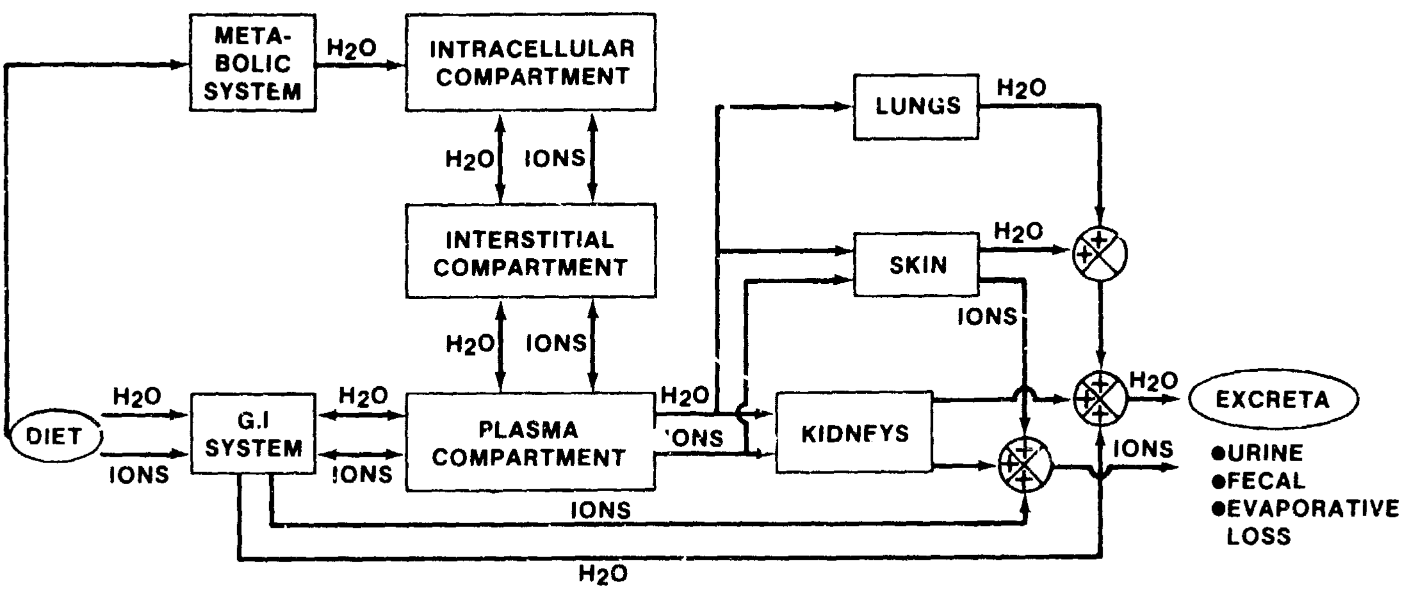
Integrated Metabolic Balance Analysis

This paper represents the culmination of a series of analytical studies designed to characterize the major fluid, electrolyte, and metabolic changes in the Skylab crewmembers. As illustrated in Figure F-1, the fluid and electrolyte system may be characterized by the volume of the major fluid compartments (plasma, interstitial, and intracellular), the electrolyte concentrations (primarily sodium and potassium) in these compartments, and the metabolic input and output flowpaths for water and ions (dietary inputs, metabolic water generated, fecal loss, urine excretion, evaporative loss). Some of these quantitites or fluxes were measured directly either during the flight on a daily basis (as in the case of water and electrolyte balance studies), at frequent intervals (as in the case of plasma concentrations), or at the beginning and end of flight (as in the case of body fluid compartments). The specific measurements used in this analysis are summarized in Figure F-2. It was the objective of this overall study to assemble this diverse and voluminous collection of data, develop the appropriate analytical techniques, and produce three categories of results: a) complete partitional metabolic balances for water, sodium, potassium, nitrogen, and energy; b) time-continuous profiles of the various volumes, concentrations, and metabolic fluxes as indicated in Figure F-1; and c) a quantitative explanation of body weight loss in space flight showing dynamic behavior of body water, body protein, and body fat.

The integrated metabolic balance approach that developed is illustrated schematically in Figure F-3. This approach was based on fundamental equations of conservation for mass, water, and energy, and enabled a comprehensive characterization of body changes which occur during extended space flight. Some quantities listed in Figure F-3 were not measured directly, or were measured very infrequently. These included body water, body sodium, body nitrogen, body fat, evaporative losses, and metabolic water. Application of standard metabolic balance analysis combined with several new techniques permitted these quantities to be derived in sufficient resolution

FIGURE F-1

MAJOR ROUTES OF FLUID-ELECTROLYTE METABOLISM



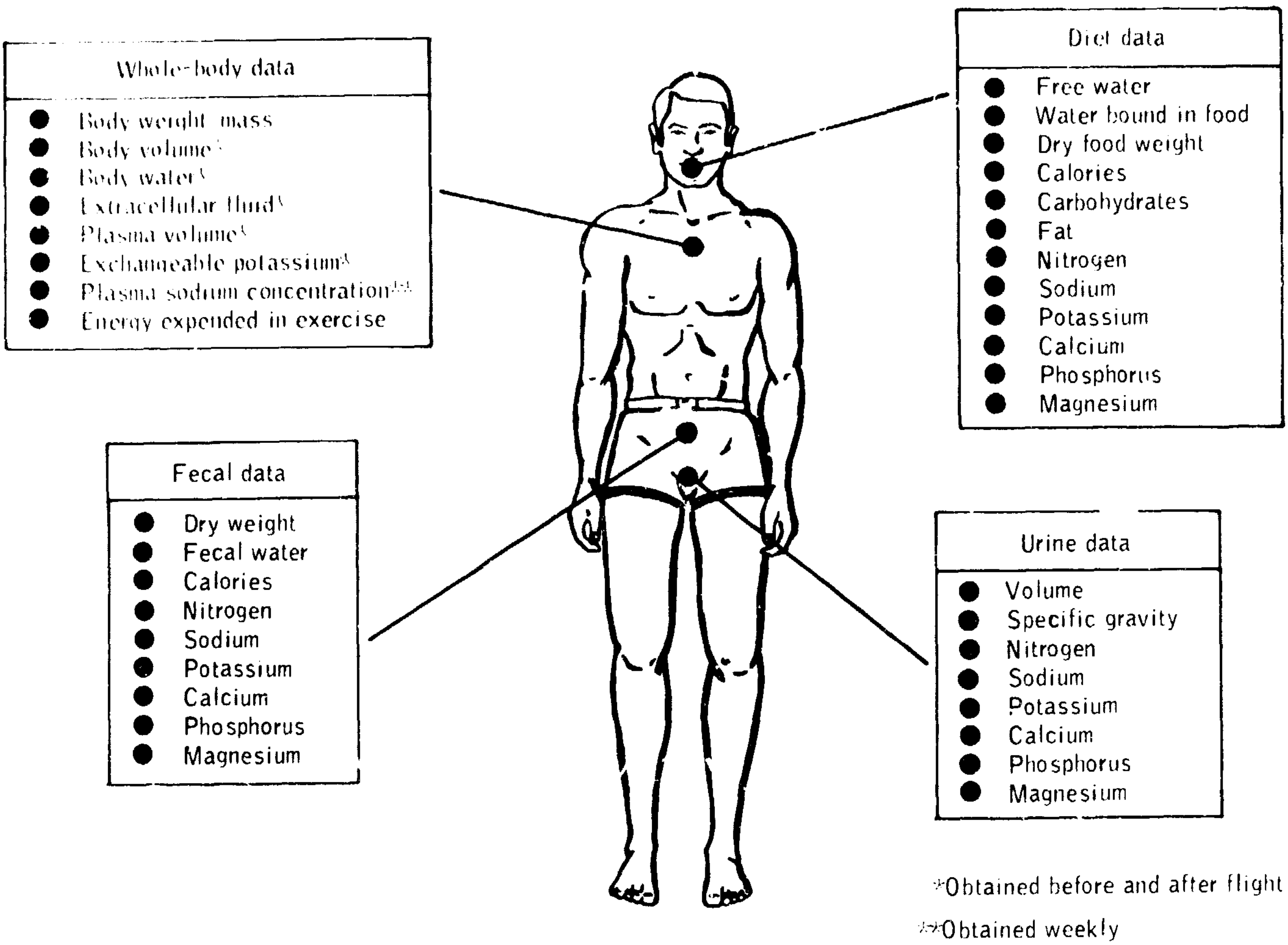


FIGURE F-2

METABOLIC BALANCE DATA COLLECTED ON SKYLAB CREW

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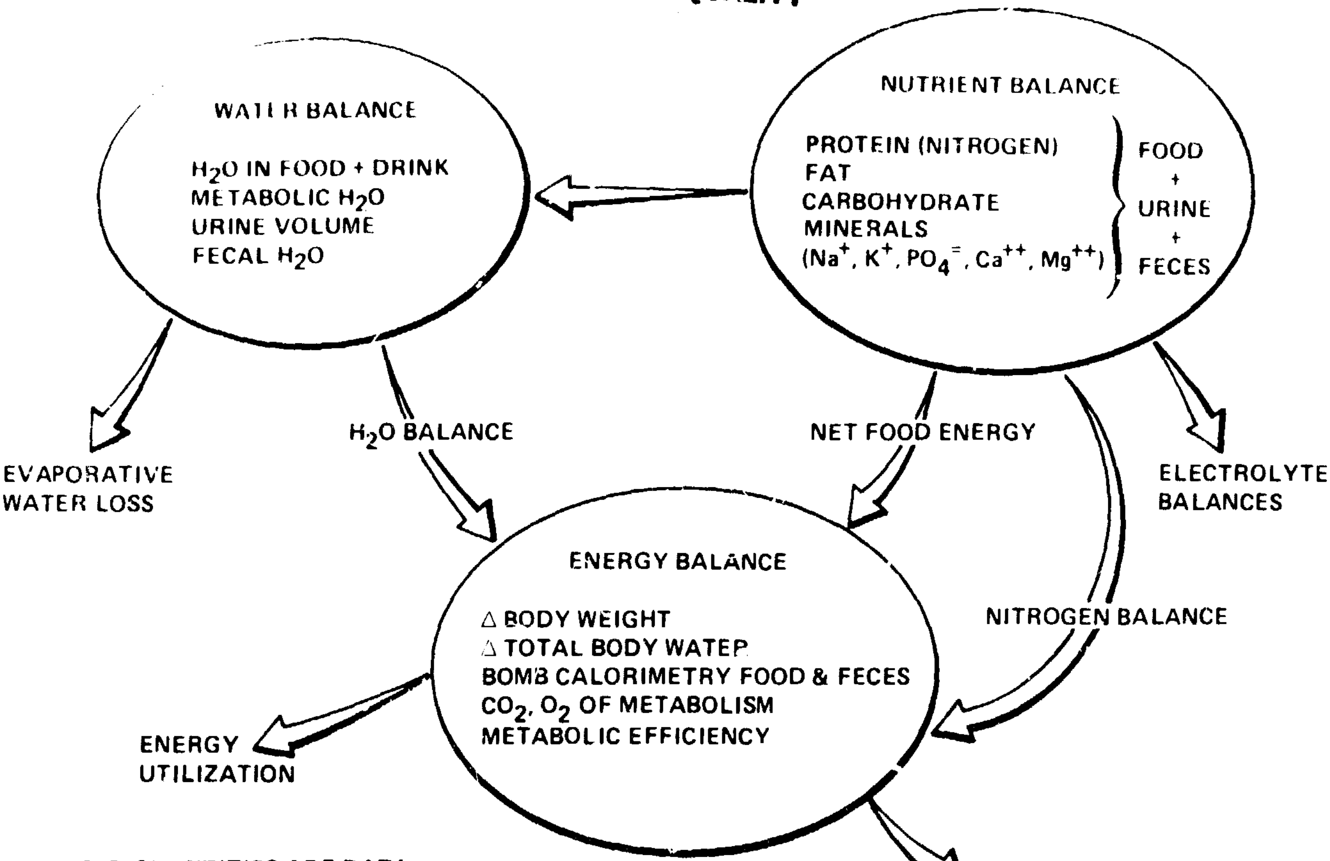

ENCLOSED QUANTITIES ARE DATA REQUIRED TO DERIVE OUTPUT QUANTITIES USING METABOLIC BALANCE EQUATIONS.

INTEGRATED METABOLIC BALANCE ANALYSIS

FIGURE F-3

so as to provide their time-varying behavior as well. One of these new techniques was based on combining metabolic balance and total body determinations of a specified quantity in such a manner as to allow cumulative balances to be computed without accumulating the large statistical errors that normally occur when this is done. A second innovative technique that was employed was the use of a mathematical model of whole-body fluid-electrolyte regulation. Computer simulation of this model for a weightlessness state, driven by the recorded crew dietary intake of water and salt, resulted in plausible estimates of daily changes in such quantities as the major fluid compartments, evaporative losses, electrolyte concentrations, and the hormones that regulate renal excretion (Figure F-4). Some of these parameters were not amenable to experimental measurement, and therefore, these model predictions complemented the collection of data. Also, the mathematical model provided a means to understand the feedback control mechanisms which regulate the volumes and fluxes illustrated in Figure F-1. By this dual approach (data analysis and model simulation), it was possible to interpret the Skylab metabolic balance findings in terms of a holistic theory of body fluid-electrolyte regulation as it is affected by weightlessness.

The present report addresses the question "why do astronauts lose weight in space"? This question is answered in terms of changes in body composition and energy balance. Figure F-5 illustrates the mass and energy balance factors which enter into the equation describing body mass changes. The changes in body mass can be discussed from several vantage points as shown in this figure. From an energy balance viewpoint, the loss of body tissue, particularly body fat, implies an imbalance between caloric intake (diet) and caloric output (basal metabolism + exercise). From a mass balance viewpoint, body mass can change in accord with alterations in three major substances: muscle (dry), fat, and water. The changes in body water, in turn, can be said to be caused by changes in one or more components of the water balance: intake, metabolic water, urine, fecal water, and evaporation. Also, it is possible to trace the loss of body water to the major fluid compartments of the body, as shown in Figure F-5. All of these viewpoints are discussed in this report using the extensive Skylab data base to provide the information necessary to integrate the energy balance, mass balance, water balance and body fluid volumes of the astronauts.

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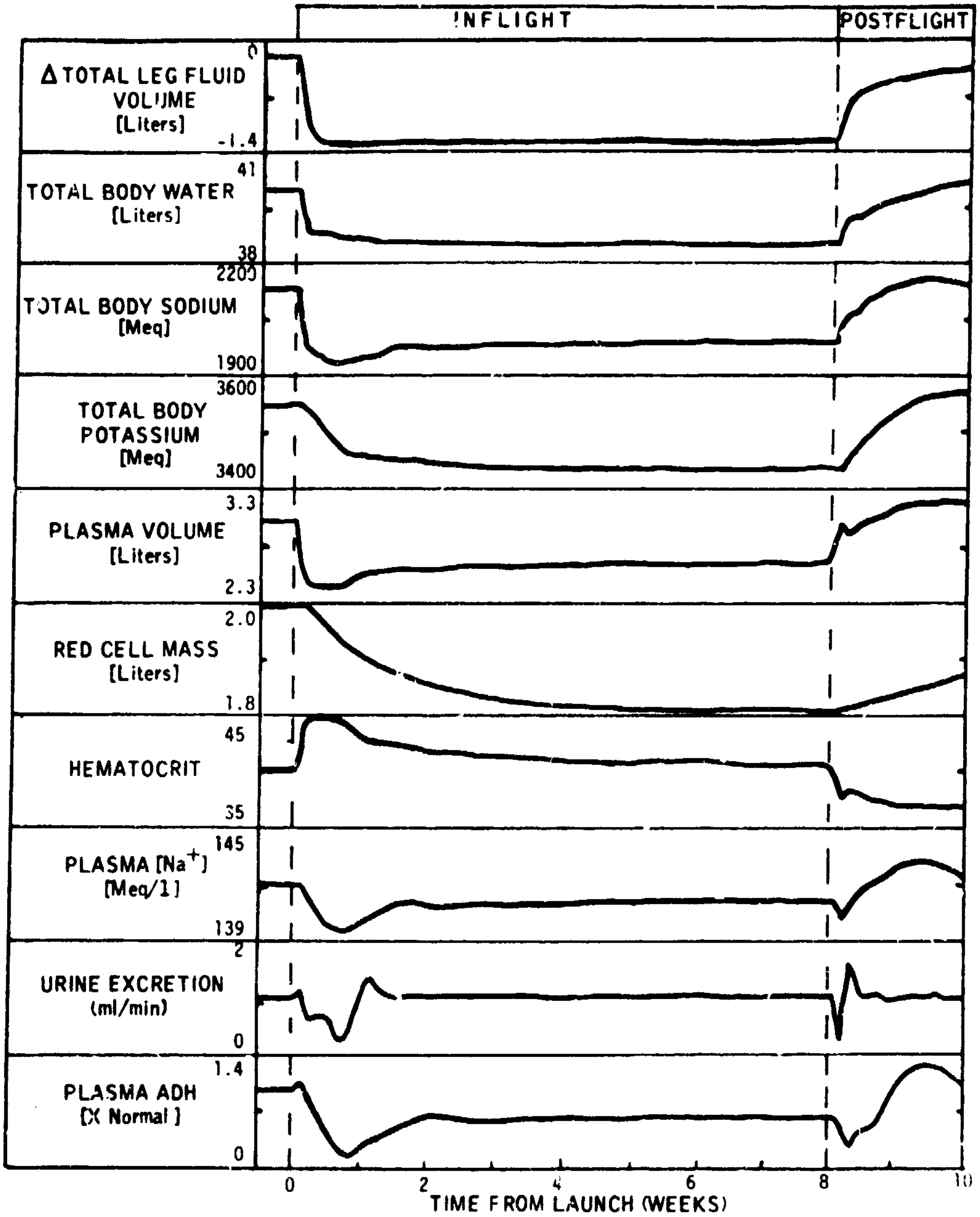
FIGURE F-4

SIMULATION OF COMPOSITE SKYLAB MISSION



BODY COMPOSITION AND ENERGY BALANCE FACTORS RELATED TO BODY MASS CHANGES

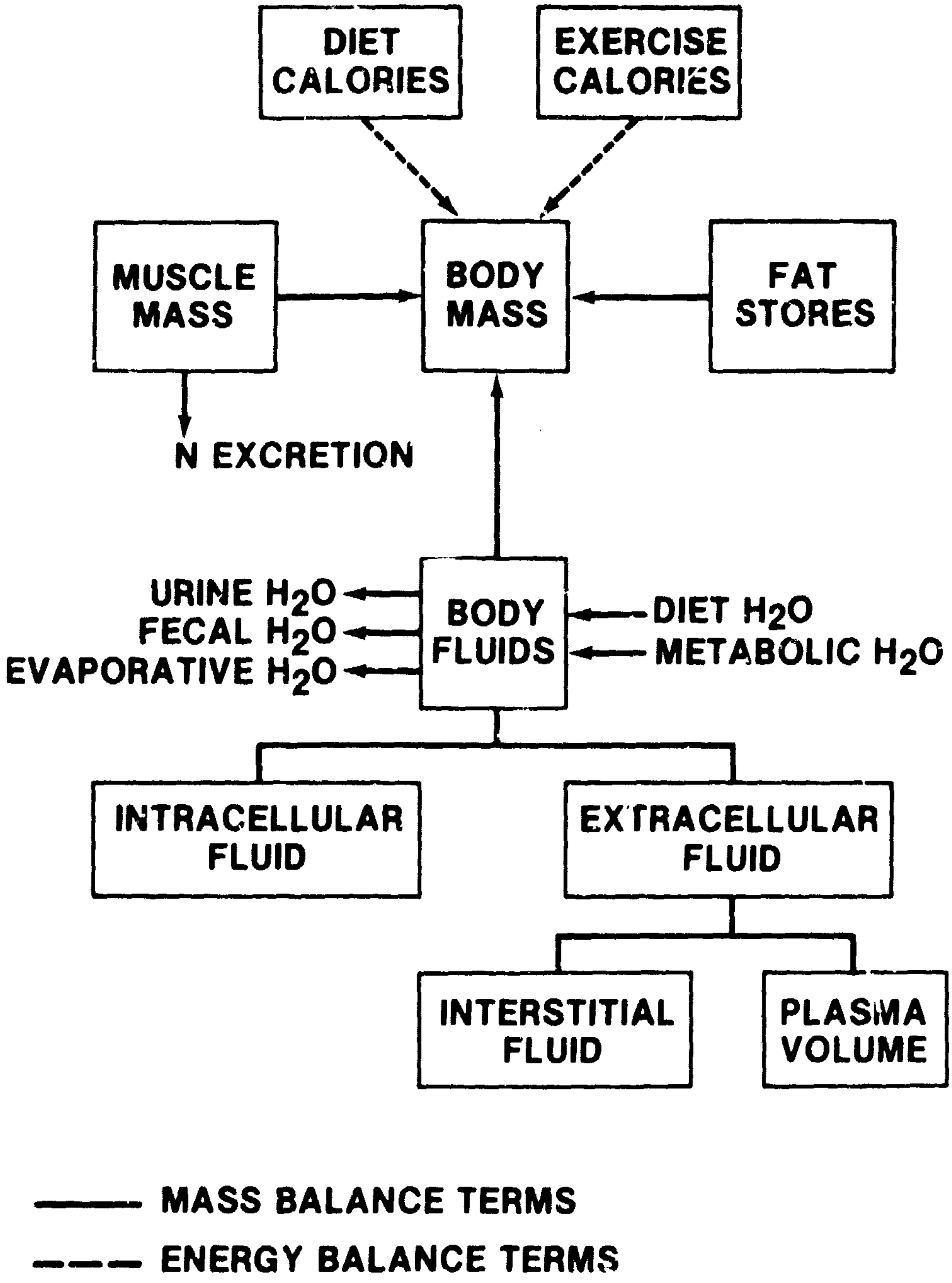


FIGURE F-5

The original experimental design for these Skylab studies was primarily aimed at obtaining metabolic balances for the purpose of determining alterations in excretion from the body and gross changes in body composition. It was not originally envisioned that the data would provide enough information or resolution to determine time-continuous profiles of changes in the major body constituents. The desire to express body composition changes in this format was driven by the need to validate computer simulations of the fluid-electrolyte model. However, the data analysis portion of those modeling studies, contained in this report, represents a contribution in its own right. This integrated approach to understanding metabolic balance, including the use of whole-body measurements where available, and mathematical models to obtain unmeasured quantities, has, therefore, enhanced the utilization of the unique Skylab data base.

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ENERGY BALANCE AND THE COMPOSITION OF WEIGHT LOSS DURING PROLONGED SPACE FLIGHT

INTRODUCTION

Based on our collective experience from Mercury through Skylab, and including bed-rest studies which mimic some of the hypogravic effects of weightlessness, significant changes in gross body composition can be expected during space flight (Berry, 1973; Rambaut, et al., 1975; Rambaut, et al., 1977a; Greenleaf, et al., 1976). Alterations in water balance and energy balance, hypokinetic deconditioning, and exposure to weightlessness have all been implicated as causitive factors to explain the nearly constant finding of weight loss in astronauts returning from space flight. Interpretation of this weight loss in terms of the major body elements and tissues is essential for understanding metabolic processes in weightlessness and predicting weight losses in future missions. Also, since diet and activity affect lean and fat tissues differently, a knowledge of expected changes will assist in establishing caloric and exercise requirements. An inadequate caloric intake should result in a loss of body fat, while a reduction in exercise training would be expected to reduce the tone if not the mass of skeletal muscle. It is important to ascertain if these relationships are as valid in zero-g as they are in one-g.

