



# RESEARCH OPPORTUNITIES IN NUTRITION AND METABOLISM IN SPACE

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WASHINGTON, D.C. 20546

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LIFE SCIENCES RESEARCH OFFICE  
FEDERATION OF AMERICAN SOCIETIES  
FOR EXPERIMENTAL BIOLOGY  
9650 Rockville Pike  
Bethesda, Maryland 20814



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## FOREWORD

The Life Sciences Research Office (LSRO), Federation of American Societies for Experimental Biology (FASEB), provides scientific assessments of topics in the biomedical sciences. Reports are based upon comprehensive literature reviews and the scientific opinions of knowledgeable investigators engaged in work in specific areas of biology and medicine.

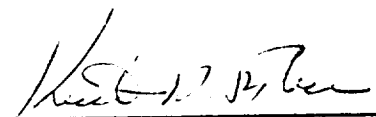
This technical report was developed for the National Aeronautics and Space Administration (NASA) in accordance with the provisions of Contract Number NASW 3924. It was prepared and edited by Philip L. Altman, M.S., Senior Staff Scientist and Kenneth D. Fisher, Ph.D., Director, LSRO.

The LSRO acknowledges the contributions of the investigators and consultants who assisted with this study. The report reflects the opinions expressed by an ad hoc Working Group that met at the Federation on August 28-29, 1985, and other consultants who contributed to the study. The study participants reviewed a draft of the report and their various viewpoints were incorporated into the final report. The study participants and LSRO accept responsibility for the accuracy of the report; however, the listing of these individuals in Section VII does not imply that they specifically endorse each study conclusion.

The report was reviewed and approved by the LSRO Advisory Committee (which consists of representatives of each constituent Society of FASEB) under authority delegated by the Executive Committee of the Federation Board. Upon completion of these review procedures, the report was approved and transmitted to NASA by the Executive Director, FASEB.

While this is a report of the Federation of American Societies for Experimental Biology, it does not necessarily reflect the opinion of each individual member of the FASEB constituent Societies.

May 19 1986  
(Date)

  
Kenneth D. Fisher, Ph.D.  
Director  
Life Sciences Research Office

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## SUMMARY

The nutrients provided to meet the metabolic needs of astronauts as related to work and exercise have been considered adequate for space flights of short duration. However, with the advent of the 90-day tours projected for the Space Station in 1992, nutrition and metabolism merit reconsideration. Energy deficits and body weight losses that were easily sustained on short missions cannot be tolerated on missions of long duration. Also, incorrect assumptions and extrapolations, such as those made in the past, must be avoided.

During the early space missions, it had been assumed that fewer calories than normal would be required because of the reduced muscular load in a weightless environment. Later flights revealed that the metabolic cost was higher than had been presumed because the tasks that usually require friction for their reactive force were dependent on muscular work to supply that force. As a result of the experience gained from longer flights, during which a significant loss in body weight occurred, the total energy content of the space diet was increased from an average low of 2500 kcal/day to about 3000 kcal/day. In an effort to meet energy demands for sustained performance, the proportions of protein, fat, and carbohydrate were adjusted to provide more protein and carbohydrate and less fat.

Despite increased food intake by the astronauts, inflight weight losses were not mitigated entirely, possibly because of the deleterious effect of the weightless environment on metabolic efficiency, the fluid shifts from lower to upper parts of the body, and the periods of increased stress. Also, the extremely high metabolic cost inflight was accompanied by muscle protein breakdown and an alteration in body composition -- primarily protein, fat, and water. However, the physical condition of the astronauts seemed to improve when the increase in caloric intake was accompanied by an elevated level of exercise. On the longer Soviet space flights, the total energy content of the diet, and both the intensity and variety of the exercise program were progressively increased.

In addition to unrealistically low estimates of energy requirements and inadequate assumptions of metabolic needs on the early space missions, the food items were sufficiently unpalatable that intended quantities were not always consumed. However, from the time of the orbital Mercury flights to the present Shuttle, there has been steady progress in the development of the space food systems. The variety of foods and dispensing techniques have been increased and palatability improved. Because storage has always been a problem in terms of weight and bulk, dehydrated and thermostabilized foods that could be reconstituted with water aboard the spacecraft have been preferred by NASA. In an effort to provide a diet meeting

the necessary requirements for calories, electrolytes, and nutrients compatible with metabolic balance, a standardized menu was designed that nevertheless accommodated individual food preferences.

Certain physiological and behavioral changes are associated with life in a weightless environment. The major biologic effects include bone demineralization, muscle atrophy, body fluid changes, and neurophysiological dysfunctions. The use of various nutrients to ameliorate or prevent space-related changes has been attempted, but results are difficult to interpret given the many body functions involved in the interrelationships between physiology and nutrition.

The major countermeasures being explored to reduce the effects of space flight on the skeleton are the use of various weight-loading exercises or artificial gravity regimens that counteract the loss of gravitational and muscular stress, and nutritional and pharmacological manipulations. Supplements of calcium and phosphorus show some promise as countermeasures, as well as drugs, such as nontoxic diphosphonates. Also, full-spectrum light has been proposed as a possible countermeasure for bone demineralization.

Inflight exercise is considered the primary countermeasure against muscle atrophy, using such aids as bicycle ergometers and treadmills, supplemented by a compressional suit that produces a load on the support-motor system. Food as a countermeasure to muscle atrophy deserves consideration also because there is evidence that muscle will probably maintain its function if properly nourished and exercised at reasonable load levels.

The provision of adequate caloric and nutrient content in the space diet may be effective in ameliorating body fluid changes, counteracting electrolyte losses, and maintaining metabolic regulation. The problem of reduced plasma volume may be partially alleviated by water and electrolyte replenishment, as well as by vigorous exercise regimens. Exercise appears to diminish the loss of electrolytes associated with changes in muscle and bone and in mineral metabolism.

Some of the constituents of food, especially neurotransmitter precursors, may be effective in modifying behavior and performance; two such constituents are tryptophan and tyrosine. The latter is the precursor of dopamine, epinephrine, and norepinephrine -- brain neurotransmitters associated with motor activity, mood, and behavioral response to acute stress. The effects of food constituents are subtle compared with many drugs, but the efficacy of food in the modification of performance and behavior should not be overlooked.

The LSRO ad hoc Working Group concluded that nutrition and metabolism should be considered over a broad spectrum in terms of extended periods in space ranging from 90-day missions in the mid-1990s to missions of several years' duration at the turn of the century. To provide protocols for the Space Station, methodology associated with nutritional and metabolic requirements should be tested on Shuttle missions. Operational data should be obtained on each current mission for evaluation and possible extrapolation to long-term flights.

Among the specific recommendations made by the Working Group for obtaining the information necessary for determining nutrient and metabolic needs of the astronauts who will man the Space Station were the following: (1) validate energy requirements; (2) quantitate energy expenditure task-by-task; (3) collect computer-generated food consumption and nutrient intake data; (4) estimate effects of a constant standard diet, and determine dietary nutritional quality and effects of nutrient interactions; (5) establish an optimum mix of protein, fat, and carbohydrate; (6) develop adjusted Recommended Dietary Allowances and determine necessity for vitamin-mineral supplements; (7) review military studies on nutritional quality, acceptability, palatability, and stability of rehydrated foods; (8) determine behavior and performance response to particular food constituents; (9) quantify safe exogenous vitamin D intake range and consider heavy metal and other toxic element accumulations; (10) conduct neutron-activation studies of certain nutrients; (11) develop appropriate body composition methodology and estimate water balance; (12) determine effective nutrient intervention as countermeasures to bone demineralization and muscle atrophy; and (13) address concerns related to food and water contamination.



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## I. INTRODUCTION

Optimal health of astronauts has been a vital concern of NASA since the inception of manned space flight. Criteria for both astronaut selection and development of life-support systems have included consideration of flight crew health and safety before, during, and after space missions. Major components of the life-support systems have been directed to meeting nutritional needs of astronauts over increasing time periods, meeting metabolic requirements of activities during space flight, and providing possible countermeasures to physiological effects of weightlessness.

The weightless environment is a unique biological situation. The inflight energy requirements and cost of metabolic (primarily physical) activities of astronauts are dependent on the system for supplying oxygen, water, and food. The weight of life-support equipment, including the food systems, precludes putting more provisions for life support on board than necessary. In early flights of short duration, the need for food was limited and oxygen and water were of primary concern. Beginning with Apollo and Skylab, the weight of food supplies became an important engineering and logistic concern which impacted on total availability of energy and nutrients.

Similarly, astronauts themselves are no less unique. Based on rigid selection criteria, the U.S. Astronaut Corps consisted of healthy, physically-fit, mentally well disciplined, college educated, middle-aged males. Initially, all had extensive flight-test experience in high performance aircraft. As a group, they were characterized as physically well-conditioned with a low-risk profile for cardiovascular disease (nonsmokers, low serum cholesterol, above average high-density lipoproteins, moderate to below average weight, and relatively high lean body mass). As the program has developed, selection criteria have changed to include both males and females of a wider age range. While flight crew personnel are essentially similar types of persons, mission specialists with special skills and training have been added. Nevertheless, as a group, all are similar in that they are physically-fit, mentally well disciplined, and in good health.

Assessments of the biomedical effects of space flight, including measurements related to metabolism and nutrition, have been part of the medical support program for astronauts since the beginning of manned space flight. Table 1 lists types of measurements and some results obtained from Mercury, Gemini, Apollo, and Skylab missions.