Prior to Skylab, a definitive analysis of spaceflight-related body composition changes had been hampered by the difficulty in quantitating inflight physical activity, ensuring an adequate caloric intake as well as operational constraints which precluded direct measurements of tissue loss. On the more recent Skylab missions (three flights lasting 28 days, 59 days, and 84 days) a major effort was directed at describing, and partly controlling, the more essential components of body weight as well as quantitating caloric balance. This report is concerned with relating the energy balance of the Skylab crewmen to their changes in body composition and describing the relevant data in more detail than has been heretofore presented.

On missions lasting less than half a week (Mercury and some Gemini flights), a loss in weight of several kilograms was ascribed almost completely to a negative water balance (Webb, 1967). An analysis of the longer Apollo mission (about 12 days) indicated that of the total weight loss (average: 3.5 kg; range: 0.8 to 5.9 kg) only half could be attributed to water loss. The remainder consisted of tissue loss (both fat and fat-free solids), implicating the presence of a negative energy balance resulting from an estimated caloric deficiency of about 1000 kcal/day (Rambaut, et al., 1973; Johnson, et al., 1974). Several studies have described the net changes in body composition of the Skylab astronauts whose weight loss averaged 2.8 kg (range: -0.1 to 4.2 kg) (Rambaut, et al., 1977a; Whittle, 1979; Thornton, 1978; Leonard, 1979). These investigators, reporting changes in the composition of body mass between the preflight and postflight period, suggested a consistent loss of water on all crewmen but more variability in the protein and fat components. Several factors were proposed to account for this variability including differences in diet, exercise, and adaptive metabolic effects.

The only information available for quantitatively discerning body composition changes as a function of time during the flight interval itself is from the onboard collection of daily metabolic balance and body mass data obtained during the Skylab program. An analysis based on the composite data from the three Skylab missions was performed by Rambaut, et al. (1977b), but the present study is more definitive, for a number of reasons, primarily because each Skylab mission is treated separately. Thus, it is possible to distinguish more readily between factors that were not identical on each flight, such as exercise, diet, and mission duration. The computational approach in the present report is also believed to be superior; caloric deficits are taken into account in determining fat losses by using energy balance, rather than water balance, considerations. The dynamic resolution of this analysis also improves upon that of Rambaut, et al. (1977b) by computing daily, rather than monthly, changes in body composition. Finally, the present study has been extended to estimate caloric and exercise requirements for space flight.

Losses in weight due to tissue catabolism, as inferred by metabolic balance, must be consistent with energy balance considerations and with direct measurements of body composition changes. Numerical procedures were developed for this analysis that take these factors into account, especially the metabolic balances of energy and nitrogen as well as total body water and mass determinations. This method avoids the accumulation of errors that are inherent in cumulative balance techniques and provides more useful information than is possible from standard balance methodology. The result is a continuous-time profile of daily total body changes of water, protein, and fat throughout the mission. Visualization of these changes facilitates an understanding of the gross metabolic disturbances which can occur in prolonged space flight.

EXPERIMENTAL PROCEDURES

Between July 1973 and February 1974 the Skylab spacecraft was occupied by three different crews of three men each. Physical characteristics of the nine Skylab crewmembers are summarized in Table A-1 (Appendix A). The first crew remained onboard for 28 days, the second for 59 days, and the third for 84 days. Energy balance and body composition analyses were based on the measurement of input and output constituents as well as the whole-body measurements of selected quantities. These procedures have been described elsewhere in detail by the principal investigators and can be summarized as follows. Metabolic balance studies were performed by carefully controlling dietary intake and recording all urinary and fecal output (Whedon, et al., 1974; Rambaut, et al., 1977a, 1977c, 1977d; Leach, et al., 1978). Input and output samples were collected and analyzed for nutrients (carbohydrates, fats, and nitrogen), electrolytes (sodium, potassium, calcium, magnesium, and phosphorus), fluids, and calories (bomb calorimetry). Measurements were performed daily during a two to three week preflight period, the inflight period, and a two week postflight phase; more than 900 man-days were included in these studies. In addition, whole-body measurements were performed daily for body weight/mass, and during pre- and postflight for body water. Body mass was determined preflight by conventional scales and by a device operating on the principle of oscillating masses during periods of weightlessness (Thornton and Ord, 1977; Thornton, 1978). Total body water was obtained by the dilution of isotopic hydrogen (^{3}H) (Leach and Rambaut, 1977). In addition, body potassium (whole-body counting of ^{40}K) and body volume (stereophotogrammetry) measurements were performed prior to and following each flight; this data was not used directly in the current study but supports its general conclusions as demonstrated elsewhere (Leonard, 1979). Detailed accounts of the collected data have been summarized in the appendix of the present report and other reports (Leonard, 1977a, 1977b, 1977c, 1979).

COMPUTATIONAL METHODS

The analysis for deriving the body compositional changes was based on two formulations, one an equation of body composition and the other, an equation of energy balance. In the first of these equations, the change in body weight (WGT) was assumed to be due to changes in total body water (TBW), body protein (PRO), and body fat (FAT), i.e.

$$\Delta WGT = \Delta TBW + \Delta PRO + \Delta FAT \tag{1}$$

In the second equation, net energy utilization (EUTIL) was computed as the sum of energy intake from diet (EDIET) minus energy excreted in urine (EURINE) and feces (EFECES) plus energy available from body tissue catabolism (energy from body fat = EFAT; energy from body protein = EPRO), i.e.

$$\begin{aligned} EUTIL^* &= \text{Work (internal + external) + Heat Lost} \qquad (2) \\ &= EDIET - EURINE - EFECES + EFAT + EPRO \end{aligned}$$

As suggested by equation (2) the net energy available from food and tissue metabolism is utilized entirely to perform work and produce heat. EUTIL is starred (*) to designate that it could not be measured directly or indirectly on a daily basis (i.e. by measuring work and heat lost or oxygen consumption) as were the other terms in equation (2). Rather, it was assumed that EUTIL*, expressed as a daily average quantity for the preflight, inflight, or postflight phases was constant throughout that phase for each crewmember.

For convenience, the description of the computational procedure has been divided into three parts: (a) determination of the mean energy utilization, EUTIL*, (b) determination of daily estimates of body water and body fat changes, and (c) determination of cumulative estimates of weight and tissue changes.

(a) Mean energy utilization, EUTIL*

EUTIL* was determined from equations (1) and (2) by assuming each term in these equations represented overall mission quantities. For example, ΔWGT, which normally refers to daily changes in body mass, would designate, in this part of the analysis, the change in net mass between the day of launch and day of recovery. When used in this way, it was convenient to place a bar over the term, i.e., $\Delta\overline{WGT}$. Each term in equation (1), so designated, can be estimated except for $\Delta\overline{FAT}$. Body weight (ΔWGT) was measured directly, body water ($\Delta\overline{TBW}$) was found by isotope dilution techniques, and protein losses ($\Delta\overline{PRO}$) were estimated by cumulative nitrogen balance, using the factor 6.25 to find the protein equivalent of nitrogen (Calloway, 1974).[1] Overall mission fat losses for each subject were thereby calculated by solving equation 1 for $\Delta\overline{FAT}$. Using the caloric equivalent of this loss, $\overline{EFAT}$, it was possible to compute the cumulative energy utilized, $\overline{EUTIL}$, from equation (2). The other terms required in equation (2) for this calculation were measured either directly or indirectly as follows. EDIET was determined from the caloric equivalent of the dietary content of protein, fat, and carbohydrate (McHattie, 1960; Consolazio, et al., 1963), EURINE was derived from urine nitrogen (N_{urine}) and taken to be 8.32 N_{urine} (Merrill and Watt, 1973), EFECES was measured directly by bomb calorimetry, and EPRO was estimated from the caloric equivalent of the nitrogen balance losses (i.e., EPRO = 5.65 x 6.25 x NBAL). Each of these terms representing daily quantities was summed over the entire mission phase and used in equation (2). The value of $\overline{EUTIL}$ obtained from this calculation was divided by the number of mission phase days to estimate EUTIL*. Values of EUTIL*, so computed, are shown in Table A-2 (Appendix A).

(b) Daily estimates of body water and body fat changes

Daily changes in body fat were determined by solving equation (2) for EFAT, using the constant value of EUTIL* as determined above and daily measured values of the other components EDIET, EURINE, EFECAL, and EPRO as indicated in Table 1. Daily body fat changes were converted from energy (EFAT) to mass equivalents (ΔFAT) and inserted into equation (1) which could then be used to solve for daily body water changes (ΔTBW). Daily body mass

[1]See Table 1 for a summary of the methods used to compute each term in this analysis.

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TABLE 1

METHODS FOR COMPUTING TERMS IN BODY COMPOSITION EQUATIONS

QUANTITY	SYMBOL	METHOD OF COMPUTATION
Body Mass, gm	$\Delta\overline{WGT}$ and ΔWGT	Direct body mass/weight measurements
Body Water, gm	$\overline{TBW}$	Isotope dilution (tritium) method performed before and after flight
	ΔTBW	Solve Equation (1) for TBW
Body Protein, gm	ΔPRO	Nitrogen balance: $\Delta PRO = 6.25 \times NBAL$ $= 6.25 \times (N_{diet} - N_{urine} - N_{feces})$
Body Fat, gm	$\Delta\overline{FAT}$	Solve Equation (1) for $\Delta\overline{FAT}$
	ΔFAT	$\Delta FAT = -EFAT/9.461$
Energy in Diet, kcal	EDIET	From stoichiometric relationships and known amounts of carbohydrates, fats, and protein in diet: EDIET = 4.182 x diet carbohydrate (gm) +9.461 x diet fat (gm +5.65 x diet protein (gm)
Energy in Urine, kcal	EURINE	From urinary nitrogen: $EURINE = 8.32 \times N_{urine}$ (gm)
Energy in Feces, kcal	EFECES	From bomb calorimetry
Energy in Catabolized Protein, kcal	EPRO	$EPRO = -5.65 \times \Delta PRO$
Energy in Catabolized Fat, kcal	$\overline{EFAT}$	$\overline{EFAT} = -9.461 \times \Delta\overline{FAT}$
	EFAT	Solve Equation (2) for EFAT using EUTIL*
Net Energy Utilized, kcal	$\overline{EUTIL}$	From Equation (2)
	EUTIL*	$EUTIL^* = \overline{EUTIL} \div$ days of mission phase

Note: (1) Bar over symbol denotes overall mission phase mass losses or cumulative energy quantities summed over mission phase. Symbols without bar refer to daily values of that quantity.

(2) $\overline{EDIET}$, $\overline{EURINE}$, $\overline{EFECES}$, $\overline{EPRO}$ AND $\Delta\overline{PRO}$ are computed by summing the daily amounts of each quantity (as defined above) over each mission phase; (i.e., $\overline{EDIET} = \Sigma EDIET$)

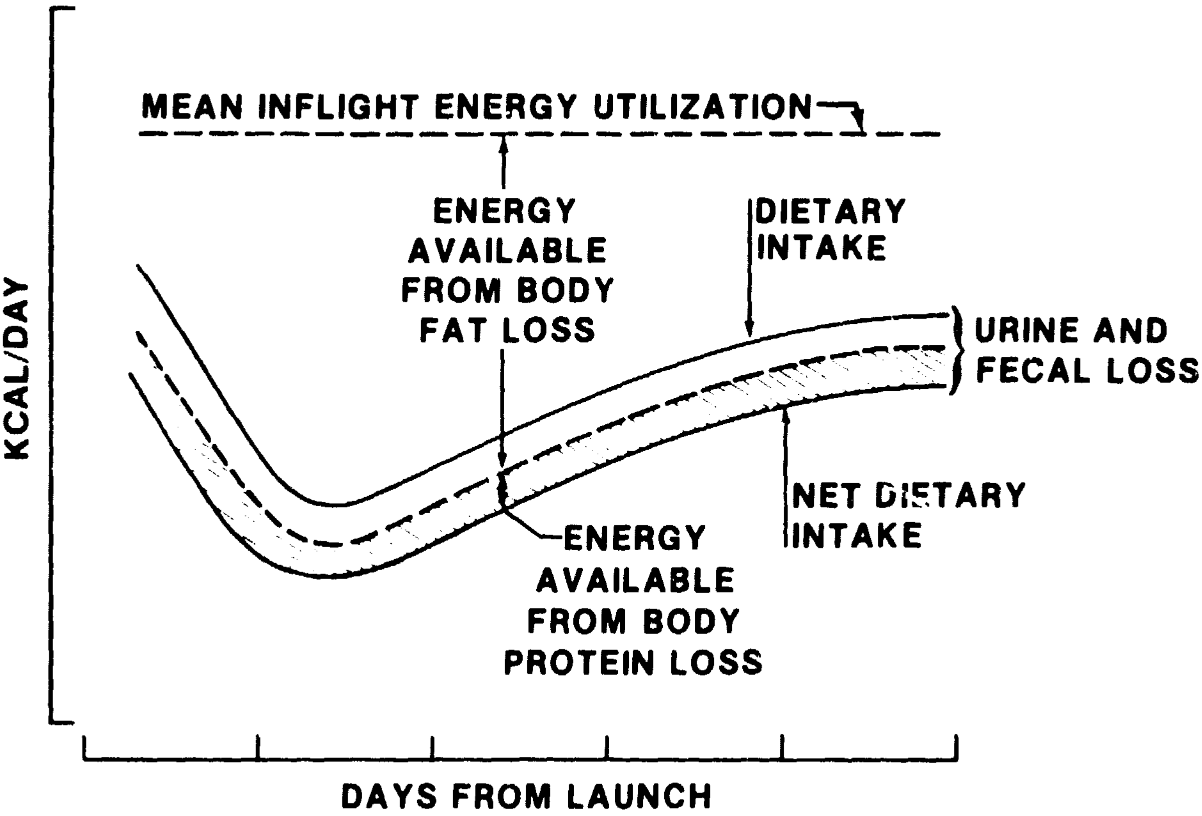
changes (ΔWGT) and body protein changes (ΔPRO) used in this computation were estimated as previously described.

(c) Cumulative estimates of weight, water, and tissue changes

Cumulative changes in each of the quantities in equation (1) were calculated by simply summing the consecutive daily balances over any desired time interval. The interval of each day's balance period is taken to be from morning-to-morning. The experimental protocol specified that each day would begin after the last urine and fecal void prior to breakfast. Body mass measurements were made each day after overnight fasting. It was convenient to use the morning of the day of launch as the reference point from which cumulative balances were computed. Thus, the prelaunch period required a backward calculation from the point of reference.

The calculation schema for the inflight period is shown graphically in Figure 1. The average net dietary intake (i.e., EDIET - EURINE - EFECES) is indicated by the lowest solid curve. The dashed horizontal line represents the average energy utilization (EUTIL*) for the inflight period. The difference between mean energy utilization and net diet intake is the deficit between net calories derived from the diet and the energy actually required. This energy difference is assumed to be supplied by fat and protein tissue catabolism (carbohydrate stores in the body being assumed insignificant) as suggested by equation (2). The area bounded between the horizontal dashed and lower solid lines and any two time intervals is the energy equivalent of the cumulative tissue loss (protein + fat) during that interval. If daily protein changes can be assumed from the nitrogen balance (hatched area in Figure 1), it is possible to derive daily fat losses from this area of the graph as shown. The difference between total weight loss and the sum of fat and protein losses is then taken to be the daily change in body water, as indicated by equation (1).

Figure 2, using average data for the Skylab crew, illustrates the general analysis of Figure 1. All nine subjects are included in this data for the preflight and first month inflight periods. The decline in food intake is associated with the onset of motion sickness symptoms in zero-g. The greater

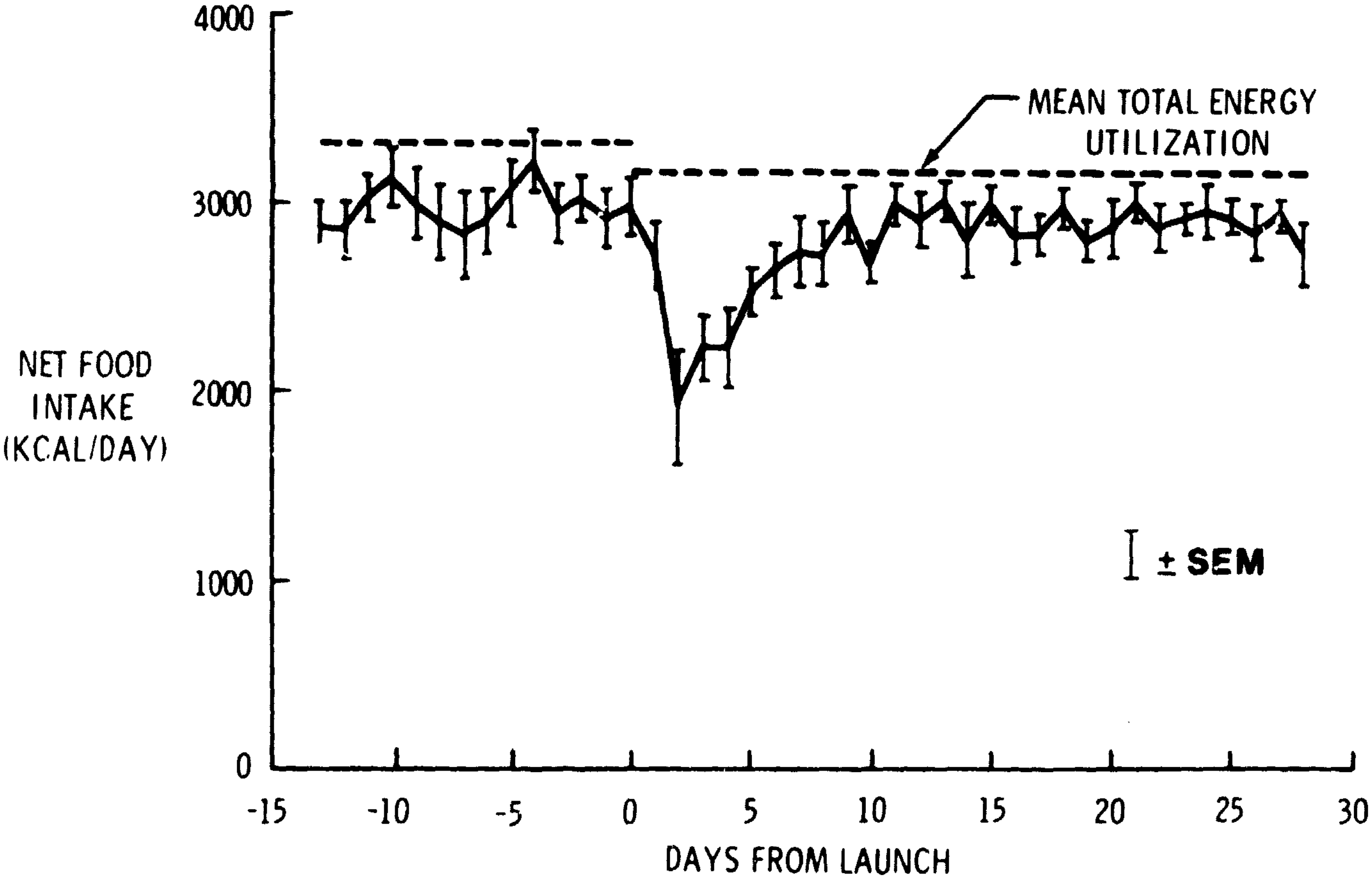


ESTIMATION OF TISSUE LOSSES
FROM ENERGY BALANCE COMPONENTS

FIGURE 1

FIGURE 2

NET FOOD INTAKE OF SKYLAB CREW (N=9)



the difference between net food intake and energy utilization, the larger is the energy balance deficit. On the average, therefore, it is apparent that the Skylab crew was in negative energy balance (mean first month deficit = 350 kcal/day), accompanied by a loss of body tissue.

The major assumptions used in this analysis and their justifications include the following:

a) The daily net energy utilization for each crewmember was constant during each phase of the mission. This assumption was justified on the basis that each subject adhered to a fairly standard and strict work and exercise schedule, especially during the inflight phase (Rambaut, et al., 1977b). While this assumption is not subject to independent verification, it does allow estimations of time-varying changes in body composition which can be examined for reasonableness and challenged by other related evidence. It is important to note that each day's error between the true energy utilization and the constant value assumed, tend to average out rather than accumulate.

b) Changes in body protein over prolonged time intervals can be estimated from the cumulative nitrogen metabolic balance. The balance procedure was uncorrected for the approximately 0.5 g/d nitrogen said to be lost via shedding of cutaneous epithelium, loss of hair, nail fragment, and various skin secretions (Calloway, et al., 1971). The cumulative uncorrected nitrogen balance has been used by others who have claimed meaningful results (Yang and Van Itallie, 1976). Errors in the nitrogen balance method (both corrected and uncorrected) have been previously hypothesized and discussed (Hegsted, 1976; Forbes, 1972; see summary in Appendix C) but sources of methodological errors in carefully controlled studies were not apparent (Steffee, et al., 1976).

In this study, preflight nitrogen balances are in good agreement with the results of other investigators who used similar dietary and exercise levels (Steffee, et al., 1976; Krzywicki, et al., 1978). In addition, overall inflight losses of body protein from the nitrogen balance were in good agreement with several other methods previously examined including those based on whole body exchangeable potassium, potassium balance, body density, and body water (Leonard, 1979; see Table 2). The effects of unmeasured nitrogen losses were examined by assuming a range of reasonable values for skin secretions with the result that the overall mission losses of nitrogen were unreasonably high (Figure C-1, Appendix C). Finally, the trends observed in the uncorrected cumulative nitrogen balance showed a remarkable similarity among all Skylab crewmembers.

c) Daily balances for water and fat may be sequentially accumulated without increasing error. This is accomplished by employing a method that combines daily balances with end-points restricted by whole body measurements, in accord with suggestions previously proposed by Hegsted (1976). For example, the sequential accumulation of the daily inflight water balance obtained by this method is forced to agree with the direct measurements of total body water which were obtained at the beginning and end of the mission. Daily weight measurements govern the maximum weight loss composed of the sum of water, protein, and fat. Using an energy balance as an integral part of body composition balance analysis, as suggested by Grande (1968), ensures that fat losses would be based on the degree of caloric intake deficit. An alternate method of deriving continuous inflight body composition based on mass balance rather than energy balance was examined (Leonard, 1977a, 1977b). Agreement between the two methods was very reasonable except for the situation when caloric deficits were highest. In those cases, the present analysis demonstrated more plausible results.