A major goal of the Mercury Program (1961-1963) was to establish that manned space flight was feasible. Prior to the Mercury Program, a number of physiological and behavioral effects

Table 1. Examples of Biomedical Studies in United States Manned Space Program

Date	Mission	Flight Length	Biomedical Studies*
1963	Mercury 9	34 hours	Postflight cardiovascular impairment, orthostatic intolerance, dizziness, weight loss, hemoconcentration.
1965	Gemini 3	5 hours	Inflight cardiopulmonary monitoring of ECG, blood pressure, and respiration rate.
1965	Gemini 4	4 days	Metabolic observations and comprehensive medical evaluations, including high metabolic cost of EVA, minimal loss of bone calcium and muscle, moderately decreased postflight exercise capacity and red cell mass, confirmed postflight orthostatic intolerance.
1965	Gemini 5	8 days	
1965	Gemini 7	14 days	
1971	Apollo 15	12 days	Metabolic balance study, including heart rate, biochemistries, and body weight changes; cardiac arrhythmias and extrasystoles observed during lunar surface EVA and return flight.
1972	Apollo 16	10 days	Metabolic balance study, including assessment of energy metabolism, biochemical analyses, body volume measurements.
1972	Apollo 17	13 days	Metabolic balance study, including assessment of energy metabolism, biochemical and urinary analyses, food acceptability
1973	Skylab 2	28 days	First detailed metabolic studies, including recording of dietary intakes, collection of urine and feces, caloric and nitrogen balances, bone minerals, muscle loss and function, fluids and electrolytes, endocrine gland functions, body mass; blood, urine, and fecal biochemistries; red cell metabolism, blood volume, cardiovascular and pulmonary function; task and work performance.
1973	Skylab 3	59 days	
1973-74	Skylab 4	84 days	

\* Data compiled from several reports on Mercury, Gemini, Apollo, and Skylab missions.

of weightlessness were predicted from animal studies and knowledge of the effects of reduced gravity. Some of these, such as anorexia, nausea, muscle atrophy, bone demineralization, and reduced exercise capacity were thought to be partially amenable to dietary intervention.

The six manned Mercury flights were of short duration, with the longest lasting about 34 hours. The astronauts were essentially immobile, requiring minimal physical exertion. Nutrients were provided as dry, bite-sized, and tubed foods (Popov, 1975). Dietary components were based on the Recommended Dietary Allowances (National Research Council, 1958). Some weight loss was evident, primarily from dehydration (Nicogossian and Parker, 1982).

Based in part upon results of the Mercury flights and recommendations received from advisory groups (Chichester, 1963, 1965, 1966), NASA expanded its efforts to develop appropriate diets for meeting nutritional and metabolic needs of space flight. The Gemini Program (1965-1966) required considerable investigation of food packaging, preservation, and storage. In addition, provision for oxygen, water, and food supplies became a subject for both biomedical concerns and engineering tradeoffs. Results of Gemini flights provided a rich source of data on nutrient needs, energy requirements, variability in food acceptability, and possible needs for dietary supplements. Extravehicular activities (EVA) established metabolic demands of heavy physical work under conditions of weightlessness.

In the next series of orbital and lunar flights (Apollo, 1968-1973), meal menus and food selections were expanded in terms of variety. On the Apollo 8 flight around the moon, the food was rehydrated so it could be eaten with a spoon (Smith et al., 1975). Crude analyses of the food on Apollo missions revealed that the energy intake was considerably less for the crew members than for individuals performing equivalent work on the ground, with the lowest being 1250-1350 kcal/day on Apollo 10 (Rambaut et al., 1975). The observation of some cardiac arrhythmias during Apollo 15 resulted in supplementing rehydratable beverages in the subsequent diets with potassium. Bed rest and chamber studies were used to estimate metabolic needs for EVA and lunar surface activities. Body composition changes were also measured in these ground-based studies. A number of biomedical studies on effects of weightlessness were conducted during the Apollo flights. The most notable findings related to inflight nutrition and metabolism were that food consumption was less than optimal energy-wise, and that post-flight rehydration and recovery of body weight took place rapidly.

Skylab (1973-1974) afforded the first opportunity to study more critically the energy and nutrient requirements of astronauts over extended periods of time (e.g., the 84-day-Skylab 4 flight). Food was packaged at 5 psi, consistent with

the ambient pressure of the spacecraft. Foods were individually tailored for each crew member, and metabolic balance studies were conducted, which required a meticulous record of food consumption and collection of excreta hour by hour (Whedon et al., 1977). The intakes of key nutrients and proteins were maintained as a constant from day to day. A shortfall of sodium on a particular day could be noted and an adjustment made with a supplement. For 3 weeks prior to, and after the flight, astronauts were fed the same food they would receive in space, so that metabolic baseline data could be established.

The energy expenditure inflight on Skylab was no less than that observed in bed rest and chamber studies on the ground, given an equivalent amount of work. However, as flights were extended, energy demands increased, even though O<sub>2</sub> consumption/CO<sub>2</sub> output measurements made while astronauts were exercising on the bicycle ergometer showed no inefficiency in metabolism. These Skylab studies on energy expenditure represent one of the more complete data sets available for prediction of energy expenditures associated with the Space Station.

In Skylab, a negative nitrogen balance developed inflight and persisted for 3 weeks, but after about a month nitrogen balance varied from negative to slightly positive. Nitrogen loss appeared to decrease in response to the amount of exercise done inflight (Leach and Rambaut, 1977). Changes in total body potassium and body volume, as well as nitrogen and water imbalances, were reflective of changes in body composition. As flight time increased, muscle mass declined, but the losses seemed to be reduced by exercise. There were losses in bone mass, and increases in urinary excretion of calcium within the first 30 days of flight with a leveling off thereafter. However, calcium in the stools increased throughout the flight, and malabsorption of calcium may have developed in the course of long-term flight. The loss of red cell mass in the course of flight was established and may have nutritional implications.

The Shuttle flights, which started in 1981, have been of limited duration (4-8 days) and have included only a few studies related to nutrition and metabolic demands. Nutritional requirements for Shuttle flights have been based on results of Gemini, Apollo, and Skylab, as well as ground-based studies. Indeed, major emphasis of biomedical experiments since Skylab has focused on understanding and developing countermeasures for the potentially adverse biological effects of space flight:

- Bone demineralization
- Muscle atrophy
- Fluid and electrolyte shifts
- Loss of red cell mass
- Space motion sickness and related vestibular effects
- Cardiovascular deconditioning

With the Space Station program, NASA is entering a new era which will place greater demands on provision for oxygen, water, and food. If an open system is to be used, resupply of essential commodities will be necessary at frequent intervals. If a regenerative life support system is to be used, the nutritional and energy requirements of Space Station crews will need to be included in the system design. According to original plans, the Space Station will be in orbit in 1992. Food will be stored on board and resupplied, but water and oxygen will be supplied by a regenerative system. Nominally Space Station crews will consist of six individuals whose tour of duty will be 90 days. The number of 90-day tours an astronaut would be permitted is influenced by the possibility that bone and muscle losses may be irreversible, as well as the danger of exposure to total radiation doses of up to 10-15 rems over a 90-day period. Although 10-15 rems is within the permissible exposure limits currently in use by NASA, it is a substantial dose compared with permissible doses of ground-based nuclear workers (Nicogossian and Parker, 1982).

NASA will need to supply safe food and adequate nutrition within the physical and logistical constraints of the Space Station. Nutrient specifications and primary technical specifications for the food systems of previous spacecraft will require reexamination to assist in determining the capabilities of the Space Station to meet nutrient and energy needs of astronauts for periods of 90 days. A variety of foods can be expected to be required. Commercially prepared foods in dehydrated and thermostable form most probably will be used because weight of water is an important factor. Food will be prepared quickly by reconstitution with hot water, or with cold water and a portable warmer. The food system will probably be similar to that used on the Shuttle for which some repackaging of foods provides standard menus available in 4- to 7-day cycles. On previous Shuttle flights, the meals have provided between 2700-3000 kcal/day, and complete multivitamin/mineral supplements have been provided but few have been consumed.

There are few data to judge whether the quantities of nutrients provided meet all of the metabolic needs during long-term flights, but the results of the Skylab missions suggest that deficits may exist. Both the Skylab and Soviet experiences with components of the diet have been in the form of "real foods" produced on Earth. If, for long-term flights that approach is to be supplemented or replaced by a bioregenerative food system, then it will be essential to show that such a system would be equivalent in meeting the astronauts' energy and nutritive requirements.

Among other functions, the Space Station will serve as a science laboratory. Experiments to determine the nutritional and life support requirements for a trip to Mars will probably be performed on the Space Station. Therefore, it will be necessary

to obtain detailed information on the nature of energy metabolism in space and its associated nutrient requirements over the long term.

Results of investigations on previous NASA space missions have shown that a number of biological measurements can be made during flight. These range from continuous electrocardiograms to maintenance of food consumption records. Because maintenance of flight crews for periods of 90 days in the Space Station represents a new venture in terms of meeting nutrition and energy requirements, there is a need to examine available data bearing on these aspects of space flight.

NASA's 1986 Long-Range Program Plan (National Aeronautics and Space Administration, 1985) does not mention a discrete research program on nutrition and metabolism. Tasks currently funded by NASA related to nutrition and metabolism include the nutritional control of brain neurotransmitters, diet and renal stone formation, and operational food service and quality. This low level of emphasis may reflect that available capabilities for nutritional support are considered adequate for the short-duration space flights. However, the advent of the Space Station puts nutrition and metabolism in a different perspective.

## II. OBJECTIVES AND SCOPE OF THE STUDY

The objectives of the LSRO study on nutrient requirements for meeting metabolic needs in manned space flights are to:

- review extant knowledge on the subject;
- identify significant gaps in knowledge;
- formulate suggestions for possible research; and,
- produce a documented report of the foregoing items that can be used for program planning.

In accordance with NASA's request for this study, the report focuses on issues of nutrition and metabolism that relate primarily to the contemplated United States Space Station, secondarily to the Shuttle Program as an orbital test bed for operational studies, and incidentally to scenarios for future long-term space flights.