RESULTS AND DISCUSSION

Overall Mission Weight and Tissue Losses

The losses of body mass and its tissue components are summarized in Table 3 and Figure 3 for each mission and for the mean Skylab losses. Data for the individual crewmembers are provided in Table A-3 (Appendix A). The time period for these changes was taken to be from the morning of launch to the morning of recovery day. Body weight/mass was the only quantity measured directly. Total body water was measured within one day of splashdown and adjusted to reflect values at the morning of recovery day (see Table A-4, Appendix A). This correction, for water replenishment and water lost, was

TABLE 2

SKYLAB INFLIGHT LOSSES OF LEAN BODY MASS
AND BODY FAT FROM SEVERAL METHODS (N = 9)
(MEAN ± SD)

METHOD	ΔLBM (kg)	ΔFAT (kg)
1) TOTAL BODY WATER	-1.2 ± 1.1**	-1.4 ± 1.8*
2) TOTAL BODY POTASSIUM	-1.5 ± 1.9*	-1.1 ± 2.7
3) TOTAL BODY POTASSIUM + TOTAL BODY WATER	-1.1 ± 0.8**	-1.5 ± 1.6*
4) BODY DENSITY	-1.5 ± 3.5	-1.1 ± 3.3
5) "COMBINED"	-1.6 ± 1.1**	-1.0 ± 1.2
6) NITROGEN BALANCE	-1.6 ± 0.9**	-1.0 ± 1.8

* (p <.05)

** (p <.01)

Taken from Leonard (1979)

TABLE 3

INFLIGHT BODY MASS CHANGES IN EACH SKYLAB MISSION
(MEAN ± SD)

A. TOTAL LOSSES (gm)

	28-DAY MISSION	59-DAY MISSION	84-DAY MISSION	SKYLAB MEAN
ΔMass	-2330 ± 1100	-3900 ± 300	- 930 ± 810	-2390 ± 1460
ΔWater	- 890 ± 1040	-1530 ± 1740	-1000 ± 530	-1140 ± 1090
	(-1020)[a]	(-1260)	(-910)	(-1160)
ΔTissue	-1440 ± 960	-2370 ± 1440	+ 62 ± 790	-1250 ± 1430
ΔProtein	- 290 ± 110	- 320 ± 40	- 350 ± 310	- 320 ± 170
ΔFat	-1160 ± 860	-2060 ± 1440	+ 410 ± 940	- 930 ± 1440

B. AVERAGE DAILY LOSSES (gm/day-kg body wgt)[b,c]

	28-DAY MISSION	59-DAY MISSION	84-DAY MISSION	SKYLAB MEAN
ΔMass	-1.10 ± 0.42	-0.93 ± 0.10	-0.16 ± 0.14	-0.73 ± 0.47
ΔWater	-0.42 ± 0.45	-0.32 ± 0.34	-0.17 ± 0.09	-0.30 ± 0.31
ΔTissue	-0.68 ± 0.41	-0.60 ± 0.43	+0.01 ± 0.13	-0.43 ± 0.45
ΔProtein	-0.14 ± 0.14	-0.08 ± 0.02	-0.06 ± 0.05	-0.09 ± 0.05
ΔFat	-0.55 ± 0.37	-0.53 ± 0.42	+0.07 ± 0.16	-0.33 ± 0.42

NOTES:

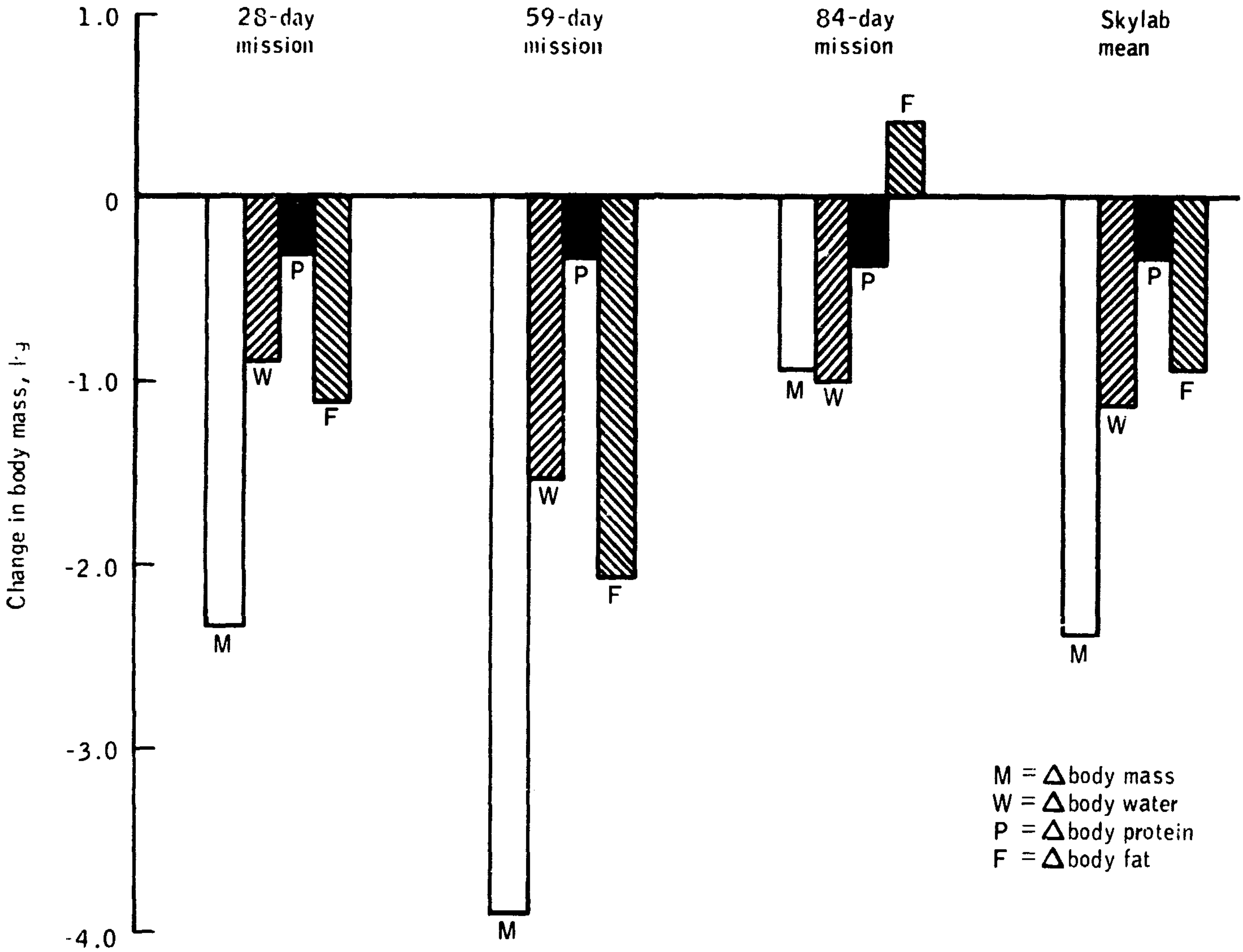
a) Values in parentheses are water losses estimated from protein and fat losses based on 74 percent water content of lean body mass and 15 percent water content of adipose tissue.

b) Values in part B normalized with respect to mean body weight of the preflight period.

c) Values are shown for each three-man crew and, in last column, for all nine subjects.

FIGURE 3

CHANGES IN BODY COMPOSITION IN EACH SKYLAB CREW AS A RESULT OF EXPOSURE TO WEIGHTLESSNESS



achieved using data from the water metabolic balance (Leonard, 1977a). Body protein, fat, and total tissue changes were estimated from equations (1) and (2).

As shown in Table 3, the average loss of water, fat, and protein for the nine crewmen was found to be 48, 39, and 13 percent, respectively, of the total body mass loss of 2.4 kg. No trends of statistical significance, relating weight changes to mission duration, were noted from this data. Compared to the 28-day mission the losses of all quantities were more severe after the 59-day mission but less severe (with the exception of body protein) after the 84-day mission. On the two shortest missions, body fat losses accounted for about one-half of the total weight loss, the remainder being attributed to lean body mass (i.e., water and protein) loss. There was an apparent net increase in body fat on the longest mission, mainly the results of gains in at least one, and perhaps two, crewmen. Protein losses were relatively constant on all missions and therefore apparently independent of mission length. Taking into account the expected amounts of water in normal muscle and fat tissue, the computed water loss in all missions was found to be totally consistent with the independently estimated losses of protein and fat (see values in parentheses in Table 3).

Table 3(B) shows the same data as in Table 3(A) after converting it to a daily loss per kg body weight by dividing by the mission length and preflight body weight. The trend in all cases is toward smaller rates of loss as mission length increased. Several interpretations of this trend can be made. First, there may be an adaptive or regenerative effect of weightlessness whereby recovery of an early loss of weight occurs on missions beyond two months in duration. Second, factors other than mission length may be significant determinants of weight loss and were absent or present to a lesser extent in the longest missions. Two such factors might be diet and exercise. These will be discussed later. Finally, the data could suggest that the majority of weight loss occurs early in flight. This loss, which persists throughout the mission, is due to weightlessness per se, and therefore is independent of mission duration. Dividing this loss by an increasing number of days gives the false impression of a decreasing rate of loss for missions of longer durations. The remaining results will help suggest the more plausible of these hypotheses.

Energy Balance

The energy balance (equation (2)) for each mission is shown in Table 4 for the two week preflight period and for the entire inflight phase. Corresponding balance data for each crewmember is summarized in Tables A-5 and A-6 (Appendix A) for the preflight and inflight periods, respectively. Additional data regarding dietary intake utilization is provided in Tables A-7 to A-9 (Appendix A). Inflight dietary intake averaged 3140 ± 350 (sd) kcal for all nine subjects, which was only slightly lower than the preflight average of 3218 ± 400 kcal. Although this difference is not statistically significant, examination of the data for the individual crewmen provides a clue to the weight loss mechanism. Five of the nine crewmen decreased their mean caloric intake during flight and these subjects lost 75 percent more weight than the other crewmen who increased or maintained their preflight intake. Small differences in caloric intake maintained for long periods of time are known to produce significant weight changes.

About nine percent of the total calories consumed was excreted in urine and feces (Leonard, 1977b). This fraction was nearly constant for all crewmen during preflight and inflight phases (see Tables A-5 to A-9, Appendix A).

The catabolism of body tissue, especially fat, contributed to the total energy available in all phases shown in Table 4 except for the inflight phase of the 84-day mission which indicates a small gain in body fat. In the case of the inflight phase of the 28-day mission, the metabolism of body tissue contributed as much as 14 percent of the total estimated utilized energy. Amounts of fat loss as high as those indicated in the 28-day and 59-day missions are presumably due to a calorie-deficient diet (Thornton, 1978).

A negative energy balance (accompanied by loss of energy-bearing tissue) exists when energy intake is less than energy utilization. The net caloric intake was less than the net energy utilization for the 28-day mission, and this difference diminished for each longer mission. (See Tables 4, A-8, and A-9 (Appendix A) for quantitative changes and Figure A-1 (Appendix A) for graphical interpretation). These differences, averaged over the inflight period, are -448 kcal/d, -360 kcal/d, and +23 kcal/d for the 28-day, 59-day,

TABLE 4

ENERGY BALANCE FOR EACH SKYLAB CREW (kcal/day)
(MEAN ± SD, N=3)

ENERGY BALANCE COMPONENT	PREFLIGHT 28-DAY MISSION	PREFLIGHT 59-DAY MISSION	PREFLIGHT 84-DAY MISSION	INFLIGHT 28-DAY MISSION	INFLIGHT 59-DAY MISSION	INFLIGHT 84-DAY MISSION
Total Diet	3086 ± 147	3354 ± 749	3214 ± 61	2930 ± 88	3225 ± 608	3260 ± 106
Excreta:						
Urine	107 ± 3	122 ± 38	124 ± 10	139 ± 10	145 ± 38	153 ± 7
Feces	148 ± 9	135 ± 32	145 ± 15	106 ± 2	141 ± 36	136 ± 31
Total Excreta	255 ± 8	257 ± 70	269 ± 6	245 ± 11	286 ± 74	289 ± 36
Body Tissue Loss:						
Protein	-107 ± 3	-124 ± 18	-98 ± 20	58 ± 23	30 ± 4	23 ± 21
Fat	512 ± 297	490 ± 226	413 ± 416	391 ± 289	330 ± 231	-46 ± 105
Total Tissue	405 ± 295	366 ± 238	315 ± 423	449 ± 309	360 ± 231	-23 ± 94
Net Energy Utilization	3236 ± 434	3463 ± 480	3260 ± 462	3134 ± 383	3299 ± 338	2948 ± 97

NOTES:

a) Diet calculated from 4.182 x carbohydrates + 9.461 x fat + 5.65 x protein
b) Urine energy = 8.32 x urine nitrogen
c) Energy available from body tissue loss: 5.65 kcal/gm protein, 9.461 kcal/gm fat
d) Minus sign means a gain in body tissue
e) Energy Utilization = Intake - Excreta + Energy from body tissue loss

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and 84-day missions, respectively. (A positive sign indicates a positive energy balance, whereby tissue is stored). Thus, the inflight period of the 84-day mission is the only fl ,nt segment (including preflight and inflight phases) in which there was no apparent net loss of tissue. The intention of the biomedical flight staff to decrease the energy balance deficit of each consecutive Skylab mission by having the crew increase their caloric intake was, therefore, realized, as is graphically illustrated in Figure A-1 (Appendix A).

This analysis supports the findings of other investigators who examined data from the earlier Gemini and Apollo flights. They concluded (without benefit of a complete energy balance) that the energetic cost of life in space was higher than indicated by the actual total energy content of the food consumed (Rambaut, et al., 1973; Vanderveen and Allen, 1972). The present data provides quantitative substance to that argument, even for flights in which food consumption was much higher than that of the pre-Skylab missions. However, the differences between energy supply and demand are rather small. In the cases of the 28-day and 59-day missions, total energy utilization is only 7 and 2 percent higher, respectively, than gross dietary intake.

Increase in Diet and Exercise

As noted above, the inflight diet, which was rigidly controlled, was intentionally increased on each subsequent mission by three to four kcal/d per kg body weight (see Table A-9, Appendix A). This was done to test the assumption that an inadequate caloric intake was responsible for a continuous and gradual decrease in body weight loss throughout the first mission.

The time devoted to exercise and the number of exercise devices employed also was increased on each subsequent mission in an attempt to provide the crew with an optimal exercise program (Rummel, et al., 1975). The benefit of additional exercise was demonstrated by a superior postflight exercise and strength performance and an increased feeling of well-being during the flight (Thornton and Rummel, 1977).

Bicycle ergometry exercise was utilized by all crewmembers. In addition, a commercial mini-gym exerciser was used by the crews of the two longest missions, and a treadmill type device was available on the longest mission. Quantitative estimates of exercise workload are available only for the bicycle ergometer (Michel, et al., 1977). These data, summarized in Table 5, tend to reflect the relative time and intensity devoted to total exercise by each crew.

The relationship between diet, exercise, and body tissue loss of the three crews is made more apparent and meaningful when these quantities are expressed in the common units of kcal per day per kilogram preflight body weight as shown in Table 6 and Figure 4. The proportions of energy expended for exercise and energy available from tissue loss i relation to total energy consumed can be easily discerned from this data. For example, examination of the inflight data for the nine individual crewmen (Tables A-6 and A-10, Appendix A) shows the following ranges for diet and exercise: a) caloric intake varied from 35.8 to 49.7 kcal/d-kg, b) the caloric value of exercise varied from 1.4 to 5.1 kcal/d-kg, corresponding to 4 to 12 percent of the caloric intake, and c) the caloric value of tissue lost varied from -4 percent (a gain in tissue) to 26 percent of caloric intake.

Table 6 and Figure 4 also show the direct relationship between increasing dietary intake, increasing exercise, and decreasing tissue loss with increasing mission duration. The increase in dietary intake more than offsets the increase in exercise expenditure, as indicated by the difference between diet and exercise (i.e., "diet-exercise" in Table 6) which also increases with mission duration. The crew that exercised the most (the 84-day mission) also lost the least body fat, which would be paradoxical were it not for the fact that their caloric intake was also the highest. The data in Table 6, while not including exercise other than bicycle work, suggests that excess calories may have been available on the 84-day mission for actually increasing fat stores relative to the other two crews.

TABLE 5

INFLIGHT EXERCISE (BICYCLE ERGOMETER)

(MEAN ± SD, N=3)

MISSION	TOTAL MISSION USEFUL EXERCISE (W-min x 10^3)	AVERAGE DAILY USEFUL EXERCISE (W-min/day)	AVERAGE DAILY* TOTAL WORK (kcal/d-kg Bwgt)
28-DAY	55 ±9	1951 ±315	1.77 ±.52
56-DAY	276 ±95	4686 ±1615	4.12 ±.63
84-DAY	411 ±60	4894 ±716	4.62 ±.56

*Convert useful bicycle work (W-min/day) to total work (kcal/d-kg Bwgt) expended on exercise by dividing Daily Useful Exercise column by 0.22 (mechanical efficiency of bicycle riding) and preflight body weight. Convert this quantity from W-min to kcal using conversion factor 70 W-min per kcal. (Bwgt = body weight; W-min = watt-minutes)

Data from Michel et al., 1977.

TABLE 6

INFLIGHT ENERGY CONSUMED IN DIET, EXPENDED ON EXERCISE, AND AVAILABLE FROM TISSUE LOSS (kcal/day-kg Bwgt)

(MEAN ± SD, N=3)

	28-DAY MISSION	59-DAY MISSION	84-DAY MISSION
Diet[1]	40.4 ± 5.5	44.3 ± 2.1	47.3 ± 3.0
Exercise[2]	1.77 ± 0.52	4.12 ± 0.63	4.62 ± 0.56
Diet-Exercise	38.6 ± 5.0	40.2 ± 2.1	42.7 ± 3.3
Tissue Loss[3]	5.94 ± 3.75	5.43 ± 4.01	-0.35 ± 1.36

Note 1. Calculated from caloric equivalent of carbohydrate, fat, and protein.

2. Obtained from Table 5.

3. Obtained from Table 4.

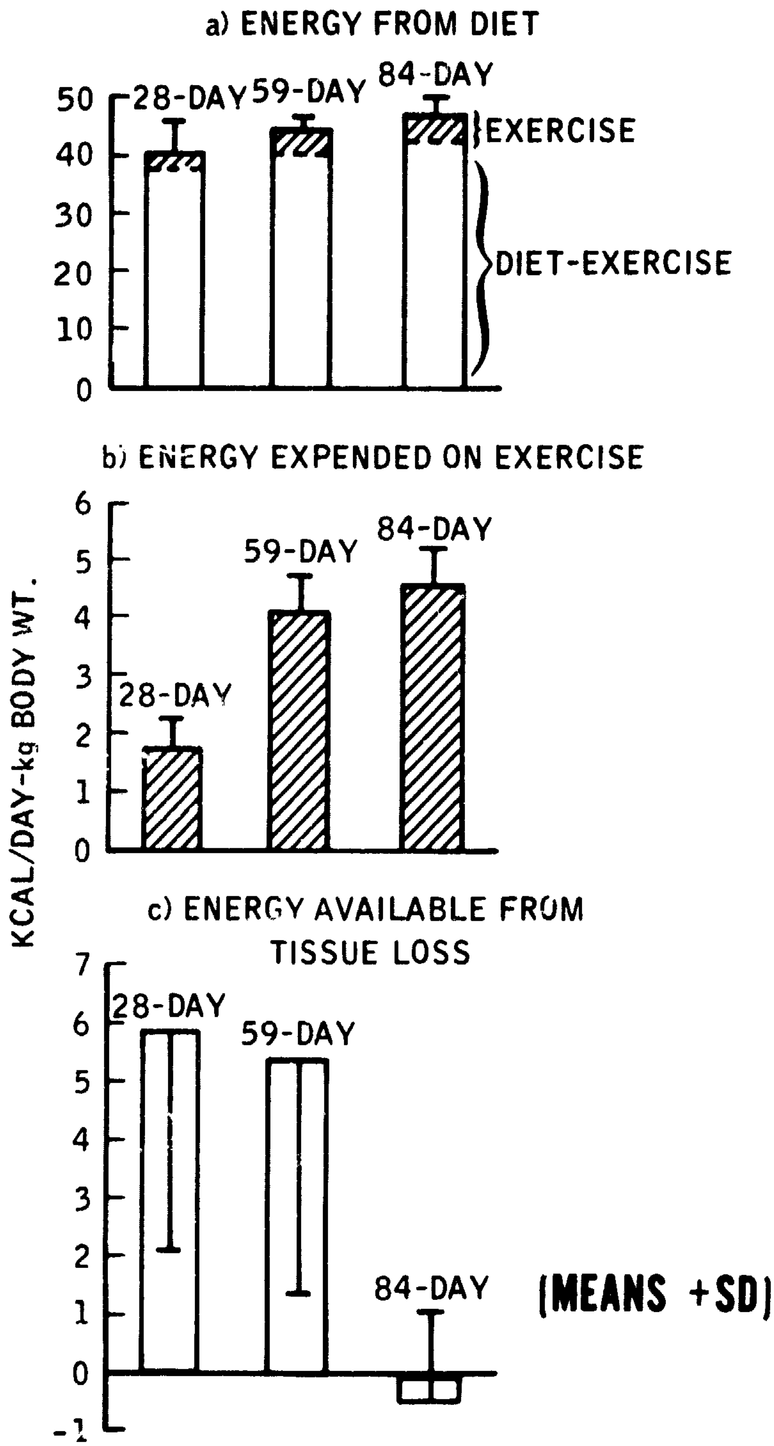


FIGURE 4 INFLIGHT ENERGY COMPONENTS FOR EACH SKYLAB CREW (DIET, EXERCISE, TISSUE LOSS)

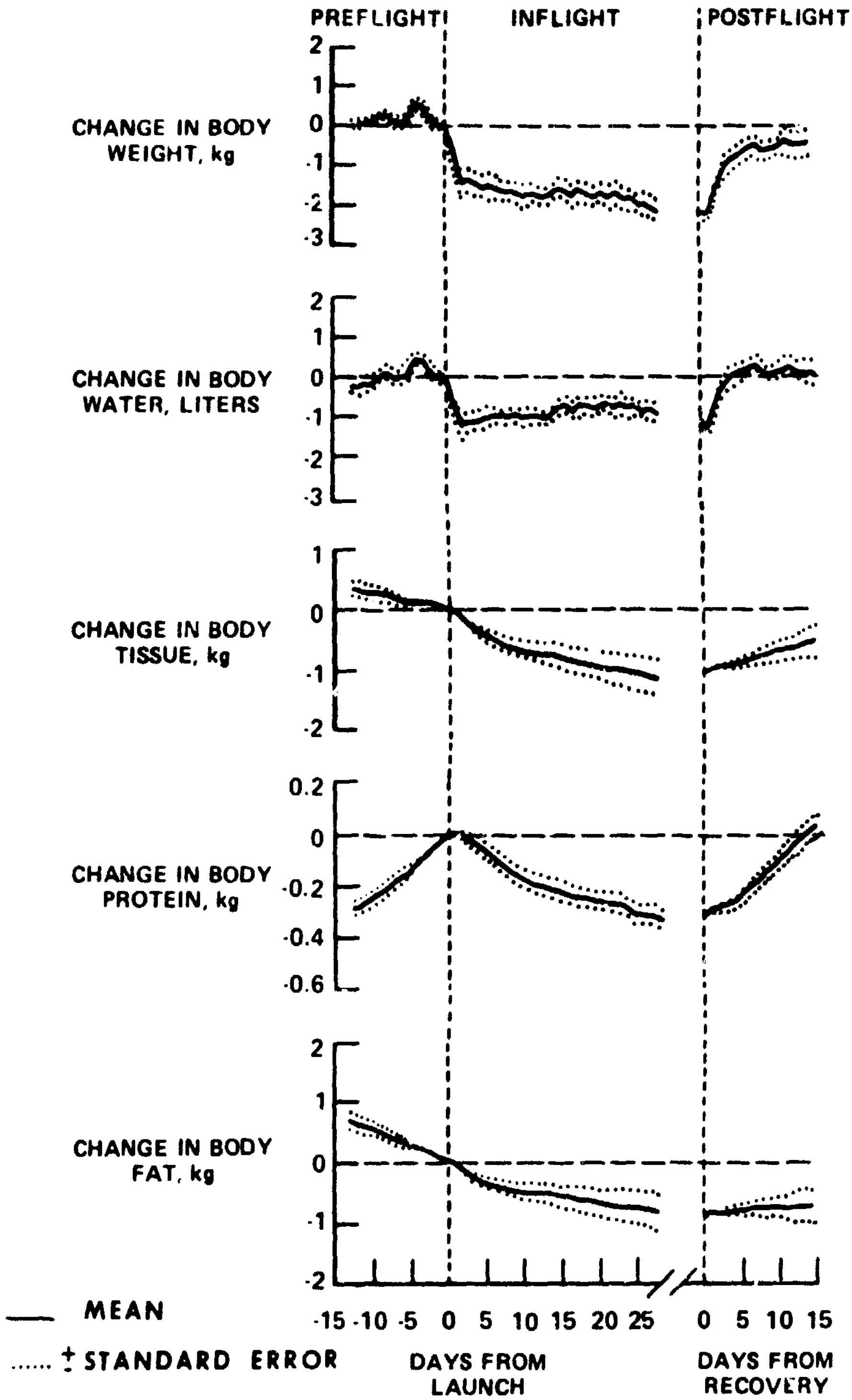
Continuous Changes During First Month: Skylab Mean

The dynamic profile for the changes in weight/mass, total body water, protein, and fat are shown in Figure 5. This data represents the average responses of all nine Skylab crewmen and includes a preflight period, the first month inflight (i.e., the longest inflight interval common to all three missions), and a postflight period. The values on this and subsequent figures are shown as changes from the morning of launch. The curve labeled "body tissue" is the sum of protein and fat losses (i.e. dry weight). Protein losses were obtained directly from the nitrogen balance and represent dry tissue. For convenience, the sum of protein and water losses will be designated as lean body mass losses.

The following information emerges from the average response shown in Figure 5:

a) Body mass decreases dramatically during the first two days following launch as a result of water loss of more than one liter. Body water remained relatively constant at this reduced level (with some replenishment), while body mass continued to decline gradually in accord with the behavior of dry tissue loss. If the graphs of body mass and body water changes are overlayed (e.g. see Figure A-2, Appendix A), the differences between the two curves represent the dry tissue loss. At the end of 28 days inflight, ΔWGT = -2.2 ± 0.94 kg (sd). Water accounts for 46 percent of the total mass loss, the remainder being attributed to tissue. These proportions are also similar to those found when the second and third months of flight are included in the Skylab average (see Table 3).

b) The time course of the body mass changes (ΔWGT) can be explained by the losses of water (ΔTBW), protein (ΔPRO), and fat (ΔFAT), each proceeding at different rates. Water is lost most rapidly, followed by fat and then by protein. (The slope of protein loss appears steeper than fat because the protein scale is expanded by about five times that of the other quantities in Figures 5 and 7 - 10.)



MEAN CHANGES IN BODY COMPOSITION DURING FIRST INFLIGHT MONTH OF ALL SKYLAB CREWS (N = 9)
(Values are shown as changes from morning of launch)

FIGURE 5

c) At the end of 28 inflight days the component losses (mean ± sd) are computed as: ΔTBW = -1.02 ± 0.69 kg, ΔFAT = -0.85 ± 0.91 kg, and ΔPRO = -0.34 ± 0.08 kg. Lean body mass normally contains 75 percent water and 25 percent protein (Pace and Rathburn, 1945) which is almost precisely the loss ratio found in this analysis after one month. These values also show that 62 percent of the total mass loss is attributed to lean body mass while 38 percent can be atttributed to fat.

d) The loss of protein and fat is consistent with an average inflight caloric deficiency of about 350 kcal/day estimated during this 28-day period (difference between energy requirements and net energy intake), as shown in Figure 2. The rate of tissue loss is much greater during the first week than the last two weeks of the first inflight month, explicable by the relative degrees of caloric deficiency.

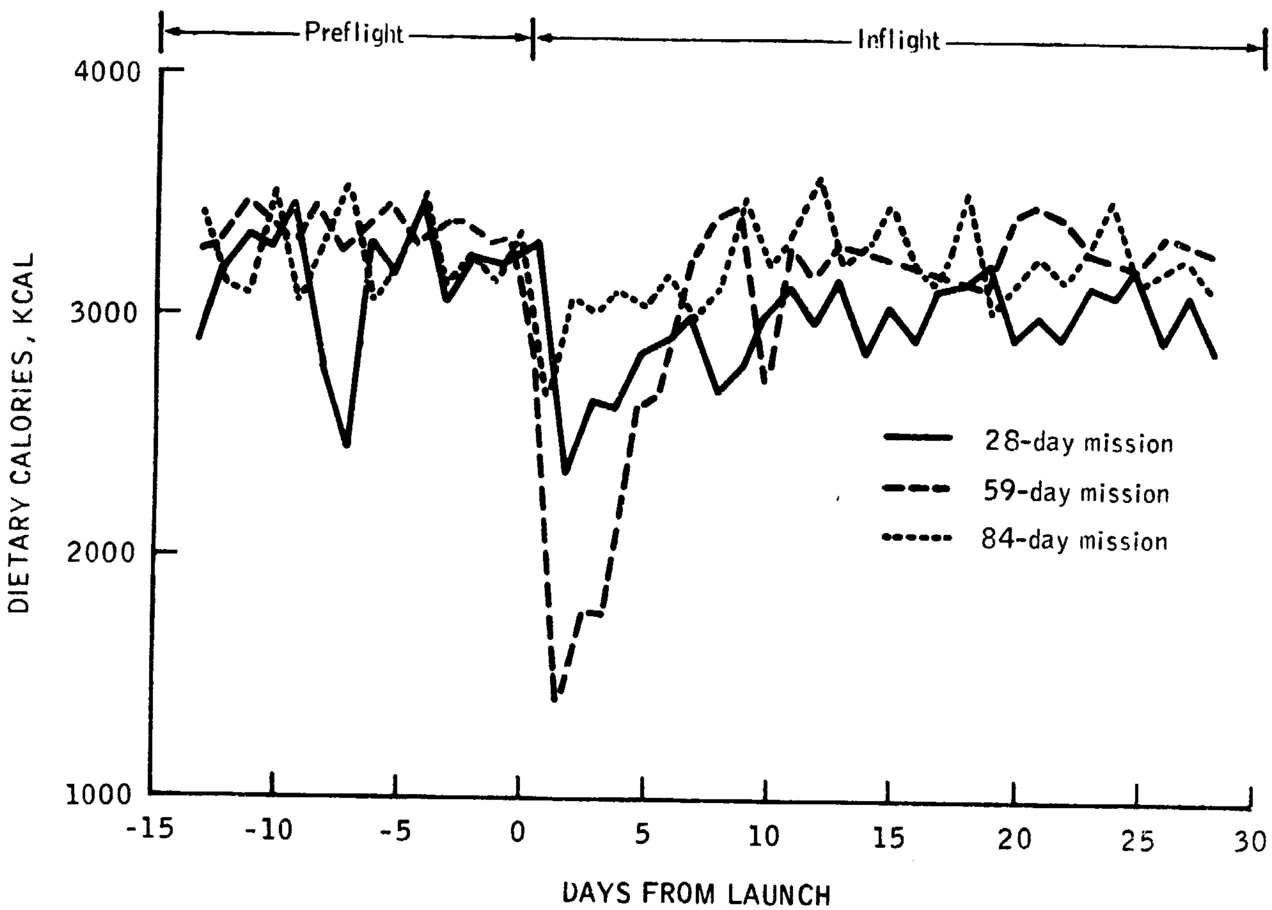
e) The behavior of mean body protein changes can be described as follows: an increase in body protein during the preflight period, a rapid reversal of protein balance after launch, and an exponential decline over the first month, followed by complete recovery during the postflight period.

f) The preflight period was characterized by increases in protein mass and decreases in fat stores. This behavior could be expected for subjects on a controlled diet high in protein who are engaged in certain forms of physical conditioning (Krzywicki, et al., 1978).

g) During the postflight period weight gain was nearly as rapid as the original inflight loss and was also primarily due to changes in body water. While postflight recovery of protein was at rates similar to the preflight rates of retention, fat losses, on the average, did not recover.

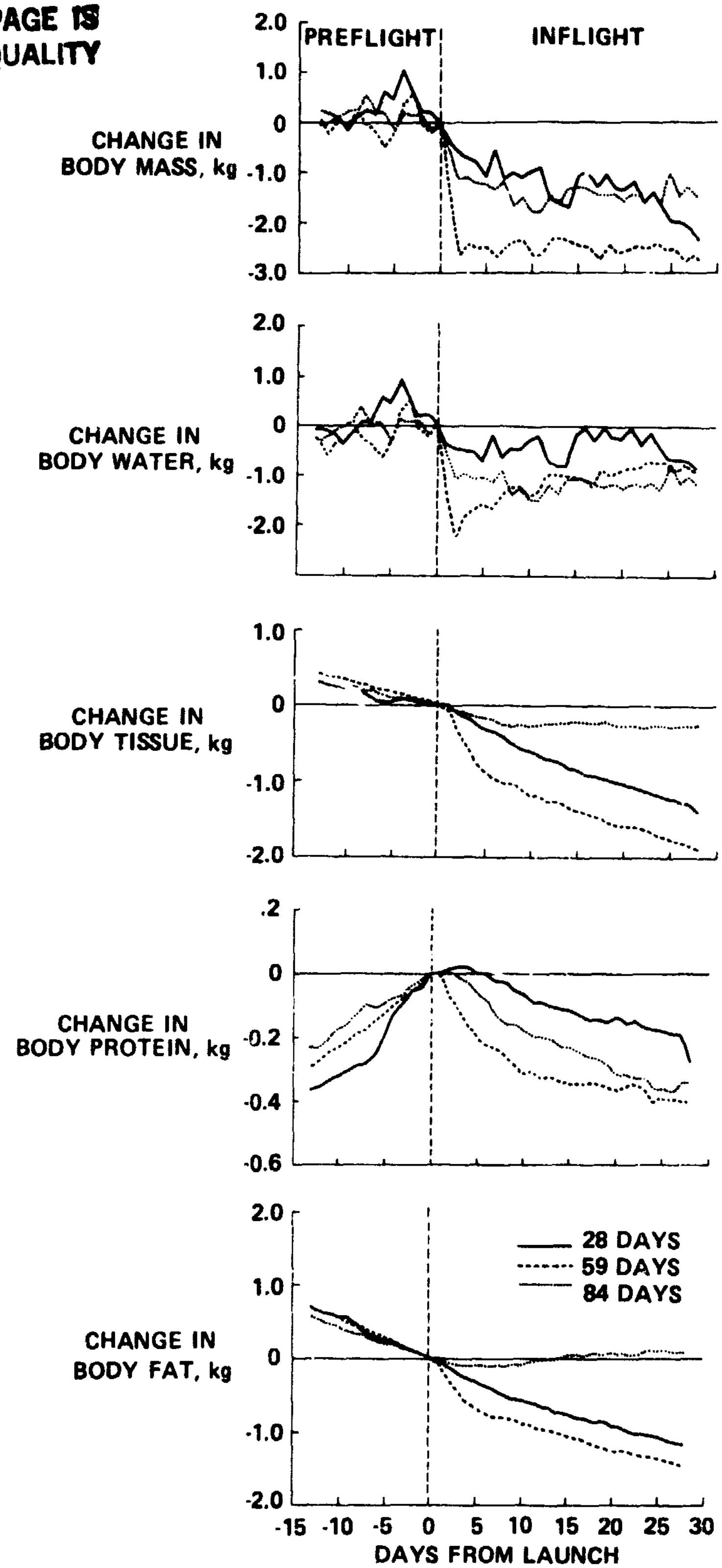
Continuous Changes During First Month: Mission Differences

Differences in diet and body composition changes between the three missions are presented in Figures 6 and 7. The relationship between diet, exercise, and body composition changes may be examined more readily by studying only the first month inflight when data for all crewmen are represented.



DIET CALORIES DURING PREFLIGHT AND FIRST MONTH INFLIGHT FOR EACH SKYLAB CREW (N = 3)

FIGURE 6



CHANGE IN BODY COMPOSITION DURING FIRST MONTH INFLIGHT FOR EACH SKYLAB CREW (N = 3)

(Values are shown as changes from morning of launch.)

FIGURE 7

The absolute mean value of caloric intake increased on each longer mission (see Table 6), but the relative change during the first month inflight was in a different ranking; specifically, the 28-day, 59-day, and 84-day crews showed a -5, -11, and -0.6 percent decrease, respectively, in mean caloric intake for the first month compared to their preflight control (see Figure 6). Thus, considering only the first inflight month, the 59-day crew had, by far, the largest relative decrease in caloric intake as well as the sharpest and most sustained (although temporary) decline in water intake (see Figure B-1, Appendix B). The greater part of each crew's decreased intake could be attributed to the first week following launch. This period coincided with incidences of motion sickness symptoms which were the most severe for the 59-day crew compared to the two other crews.[1] During the period of severely reduced intake, the highly motivated crew adhered to their schedule of work and activity so that a true negative energy balance may be assumed. These differences in caloric and fluid intake between preflight and inflight and between missions are offered as a possible explanation to account for many of the intramission differences of weight, fluid, and tissue loss.

[1]Interestingly, the crew that was said to have essentially few symptoms of space motion sickness (i.e., 28-day mission) also had a large dietary decrease for a week after launch. This crew may have eaten less because of a heavy activity schedule that included the repair of a heat shield. However, this procedure was complete by the third inflight day. The possibility exists that the mechanisms which regulate caloric intake in proportion to energy expenditure are not always operative during weightlessness for reasons other than motion sickness. The hypothesis that caloric intake is not always closely correlated with motion sickness is supported by the data (Figure 6) from the 84-day crew that showed the second highest incidence of motion sickness but had the least drop in caloric intake during the first few days inflight. A similar form of anorexia was described in the Apollo crew who generally ate less food than was provided and did not exhibit signs of motion sickness (Johnson, et al., 1974).

A caloric deficit by itself would be expected to result in fat loss and perhaps some muscle loss (Vanderveer and Allen, 1972). A deficit in water intake would deplete body water and further attenuate the total body mass loss. Therefore, it was not surprising to find that the crew of the 59-day mission exhibited the largest decreases and rates of decrease in total body weight, water, protein, and fat (Figure 7), especially during the first week in weightlessness when intake of water and food was at a minimum. In contrast, and equally as expected, the crew having the most adequate caloric intake (the 84-day mission) showed the least loss in fat and total tissue. By the end of the first month in flight, this crew also showed the smallest losses in total body mass and a small gain in fat.

The differences between the body mass and body water responses for each mission as shown in Figure 7, reflect tissue loss (primarily fat loss) and reveal relationships in these quantities that were different in each mission. The smallest changes in body water occurred on the 28-day flight. Although body weight continued to fall throughout that mission, water loss did not. This is consistent with an inadequate diet causing losses in fat tissue which contains relatively little water, and smaller losses of lean body tissues which contain nearly 75 percent water. On the other hand, the crew of the 59-day mission repleted almost half of the body water which was lost during the first two days. Partial recovery of body water was not associated with recovery of body mass for this crew, due to a hypocaloric diet-induced fat loss. The increase in body water toward levels maintained by the other crews apparently is not a result of an increase in water-bearing protein tissues because this quantity declined. Rather it suggests the occurrence of a simple rehydration response to the unusually large water deficits incurred during the early episodes of space motion sickness. For the 84-day mission there is only a slight difference between the body mass and body water curves. Both quantities fall at launch and maintain their levels during the first month. The small but constant tissue loss that is reflected by these responses of the 84-day crew is a result of two effects: a) a tendency for small quantities of fat to be stored, and b) a somewhat greater depletion of body protein. Only on the longest flight are fat changes so small that protein losses comprise a significant fraction of total tissue loss.

The behavior of protein loss on all three missions (Figure 7) was similar to the average response discussed in relation to Figure 5 and was also consistent for all nine crewmembers. The overall uniformity of this response was unexpected in light of the potential errors of the nitrogen balance (see Apendix C), but the general trend was not. The dramatic shift at the time of zero-g entry from a positive to a negative nitrogen balance is in agreement with the direction of the potassium balance (Leonard, 1977b), calf girth measurements (Hoffler, 1977), and the general wisdom that the large fraction of the body's musculature devoted to opposing gravity is virtually unused in weightlessness and disuse atrophy will rapidly occur (Thornton, 1978). It seems reasonable to suggest that the large caloric deficits of the 59-day crew may have been responsible for the most severe decline in protein mass among the three crews. However, the fact that the crew with the most adequate intake did not show the least protein loss suggests that protein loss is not preventable by increasing caloric intake. The amount of protein in the scheduled diet was certainly high enough (i.e., over 120 grams per day) to eliminate this as a factor responsible for inducing protein losses. The relative differences between the protein losses of the three missions bore no simple and plausible relationships to any of the variables examined such as diet, exercise, or preflight lean body mass. These relationships and their impact on the observed results will be discussed below, after the longer term responses have been presented.

Continuous Changes in Body Composition: Long-Term Responses

The continuous changes in body composition for each entire mission, including the preflight and postflight periods, are illustrated in Figures 8, 9, and 10. The same data is presented in a different format in Figures A-3 to A-7 (Appendix A). Longer term responses for the period beyond the first month are exemplified by the results of the 59-day and 84-day missions.

Observable in Figure 9 is a small decline in body mass during the second month of the 59-day mission, reflecting a continuing loss of fat. Also, rehydration of water continues to some extent. The 84-day mission (Figure 10) was characterized by the greatest stability of body mass, water, and total body tissue. This was the only flight on which no net change in tissue mass

FIGURE 8

CHANGES IN BODY COMPOSITION DURING SPACEFLIGHT 28 - DAY MISSION

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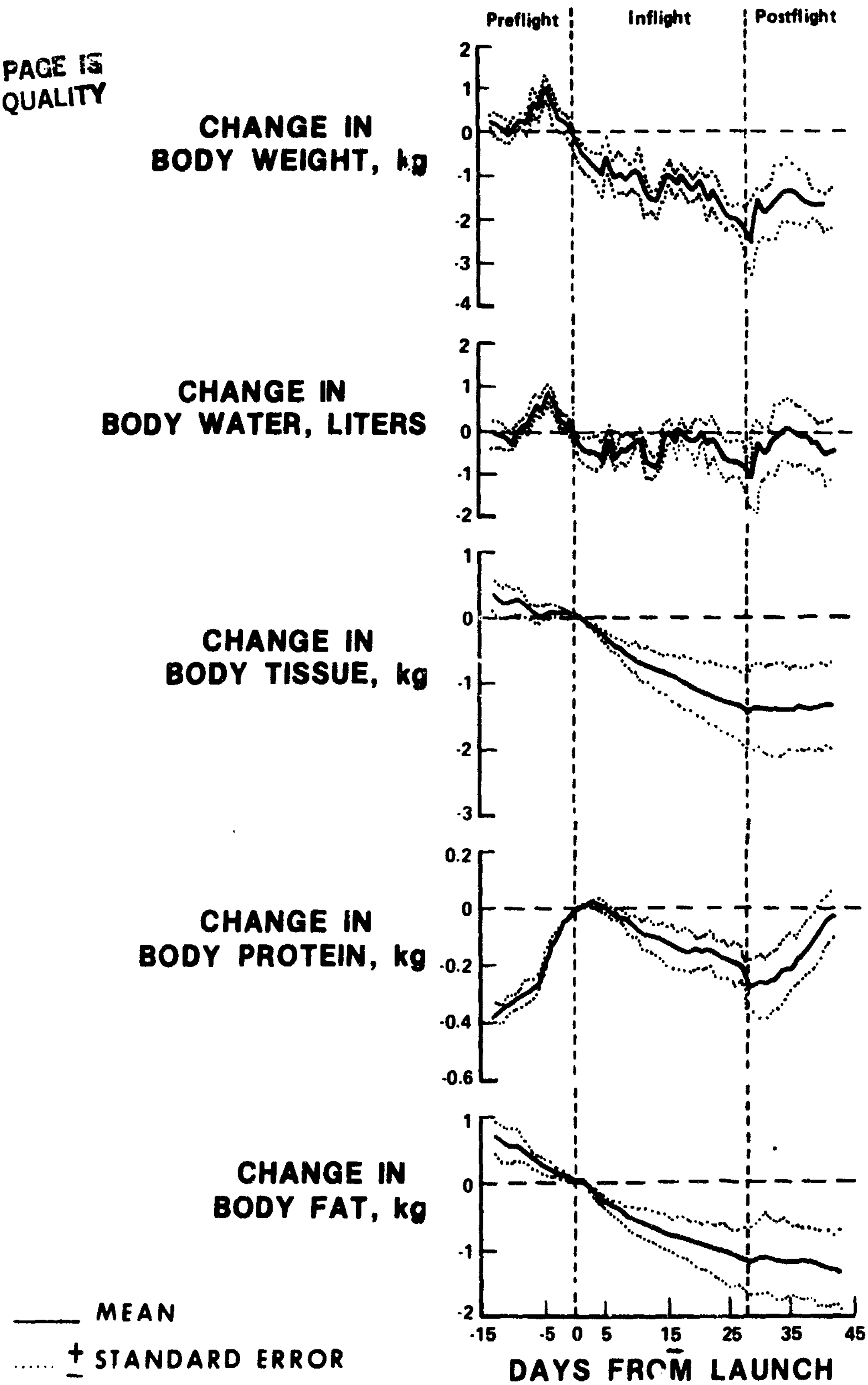