Members of the LSRO ad hoc Working Group on Nutrition and Metabolism were provided with pertinent articles and summaries on the subject. At the meeting of the Working Group, presentations were made by NASA Headquarters program staff on past experiences relative to space-flight nutrition and metabolism, as well as scenarios for future flights. The discussions of the ad hoc Working Group focused on (1) metabolic needs related to work and exercise; (2) nutrients required to meet such needs; (3) food types, management, and records; and (4) nutritional amelioration or prevention of space-related physiological and behavioral changes.



### III. BACKGROUND INFORMATION

#### A. METABOLISM

The metabolic changes related to space flights of short and long duration that are discussed in this section are summarized in Table 2.

##### 1. Energy Sources

The oxidation of liver glycogen and stored cellular lipids serves as the major energy source to support increased metabolism during physical activity. Their relative contribution to the total body metabolism depends on factors such as the intensity and duration of the activity, the diet consumed on the days before the work or exercise, and the state of physical training (Buskirk and Mendez, 1980; Gollnick, 1985). With light, prolonged activity there is a progressively greater use of fat until it can contribute up to 80% of the total caloric expenditure. However, as exercise or work intensity increases, the relative contribution of fat to the metabolism is less and that of carbohydrate (CHO) greater. Consumption of a diet rich in fat and protein produces a shift toward a greater use of fat with a concomitant reduction of both the intensity and duration of effort that can be sustained. Conversely, ingestion of a CHO-rich diet increases the percentage of CHO used and increases endurance. The concentration of glycogen in muscle is reduced by fat-protein diets and elevated by CHO-rich diets. Endurance training results in a shift of the metabolism toward a greater use of fat during the same absolute and relative work/exercise loads. This produces a glycogen sparing that is associated with improving endurance capacity (Gollnick, 1985).

As noted by Gollnick (1985), endogenous CHOs serve as the primary fuel during intense muscular activity. Therefore, proper management of CHO intake before, during, and after exercise or hard work is crucial to endurance performance. To minimize the risk of chronic muscular fatigue and to assure optimal performance, CHO must be included in the diets of individuals engaged in prolonged, severe physical activity. The benefits of ingesting CHO during exercise are measurable only in strenuous exercise lasting more than 2 hours, where greater demands are placed on blood-borne glucose as the major CHO source for muscle metabolism. The form of CHO ingested -- whether glucose, fructose, or sucrose -- may produce different blood glucose and insulin responses, but the rate of muscle glycogen resynthesis is about the same regardless of the sugar consumed (Costill, 1985). Despite these benefits, the consumption of a carbohydrate-rich diet may have some adverse effects (see p.64) that could limit its use at times when astronauts must count on peak intellectual performance. Also, ingestion of any food a few hours before exercise is metabolically counter-productive and should be discouraged (Jéquier, 1986).

Table 2. Metabolism Related to Space Flight

Specification	Short-term Flights* (1-14 days)	Long-term Flights* (>2 weeks)
Heart Rate(bpm)	Peaks during launch and reentry; normal or decreased IF; increased PF. Apollo: 74 preF, 90 IF, 79 PF.	Normal or slightly increased IF; increased PF. Skylab: 61 preF, 60 IF, 72 PF.
Before exercise		
During exercise	Gemini EVA: 137 avg IF, 155- 180 peak IF.	Skylab: 156 preF, 155 IF, 162 PF.
After exercise	Apollo: 122 preF, 129 IF, 122 PF.	Skylab: 110 preF, 90 IF, 110 PF.
Stroke Volume & Cardiac Output	Decreased PF; gradual recovery after 5 d PF.	Variable, usually increased during 1st mo IF; decreased PF with gradual recovery 5-21 d dependent on level of IF exercise.
Exercise Capacity	Increased heart rate for same O <sub>2</sub> consumption, with no change in efficiency; no change or decreased PF.	High exercise capacity IF; decreased PF (recovery time inversely related to amount of IF exercise, rather than mission duration).
Extravehicular Activity (kcal/h)	Apollo, lunar surface: 234(99-351). Skylab: 230(145-330).	
Net Energy Utili- zation (kcal/d)	Skylab: 3319 preF, 3127 IF, 2862 PF.	
O <sub>2</sub> Consumption (kcal/h)		
Before exercise	Apollo: 81 preF, 85 IF, 85 PF.	Skylab: 72 preF, 83 IF, 70 PF.
During exercise	Apollo: 565 preF, 553 IF, 608 PF.	Skylab: 794 preF, 757 IF, 754 PF.
After exercise		Skylab: 206 preF, 207 IF, 226 PF.

Table 2. (cont.)

<b>O<sub>2</sub> Consumption (l/min)</b>		
Before exercise	Apollo: 0.279 preF, 0.291 IF, 0.294 PF.	Skylab: 0.248 preF, 0.285 IF, 0.240 PF.
During exercise	Apollo: 1.94 preF, 1.90 IF, 2.09 PF.	Skylab: 2.73 preF, 2.60 IF, 2.59 PF.
After exercise		Skylab: 0.709 preF, 0.710 IF, 0.776 PF.
<b>Respiratory Quotient (CO<sub>2</sub>/O<sub>2</sub>)</b>		
Before exercise	Apollo: 0.83 preF, 0.96 IF, 0.92 PF.	Skylab: 0.95 preF, 0.97 IF, 0.88 PF.
During exercise		Skylab: 0.95 preF, 1.00 IF, 0.98 PF.
After exercise		Skylab: 1.28 preF, 1.33 IF, 1.21 PF.
<b>Minute Volume (l/min)</b>		
Before exercise	Apollo: 8.07 preF, 9.79 IF, 10.00 PF.	Skylab: 7.70 preF, 10.08 IF, 10.11 PF.
During exercise	Apollo: 52.4 preF, 54.7 IF, 54.3 PF.	Skylab: 82.37 preF, 83.30 IF, 85.95 PF.
After exercise		Skylab: 30.52 preF, 30.29 IF, 36.09 PF.

\* Data compiled from several reports on Mercury, Gemini, Apollo, ASTP, Vostok, Voskhod, and Soyuz missions.

+ Data compiled from several reports on Skylab and Salyut missions.

**Abbreviations:**

preF = preflight  
IF = inflight  
PF = postflight

Protein, on the other hand, contributes only 5-15% of the total energy expenditure during exercise; therefore, high-protein diets do not improve work performance or endurance (Dohm et al., 1985). The protein requirement during heavy work is not increased, and protein nitrogen is only necessary to meet the general demands of growth, development, and maintenance (World Health Organization, 1985). There is no reason, therefore, to justify a high-protein diet for heavy work or exercise unless body tissues are damaged and excessive tissue repair and rebuilding are required (Buskirk and Mendez, 1980).

Both dietary factors and levels of physical activity differentially affect the major classes of serum lipoproteins. Individuals engaged in relatively higher amounts of physical activity tend to have lower levels of low-density and very-low-density lipoprotein cholesterol and higher levels of high-density lipoprotein cholesterol than their sedentary counterparts (Wood et al., 1985). However, higher levels of physical activity are also associated with lower adiposity and elevated caloric intake, two factors that themselves have independent roles in the regulation of lipoprotein levels. Changes in adiposity appear to be responsible for some, but not all, of the lipoprotein changes associated with exercise. During a 2-year study during which sedentary, middle-aged men engaged in a progressive running program, adiposity expressed as percent of body fat decreased whereas caloric intake, notably in the form of CHOs, increased. Elevated physical activity levels alter the relationships among adiposity, dietary intake, and lipoproteins that prevail in the sedentary state (Wood et al., 1985).

## 2. Metabolic Balance

Metabolic balance studies were conducted during the 14-day Gemini VII orbital space flight, but technical difficulties put constraints on the interpretation of data (Lutwak et al., 1969). It was evident that phosphorus balances were negative throughout the flight and calcium balances were positive until the eighth day when they became negative. Negative metabolic balances inflight were observed for phosphorus, calcium, magnesium, and nitrogen during the 12-day Apollo 15 flight (Rambaut et al., 1975), as well as during Skylab missions 2, 3, and 4 (Whedon et al., 1977).

Fluid and caloric balance studies on the 13-day Apollo 17 revealed that caloric requirements of the mission were considerably greater than actual caloric intake resulting in a mean 1 kg loss of lean body mass and a 2.3 kg loss of adipose tissue per crew member. (Johnson et al., 1973). During the three Skylab missions, energy balance was determined by measuring daily energy intake and the energy content of urine and feces. Data for body composition changes showed losses in body weight during the first and second months of flight, in body water and protein during the first month, and in fat during the first three months of flight. Before going into space, the average energy utilization was 41.7 kcal/kg per day, but by the third month

in space the average rate was 43.7 kcal/kg per day. This constituted an average increase of 4.8% or 1.6% per month. The increase in the "normalized" net energy input, computed by dividing the daily net energy input of each crew member by the estimated quantity of total body potassium, was about 3.7% per month (Rambaut et al., 1977a).

In the Skylab missions, dietary intake of several key nutrients (calcium, nitrogen, phosphorus, magnesium, potassium, and sodium) was carefully monitored to investigate metabolic balance during space flight, and to assess the condition of the musculoskeletal system. Inflight urinary excretion of nitrogen and phosphorus was increased compared with pre- and postflight levels. A negative balance was observed throughout most of the early inflight period. Negative or only slightly positive nitrogen and phosphorus balances persisted for the latter parts of the Skylab missions, despite high protein and caloric intake. Postflight nitrogen and phosphorus balances were markedly positive, indicating a return to retention of these substances (Rambaut et al., 1979; Whedon et al., 1977). Negative potassium balances have been recorded by Soviet researchers even 5 days postflight, which is probably a manifestation of muscular atrophy, since reduction of cell mass results in a concomitant loss of potassium from cells (Gazenko et al., 1980). The pattern of changes in nitrogen and potassium balances suggests that muscle tissue is most affected by weightlessness early in flight; however, nitrogen continues to be lost throughout the duration of the space mission.

### 3. Body Composition and Energy Balance

Early speculation on the amount of food required to maintain body weight in zero gravity was based on the assumption that space crews would require fewer calories than normal, because of the reduced muscular load (Rambaut et al., 1977b). In part, these speculations were not correct because the Gemini missions on which they were based involved little movement and energy expenditure. The information obtained from later space missions indicated that movement in a weightless environment entails a higher metabolic cost than predicted (Nicogossian and Parker, 1982). Although locomotion in zero gravity demands less energy than in 1 G, those tasks that ordinarily depend on friction for their reactive force require muscular work to supply that force. Furthermore, only a small amount of the basal energy expenditure is attributable to direct gravity effects (Nicogossian and Parker, 1982).

Relationships between body composition and energy intake influence the effects of exercise because undernutrition produces a significant loss in lean body mass and body fat, whereas overnutrition produces a significant increase in both (Forbes, 1985a). Exercise and/or training alone have not been shown to increase lean body mass or markedly decrease body fat,

unless androgens are given. However, exercise and/or training will augment maximum oxygen consumption, muscle strength, and endurance. The relative proportion of lean body mass loss depends both on the initial body composition of the subject and the magnitude of the energy deficit. Obese individuals on low-energy diets lose 12.5-25.0% of their weight as lean body mass, whereas lean body mass makes up 57% of the weight loss in thin individuals. Fasting results in a larger contribution of lean body mass (average 47%) to total weight loss than do low-energy diets (Forbes, 1985a).

Thornton and Ord (1977) noted that the pattern of body-weight loss on Skylab 2 (28 days) was consistent with that of a simple metabolic deficit and coincident with extravehicular activity (EVA). On Skylab 3 (59 days) and Skylab 4 (84 days), both food and exercise were increased, but the time course of losses and gains on orbital insertion and recovery indicated that fluid shifts were involved, as well as periods of increased stress. Apparently all three mechanisms originally proposed were operative, but a simple metabolic loss may have been the most significant. The caloric intake required for an extrapolated zero loss is extremely high indicating a surprisingly high metabolic cost inflight (Thornton and Ord, 1977).

As a result of observed weight losses on early space missions, which were partly due to insufficient caloric intake, the food supply for the astronauts was increased; for example, on Skylab 3100 calories/day were provided. However, inflight weight losses cannot be entirely countered by increased food intake because of muscle protein breakdown and changes in body composition. The preflight period, during which the astronauts engaged in intense physical training, was characterized by protein accretion and loss of fat (Rambaut et al., 1979). The first 28 days of flight were characterized by losses of water, protein, and fat. Later inflight periods showed more losses of fat, but slight gains in protein, water, and, eventually, body mass.

The reasons proposed for weight loss during space flight were that: (1) during weightlessness, fluid is shifted from the lower portions of the body to the chest area where it is sensed as an excess and excreted by the kidneys in accord with the Gauer-Henry theory; (2) at least a portion of the loss may be metabolic since food quantities and opportunities to eat are often minimal; and (3) under certain conditions there are periods of high physical activity accompanied by heat and other stresses which can result in rapid loss (Thornton and Ord, 1977).

The changes in energy balance were accompanied by alterations in body composition during the Skylab missions. Energy output included calories from food intake and from utilization of endogenous fat and protein stores, and loss of calories through feces and urine as measured by bomb calorimetry. Body fat was utilized in the preflight period, and also during

each of the inflight periods. Protein accretion occurred during the preflight period and later inflight as well, but endogenous protein was broken down during the first 28 days inflight. Food intake was markedly reduced during the first inflight period, but increased during the 56- and 84-day Skylab missions (Nicogossian and Parker, 1982).

There is a direct relationship between increased dietary intake, increased exercise, and decreased tissue loss as mission durations are increased. Of the nine crew members on Skylabs 2, 3, and 4, five decreased their mean caloric intake during flight and as a group lost 75% more weight than those who increased or maintained their preflight intake (Leonard, 1982). Thus, a caloric deficit results in mixed metabolic losses of both fat and muscle (Vanderveen and Allen, 1972). The crew of Skylab 4 had a higher level of exercise and dietary intake than those of Skylabs 2 and 3. Skylab 4 was the only flight on which no net change in tissue mass was observed, reflecting the combined adequacy of diet and exercise leading to an improved physical condition. Independent analyses by Whittle (1979) and Leonard (1982) suggest that weight, fat, and protein losses can be prevented if caloric intake is approximately 46-50 kcal/day for each kg of body weight and exercise energy expenditure is about 5-6 kcal/day for each kg of body weight. In establishing caloric requirements, the level of exercise and other activity, as well as individual variation in basal metabolism and metabolic efficiency, should be considered (Leonard, 1982).

The major components of body composition (water, protein, and fat) changed significantly among the Skylab crew members inflight. The kinetics and direction of these changes were different for each component, suggesting different influencing mechanisms. Also, the body mass of each component appeared 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 loss of one liter of water in the first two days, moderate protein losses amounting to about 0.3 to 0.5 kg muscle (cell solids) appeared to abate after about a month, while fat losses varied considerably in magnitude -- from small gains to losses representing 50% of total body mass loss -- observed over a period of months. Water, fat, and protein losses were significantly greater if a temporary anorexia, observed early in flight, was present. About 60% 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 (Leonard, 1982).

Though net energy utilization declines during the early part of a space mission, it increases beyond preflight levels during the later phases of the mission suggesting that either energy expenditure is increasing or metabolic efficiency is decreasing. As lean body mass declines, proportionately more work is required per unit of muscle tissue, but nevertheless it is also possible that the weightless environment has a deleterious effect on metabolic efficiency (Rambaut et al., 1977a).

#### 4. Exercise

Some crew members believed they derived some psychological and physiological benefits from inflight exercise, even though scientific documentation was lacking. Given the benefits of high levels of physical activities in normal gravity, it may be assumed that inflight exercise would probably be beneficial in maintaining well-being and conditioning. Additionally, the "fullness in the head" feeling and the sinus problems experienced by crew members inflight were apparently relieved by the heavy leg exercise of bicycle ergometry, which evidently facilitated the return of blood to the lower extremities. Even though the bicycle ergometer was a very effective stressor of the cardiovascular system, it would have to be supplemented on missions of long duration to assure maintenance of muscular strength in antigravity muscles which were not exercised adequately by the ergometer (Michel et al., 1977).

Bicycle ergometry was used as a means of exercise by crew members on Skylab 2 (Michel et al., 1975), Skylab 3 (Rummel et al., 1976), and Skylab 4 (Michel et al., 1977) for periods of 28, 59, and 84 days, respectively. The respective daily average exercise in watt-min/kg body wt was 31.3, 65.0, and 72.3. Though the Skylab 3 crew exercised about 107% more and the Skylab 4 crew exercised 130% more than the Skylab 2 crew, the inflight and postflight responses, in general, were similar. The amount of exercise inflight was apparently effective in maintaining a normal exercise cardiac response inflight, as well as in shortening the length of the postflight readaptation period. There appears to be no consistent correlation between length of the postflight readaptation period and mission duration. However, the amount of exercise performed inflight was inversely related to the length of time required postflight to return to preflight exercise cardiac status. Although it was not observed inflight, all of the crew members on the three Skylab missions showed a significant decrement in submaximal exercise response compared with preflight values, as evidenced by decreases in oxygen uptake, cardiac output, and stroke volume. These post-flight decrements reflected the deconditioning effects of space flight, particularly those of the cardiovascular system (Levy and Talbot, 1983).

The Soviet's Salyut-6 mission of 175 days provides data that may be useful when considering Space Station missions (Yegorov, 1979). The Salyut-6 crew members exercised for a minimum of 2.5 hours daily, using a bicycle ergometer and a treadmill equipped with a pulling system that provided a load of approximately 50 kg directed parallel to the long axis of the body. The daily average work load on the bicycle ergometer was 38,000-40,000 kg and the total distance on the treadmill was 3.9-4.3 km. In addition, they performed daily muscle building exercises with elastic chest expanders. To produce an axial load on the musculoskeletal system, the special elasticized "penguin"

suit was worn each day but removed before bed time. It provided partial compensation for the absence of gravity by opposing movement, and functioned as a constant gravitational load on muscles of the legs and trunk (Yegorov, 1981).

The prolonged exposure to weightlessness in Salyut-6 resulted in body mass and leg volume decreases. During the first few days of the 175-day mission, there was a significant loss in leg volume, but during the subsequent 2 to 3 months, the volume decreased at a lower rate and then remained relatively unchanged. No correlation was established between leg volume and flight duration. Also, as the flight time increased from 3 to 6 months, bone density losses reportedly did not increase whereas, in bed rest studies, heel bone losses were significantly higher. Therefore, it is possible that the combination of increased physical exercise and other countermeasures may have assisted in stabilizing or reversing changes in muscle and bone (Vorobyev et al., 1983).

## 5. Energy Expenditure and Extravehicular Activities

Data on energy expenditure during some of the Mercury, Gemini, and early Apollo flights, as well as the Shuttle missions, were based on analyses of the lithium hydroxide canisters postflight to arrive at the total CO<sub>2</sub> absorbed. These data provide one number per mission and are averaged over the duration of the mission, and the number of crew members on board, as shown in Table 3 (Michel, 1969; Waligora, 1985). For the first eight Shuttle flights totaling 998 hours, the metabolic rates for the 26 crew members engaged in spacecraft operations averaged 114 kcal/hour for each man (Waligora, 1985).