FIGURE 9

CHANGES IN BODY COMPOSITION DURING SPACEFLIGHT 59 - DAY MISSION

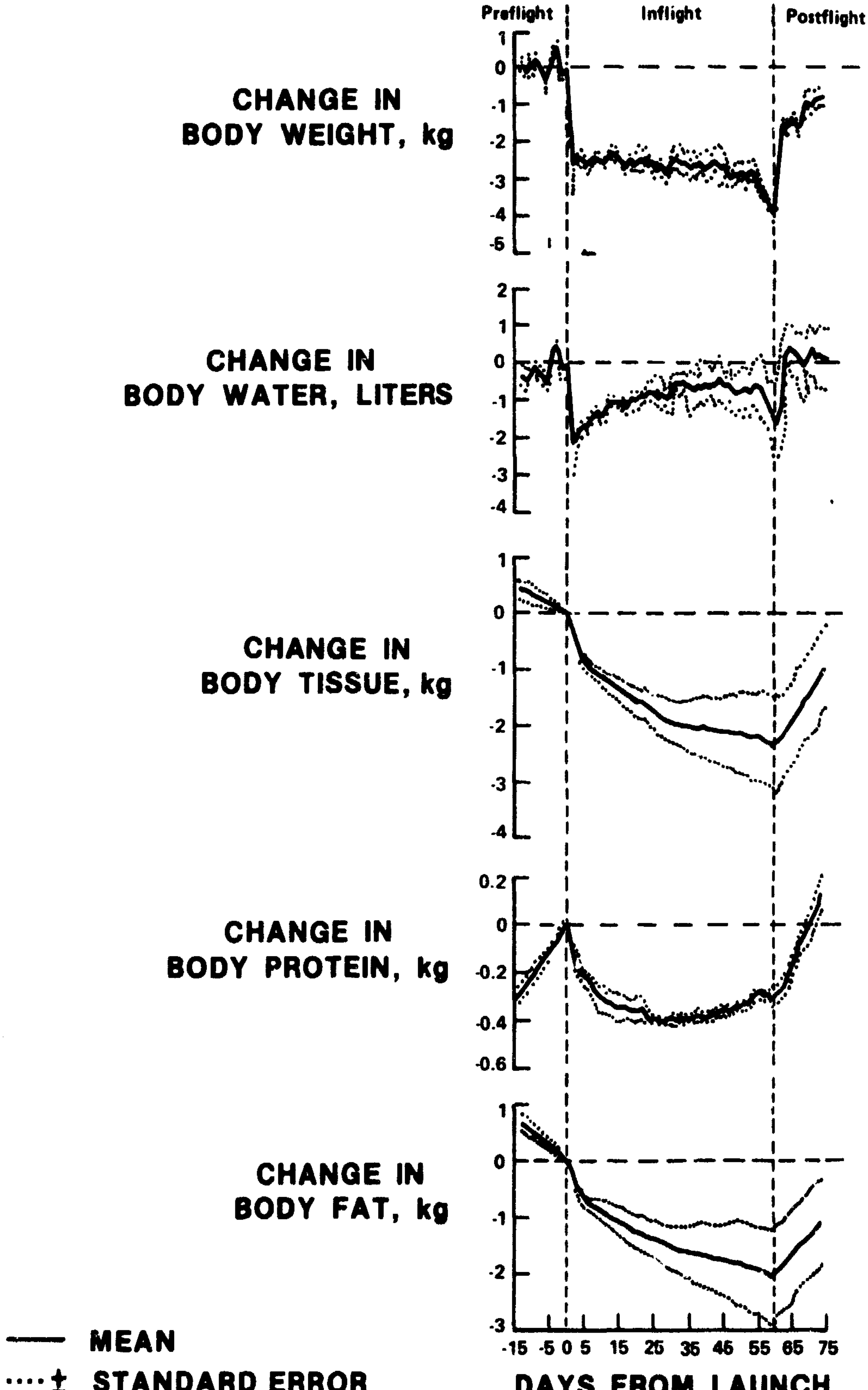

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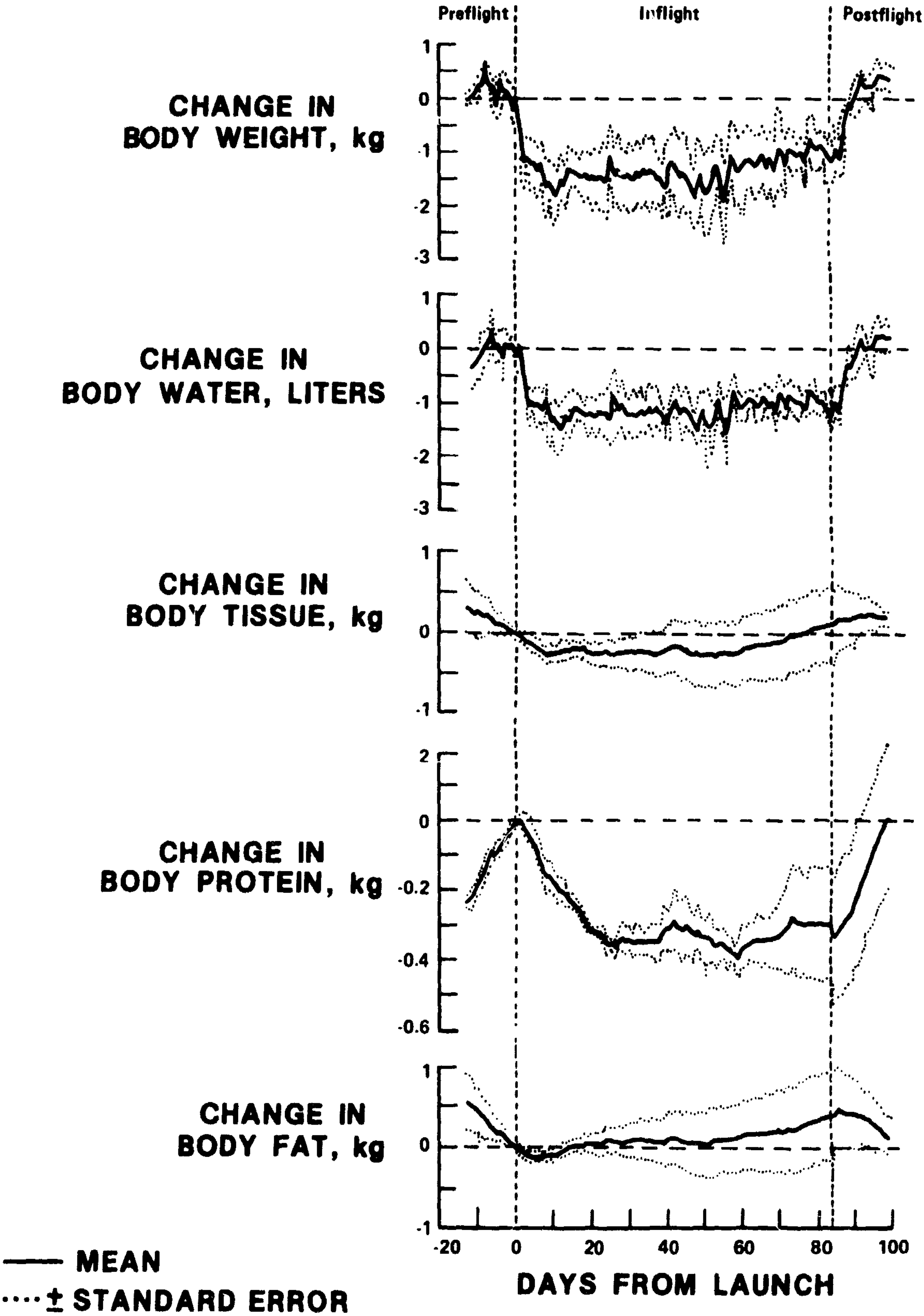
FIGURE 10

CHANGES IN BODY COMPOSITION DURING SPACEFLIGHT 84 - DAY MISSION



was observed. This stability undoubtedly reflects the combined adequacy of diet and exercise, and an improved physical condition. By most accounts this crew returned from space in better general health than any other crew (Rummel, et al., 1975). The crew of this mission exercised the hardest of all three missions and also had the highest level of dietary intake. Because of this, it is difficult to separate out the effects of flight duration, exercise, and diet.

The most important trend observed in this data that was not discernable in the first month's results, already discussed, is the leveling off of protein losses during the second and third months. This behavior is supported by other Skylab data such as mineral balance (Rambaut, et al., 1977b; also see below) and leg volume recordings (Thornton, 1978) which indicated relative stability of lean tissue during the last two months inflight. As in the analysis of the first month's data, these long term trends in protein appear to be independent of the amount of exercise performed.

Electrolyte Losses

Metabolic balances were performed on a variety of electrolytes that are associated primarily with musculoskeletal tissue (Leonard, 1977b). A summary of these analyses is presented in Table 7. The data were analyzed in four different time intervals: preflight, first month inflight, second month inflight, and third month inflight. In this treatment, the data from all nine Skylab crewmen are represented in the first two of these periods, while six subjects are represented during the second month, and three, during the third month. These balances are uncorrected in the sense that losses from the skin and sources other than urine and fecal excreta were not measured. Normally, this results in a positive balance during the control period. In all cases, the inflight balance is less than the preflight balance suggesting a net loss during space flight. There does not appear to be a trend suggesting continued mineral loss as a function of time in space. The sum total of these minerals (excluding nitrogen which has been discussed separately) is estimated to be 50 gms, which is insignificant relative to the total loss in body mass. Nevertheless these results support other findings that indicate a general loss of musculoskeletal tissue.

TABLE 7

METABOLIC BALANCES OF INTRACELLULAR MINERALS

		PREFLIGHT	1ST INFLIGHT MONTH	2ND INFLIGHT MONTH	3RD INFLIGHT MONTH
		(N=9)	(N=9)	(N=6)	(N=3)
I.	Nitrogen (g)				
	Diet	18.8	17.2	19.3	19.4
	Urine	14.1	17.7	17.6	17.7
	Fecal	1.5	1.3	1.5	1.5
	Balance	3.2	1.8	0.2	0.2
II.	Potassium (meq)				
	Diet	103.3	96.3	101.7	98.1
	Urine	74.4	81.6	79.9	78.6
	Fecal	11.9	10.7	12.6	10.8
	Balance	17.0	4.0	9.2	8.7
III.	Calcium (mg)				
	Diet	872	872	940	974
	Urine	166	288	291	242
	Fecal	699	602	819	900
	Balance	7	-18	-170	-168
IV.	Phosphorus (mg)				
	Diet	1749	1716	1861	1801
	Urine	1055	1271	1202	1181
	Fecal	514	469	596	601
	Balance	180	-24	63	19
V.	Magnesium (mg)				
	Diet	311	302	333	310
	Urine	109	131	116	120
	Fecal	176	155	192	175
	Balance	26	16	25	15

The dynamics of intracellular and extracellular changes can be inferred by the behavior of body water, sodium, and potassium. These quantities are shown in Figure 11. Body water data were obtained from the present study while the electrolyte data were derived from metabolic balance methods corrected by whole-body measurements (Leonard, 1977a; 1977b; Grounds, 1978). The loss of sodium, the major extracellular ion, from the body is much more rapid than the loss of potassium, the primary intracellular ion. Also, inflight water and sodium depletion parallel each other, as do potassium and nitrogen losses. (Nitrogen losses are shown in Figure 5 as protein changes). Taken as a whole, this data supports the notion that initial loss of body weight in space flight is primarily a result of extracellular fluid loss, and further, that the more gradual loss of body mass reflects intracellular degradation.

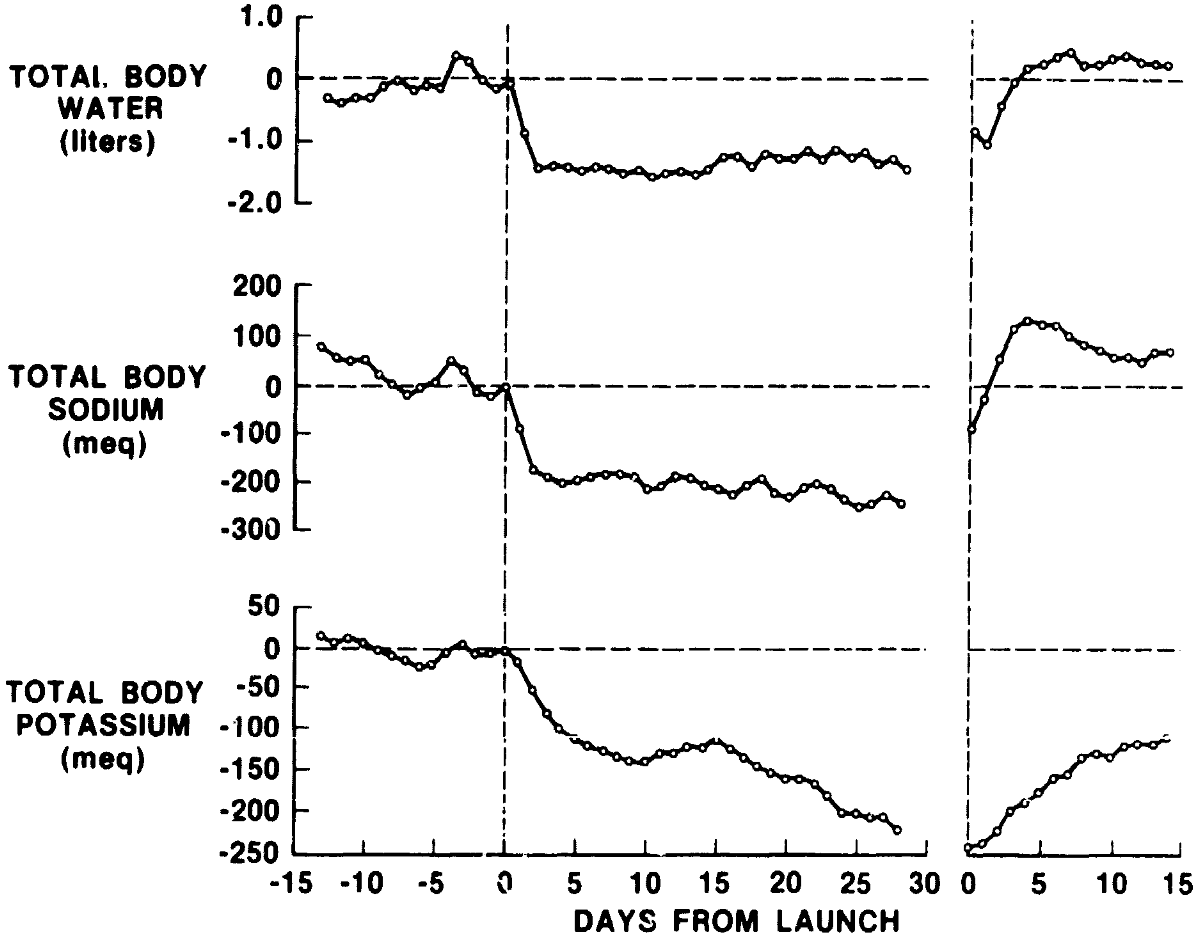
Estimates of Caloric and Exercise Requirements

The three Skylab missions, by virtue of their wide variance in dietary intake, exercise expenditure, and weight loss, provide a basis for estimating the minimum caloric food content and exercise required to prevent significant loss of body mass. An example of a linear regression analysis performed is shown in Figure 12 in which the normalized daily rate of body weight loss (determined by dividing total mission loss by mission duration) is plotted as a function of normalized daily dietary intake for each of the nine Skylab crewmembers. The line determined by least squares regression can be extrapolated to zero weight loss to determine the caloric intake requirement, which in this case is 49.5 kcal/d-kg Bwgt. Additional analyses were performed using body fat and body protein losses as dependent variables and exercise expenditure as an independent variable.

The analysis was similar to that reported by Whittle (1979) who used biostereometrically determined regional body losses rather than whole body losses to estimate caloric and exercise requirements of the Skylab crew. The following factors and assumptions were used in the present analysis:

FIGURE 11

BODY WATER AND ELECTROLYTE CHANGES DURING PROLONGED SPACEFLIGHT SKYLAB MEAN (N = 9)



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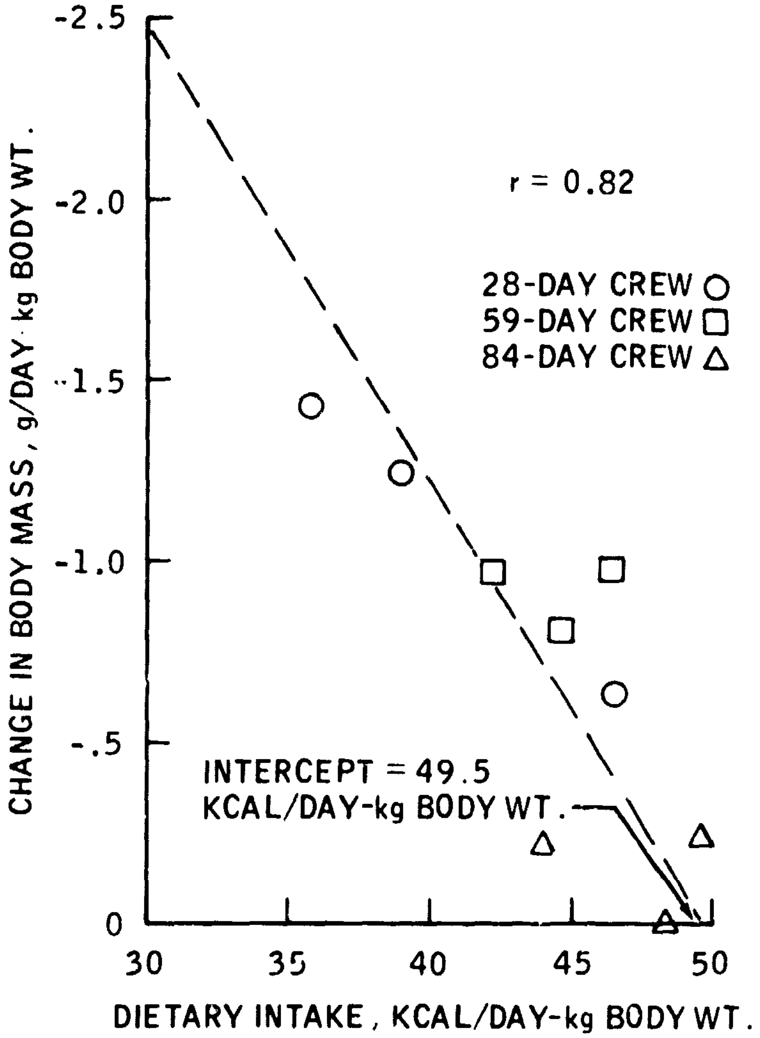

CHANGE IN BODY WEIGHT AS A FUNCTION OF DIETARY INTAKE FOR SKYLAB CREWMEN.

FIGURE 12

a) A regression equation was employed which is in a form similar to that used by Whittle (1979):

$$\Delta M/\Delta T = \text{CONSTANT} \times (E_0 - E_R)$$

where ΔM = change in body mass, body fat, or body protein (gm/kg Bwgt) that is observed over the inflight time interval, ΔT (days).

E_0 = observed energy intake from food (kcal/d-kg Bwgt) or observed energy expenditures for exercise (kcal/d-kg BWgt)

E_R = energy required from food at which no change in body mass or body fat occurs (kcal/d-kg Bwgt) or energy required for exercise at which no change in body mass or body protein occurs (kcal/d-kg Bwgt)

b) Using this equation, both caloric intake and exercise energy expenditures were separately correlated with the average rate of body mass loss ($\Delta M/\Delta T$). In addition, caloric intake was correlated with body fat on the assumption that an adequate diet would prevent the loss of body fat. Exercise was correlated with body protein on the assumption that an adequate exercise level would prevent the loss of body protein.

c) All quantities (food intake, exercise, body mass loss) were normalized with respect to preflight body weight rather than lean body mass (as was done by Whittle) because the former gave somewhat better correlations.

d) The introduction of the term ΔT attempts to account for the effect of different mission lengths. Whittle used this term in performing correlations with caloric intake but omitted it (i.e., instead, used the absolute value ΔM on the left side of the regression equation) in performing correlations with exercise, partly on the grounds that this produced higher correlation coefficients. In the present study, it was found that better correlations throughout were found using the time interval term.

e) In order to better account for the effects of different mission lengths, two sets of regression analyses were performed using: (a) data representing mass changes, intake calories, and exercise for the entire mission, and (b) data representing these quantities for only the first month. The first analysis employs data from crewmen who spent varying amounts of time in space flight while in the second analysis the inflight interval that was examined was identical for all crewmen.

f) Interactions between exercise and caloric intake were ignored due to limited data, in accord with the analysis of Whittle.

The results of this study are summarized in Table 8. The first two columns of data are the regression coefficients and zero-weight-loss-intercept, respectively, for the entire mission analysis. The last two columns are the corresponding quantities for the first month's analysis.

Regressions using the data from the entire mission suggest that weight, fat, and protein losses can be prevented if caloric intake is approximately 46 - 50 kcal/d-kg Bwgt and if exercise energy expenditure is approximately 5 - 6 kcal/d-kg Bwgt. By way of comparison, the highest level of caloric intake of any crewmember was 49.7 kcal/d-kg and the highest level of exercise was 5.1 kcal/d-kg. Regressions from the first month's data produce similar caloric requirements as for the entire mission. The exercise requirements using the first month's data cannot be considered meaningful because of the weakness of the correlations.

These caloric and exercise requirements are similar to those obtained by Whittle (1979), if allowance is made for net calories consumed instead of total calories, normalization by lean body mass (LBM) instead of total body mass, and useful bicycle work being 22 percent of total bicycle work. If these factors are considered, the following comparison (in consistent units) is found:

TABLE 8

FOOD, EXERCISE, AND WEIGHT LOSS CORRELATIONS[1]

VARIABLES		ENTIRE MISSION		FIRST MONTH	
		Regression Coefficient	Intercept kcal/d-kg Bwgt	Regression Coefficient	Intercept kcal/d-kg Bwgt
I. Caloric Intake vs	ΔWGT	.82**	49.5	.67*	48.9
	ΔFAT	.49	45.7	.56	44.7
II. Exercise vs	ΔWGT	.70*	4.97	-.18	2.97
	ΔPRO	.85**	5.67	-.28	1.34

Units: Caloric intake and exercise (kcal/d-kg Bwgt)

ΔWGT, ΔFAT, ΔPRO (gm/d-kg Bwgt)

* = ($p < .05$)

** = ($p < .01$)

Note 1. Data used in correlation analysis appears in Table A-10 (Appendix).

	Present Study	Whittle (1979)	Units
Net Caloric Requirements	48 - 52	47 - 51	kcal/d-kg LBM
Useful Bicycle Work	87 - 100	80 - 100	Watt-min/d-kg LBM

An analysis by Thornton (1978), similar to the one of Figure 12, resulted in a caloric intake requirement only slightly higher than that derived here; i.e., 49 - 51 kcal/d-kg Bwgt.

Another method of estimating caloric requirements is from the net energy utilization data (Table 4 and Table A-6, Appendix A). The average inflight value of this quantity, for the nine crewmen is 3127 $\pm$ 300 kcal/day. Accounting for the 9 percent loss of diet calories in urine and feces, a value of 3127 x 1.09 = 3410 kcal/d or 47.5 kcal/d-kg Bwgt is obtained for an estimate of dietary intake with no tissue loss or gain. This value is similar to the estimates from linear regression discussed above.

The correlation coefficients using caloric intake as independent variables were much stronger for both time intervals examined, compared to those obtained using exercise as an independent variable. In the latter case, the correlation coefficients were much stronger for the entire mission data than for the first month's data. We interpret this to mean that, on Skylab, tissue loss may have been dependent on caloric intake but not on exercise. The greatest loss of fat and protein occurs during the first month and the most meaningful correlations, if they exist, should be obtained during this interval.

The correlations of either caloric intake or exercise with total body weight loss should be cautiously interpreted. It has been suggested earlier that loss of at least a liter of fluid is obligatory upon entering weightlessness, and this quantity would be independent of either calories consumed or exercise performed. Because of this it is somewhat surprising that the correlation coefficients were so strong.

The caloric intake requirement of 46 - 50 kcal/d-kg Bwgt found in this study may be too low. Five of the nine crewmen consumed diets that fell in this range but only two of them showed no fat loss. No astronaut, however, reached the level of 50 kcal/d-kg Bwgt. In establishing caloric requirements one must consider the level of exercise and other activity as well as individual variation in basal metabolism and metabolic efficiency. Not all of these factors were accounted for in this study.

Interpretation of Body Composition Changes

The considerable variability of body composition changes between the different crewmembers and their time course during prolonged space flight partly reflect the complex relationships between diet, exercise, physical condition, and energy balance that are normally observed in terrestrial conditions. In addition, other changes were observed that appear to be unique responses to the weightless environment. Interpretation of the Skylab data, with the view of identifying and isolating the zero-g factors, is made more difficult because each successive crew remained in flight a month longer, exercised longer and harder, and received a larger caloric intake per kilogram body weight. Furthermore, each crew comprised a very small statistical sample. Therefore, differences due to flight duration, exercise levels and caloric intake may be difficult to distinguish from each other since they could be masked by differences among the particular subjects. Nevertheless, the data does lend itself to a reasonable interpretation which must eventually be verified by more direct measurements.

It is convenient to divide the discussion of body composition changes into the categories defined by each component studied:

Body Water - There appears to be an obligatory loss of at least one liter of body water that can occur within the first two days of space flight. Each of the crewmembers lost varying amounts of water early in flight, some less and some more than a liter, but at the end of one month inflight, the body water response appeared to converge toward a one liter loss (see Figure 7). The initial water deficit was primarily a result of reduced fluid intake (see Figure B-1, Appendix B), because urine and evaporative water losses, on the average, were equal to or below control levels during this period (Leonard, 1977a; Leach, et al., 1978). Those crewmembers exhibiting severe space motion sickness symptoms (first week of the 59-day mission) reduced their intake by the greatest amount and lost the greatest amount of body water. Following motion sickness and after normal intake was resumed, some body water repletion was evident in these crewmembers.

The reduction in body water is maintained throughout the flight in spite of <u>ad libitum</u> drinking. This is presumptive evidence of fluid-regulating mechanisms which are continually responding to relieve an effective central hypervolemia created by a tendency in zero-g for fluids to shift towards the head (Thornton, et al., 1977; Gauer, 1975; Pace, 1977; and Leonard, et al., 1977). Shifts up to two liters of fluid from the legs, observed on Skylab (Thornton, 1978) can easily account for the body water losses, if one assumes a large fraction of this fluid (when translocated to the upper body) is excessive for normal zero-g health and is eliminated from the body. Measurements of the body fluid compartments before and after each mission, using isotope tracers, revealed mean net losses of plasma volume (-0.41 liters) and intracellular fluid volume (-0.49 liters) (Leach and Rambaut, 1977). Nearly half of the intracellular fluid loss can be traced to loss of red cell mass (-0.23 liters) (Johnson, et al., 1977). Thus, most of the loss in total body water (-0.82 liters) measured during the first day of recovery (after some fluid replenishment had taken place) can be attributed to these compartments (see Table B-1, Appendix B).