Metabolic expenditures during Apollo missions at zero gravity ranged from 115 to 500 kcal/hour (Waligora and Horrigan, 1975), and were estimated from the heart rate, which is based on the correlation between heart rate and metabolic rate established preflight for each crew member. Because all errors in the heart rate method tended to increase the estimated metabolic rate, these rates can be considered maximum values.

Extravehicular activities in the space environment require a pressurized space suit capable of supplying all of the components of a life support system for 7-8 hours (Nicogossian and Parker, 1982). Currently available pressure suits are designed to provide positive pressure, appropriate O<sub>2</sub> partial pressure, CO<sub>2</sub> removal, and sufficient cooling to remove the metabolic heat generated by physical activity. The space suits accommodate peak workloads and different metabolic rates by means of thermal control and CO<sub>2</sub> washout capabilities. However, these space suits have upper limits of thermal control and CO<sub>2</sub> scrubbing capacity which cannot be exceeded.

Table 3. Summary of Flight Metabolic Data

Mission		Energy Expenditure kcal/hour	Mission		Energy Expenditure kcal/hour
Mercury*	8	123	Apollo*	7	100
	9	89		8	98
Gemini*	4	95		9	93
	5	80		10	85
	7	87	Shuttle <sup>+</sup>	1	107
	9	95		2	149
	10	92		3	112
	11	100		4	109
	12	112		5	113
				6	111
				7	101
				8	110

\* Michel, 1969

<sup>+</sup> Waligora, 1985

Problems encountered during the Gemini missions led to the development of a liquid-cooled garment (LCG) for the Apollo program. At work rates up to 400 kcal/hour it suppressed sweating, and at work rates as high as 500 kcal/hour it permitted sustained operations without thermal stress. On Apollo missions 11, 12, 14, 15, 16, and 17, the average metabolic expenditures (in kcal/hour) by task for lunar surface EVAs at 1/6 G were as follows:

- Performing overhead activities, such as getting in and out of the vehicle, 270
- Deploying the surface experiments, 244
- Making geological surveys, 244
- Riding in the lunar roving vehicle, 123.

These rates were calculated from: (1) the temperature differential between the coolant water flowing into and out of the LCG, and (2) the decrease in pressure in the O<sub>2</sub> supply bottle. The average metabolic rate over the entire Apollo program during EVAs totaling almost 159 hours, was 234 kcal/hour (Waligora and Horrigan, 1975).

During EVAs of more than 83 hours for Skylab missions 2, 3, and 4, the metabolic rate averaged 230 kcal/hour (Waligora and Horrigan, 1977). The highest expenditure of 500 kcal/hour was reached while the Commander of Skylab 2 was trying to cut a strap that was keeping the solar panels from deployment.

Metabolic rates derived from heart rates during Shuttle mission EVAs averaged 225 kcal/hour, with minimum and peak rates of 117 and 389 kcal/hour, respectively, obtained from a one-minute point in time reading; similar metabolic rates based on O<sub>2</sub> consumption averaged 196 kcal/hour for 22 EVAs (Waligora, 1985), and the mean energy expenditure for 12 EVAs was 223 kcal/hour (Guy, 1985).

Metabolic expenditures during Apollo, Skylab, and Shuttle mission EVAs are shown in Table 4.

## B. NUTRITION

The dietary data for short- and long-term space flights discussed in this section are summarized in Table 5.

### 1. Recommended Dietary Allowances

Diets for space flights have been based on the Recommended Dietary Allowances (RDAs) established by the National Research Council (1958). Estimates of the RDAs (National Research Council, 1980) are determined by a number of techniques: (1) collection of data on nutrient intake from the food supply of apparently normal, healthy people; (2) review of epidemiological observations when clinical consequences of nutrient deficiencies are found to be correctable by dietary improvement; (3) biochemical measurements that assess a degree of tissue saturation or adequacy of function in relation to nutrient intake; (4) nutrient balance studies that measure nutritional status in relation to intake; (5) studies of subjects maintained on diets containing marginally low or deficient levels of a nutrient, followed by correction of the deficit with measured amounts of that nutrient; and (6) in some few instances, extrapolation from animal experiments in which deficiencies have been produced by the exclusion of a single nutrient from the diet. The resultant RDAs were designed for people functioning at 1 G, not at zero gravity. Thus, the diets designed for astronauts have been nutritionally adequate by conventional standards, but they may be somewhat deficient because of inadequate caloric or nutrient intake or the enhanced demands of space flight.

### 2. Caloric and Nutrient Content

During Apollo missions 7-17, which totaled 103 days, the average daily nutrient intakes were 76 g protein, 61 g fat, and 269 g carbohydrate; for four missions totaling 44 days' duration, the average daily fiber content was 5.4 g. The vitamin content of the Apollo diet exceeded the RDA for A, B<sub>6</sub>, B<sub>12</sub>, C, E, and riboflavin, but was marginal for folic

Table 4. Metabolic Expenditures During Extravehicular Activities

<u>Apollo Mission</u>	<u>Metabolic Rate kcal/hour</u>	<u>Skylab Mission</u>	<u>Metabolic Rate kcal/hour</u>	<u>Shuttle Mission</u>	<u>Metabolic Rate kcal/hour</u>
11	227	2	330	STS-6	146
	302		260		206
	246		315		
	252		280	41-B	191
12	221	3	265		239
	252		240		166
	202		310		186
	234		250	41-C	204
14	229		225		246
	252		180		235
	277				194
	247	4	230	41-G	237
15	252		250		159
	204		155	51-A	153
	260		205		202
	204		145		159
	219		220		191
	255		185	51-D	222
16	197	Average	230		181
	209			51-I	200
	204				192
	207				211
	275				202
	272				
17	207			Average	196
	209				
	234				
	237				
Average	234				

Waligora and  
Horrigan, 1975

Waligora and  
Horrigan, 1977

Waligora, 1985

Table 5. Dietary Data Related to Space Flight

Specification	Short-term Flights* (1-14 days)			Long-term Flights* (>2 weeks)				
	<u>Flight</u>	<u>Provided</u>	<u>Consumed</u>	<u>Flight</u>	<u>Provided</u>	<u>Consumed</u>		
Energy Value (kcal/d)	Mercury	2500	695	Skylab	2400-3400	2850-3140		
	Gemini	2500-2750	1000-2200	Salyut	3200	3000		
	Apollo	2800-3000	1250-2900					
	Vostok	2800	2500-2750					
	Voskhod	3600						
	Soyuz	2800	2660					
	Shuttle	3000	1100-2655					
Macronutrient Composition (g/d)	<u>Flight</u>	<u>Protein</u>	<u>Fat</u>	<u>CHO</u>	<u>Flight</u>	<u>Protein</u>	<u>Fat</u>	<u>CHO</u>
	Gemini	102	100	372	Skylab	111	83	412
	Apollo	102	100	372	Salyut	135	110	380
	Vostok	117	83	311				
	Voskhod	150	130	430				
	Soyuz	140	88	345				
	Shuttle	107	83	359				
Mineral Composition (mg/d)	<u>Flight</u>	<u>Mineral</u>	<u>Value</u>	<u>Flight</u>	<u>Mineral</u>	<u>Value</u>		
	Apollo	Calcium	1168	Skylab	Calcium	750		
		Phosphorus	1646		Phosphorus	1600		
		Sodium	5101		Sodium	3600		
		Potassium	2728		Potassium	3945		
		Magnesium	249		Magnesium	300		
	Shuttle	Calcium	1210					
		Phosphorus	1706					
		Sodium	4506					
		Potassium	3238					
		Magnesium	387					

\* Data compiled from several reports on Mercury, Gemini, Apollo, Vostok, Voskhod, Soyuz and Shuttle missions.

+ Data compiled from several reports on Skylab and Salyut missions.

acid, nicotinate, pantothenate, and thiamin. The mean energy intake was  $1877 \pm 415$  kcal/day and when compared with the RDA of about 2900 kcal/day, it is apparent that the average energy deficit incurred by each Apollo astronaut resulted in a mean loss in body weight of 3.9 kg. The evidence suggests that either weightlessness or some other aspect of the mission environment caused the crew members to restrict food intake below quantities available and necessary to maintain body weight (Rambaut et al., 1973, 1975). It is possible that the vomiting, which may accompany space motion sickness during the early stages of flight, may interfere with accurate estimates of caloric and nutritional intake in some crew members.

Rambaut et al. (1977b) noted that vitamin A intake exceeded the RDAs by as much as 200% inflight during the Skylab missions. Vitamin D, in a dietary supplement, constituted 100% of the RDA, which was considered advisable considering the inflight absence of ultraviolet light. The B vitamins and vitamin C were present in amounts almost 10 times the RDA because Soviet findings had revealed that blood concentrations of these vitamins fell during low-frequency vibratory conditions (Rambaut et al., 1977b). The 10-15% decreases in red cell mass inflight led to the recommendation that a supply of folic acid about 200% of the RDA, as well as adequate intake of zinc, iron, and copper, be made available (Rambaut et al., 1977b). Protein intakes, which were similar pre-, in-, and postflight, ranged from 80-160 g and were of high quality based on ingredients used and on actual amino acid analyses. Generally, carbohydrate consumption was higher inflight averaging 400 g/day than on the ground, 350 g/day. Fat intake was lower, and crude fiber intake (about 5-10 g/day) was the same, inflight and on the ground.

As in Skylab, there were 70 food items in the 6-day menu for the 175-day Salyut-6 manned space flight. The caloric value of the daily diet was increased from the 2800 kcal in Salyut-4 flights to 3150 kcal. The macronutrient and mineral content of the daily Salyut-6 diet was 125 g protein, 110 g fat, 380 g carbohydrate, 800 mg calcium, 3.0 g potassium, 1.7 g phosphorus, 4.5-5.0 g sodium, 0.4 g magnesium, 50 mg iron, plus a multiple vitamin supplement. On this diet, the crew members were reported to have maintained a good health status and a high work capacity (Vorobyev et al., 1983; Yegorov, 1981).

According to the RDAs (National Research Council, 1980), the proportions of protein, fat, and carbohydrate consumed by adult males in the United States, whose energy requirements are approximately 2300-3100 kcal/day, are 15, 40, and 45%, respectively. These proportions are shifted for athletes in training, particularly those requiring more than 3000 kcal/day, to 15% protein, 30% fat, and 55% carbohydrate (Buskirk, 1981). For U.S. astronauts, the proportions for the Gemini, Apollo, Skylab, and Shuttle missions averaged 18.5, 15.75, and 65.75%, respectively (Leonard, 1982; Popov, 1975; Sauer and Rapp, 1981, 1983). For the USSR cosmonauts on the Vostok, Voskhod, Soyuz, and Salyut

missions, the proportions averaged 22.75, 16.75, and 60.5%, respectively (Popov, 1975). Tolerance to the three major energy sources was not uniform; therefore, if their proportions are shifted severely in an effort to permit correlation with energy expenditure, the ability of crew members to adjust to the altered dietary patterns would have to be tested.

On the basis of experience, and particularly with the advent of longer flights and extensive inflight exercise programs, total energy content of the diet in U.S./USSR space programs has been progressively increased (Popov, 1975). For example, in the first Soviet flights, daily caloric intake was about 2600 kcal. In the first phase of the Soyuz program, it was about 2800 kcal. By the time of Salyut-1, this had been raised to 2950 kcal. The Salyut-4 diet provided 3000 kcal. On Salyut-6, the caloric allowance was 3150 kcal. For a detailed history of the development of the Soviet daily food allowance, consult Popov (1985). Energy content of American diets in space had been somewhat lower, averaging about 2500 kcal except in the Apollo lunar landing missions, where it was 2800-3000 kcal. Table 6 shows the caloric and nutrient content of a typical Apollo meal. By the time of Skylab, the energy content of the space diet was equivalent to that of the normal pre-mission diet.

On the Space Transportation System (Shuttle) Orbital Flight Tests (OFT), a standard menu was designed to provide the following nutrients in three meals per person per day (Sauer and Rapp, 1981, 1983):

Energy (kcal)	3000	Thiamin (mg)	1.4
Protein (g)	56	Vitamin B <sub>6</sub> (mg)	2.0
Carbohydrate (g)	200	Vitamin B <sub>12</sub> (µg)	3.0
Vitamin A (IU)	5000	Calcium (mg)	800
Vitamin D (IU)	400	Iodine (µg)	130
Vitamin E (IU)	15	Iron (mg)	18
Phosphorus (mg)	800	Magnesium (mg)	350
Ascorbic acid (mg)	45	Zinc (mg)	15
Folacin (µg)	400	Potassium (mEq)	70
Niacin (mg)	18	Sodium (mEq)	150
Riboflavin (mg)	1.6		

In order to accommodate individual food preferences during flight, a pantry, which was selected and approved by each crew, was provided to supplement the menu. The purpose of the pantry was to provide additional beverages as well as snacks and to serve as a contingency food supply in case of emergency. During a nominal mission, pantry items could be exchanged for menu items. The pantry supplied enough food to provide approximately 2100 calories per person for 3 days. Table 7 shows the daily intake aboard the four OFT Shuttle flights (Sauer and Rapp, 1981, 1983). Energy requirements were derived by Johnson Space Center scientists from previous flight data. Potassium (and sodium) recommendations were based on the advisability of increasing potassium to avoid cardiac arrhythmias. .

Table 6. Typical Composition and Caloric Content of Apollo Daily Meal

Food Composition of Daily Menu				
<u>Meal A</u>	<u>Meal B</u>	<u>Meal C</u>		
Fruit cocktail	Chicken salad	Beef stew		
Bacon squares	Beef with vegetables	Potato salad		
Strawberry cubes	Butterscotch pudding	Sweet pastry cubes		
Cocoa	Fruitcake	Grapefruit drink		
Orange drink	Pineapple-grapefruit drink			
Food Values				
<u>Constituents</u>	<u>Meal A</u>	<u>Meal B</u>	<u>Meal C</u>	<u>Total</u>
Energy (kcal)	759	1123	911	2793
Protein (g)	28.5	45.2	28.7	102.4
Fat (g)	25.4	42.0	32.4	99.8
Carbohydrate (g)	106.4	140.0	125.7	372.1
Ash (g)	7.0	6.8	7.3	21.1
Calcium (mg)	176.0	505.0	486.0	1168.0
Phosphorus (mg)	342.0	712.0	592.0	1646.0
Iron (mg)	3.3	4.8	4.9	13.0
Sodium (mg)	1659.0	1526.0	1916.0	5101.0
Potassium (mg)	818.0	863.0	1047.0	2728.0
Magnesium (g)	64.3	89.5	95.3	249.1
Chloride as NaCl (g)	4.30	3.05	3.94	11.29

Popov, 1975

Table 7. Mean Daily Inflight Nutrient Consumption per Person per OFT Mission

Nutrient	STS Flight				Recommended Levels	
	#1(2 days)	#2(2 days)	#3(8 days)	#4(7 days)	JSC**	RDA <sup>++</sup>
RH <sub>2</sub> O (g)*		1134	1393	1710.8		
NH <sub>2</sub> O (g) <sup>+</sup>		88.4	353.0	325.5		
Kilocalories	2656	1100	1910	2446	3000	
Protein (g)	106.8	58.5	66.1	85.6	56	56
Fat (g)	83.1	28.0	49.6	73.5		
Carbohydrate (g)	358.6	152.0	280.2	319.2		
Calcium (mg)	1210	687	885	954	800	800
Phosphorus (mg)	1706	916	1210	1474	800	800
Sodium (mg)	4506	1782	3010	3506	3450	
Potassium (mg)	3238	1362	2244	2558	2737	
Iron (mg)	27.1	12.4	16.6	20.2	18	10
Magnesium (mg)	387	154	229	286	350	350
Manganese (mg)			1.6	2.2		
Copper (mg)			1.9	2.2		
Zinc (mg)	17.6	9.4	10.1	11.6		15
Chloride (mg)			4407	4784		
* RH <sub>2</sub> O = rehydration water + NH <sub>2</sub> O = moisture in food						
** JSC = Johnson Space Center ++ RDA = Recommended Dietary Allowances						

Sauer and Rapp, 1981, 1983

### 3. Nutrient Requirements and Energy Expenditure

Nutrient requirements can be altered by environmental stress, such as weightlessness, temperature extremes, and hyperactivity, thus creating dietary interactions that can alter the nutrient balance of the body as noted in the following examples (Olson, 1984). A high energy intake increases the need for thiamin which is required for a number of metabolic functions. High phosphate and calcium levels may exacerbate zinc deficiency, and high zinc intake may exacerbate existing copper deficiency. High protein levels from purified protein sources can increase calcium excretion, as well as increase the need for zinc and vitamin B<sub>6</sub>. Nutrient absorption or bioavailability may be altered, also. For example, certain insoluble food components, some types of fiber and phytate in certain whole grain cereals and legumes, may decrease the availability of magnesium, calcium, and various trace elements in the gastrointestinal lumen. Still another type of interaction is the suppression or inactivation of nutrients by environmental factors or ingestion of other foods, such as vitamin C inactivation by heat or oxidation, or the inactivation of biotin by the avidin in raw egg white (Dufour, 1984).

A nutritionally adequate diet can be related to the body's total energy expenditure as expressed in the activity of muscles, organs, systems, and mental/nervous processes. This need is regulated by thirst, appetite, digestion, and metabolism, as well as by physical activity. Weightlessness results in a substantial loss of the fluids and electrolytes that govern many of these functions (Leach, 1981), and the changes in physical work requirements may cause not only an altered energy output, but also a loss of protein nitrogen through muscle atrophy (Ushakov, 1980). The reduction in electromechanical stresses and other factors bring about a loss of calcium from bone. It has been suggested that metabolic and digestive processes undergo substantial changes, partly as a result of the altered stress environments and physical confinement (Popov, 1975).

Physical activity is the major variable affecting caloric expenditure and intake. Normally the responsiveness of the appetite mechanism is sufficiently precise to compensate for changes in daily physical activity, so that body weight and composition remain relatively constant. The caloric requirements of moderately active individuals might be increased by about 300 kcal over the needs of individuals engaged in light activity, but for very active persons the increase might be as great as 600-900 kcal/day (Buskirk and Mendez, 1980).

In order to explore the stimulation of energy expenditure following meal ingestion after exercise, Bielinski et al. (1985) gave 10 young male volunteers a mixed meal of 18% protein, 27% fat, and 55% carbohydrate on two occasions: (1) after a 4-hour resting period, and (2) on the next day, 30 minutes after

completion of a 3-hour exercise at 50% of maximal oxygen consumption. Lipid oxidation made a greater contribution to total energy expenditure when the meal was ingested during the post-exercise period than when compared with the meal ingested without previous exercise. During the night following the exercise, the stimulation of energy expenditure observed during the early recovery period gradually diminished. However, resting energy expenditure measured the next morning was significantly higher (+4.7%) than that measured without previous exercise. The conclusion is that intense exercise stimulates both energy expenditure and lipid oxidation for a prolonged period (Bielinski et al., 1985).