Fluid balance studies, previously performed, complement the present energy balance analysis (Leonard, 1977a, 1977b, 1977c). Figure B-2 (Appendix B) indicates a mass balance approach for estimating evaporative water losses from the Skylab crew, and a water balance approach for partitioning fluid intake and output. The crew data used in computing these metabolic balances is summarized in Tables B-2 and B-3 (Appendix B), and the results of the partitional water balance are provided in Table B-4 (Appendix B). Overall, these results suggest that the negative inflight water balance was due mainly to a decreased water intake (-5 percent) in spite of a smaller decrease in output (-3 percent). Although there was a small increase in urine volume (+2 percent), net water output declined because of an unexpected decrease in evaporative water loss (-8 percent). Note that the values shown in Table B-4 (Appendix B) are averaged over the entire mission, and therefore, mask the dramatic changes in water balance which occur near launch and recovery.

Body Tissue - In this study, the loss of body tissue was directly related to the difference between net energy utilization and net caloric intake. The results support the premise that body fat is the material preferentially used to compensate for energy deficits due to inadequate energy intake (Grande, 1968). On the average, about three times as much weight in body fat was consumed than body protein, and since the caloric value of fat is nearly twice that of protein, the body received nearly six times as much energy from the fat loss. These proportions were nearly twice as great for the crews of the two shorter missions.

Thornton (1978) has suggested the following guidelines for understanding the effects of exercise and diet on tissue storage in terms of experiences found in one-g. These are compared parenthetically to the inflight changes estimated in this study.

(a) A calorically inadequate diet will result in fat and muscle losses, with the ratio depending on individual body fat precentages. (Significant losses of fat and muscle were observed, but no strong correlations were found between preflight body fat and zero-g losses).

(b) An inadequate diet coupled with insufficient exercise results in even more rapid muscle loss. (Protein loss was most severe when inflight dietary intake decreased most from preflight levels. However, within the limits of experimental accuracy, whole body protein losses, as reflected by several indices, did not appear to be related to the amount of exercise performed).

(c) With diet adequate to maintain body mass but insufficient exercise, the muscles will atrophy and fat will be deposited. From a caloric point of view, this condition represents the conversion of muscle into fat. (This phenomena may have been observed in the crew of the 84-day mission).

(d) With an adequate diet during periods of exercise training, a loss of fat and increase in lean body mass will occur. (This situation was observed on all missions during the preflight control period).

Body Fat - Of all the components examined the changes in fat stores appeared to have the most variability between crews. This undoubtedly reflected the wide range of caloric intake in the controlled diet as modified by the varying degrees of exercise. Caloric intake was probably inadequate for the crews on the two shortest missions. This conclusion is supported by the extent of their fat losses which averaged nearly 50 percent of their total mass loss, a value similar to that estimated for the Apollo crews returning from two-week space missions (Rambaut, et al., 1973). On the other hand, the crew with the highest caloric intake (84-day mission) exhibited a mean gain in body fat, implying a sufficient diet. The 84-day crew also exercised the most of all Skylab astronauts, and exercise by itself is capable of decreasing fat depots. Only part of the exercise performed could be quantitated, but on that basis, it appeared that the excess calories in the diet (compared to the other crews) were greater than the extra work performed by this crew (see Table 6). This could account for the small gain in fat.

Caloric intake was less than adequate for at least two reasons: a) in the case of the 28-day and 59-day crews, a strictly controlled diet was used, based on the assumption that inflight requirements should be less than those for a one-g environment (Thornton, 1978; Rambaut, et al., 1973), and b) during the first week of each flight, a significant degree of anorexia occurred coinciding with, and undoubtedly in part related to, motion sickness symptoms. As a result of the anorexia, fat losses were shown to be particularly rapid during the week following launch. In general, the changes in body fat appear to be explained by the balance between caloric intake and energy expenditure and do not appear to have been influenced by weightlessness, per se.

Body Protein - It is now well known that atrophy of skeletal muscle occurs in response to disuse, inadequate functional load, insufficient food intake, and lack of exercise (Goldspink, 1972; Booth, 1977; Federov, et al., 1977). Space flight may be associated, at various times, with one or more of these conditions. The most important findings of this analysis, with respect to body protein changes, are that protein loss begins almost immediately after entering weightlessness and, during the first month, loss rates decrease exponentially; protein loss stabilizes after the first month of flight. These losses occur in spite of a high protein diet and in the presence of exercise training. All of these findings are consisent with the hypothesis that the postural muscles are virtually unused in weightlessness and atrophy from disuse. Furthermore, the exercise performed on Skylab was not sufficient to maintain the entire mass of anti-gravity muscles. A reduced caloric intake appears to be capable of increasing the loss of muscle mass, but increased caloric intake may not necessarily prevent this loss. These conclusions are stated guardedly because the nitrogen balance, on which the inflight behavior of muscle metabolism was based, is prone to experimental error (Hegsted, 1976 and Appendix C). Also, differences in nitrogen balance between crewmembers who exercised at different levels were small and not statistically significant. Finally, other indicators of lean body mass changes on Skylab, while not inconsistent with the above hypotheses, are not in complete accord with the crew differences as reflected by the nitrogen balance (Leonard, 1979).

The rapid loss of muscle, which levels off within one month as suggested by this study, is supported by other inflight evidence, including the behavior of potassium balance (Figure 11) (Leonard, et al., 1977b; 1979) and leg volume loss (Thornton, 1978). In addition, studies on animals whose hindlimbs were immobilized by casts showed almost identical trends (Booth, 1977).

The suggestion that protein losses are independent of exercise is in opposition to the conclusions reached by other investigators. Whittle (1979) and Thornton (1978), analyzing the Skylab data, demonstrated that the higher the level of infight exercise the smaller the expected loss in leg volume and strength. (The lower limb contains little fat and therefore is a good indicator of lean body mass). Both authors concluded that given adequate diet and sufficient exercise, muscle atrophy could be prevented. The discrepancy between these reports and the present study, both of which use data from the same individuals, may be resolved by the following considerations:

(a) The data considered by Thornton and Whittle were obtained from end-of-mission measurements, while the present study utilized continuous inflight metabolic data verified by independent end-of-mission isotope dilution and biostereometric techniques. The inflight behavior revealed the potentially important result that protein losses stabilize after one month, a condition that is obscured by using only postflight data.

(b) Thornton computed rates of lean body mass loss by dividing mission duration into losses from the entire mission. We have shown by our own calculations (Table 3 (B)) that if losses stabilize before the end of the mission, this numeric procedure can give the erroneous impression of decreasing loss rates on longer missions.

(c) The exercise devices used in Skylab (such as the bicycle and treadmill) were primarily designed to condition the leg muscles. The total muscle mass, comprising about 40 percent of body mass, is located primarily in the limbs but significant postural muscle groups are located in the hips, back, and neck. The most compelling conclusions arrived at by Thornton and Whittle were based on analysis of lower limbs only, while the present analysis uses whole-body data. Therefore, it is possible that lean body mass in the legs was maintained during intensive local exercise conditioning in zero-g while upper body lean body mass deteriorated.

Because each crewmember exercised, it is not possible to quantitatively predict the zero-g effect of a complete lack of exercise. There is also no way of determining if the increasing amounts of exercise performed by the crews of the two longest missions may have contributed to the stabilization of protein losses after one month. Other adaptive effects may have played a role in abating the loss. The present analysis does indicate that exercise of the type and intensity performed on Skylab, does not significantly reduce the amount or rate of loss of total body protein. There is no reason to question, however, that exercise does maintain strength, muscle tone, and probably mass in the legs and improves circulation similar to exercise training in one-g (Thornton and Rummel, 1977).

CONCLUSIONS

The findings presented here for the Skylab crews suggest that the major components of body composition (water, protein, and fat) undergo significant changes in space flight. The kinetics and direction of these changes are different for each component, suggesting different influencing mechanisms. Also, the body mass of each component appears to converge toward new equilibrium levels appropriate for the weightless environment as modified by the caloric intake and level of activity.

In addition to the rapid two-day loss of one liter of water, moderate protein losses amounting to about 0.3 to 0.5 kg muscle (cell solids) appear to abate after about a month, while fat losses vary considerably in magnitude (from small gains to losses representing 50 percent of total body mass loss) and may continue to change for months. Water, fat, and protein losses will be significantly greater if a temporary anorexia, observed early in flight, is present. On the average, this study showed that about 60 percent of the weight loss observed during all three Skylab missions can be attributed to loss of lean body mass, the remainder being derived from fat stores.

Since diet and exercise increased with mission length, it is difficult to completely separate out the effects of these quantities from any adaptive effects of weightlessness that might occur over longer exposures in space. However, as a working hypothesis we assume the following:

First, water losses are obligatory as a result of normal physiological responses to acute headward shifts of fluid in weightlessness and are independent of flight duration.

Second, protein losses are primarily a result of disuse atrophy of postural muscles and may be obligatory in weightlessness. While overall body protein losses were independent of exercise levels on Skylab, data form other sources indicates that locally applied exercise may help to maintain protein mass in specific areas, particularly the legs.

Third, fat losses are more variable and are probably dependent on the usual one-g influences of energy balance, i.e., fat stores increase with caloric intake and decrease with exercise. Also, changes in body fat depend on the cumulative effects of a positive or negative energy balance and are therefore, highly time-dependent.

Fourth, an anorexia of varying degrees appears to be associated with the initial period of weightlessness and this condition is only partly related to symptoms of frank motion sickness. If present, the anorexia of space flight will augment tissue losses by virtue of a caloric deficiency and enhance water loss as a result of reduced fluid intake. Differences in caloric intake between preflight and inflight, and between each of the Skylab missions, is offered as a possible explanation to account for some of the intramission differences of weight, fluid, and tissue loss.

Finally, energy requirements in a working space flight environment do not appear to be less than required to maintain body weight on the ground, contrary to former expectations. It was estimated that a caloric intake of 46 - 50 kcal/d-kg body weight would have prevented significant tissue loss (primarily fat) for the Skylab astronauts.

The procedures used in this study to analyze the metabolic balance data admittedly provide only indirect estimates of inflight tissue and fluid loss behavior. This analysis was performed and is being reported because it is unlikely that direct inflight measurements of body composition changes will be accomplished in the near future.

ACKNOWLEDGEMENTS

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APPENDIX A

ENERGY BALANCE DATA

This appendix contains supplementary information regarding the Skylab astronaut population and concerns body composition and energy balance. Each table presents individual crew data regarding physical characteristics, caloric intake, caloric output, energy utilization, body composition changes, and exercise levels. Of particular interest are the graphs comparing the three Skylab missions. The data pertaining to caloric intake and body composition changes are expressed graphically as functions of mission time. Some of this data has been presented in Figures 5 through 10 in the text, but the format in this appendix permits a more meaningful comparison because of a more uniform scale.

In the Tables of Appendices A and B, the crewmen numbered 1 to 3, 4 to 6, and 7 to 9 refer to crewmembers on the 28-day, 59-day, and 84-day missions, respectively.

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TABLE A-1

PHYSICAL CHARACTERISTICS OF SKYLAB ASTRONAUTS

(MEAN ± SD)

MISSION	SUBJECT	AGE (yr)	HEIGHT (cm)	SURFACE AREA (m^2)	BODY WEIGHT (kg)	LEAN BODY MASS* (kg)	BODY FAT (%)
28-Day	1		170	1.65	62.21	57.0	8.4
	2		183	1.96	77.89	66.9	14.1
	3		178	1.93	80.18	71.4	11.0
	MEAN	4[illegible]	177	1.85	73.43	64.9	11.2
		±1	± 7	±.17	±9.81	±7.4	±2.8
59-DAY	1		175	1.74	68.56	58.2	15.1
	2		175	1.66	61.82	53.6	13.3
	3		183	2.02	88.01	73.4	16.6
	MEAN	40	178	1.81	72.80	61.6	15.0
		±3	± 5	±.19	±13.60	±10.4	±0.5
84-DAY	1		175	1.75	67.75	57.3	15.4
	2		175	1.78	71.51	62.2	13.0
	3		175	1.77	67.60	62.5	7.5
	MEAN	40	175	1.77	68.95	60.5	12.1
		±3	± 0	±.02	2.22	±2.9	±4.2
SKYLAB	MEAN	41	177	1.81	71.73	62.5	12.8
		±2	± 4	±.13	±8.71	±6.8	±3.1

* Derived from $LBM = \frac{TBW}{0.73}$

TABLE A-2

NET ENERGY UTILIZATION(KCAL/DAY)

MISSION	SUBJECT	PREFLIGHT	INFLIGHT	POSTFLIGHT
28 Day Mission		2737	2861	3493
	2	3522	3572	2729
	3	3448	2969	2706
59-Day Mission	4	3037	3049	1485
	5	3354	3170	2248
	6	3994	3678	3633
84-Day Mission	7	2879	2842	3306
	8	3130	2973	2833
	9	3733	3031	3322
Mean		3319	3127	2862
		±414	±300	±682

TABLE A-3

INFLIGHT BODY COMPOSITION CHANGES*

(Gm)

MISSION	CREWMEMBER	Δ BODY WEIGHT	Δ TOTAL BODY WATER	ΔTISSUE SOLIDS	ΔPROTEIN	ΔFAT
28-DAY	1	- 1100	- 405	- 695	- 170	- 525
	2	- 2700	- 180	- 2520	- 390	- 2130
	3	- 3200	- 2090	- 1110	- 300	- 810
	MEAN	- 2330	- 890	- 1440	- 290	- 1155
	± SD	+ 1100	± 1040	± 960	± 110	± 855
59-DAY	4	- 3900	- 1365	- 2535	- 365	- 2170
	5	- 4200	+ 125	- 3725	- 285	- 3435
	6	- 4200	- 3345	- 855	- 295	- 560
	MEAN	- 3900	- 1530	- 2370	- 320	- 2055
	± SD	± 300	± 1740	± 1440	± 40	± 1440
84-DAY	7	0	- 770	+ 770	- 650	+ 1420
	8	- 1400	- 615	- 785	- 355	- 425
	9	- 1400	- 1600	+ 200	- 30	+ 230
	MEAN	- 930	- 995	+ 62	- 350	+ 410
	± SD	± 810	± 530	± 790	± 310	± 935
SKYLAB	MEAN	- 2390	- 1140	- 1250	- 315	- 935
	± SD	± 1460	± 1090	± 1425	± 170	± 1440

*Time period considered is from morning of launch (one-g) to morning of recovery (zero-g).

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TABLE A-4

SKYLAB CHANGES OF BODY WEIGHT/MASS AND BODY WATER

(kg)

CREWMAN	BODY WEIGHT PREFLIGHT MEAN	BODY WEIGHT $\Delta_1^{(a)}$	BODY WEIGHT $\Delta_2^{(b)}$	TOTAL BODY WATER PREFLIGHT MEAN	TOTAL BODY WATER Δ_1	TOTAL BODY WATER Δ_2
1	62.21	-2.0	-1.1	41.55	-0.75	-0.41
2	77.89	-3.6	-2.7	48.80	-0.80	-0.18
3	80.18	-4.2	-3.2	52.15	-2.15	-2.09
4	68.56	-4.0	-3.9	42.50	-0.60	-1.37
5	61.82	-3.1	-3.6	39.10	+0.50	+0.12
6	88.01	-3.9	-4.2	53.60	-1.70	-3.34
7	67.75	+0.1	0	41.85	-0.85	-0.77
8	71.51	-2.9	-1.4	45.40	-0.50	-0.62
9	67.60	-1.5	-1.4	45.65	-0.55	-1.60
MEAN	71.73	-2.8	-2.4	45.62	-0.82	-1.14
± SD	±8.72	±1.4	±1.5	±5.00	±0.75	±1.09

(a) Δ_1 = Change from preflight mean to first shipboard measurement at recovery. Body mass was measured within several hours of recovery. Body water was measured on first or second day of recovery.

(b) Δ_2 = Change fror preflight mean to morning of day of recovery (a zero-g state). Total body water changes estimated by correcting for water intake and excretion between recovery a.m. and first shipboard measurement.

TABLE A-5

PREFLIGHT ENERGY BALANCE (kcal/day)

ENERGY BALANCE COMPONENT	CREWMAN 1	2	3	4	5	6	7	8	9
Total Diet	2916	3166	3175	2851	2996	4214	3224	3149	3269
Excreta:									
Urine	106	105	110	93	108	166	116	121	135
Feces	142	158	143	110	125	171	160	146	129
Total Excreta	248	263	253	203	233	337	276	267	264
Body Tissue Loss:									
Protein	-104	-110	-106	-108	-121	-143	-117	- 78	- 98
Fat	173	730	632	497	712	260	47	326	866
Total Tissue	69	620	526	389	591	117	- 70	248	768
Net Energy Utilization	2737	3523	3448	3037	3354	3994	2878	3130	3773

Notes

a) Diet (kcal/day) = 4.182 diet carbohydrates (gm/d) + 9.461 x diet fat (gm/d) + 5.65 x protein (gm/d)

b) Urine energy = 8.32 x urine nitrogen (gm/d)

c) Energy from protein tissue loss = 5.65 kcal/gm

d) Energy from fat tissue lost = 9.461 kcal/gm

e) Minus sign denotes a gain body tissue

f) Net energy utilization = Diet-Excreta + Energy from body tissue lost

TABLE A-6

INFLIGHT ENERGY BALANCE (kcal/day)

ENERGY BALANCE COMPONENT	CREWMAN 1	2	3	4	5	6	7	8	9
Total Diet	2888	3031	2873	2888	2860	3927	3271	3149	3361
Excreta									
Urine	132	150	135	111	138	186	152	146	160
Feces	106	107	104	111	131	181	161	102	146
Total Excreta	238	257	239	222	269	367	313	247	306
Body Tissue Loss									
Protein	34	79	60	35	28	28	44	24	2
Fat	178	720	274	348	551	90	-160	[illegible]	- 26
Total Tissue	212	798	334	383	579	118	-116	72	- 24
Net Energy Utilization	2861	3572	2968	3049	3170	3678	2842	2974	3031

Notes

a) Diet (kcal/day) = 4.182 diet carbohydrates (gm/d) + 9.461 x diet fat (gm/d) + 5.65 x protein (gm/d)

b) Urine energy = 8.32 x urine nitrogen (gm/d)

c) Energy from protein tissue loss = 5.65 kcal/gm

d) Energy from fat tissue lost = 9.461 kcal/gm

e) Minus sign denotes a gain body tissue

f) Net energy utilization = Diet-Excreta + Energy from body tissue lost

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TABLE A-7

MEAN DAILY CALORIC VALUE OF DIET

CREWMAN	DAYS OBSERVED		CHO(gm)		FAT(gm)		PRO(gm)		EDIET(kcal) (Calculated)		EDIET(kcal) (Bomb)	
	Pre	Inf	Pre	Inf	Pre	Inf	Pre	Inf	Pre	Inf	Pre	Inf
1	30	28	319	376	105	79	[illegible]	101	2916	2888	2632	2498
2	30	28	382	402	101	80	108	105	3166	3031	2901	2580
3	30	28	364	394	109	72	110	97	3175	2873	2881	2497
4	20	59	331	426	98	66	95	95	2851	2888	2561	2586
5	20	59	315	368	110	76	112	107	2996	2860	2688	2511
6	20	59	490	565	132	77	163	148	4214	3927	3716	3488
7	26	84	363	398	108	100	121	118	3224	3271	3152	3202
8	26	84	358	395	108	92	113	111	3149	3149	3088	3085
9	26	84	348	385	116	109	127	128	3269	3361	3194	3285
SKYLAB	MEAN		363	412	110	83	117	111	3218	3139	2979	2859
	± SD		52	60	10	14	19	18	400	349	358	400

NOTES:

a) CHO = dietary carbohydrates; FAT = dietary fat; PRO = dietary protein

b) EDIET (Calculated) = total energy derived from diet = (4.182)CHO + (9.461)FAT + (5.65)PRO

c) EDIET (Bomb) = total energy of diet measured by bomb calorimetry

(The number of samples used to obtain EDIET(Bomb) was somewhat less than that used to compute EDIET (Calculated).)

d) Regression coefficients for EDIET(Calc) vs EDIET(Bomb): r = 0.93 (Preflight), r = 0.91 (Inflight)
Ratio Inflight/Preflight for EDIET(Calc) = .975, for EDIET (Bomb) = 0.96

TABLE A-8

ENERGY AVAILABLE AND UTILIZED

(kcal/day)

MISSION	SUBJECT	EDIET PRE	EDIET INF	EDIET NET PRE	EDIET NET INF	EUTIL PRE	EUTIL INF
28-DAY	1	2916	2888	2668	2649	2737	2861
	2	3166	3031	2903	2774	3522	3572
	3	3175	2873	2921	2634	3448	2969
	MEAN	3086	2931	2831	2686	3236	3134
	± SD	147	87	141	77	433	383
59-DAY	4	2851	2888	2648	2666	3037	3049
	5	2996	2860	2763	2592	3354	3170
	6	4214	3927	3877	3560	3994	3678
	MEAN	3354	3225	3096	2939	3462	3299
	± SD	749	608	679	539	488	334
84-DAY	7	3224	3271	2949	2959	2879	2842
	8	3149	3149	2882	2901	3130	2973
	9	3269	3361	3005	3055	3773	3031
	MEAN	3214	3260	2945	2972	3261	2949
	± SD	61	106	62	78	461	97
SKYLAB	MEAN	3218	3139	2957	2866	3319	3127
	± SD	±400	±349	±367	±306	±414	±300

NOTES

a) EDIET = total energy available from dietary carbohydrates, fats, proteins (calculated).

b) EDIET NET = EDIET – energy in urine and feces.

c) EUTIL = energy utilized = EDIET NET + energy obtained from protein and fat catabolism.