In a study of food intake and energy expenditure among British Army recruits, Edholm et al. (1970) found that serial auto- and cross-correlations of 3850 kcal/day average intake and 3750 kcal/day average expenditure were very small, with no significant relationship between food consumption and energy output on the same day. This contrasts with the significant correlation obtained when 6 or more days are combined. There must be a lag between expenditure and intake, but the duration of the lag is variable both among individuals and in the same individual. There was a positive, but not significant, correlation between body weight and the average 6-day food intake, but a negative correlation between body weight and caloric balance.

Goldman (1965) measured the energy expended by a group of soldiers performing tactical activities and found that the upper range of energy cost was 400-450 kcal/hour. Energy expenditure can be calculated given the linear relationship between respiratory minute volume and energy expenditure, particularly within the practical accuracy of field measurements. However, a large error can occur when an estimate of energy cost from ventilation volume is attempted for severely stressed individuals.

The data from Apollo, Skylab, and the Space Shuttle suggest that the energy costs of such endeavors as EVAs are relatively consistent with those associated with vigorous physical activity, such as forced marches performed by soldiers carrying standard field equipment, long-distance races engaged in by trained athletes, or other ground-based activities (Kottke, 1968).

In studies on the composition of weight loss during dietary restriction, two features stand out, namely that the proportion of the weight loss which represents lean tissue is related inversely to the initial body fat content, and the amount of food consumed. Thus, for a given food intake, obese individuals lose less lean tissue relative to total weight loss than the nonobese (Vanderveen et al., 1977), and those with the greatest energy deficit lose relatively more lean tissue than those with lesser deficits (Forbes, 1985b). Benedict et al. (1919) studied a group of young, nonobese, adult males, whose

activity was not controlled and who were given an 1800-2300 kcal diet for several weeks; they lost 7 kg and 105 g nitrogen, or 15 g N/kg body weight, so that about one-half of the total weight loss represented lean tissue. A group of obese adolescents, whose activity also was not controlled, were given a 600 kcal diet for several months, and on average lost about 30 kg of body weight, of which 7.8 kg or 26% represented lean tissue (Brown et al., 1983).

During the three Skylab missions a number of measurements designed to describe changes in the more essential components of body weight were performed. An assessment of lean body mass and fat components by six different methods indicated that of a mean inflight total body weight loss of  $2.7 \pm 0.3$  kg (SD) for all nine crew members, more than half, i.e., 1.5 kg, could be attributed to loss of lean body mass, of which 1.1 kg was body water, and the remaining 1.2 kg was derived from fat stores. The data suggest that no further loss of lean body mass took place after the first month of flight and it seemed to be largely independent of mission duration, diet, and exercise (Leonard et al., 1983).

Since diet and activity affect muscle and fat tissues differently, a knowledge of the changes that have occurred in previous space flights will assist in establishing caloric and exercise requirements on future flights. Experiments designed to study the effects of weightlessness on body composition changes have been hampered in the past by the difficulty in controlling inflight physical activity and caloric intake as well as by operational constraints that precluded direct inflight measurements of tissue loss.

## C. FOOD AND WASTE

### 1. Food Types

Much effort has been devoted in both the U.S. and Soviet space programs to determining the optimum food types for consumption during space missions. Considerations of storage time, size/weight restrictions, and practicality for consumption in weightlessness at first led to the use of freeze-dried food bars and purees, and juices packaged in squeeze tubes. The palatability of these early food items left much to be desired, which meant that the intended quantities were sometimes not consumed. In addition, early estimates of energy requirements on space missions were unrealistically low and metabolic changes were not adequately taken into account. For these reasons, space diets have undergone a considerable evolution (Nicogossian and Parker, 1982).

There has been a steady progression in the development of space food systems from the time of the orbital Mercury flights to the present Shuttle, with preparation methods ranging

from none to heating, cooling, and freezing (Huber, 1985). In the early Mercury flights, foods were pureed and packaged in collapsible tubes; later bite-sized foods were supplied, and during the last Mercury mission, freeze-dried foods were used. During the increased mission-length Gemini program, the food system included dehydrated, rehydratable, and intermediate-moisture foods totaling about 726 g and providing 2800 kcal per crew member per day in the form of 16-17% protein, 30-32% fat, and 50-54% carbohydrate. Dehydrated and intermediate moisture foods were consumed directly from the package without rehydration, but the rehydratable foods and beverages, packaged in laminated plastic bags with a valve through which a tube could be inserted, required the addition of water before the foods could be consumed.

During the Apollo missions, there was a distinct evolution in the food systems from the similarity of menus for each Apollo 7 astronaut to the highly individualized menus of Apollo 17 crew members (Huber, 1985; Smith et al., 1975). The initial Apollo inflight food system consisted of foods that required rehydration before they could be eaten and dehydrated, ready-to-eat, bite-sized foods. In the later Apollo missions, a wide variety of foods and dispensing techniques were added; the food types included not only dehydrated, rehydratable, and intermediate-moisture, but also irradiated (bread) and thermostabilized food items. The dehydrated and intermediate-moisture foods were sealed in four-ply laminated plastic, which was opened by cutting with scissors, and were consumed directly from the package. Rehydratable solid and semisolid foods were packaged in pouches that permitted insertion of the Apollo water dispenser; after complete rehydration in 5-10 minutes the pouch could be opened and the contents eaten with a spoon. Thermostabilized items were packaged in drawn aluminum cans fitted with a drink spout for beverages, and with full-panel pull-out lids or in flexible laminated aluminum foil pouches for foods which were consumed with a spoon.

The Skylab food system was designed to provide a balanced, palatable diet, which also met the necessary requirements for calories, electrolytes, and other constituents for the metabolic balance studies that were to be conducted (Johnston, 1977). Crew members were able to select their inflight diets from 70 different food items presented as freeze-dried rehydratables, thermostabilized foods, dry and moist bite-sized foods, and a variety of beverages (Johnston, 1977). Hot and cold water were available for rehydration, as well as an oven for heating. Spice packets were provided for the preparation of food to individual tastes. Menus were planned for 6-day turnaround cycles. Each crew member was required to consume his individually planned diet for 21 days preflight, throughout the flight, and for 18 days postflight.

The Soviets have taken even larger steps toward the satisfaction of individual preferences, customizing menus on an individual basis from the time of the early Soyuz flights (Nicogossian and Parker, 1982). With the advent of the Progress cargo ships in the later Salyut missions, fresh fruits, vegetables, and condiments could be supplied periodically to supplement the diet. Crews were encouraged to "order out" for items they wished to eat. In all, the tendency has been to attempt to establish an Earth-normal pattern and quality of meals while meeting energy and metabolic requirements.

The Space Shuttle has utilized the foods and packaging developed by the earlier space programs (Sauer and Rapp, 1983). Thermostabilized, rehydratable, irradiated, natural form, and intermediate-moisture foods have been used. The individual-serving packages included the Apollo spoonbowl, the Skylab beverage, bite-size, flexible foil retort pouches, aluminum and bi-metallic cans. However, a new Shuttle package was developed for rehydratable foods and beverages to replace both the Apollo spoonbowl and the Skylab beverage packages. The food package is opened by removing the flexible lid and eaten using normal utensils, whereas beverages are consumed from the square rehydratable package through a polyethelene straw inserted into the septum through which water is introduced by a needle to rehydrate the beverage. An in-suit food bar was provided for each astronaut in case an EVA had to be performed. Food consumption was estimated from an inventory of food packages returned either unused in locker trays or empty in the trash (Pool and Nicogossian, 1983).

## 2. Food Management

Both U.S. and Soviet astronauts have reported that changes in taste and odor perception of foods occur during space flights (Neilson, 1985). The greater the change, the greater the likelihood that consumption will decrease and cravings for different foods will increase. The buildup of background odors during missions may also contribute subliminally to a decrease in appetite and consumption as a result of odor fatigue or adaptation. However, the environmental control and life support systems designed for the Space Shuttle have kept such contaminants at or below acceptable levels and maintained nonhazardous breathing atmospheres (Talbot and Fisher, 1985).

Foods may be varied by changing their shapes, textures, sizes, and fiber content, without affecting nutritional content. Thus, food dislike and boredom can be decreased and diet acceptability increased. The use of colors, shapes, garnishes, and portions in meal presentation, as well as packaging color, utensil shape and size, and visual display of trays may enhance the eating experience.

The Army's experience with prolonged feeding of rations may be applicable to food service planning for the Space Station (Schnakenberg, 1985). Foods may be acceptable in terms of taste, texture, and aroma, but may not be tolerated for extended periods. Also, ease of preparation and eating may be more important than indicated. Preference and hedonic ratings of food items, as shown in space simulator and Army field studies, may not accurately predict actual food consumption during flight or in combat. For example, in a 34-day study, the U.S. Army Natick Research and Development Center determined the acceptability and preference of the troops in two combat infantry support companies subjected to prolonged feeding of "Meal, Ready-to-Eat" operational rations (Hirsch et al., 1984). The troops indicated satisfaction with the palatability, appearance, variety, and ease of preparation of the ration. However, they expressed displeasure with the small size of the portions, a desire for more variety in beverages, and a dislike of the ration for breakfast. Despite high acceptability of the ration, nutrient intake data revealed an insufficient consumption level leading to energy, vitamin, and mineral deficiencies, and subsequent body weight loss. Other factors, such as loss of appetite, absence of scheduled meals, and small portions, may be responsible for the low food intake.

### 3. Water Supply

The evolution of the potable water supply for the various space projects was described by Sauer and Calley (1975). For the Mercury flights, potable water was loaded onboard before launch and was supplied to the crew members by a simple "fill and draw" system. The Gemini spacecraft was the first to use fuel cells to provide electrical power, and by combining gaseous oxygen and hydrogen, producing water as a byproduct. Despite considerable effort, the water could not be made potable and the Gemini crew members, like their predecessors, had to rely on a fill and draw system for drinking water. By the time of the Apollo flights, the problems related to the fuel cell-generated water supply were resolved so that it could serve as the principal source of potable water. However, the water supply systems differed in the Apollo Command and Lunar modules with the former using fuel cell-generated water and the latter using water supplies loaded in storage tanks before lift off.