TABLE A-9

ENERGY AVAILABLE AND UTILIZED

(kcal/day-kg Bwgt)

MISSION	SUBJECT	EDIET		EDIET NET		EUTIL	
		Pre	Inf	Pre	Inf	Pre	Inf
28-DAY	1	46.9	46.4	42.9	42.6	44.0	46.0
	2	40.7	38.9	37.3	35.6	45.2	45.9
	3	39.6	35.8	36.4	32.9	43.0	37.0
	MEAN	44.7	40.4	38.9	37.0	44.1	43.0
	± SD	±4.5	±5.5	±3.5	±5.0	±1.1	±5.2
59-DAY	4	41.6	42.1	38.6	38.9	44.3	44.5
	5	48.5	46.3	44.7	41.9	54.3	51.3
	6	47.9	44.6	44.1	40.5	45.4	41.8
	MEAN	46.0	44.3	42.5	40.4	47.6	45.9
	± SD	3.8	±2.1	±3.4	±1.5	±5.4	±4.9
84-DAY	7	47.6	48.3	43.5	43.7	42.5	42.0
	8	44.0	44.0	40.3	40.6	43.8	41.6
	9	48.4	49.7	44.5	45.2	55.8	44.8
	MEAN	46.7	47.3	44.7	43.2	47.3	42.8
	± SD	±2.3	±3.0	±2.9	±2.3	±7.3	±1.7
SKYLAB	MEAN	45.0	44.0	41.4	40.2	46.4	43.9
	± SD	±3.6	±4.5	±3.3	±3.9	±4.9	±4.0

TABLE A-10

INFLIGHT DIET, EXERCISE, AND WEIGHT LOSS COMPONENTS*

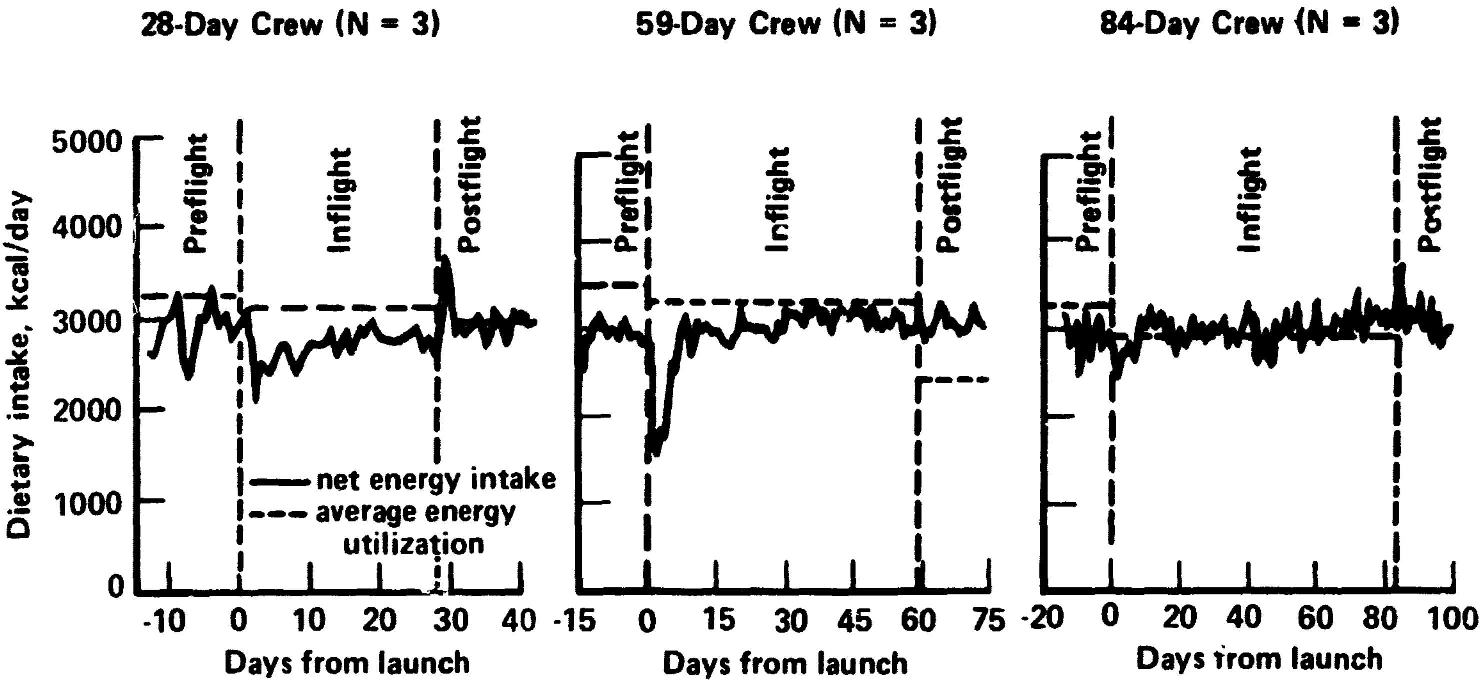
SUBJECT	CALORIC INTAKE (kcal/d-kg)	AVERAGE DAILY EXERCISE WORK † (kcal/d-kg)	ΔBWGT	ΔFAT	ΔPRO
			(gm/d-kg)		
1	46.4	2.35	-0.632	-0.302	-0.0966
2	38.9	1.35	-1.238	-0.977	-0.179
3	35.8	1.62	-1.426	-0.361	-0.133
4	42.1	3.68	-0.964	-0.537	-0.090
5	46.3	3.83	-0.987	-0.941	-0.0788
6	44.6	4.84	-0.809	-0.108	-0.0572
7	48.2	4.00	0	+0.249	-0.114
8	44.0	5.09	-0.233	-0.071	-0.0594
9	49.7	4.76	-0.247	+0.041	-0.0855

*These data used in correlations of Table 8.

†Derived from Michel et al. (1977) by dividing useful bicycle work by 22 percent efficiency. To compute total exercise performed over the mission in watt-min (W-min), multiply value in table for average daily exercise work (kcal/d-kg) by BWgt x 70 W-min/kcal x 0.22 x N, where N is the number of inflight days in the Skylab mission.

FIGURE A-1

ENERGY SUPPLY COMPARED TO UTILIZATION FOR EACH SKYLAB MISSION



The difference between net energy intake for each Skylab crew (solid lines) and the average energy utilization (horizontal dashed lines) represents the energy content of tissue stored or degraded. The average daily value of this difference decreased for each successive mission during the inflight phase. Thus, the value of inflight tissue degradation (a measure of energy balance) for each mission was computed as: -448 kcal/day (28-Day Crew); -360 kcal/day (59-Day Crew); +23 kcal/day (84-Day Crew). A negative sign indicates a negative energy balance (intake less than utilization) associated with tissue loss; a positive sign indicates a positive energy balance (intake greater than utilization) associated with tissue storage.

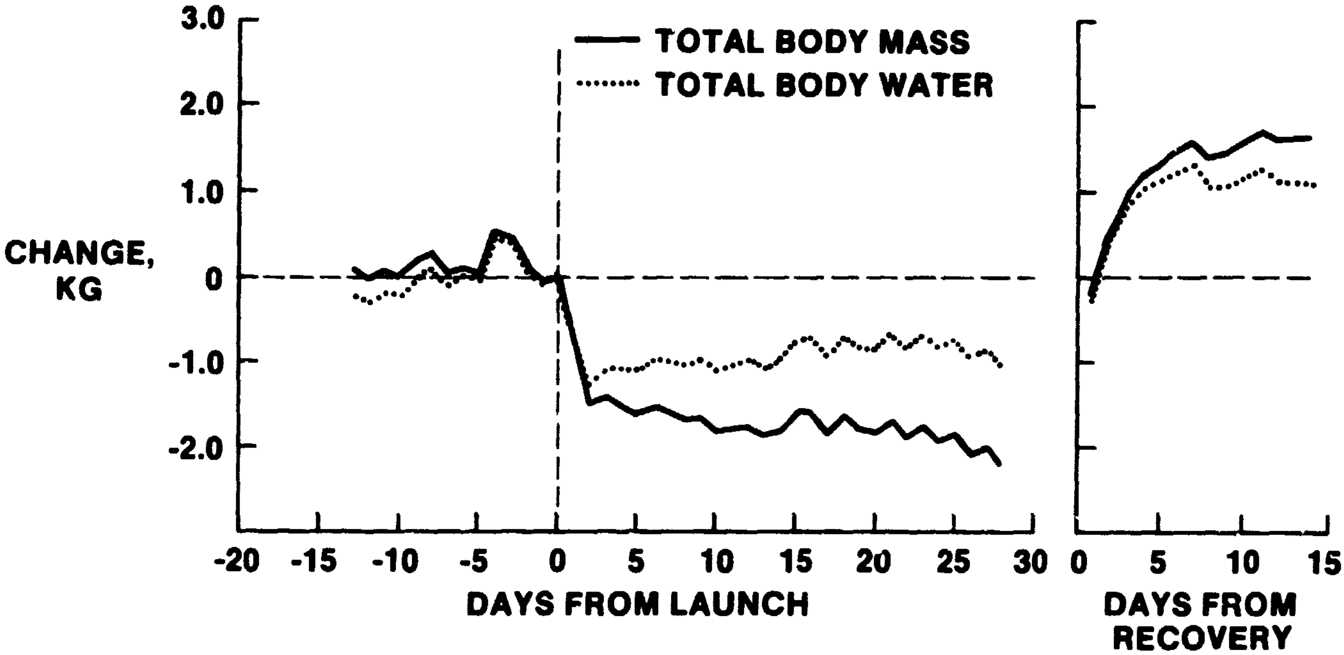
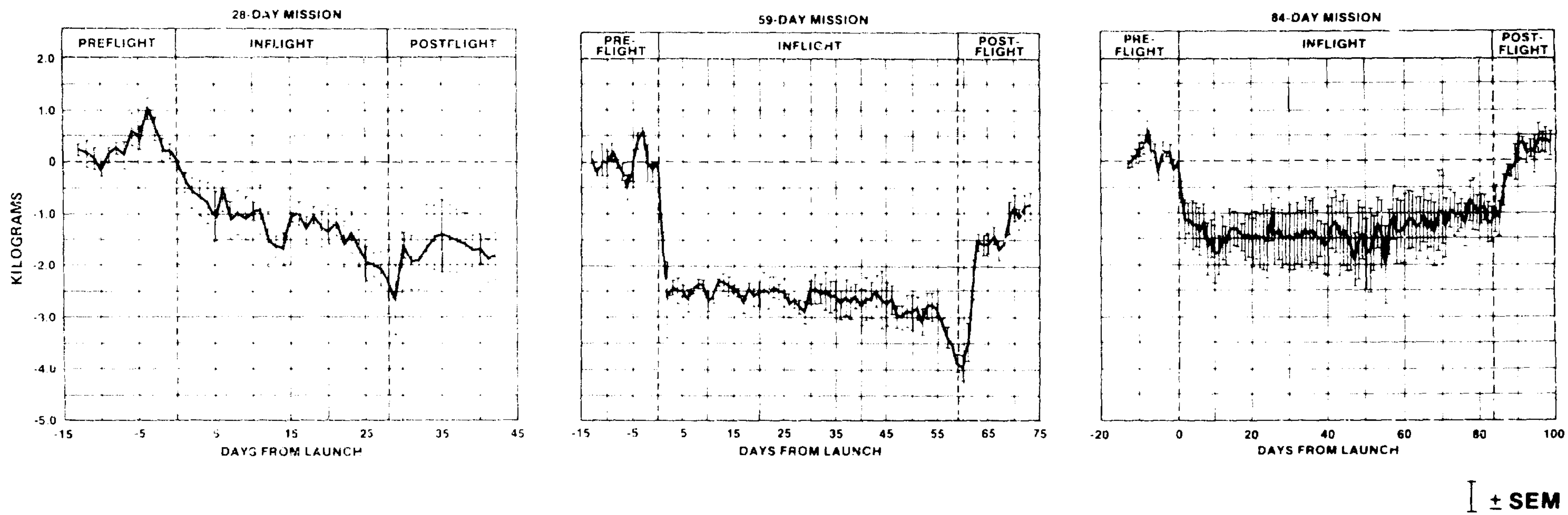


FIGURE A-2

MEAN SKYLAB RESPONSE OF BODY MASS AND BODY WATER TO LAUNCH AND RECOVERY (N=9)

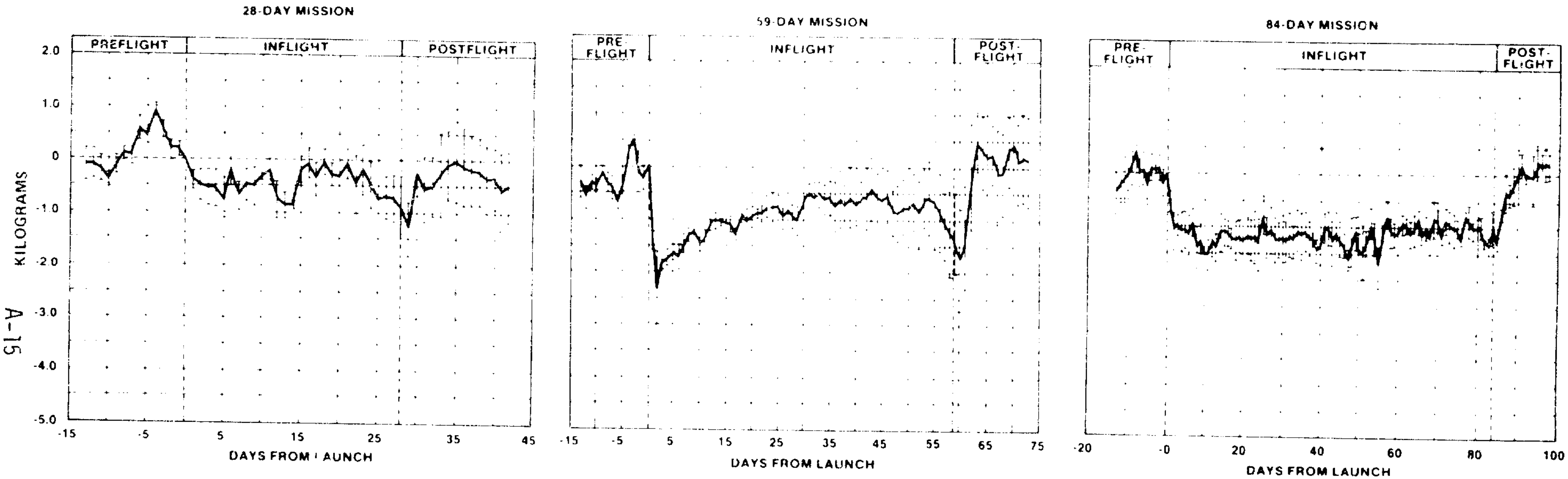
The difference between body mass changes and body water changes reflects the changes of dry tissue, comprised primarily of lean body mass (protein and water) and fat.



CHANGE IN BODY WEIGHT DURING EACH SKYLAB MISSION (N=3)

(VALUES ARE SHOWN AS CHANGES FROM MORNING OF LAUNCH)

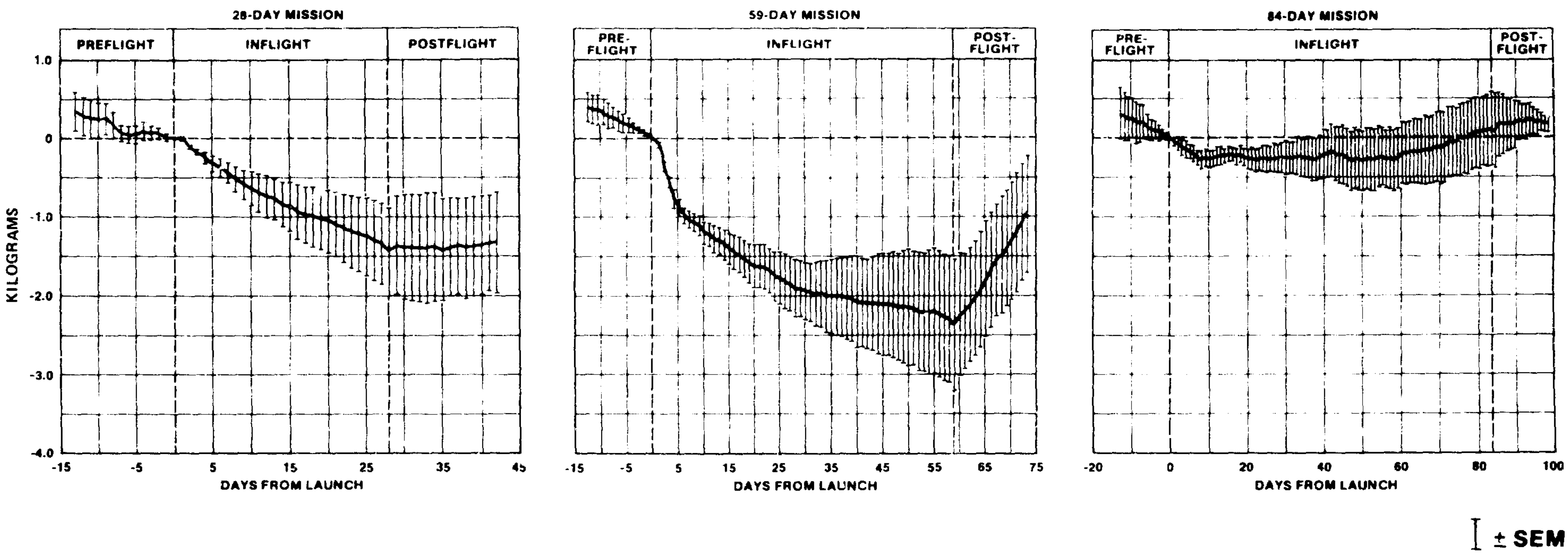
FIGURE A-3



CHANGE IN TOTAL BODY WATER DURING EACH SKYLAB MISSION (N=3)

(VALUES ARE SHOWN AS CHANGES FROM MORNING OF LAUNCH)

FIGURE A-4



CHANGE IN TOTAL BODY TISSUE DURING EACH SKYLAB MISSION (N=3)

(VALUES ARE SHOWN AS CHANGES FROM MORNING OF LAUNCH)

FIGURE A-5

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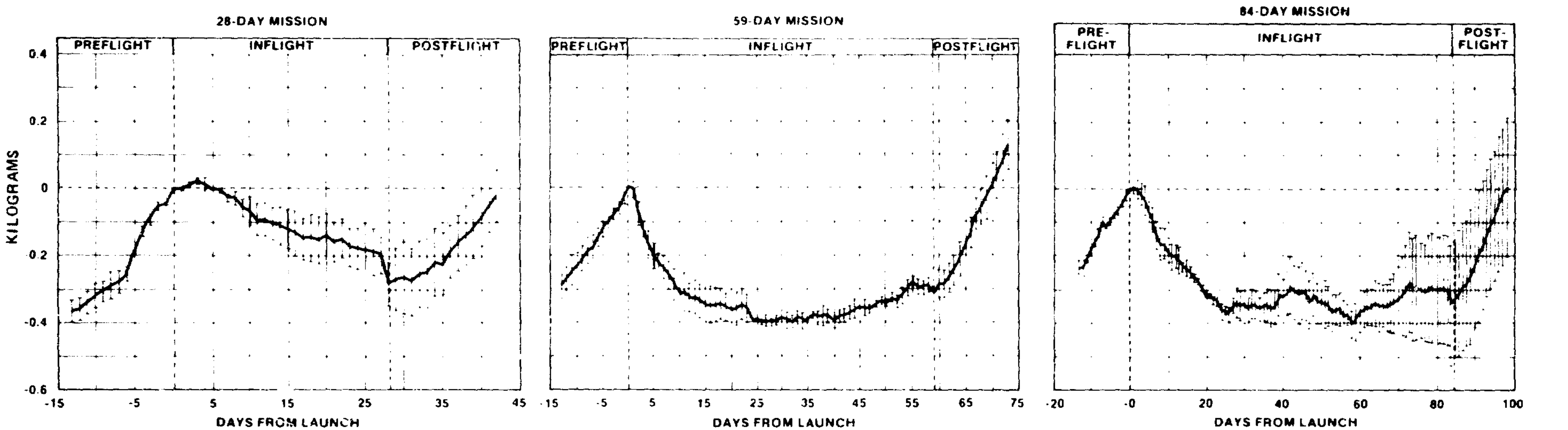
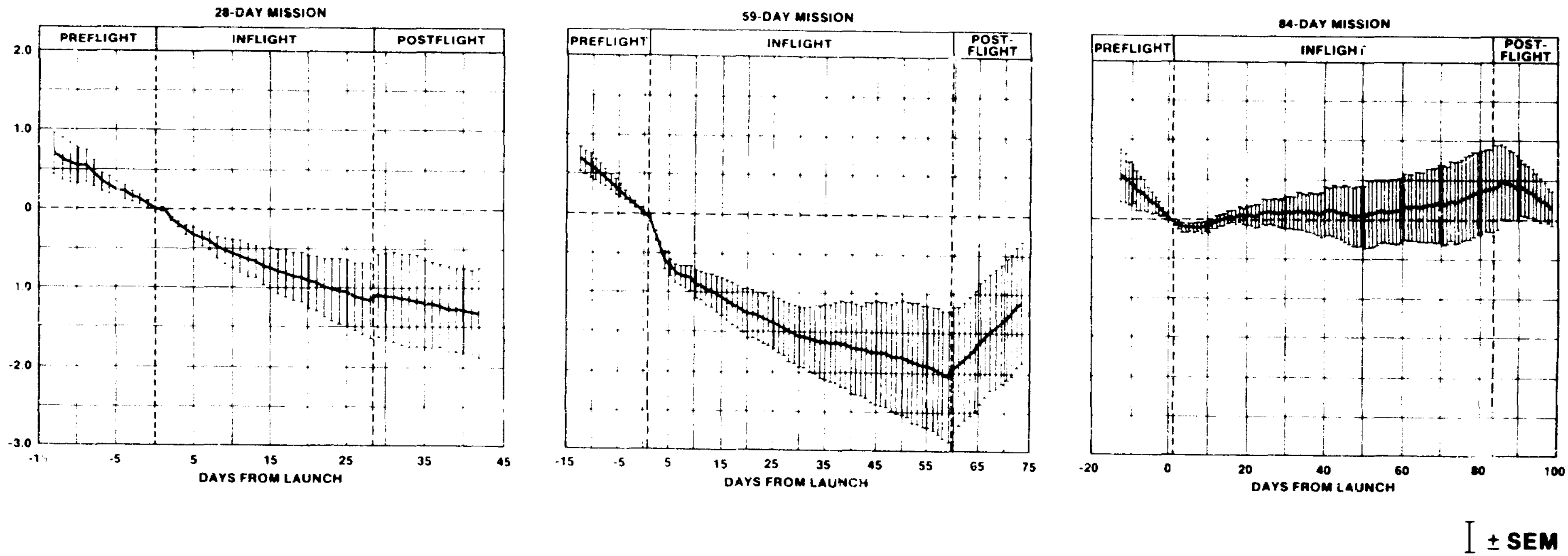


CHANGE IN BODY PROTEIN DURING EACH SKYLAB MISSION (N=3)

(VALUES ARE SHOWN AS CHANGES FROM MORNING OF LAUNCH)

FIGURE A-6



CHANGE IN BODY FAT DURING EACH SKYLAB MISSION (N=3)

(VALUES ARE SHOWN AS CHANGES FPOM MORNING OF LAUNCH)

FIGURE A-7

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APPENDIX B

WATER BALANCE DATA

Body mass changes consist of caloric (primarily fat and muscle) and non-caloric (water and electrolytes) components. Whereas Appendix A is concerned with caloric balance, Appendix B contains data concerning the Skylab crew's water balance. The total water intake during the first two weeks of flight is shown in Figure B-1. This can be compared to Figure 6 where the corresponding data for food is presented. Both food and water intake diminish to varying extents during the early portions of weightlessness.

Changes in the major body fluid compartments of the Skylab crews are presented in Table B-1. Total body water was obtained using tritium dilution, plasma volume from ^{125}I dilution, extracellular fluid from ^{35}S dilution, and interstitial and intracellular fluid were derived from these other three primary measurements.

The components of water balance are illustrated graphically in Figure B-2, particularly as they pertain to the computing of evaporative water losses from a mass balance and water balance. (Evaporative water loss was the only major route of water metabolism that was not measured in some direct manner during the Skylab program; thus it had to be computed indirectly.) Tables B-2 to B-4 provide the numerical data required for calculating the crew's water balance.

TABLE B-1

CHANGES IN BODY FLUID COMPARTMENTS OF SKYLAB CREWS

[Liters ± (SE)]

BODY FLUID COMPARTMENT	28-DAY MISSION	59-DAY MISSION	84-DAY MISSION	SKYLAB MEAN
Total Body Water	- 1.22 ± (.47)	- 0.600 ± (.64)	- 0.630 ± (.11)	- 0.82 ± (.25)
Extracellular Fluid	- 0.13 ± (.17)	- 0.870 ± (.41)	0.0 ± (.52)	- 0.33 ± (.24)
a) Plasma Volume	- 0.28 ± (.14)	- 0.[illegible]30 ± (.10)	- 0.530 ± (.08)	- 0.41 ± (.06)
b) Interstitial Fluid*	+ 0.15 ± (.50)	- 0.440 ± (.46)	+ 0.530 ± (.48)	+ 0.08 ± (.7[illegible]
Intracellular Fluid+	- 1.08 ± (.64)	+ 0.270 ± (1.04)	- 0.630 ± (.63)	- 0.49 ± (.44)

*Derived from Extracellular Fluid and Plasma Volume

+Derived from Intracellular and Extracellular Fluids

TABLE B-2

MEASURED VARIABLES USED IN BALANCE EQUATIONS

Crewman	DAYS Pre	DAYS In	H_2O IN Pre	H_2O IN In	FOOD Pre	FOOD In	PRO Pre	PRO In	FAT Pre	FAT In	CHO Pre	CHO In	URINE Pre	URINE In	H_2O FECAL Pre	H_2O FECAL In	FECAL SOLIDS Pre	FECAL SOLIDS In
1	30	28	2500	2489	555.6	578.0	10[illegible].6	100.7	104.9	79.1	318.5	375.6	1340	1383	81.0	70.3	18.4	19.7
2	30	28	2316	2313	619.3	609.6	107.9	105.0	101.2	79.7	382.3	402.4	849	1097	90.6	58.3	28.4	20.5
3	30	28	4008	3994	609.8	585.2	109.8	97.1	109.0	71.7	364.4	393.6	2642	2457	63.5	74.2	23.7	20.2
4	20	59	2214	2137	544.6	595.7	95.1	95.1	98.1	66.2	331.2	425.9	1392	1168	45.1	48.7	18.1	20.7
5	20	59	2594	2487	560.7	571.9	112.4	107.0	110.1	75.6	315.4	368.3	1110	1402	91.5	71.4	23.8	23.2
6	20	59	3227	3166	819.2	821.8	162.6	147.8	131.8	76.9	489.8	565.2	1498	1497	133.3	111.4	33.6	33.6
7	26	84	2868	2612	617.3	639.0	120.7	117.8	108.2	99.5	363.1	398.1	1739	1605	128.6	77.4	31.2	28.7
8	26	84	3325	2824	600.1	621.1	112.5	111.4	107.5	91.8	357.6	394.7	1350	1555	55.7	50.8	24.1	19.2
9	26	84	3667	3374	615.6	645.7	126.9	128.1	115.8	108.5	348.4	385.2	1092	1855	47.2	55.3	22.8	25.1
MEAN$\pm$			2971	2822	615.8	630.0	116.9	111.1	109.6	83.2	363.4	412.1	1535	1558	81.8	68.6	24.9	23.4
SD			625	591	81.7	76.5	19.4	18.4	9.8	13.8	52.4	59.7	517	407	32.7	19.2	5.3	4.9
SE			208	197	27.2	25.5	6.5	6.1	3.3	4.6	17.5	19.9	172	136	10.9	6.4	1.8	1.6

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TABLE B-3

DERIVED DATA USED IN BALANCE EQUATIONS

Crewman	DAYS		H_2O METAB.		CO_2-O_2		ΔWGT	
	Pre	In	Pre	In	Pre	In	Pre	In
1	30	28	330	335	148.1	173.8	-30.0	-39.3
2	30	28	364	353	176.5	186.1	-46.7	-96.4
3	30	28	363	336	168.6	181.5	-56.7	-114.3
4	20	59	327	344	152.6	193.9	+5.0	-66.1
5	20	59	337	330	147.7	171.9	-35.0	-61.0
6	20	59	478	460	229.8	263.5	+80.0	-71.2
7	26	84	365	375	169.8	185.0	+30.8	00.0
8	26	84	358	363	166.1	183.0	-30.8	-16.7
9	26	84	367	381	163.9	180.5	00.00	-16.7
MEAN±			365	364	169.2	191.0	9.2	53.5
SD			45	40	24.9	28.0	43.0	38.5
SE			15	13	8.3	9.3	14.4	12.8

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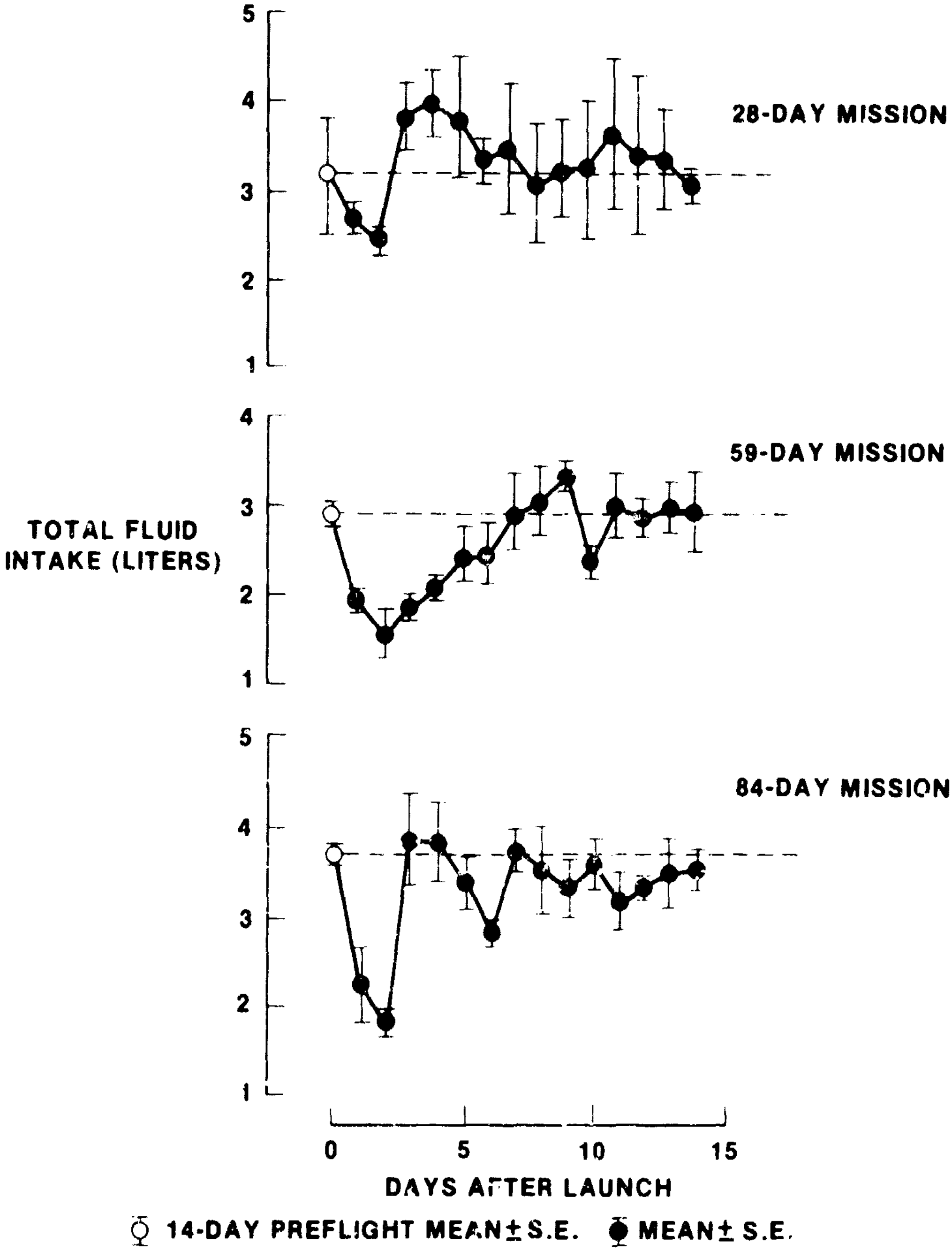
TABLE B-4

PARTITIONAL WATER BALANCE FOR EACH SKYLAB MISSION (N 3)

Mean (± SE) Daily Water Balance ml day	SL-2			SL-3			SL-4		
	Preflight	Inflight	Postflight	Preflight	Inflight	Postflight	Preflight	Inflight	Postflight
INPUT									
Water Ingested (food - drink)	2941 ± 536	2932 ± 533	314[illegible] ± 377	267[illegible] ± [illegible]	2597 ± [illegible]	2734 ± 371	293[illegible] ± 223	2937 ± 227	3359 ± 354
Metabolic Water	340 ± 10	328 ± 5	359 ± 16	368 ± 47	362 ± 67	387 ± 44	351 ± 3	359 ± 5	371 ± 13
OUTPUT									
Urine Volume	1640 ± 563	1702 ± 428	1835 ± 477	133[illegible] ± 11[illegible]	1356 ± 95	1374 ± 73	1660 ± 161	1672 ± 93	1386 ± 387
Fecal Water	79 ± [illegible]	67 ± 5	18 ± 5	99 ± 25	77 ± 13	64 ± 22	77 ± 26	61 ± 8	70 ± 20
Evaporative Water	1573 ± [illegible]2	1522 ± 103	1610 ± 125	1576 ± 272	1552 ± 435	1653 ± 534	1581 ± 274	15[illegible] ± 160	1652 ± 288
NET WATER BALANCE:									
Mean	-9	-3[illegible]	28	46	-20	90	26	-11	52
SE	± 12	± 22	± [illegible]	±1[illegible]	±1[illegible]	± 53	±25	± 4	± 8
No. of Days Observed	30	28	14	20	59	17	26	84	19

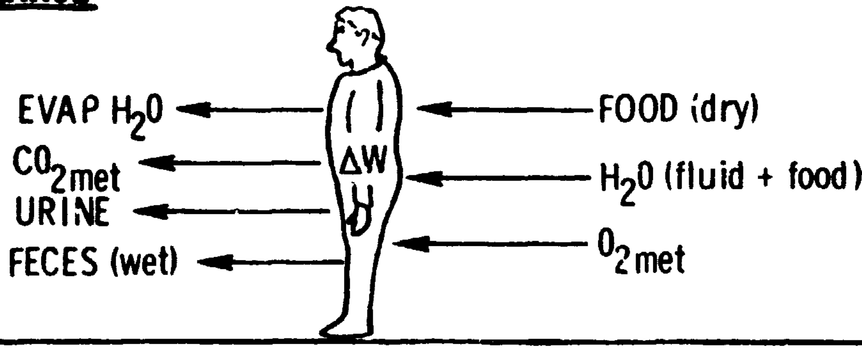


TOTAL WATER INTAKE*
AFTER LAUNCH OF EACH SKYLAB MISSION (N=3)

*INCLUDES DRINKING WATER, FLUID CONTENT OF FOODS, AND METABOLIC WATER

FIGURE B-1

CREW MASS BALANCE

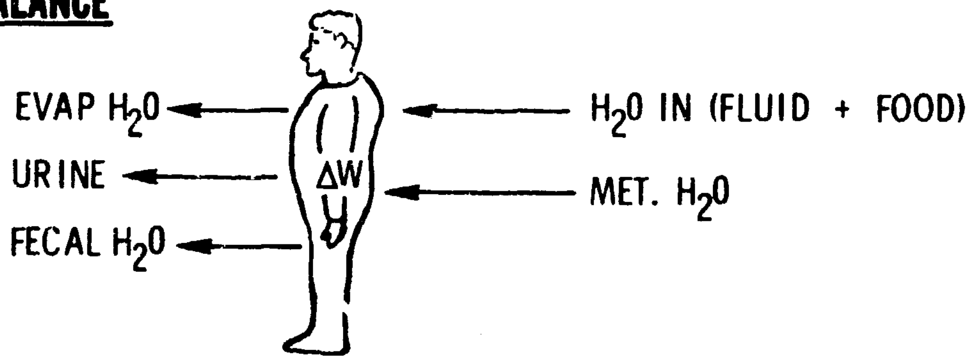


$$\boxed{\text{EVAP H20} = \text{FOOD} + H_2O - \text{URINE} - \text{FECES} + (O_2 - CO_2)_{met} - \Delta W_{body}}$$

where

$$(O_2 - CO_2)_{met} = -0.17\ \text{Pro} - 0.45\ \text{Cho} + 0.064\ \text{Fat}$$

CREW WATER BALANCE



$$\boxed{\Delta W_{H_2O} = H_2O\ \text{IN} + \text{MET. } H_2O - \text{URINE} - \text{FECAL } H_2O - \text{EVAP } H_2O}$$

where

$$\text{MET. } H_2O = 0.41\ \text{Pro} + 0.60\ \text{Cho} + 1.07\ \text{Fat}$$

FIGURE B-2

METABOLIC BALANCES USED FOR DETERMINING
BODY WATER CHANGES DURING SPACE FLIGHT

C-2

APPENDIX C

ERRORS IN THE NITROGEN BALANCE METHOD

Errors in the nitrogen balance technique have been reviewed by Hegsted (1976), and discussed by Grande (1968), Forbes (1972), Calloway, et al. (1971), and Steffee, et al. (1976). Two major errors are often mentioned. First, certain losses are not measured in the usual balance study, especially fluid or nutrients lost through the skin, thereby making the balances falsely high. Second, there is a consistent bias in most balance studies arising from an overestimation of intake (the subject may not eat all of the food offered, but cannot consume more than offered) and an underestimation of output (it is difficult to collect all excreta and impossible to collect more excreta than are actually produced), thus making the balances falsely high. In the Skylab metabolic experiments, collection of excreta and measurement of food and water intake were carefully performed, and corrections were included for food not eaten at each meal. Though the principal investigators did not perform these actual collection and reporting tasks, the highly trained and well motivated crewmen did, and it is not likely they introduced consistent errors. Rather, it is much more likely that occasional lapses in reporting occurred due to scheduling of other tasks. However, these types of errors would tend to be reduced to negligible proportions when averaged over the entire 900 man-days of observations.

An additional source of error in the balance technique is discussed by Hegsted (1976), who suggests that after a dietary change, body composition may be modified slowly and exponentially with time. For example, increasing the intake of a substance may lead to net body retentions; equilibrium of intake and output may not occur very rapidly. The conclusion to be drawn from this, when it is true, is that a short period of study (one-two weeks) may not be long enough to produce stable body composition conditions. Thus, a short-term study may lead to serious error if the balance study is designed to identify the minimal dietary requirements needed to achieve a true metabolic balance. Indeed, the possibility that the crewmembers' preflight control diet contained more protein than did their normal diets, may explain why the nitrogen balance was consistently high during the preflight control period. The physical activity level was also increased preflight, and this may have had an anabolic effect on muscle mass. However, in Skylab, the most striking finding was not so much the positive preflight nitrogen retentions but rather the shift of direction from net retention to net loss immediately following launch; this was followed by a tendency for lean body mass to approach equilibrium levels. Thus, the balance method, often criticized by Hegsted for its use in establishing malnutrition or dietary requirements, was not used for this purpose on Skylab. Rather, it was designed to show shifts in balance between one-g and zero-g environments. Intuition, as well as additional supportive experiments, suggest that some loss in anti-gravity or postural musculature should occur in weightless space flight. That body composition appears to require equilibrium after this disturbance should not require so much methodological concern (as suggested by Hegsted), but should be a valid scientific area of investigation.

With regard to other errors in nitrogen balance, Hegsted concluded that losses of nitrogen through the skin during inflight periods could not account for the net retention of nitrogen seen during the preflight control period. This conclusion is supported by the studies of Calloway, et al. (1971), in which dermal losses of nitrogen were found to be less than 0.5 g/day for sedentary men in a comfortable environment. Sweating due to heavy exercise may result in not more than another 0.5 g/liter evaporative loss.* These data should be compared to preflight control levels of more than 3 gm/day net nitrogen retentions. Such high retentions during the control phase of the study cannot apparently be eliminated by accounting for dermal losses. However, it is important to note that the preflight Skylab nitrogen balances are in good agreement with the net retention found by other investigators for the particular dietary levels employed.

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*It has been estimated that sweat losses of the Skylab crew were less than 1 liter/day.

Steffee, et al. (1976), discuss the positive net nitrogen retentions of their studies in the following way:

> "The distinctly positive balance at the high protein intake level cannot be directly explained, although it has been observed by many others. Methodological errors in estimating N intake and urinary and fecal N outputs would not appear to account for these findings which were made under carefully controlled metabolic balance conditions. Furthermore, nitrogen excretion was essentially steady throughout the balance period suggesting that the values were not caused by insufficient adjustment time to the higher protein intake level. The validity of this finding is further supported by the fact that the N intake was close to the level consumed by the subjects during their usual living conditions. However, underestimation of N losses via the integument and other unknown minor routes may partially account for the positive balances. Another explanation is that a significant proportion of the "retention" may have been caused by nitrogen loss from the body in the form of molecular nitrogen. There is now increasing evidence to indicate that this route, hitherto regarded as unlikely in mammalian organisms, may be an important factor in nitrogen loss at generous intakes of protein in healthy subjects and possibly under some pathological conditions. The evidence, based on various approaches, has been reviewed and appears to provide a likely explanation for the positive balance values obtained at the high protein intake in our studies."

It may be mentioned that Hegsted dismisses volatile N losses as a significant error in the nitrogen balance, but his evidence for doing so is not strong.

The presence of these errors in the N balance should serve as a warning to interpret the balance results with some degree of caution. They do not, however, negate the fact that the Skylab crewmen's nitrogen retention changed direction upon launch and again upon recovery. Assuming that some route of N excretion was not measured, that the losses via that pathway were sufficiently great to account for the positive preflight control balance, and that the same unmeasured error was present during the inflight and postflight periods (i.e., assume that a loss factor be substracted from each day's N balance such that the mean preflight balance equals zero), then the decrease of N balance inflight would be even more severe than was calculated. Furthermore, if this correction factor is applied to postflight data, the results would imply a small gain in protein during recovery (about 7 gm/day) compared to the inflight losses (about 25 gm/day).

Figure C-1 illustrates the cumulative protein balance of the 59-day Skylab crew for two cases: a) N-balance based on diet, fecal, and urine losses, with no correction for sweat losses, and b) N-balance corrected assuming 1 gm N/day lost via skin and sweating. The final cumulative loss for the uncorrected case is in basic agreement with other independent measures of lean body mass (see Table 2). However, the corrected balance results in nearly twice the nitrogen (and therefore lean body mass) loss as in the uncorrected case. The lean body mass loss which can be inferred by the correction factor is nearly 3.2 kg greater than the total weight loss and likely to be in error. Note, however, that in both cases considered, the time of launch and recovery represent turning points for the N balance.

In either case, whether one invokes a correction factor or not, the results qualitatively force the same interpretation. Inflight N losses are real, perhaps due to atrophy of postural muscles; they are most dramatic the first month and then their loss rate decreases significantly, and during the two week recovery period, a portion of this tissue is regained. The leveling off of nitrogen loss after a month, for the last two flights, suggests that a lower limit of protein loss is reached at that time, irrespective of the level of exercise or time in flight.

This discussion is not meant to dismiss the sources of errors in the balance technique. They are all present to varying degrees and more important for some substances than others. For example, the errors due to skin losses are definitely present for the nitrogen balance, but have been corrected to some extent in the water balance (Leonard, 1977a). However, the N balance method

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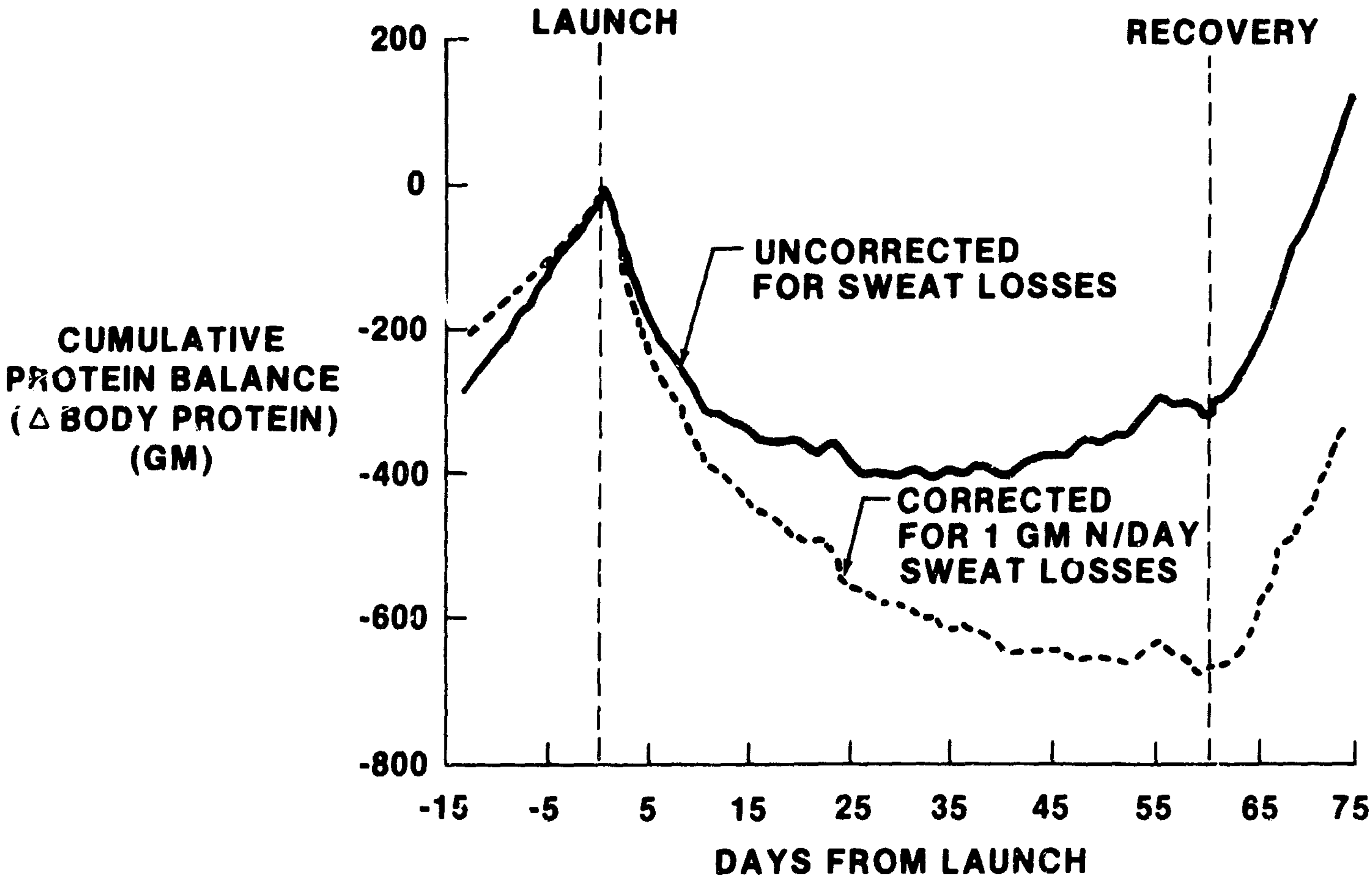
FIGURE C-1

CHANGES IN TOTAL BODY PROTEIN OF 59-DAY SKYLAB MISSION BASED ON CUMULATIVE DAILY NITROGEN BALANCE: COMPARISON BETWEEN CORRECTED AND UNCORRECTED SWEAT LOSSES.



Solid curve is based on the normal N Balance = N diet - N urine - N fecal, and the relationship, Protein = 6.25 x N Balance. Dashed line is the N Balance corrected for sweat losses by assuming an additional 1 gm N/day (i.e., 6.25 gm protein/day) lost via sweat and skin shedding. The total protein lost during the mission for the uncorrected and corrected cases is shown to be 320 and 675 gm, respectively. If protein is 19.4% of LBM, then the corresponding changes in LBM are 1.65 kg and 3.48 kg. The larger value (corrected case) is clearly erroneous because it is larger than the total weight loss. Further, the value of LBM for the uncorrected case agrees well with several other methods of determining LBM in the Skylab astronauts (Leonard, 1979). Therefore, it appears that the uncorrected nitrogen balance may provide a better indication of protein changes during space flight than does the corrected nitrogen balance.

used in Skylab was as good as any that have previously been made. Further, the shifts in balance, together with other supporting data, lead to a plausible physiological interpretation (see Table 2 and Leonard, 1979). Nevertheless, there is much room for improvement in the N balance method. In particular, the best direction for research in this regard is: a) direct measurements of skin and volatile losses, and b) estimation of total body composition by direct methods. These need to be performed not only during space missions, but in ground-based studies as well.