Potable water samples from all Apollo missions, except 8, 9 and 17 contained microorganisms ranging from 3 per 150 ml water to those too numerous to count (Sauer and Calley, 1975). The most commonly found microorganisms were Flavobacterium species. The single common-use water dispenser provided for the three Apollo crew members inflight provided no protection against microbial transfer from one individual to another. An inflight schedule designed to add chlorine to the water at approximately 24-hour intervals was only partially successful because the biocide depletion rate in the system was proportional to the area-to-volume ratio.

#### 4. Waste Collection

The urine collection and transfer processes were essentially the same up to the Apollo 12 mission (Sauer and Jorgensen, 1975), and consisted of a rubber cuff connected to a flexible collection bag. A new system, the urine receptacle assembly, employed a device that did not require intimate contact of the crew member during urine collection; it was used on Apollo 12 and on subsequent missions. During launch, extravehicular activity, and emergency modes, a special assembly worn over the space suit was provided for collection and intermediate storage of urine; it was connected by a hose to the spacecraft waste management system. Inflight fecal collection was managed with a plastic bag taped to the buttocks. After defecation, the crew member had to seal the bag and knead it in order to mix a liquid bactericide with the contents to provide the desired degree of feces stabilization. Because the task was distasteful and required an inordinate amount of time, low residue foods and laxatives were frequently used prior to launch, as well as some use of drugs inflight to reduce intestinal motility. These experiences were often cited as reasons for not consuming foods during early space flights.

The Skylab Waste Management System included equipment for the collection, measurement, and processing of all urine and feces, and for the management of trash such as food wrappers and residues, equipment bags, used towels, and the like which were discarded through an airlock into a large-volume tank (Johnston, 1977). The urine of each crew member was collected in a 24-hour pooling bag containing a measured quantity of lithium chloride which permitted calculation of urine volume postflight; a 120 ml urine aliquot was placed in a freezer for return and subsequent analysis. This procedure was repeated daily. Feces were individually collected into a bag attached under a form-fitted commode seat. The crew member weighed the bagged stool after each defecation on a mass measuring device, labeled it, and placed it in a vacuum drying processor for 16-20 hours, after which it was removed and stowed for postmission analysis.

#### D. PHYSIOLOGICAL AND BEHAVIORAL CHANGES

The use of various nutrients to ameliorate or prevent space-related physiological changes, such as bone demineralization, muscle atrophy, and body fluid changes, has been considered and investigated in a number of studies. However, the interrelationships of physiological changes and the broad effects of nutritional modification across many body functions confound the conduct and interpretation of research efforts.

The physiological changes related to space flight that are discussed in this section are summarized in Table 8. Only those changes that may be affected by nutrients are considered in the material that follows.

Table 8. Physiological Changes Related to Space Flight

Physiological Parameter	Short-term Flights* (1-14 days)	Long-term Flights* (>2 weeks)
Nitrogen and Phosphorus Balances		Negative early IF, less negative or slightly positive later IF; rapid return to markedly positive PF.
Calcium Balance	Increasing negative IF.	Positive pref, becoming increasingly negative IF; markedly negative PF becoming much less negative by day 10 but still slightly negative by day 20; several wks to return to pref baseline.
Bone Density	Os calcis density decreased PF; variable changes in radius and ulna.	Os calcis density decreased PF; amount of loss correlated with mission duration; little or no loss from nonweightbearing bones; recovery time about same as mission duration.
Muscle Strength	Decreased IF and PF; RPB in 1-2 wk.	PF decreases, particularly in leg extensors; increased exercise IF appears to reduce PF strength losses regardless of mission duration; arm strength normal or slightly decreased PF.
Electromyogram (EMG) Analysis	PF EMGs from gastrocnemius suggest increased susceptibility to fatigue and reduced muscular efficiency. EMGs from arm muscles show no change.	PF EMGs suggest deterioration of muscle tissue and increased susceptibility to fatigue; RPB in about 4 d.
Achilles Tendon Reflex	Duration decreased PF.	Duration decreased 30% or more PF; reflex magnitude increased; compensatory increase in duration about 2 wk PF; RPB in about 1 mo.
Limb Volume	IF leg volume decreases exponentially during 1st d and plateaus within 3-5 d; rapid increase immediately PF, followed by slower RPB.	Early IF period same as short missions; leg volume may continue to decrease slightly throughout mission; arm volume decreases slightly; rapid increase in leg volume immediately PF, followed by slower RPB.

Table 8. (cont.)

Total Body Volume	Decreased PF.	Decreased PF; center of mass has shifted toward head.
Body Composition		Large losses of H <sub>2</sub> O, protein, and fat during 1st mo IF; fat probably regained; muscle mass partially preserved depending on food intake and amount of exercise.
Mass	PF wt losses average about 3.4% with approx 2/3 due to H <sub>2</sub> O loss, remainder due to loss of lean body mass and fat.	IF wt losses average 3-4% during 1st 5 d; thereafter, wt gradually declines for remainder of mission; early IF losses probably due to loss of fluids and later losses are metabolic; rapid wt gain 1st 5 d PF mainly due to replenishment of fluids; PF wt loss inversely related to IF caloric intake.
Total Body Water	Decreased PF.	Decreased PF.
Plasma Volume	Decreased PF, except in Gemini 7 and 8.	Markedly decreased PF; RPB in 2 wk.
Plasma Proteins	Occasional PF elevations in $\alpha_2$ -globulin, due to increases of haptoglobin, ceruloplasmin, and 2 $\alpha$ -macroglobin; elevated IgA and C <sub>3</sub> factor.	No significant changes PF.
Serum/Plasma Electrolytes	Decreased K and Mg PF.	IF decreased Na, Cl, and osmolality, but slight increase in K and PO <sub>4</sub> ; PF decreases in Na, K, Cl, Mg, but increase in PO <sub>4</sub> and osmolality.
Serum/Plasma Hormones	PF increase in HGH, thyroxine, insulin, angiotensin I, sometimes aldosterone.	IF increase in cortisol, and decrease in ACTH, insulin; PF increase in angiotensin, aldosterone, thyroxine, TSH, GH, and decrease in ACTH.
Serum/Plasma Metabolites and Enzymes	PF increase in BUN, creatinine, glucose; decrease in lactic acid dehydrogenase, creatine phosphokinase, albumin, triglycerides, cholesterol, uric acid.	PF decrease in cholesterol, uric acid.

Table 8. (cont.)

Urine Volume	Decreased PF.	Decreased early IF; normal or slightly increased PF.
Urine Electrolytes	PF increase in Ca, creatinine, PO <sub>4</sub> , osmolality; decrease in Na, K, Cl, Mg.	IF increase in osmolality, Na, K, Cl, Mg, Ca, PO <sub>4</sub> , and decrease in uric acid; PF increase in Ca, and initial decrease in Na, K, Cl, Mg, PO <sub>4</sub> , uric acid; Na and Cl increase 2nd and 3rd wk PF.
Urinary Hormones	IF decrease in 17-OH-corticosteroids and increase in aldosterone; PF increase in cortisol, aldosterone, ADH, pregnanediol, and decrease in epinephrine, 17-OH-corticosteroids, androsterone, etiocholanolone.	IF increases in cortisol, aldosterone, total 17-ketosteroids, and decrease in ADH; PF increase cortisol, aldosterone, norepinephrine and decrease in total 17-OH-corticosteroids, ADH.
Behavior and Performance	Initial IF slowness in accomplishing tasks (or a reduced work efficiency) and diminished motor coordination and precision of movement during adaptation to weightlessness; adjustment is rapid, but PF motor dysfunction can be debilitating for days or weeks.	Same as for short-term flights.

\* Data compiled from several reports on Mercury, Gemini, Apollo, ASTP, Vostok, Voskhod, and Soyuz missions.

\* Data compiled from several reports on Skylab, and Salyut missions.

Abbreviations:

pref = preflight

IF = inflight

PF = postflight

RFB = return to preflight baseline

## 1. Bone Demineralization

Based on the information obtained from space missions, particularly Skylab, it appears that bone and mineral metabolism is substantially altered during space flight (Nicogossian and Parker, 1982). Calcium balance becomes increasingly negative throughout the flight, and the bone mineral content of the os calcis declines. The major health hazards associated with skeletal changes include the lengthy recovery of lost bone mass postflight, the possibility of irreversible bone loss (particularly the trabecular bone), the possible toxic effects of the increased release of calcium and phosphate on soft tissue such as kidney, possible urolithiasis, and the potentially increased possibility of fracture.

Studies of metabolic balance conducted on a few of the crew members participating in the Gemini and Apollo missions suggested that space flight is accompanied by an increased excretion of calcium and phosphorus. These studies were expanded for the Skylab missions and dietary intake was carefully monitored, permitting more accurate balance determinations. Whereas, urine calcium content increased rapidly but reached a plateau 30 days inflight, fecal calcium content continued to increase throughout the flights (Rambaut and Johnston, 1979). The preflight positive calcium balances were abolished and within 10 days after the start of the Skylab 4 mission gains in calcium stores obtained preflight were lost, and the body as a whole began to lose calcium. At first the rate of loss was slow but increased to almost 300 mg/day by the 84th day of flight. Rambaut and Johnston (1979) calculated that, based on the calcium lost in the first 30 days, 300 g (25%) of the 1250 g initial overall body pool might be lost 1 year inflight. This is much larger than the predicted loss of calcium from bed rest studies, and suggests that calcium losses are more severe in space than in bed rest. Similar conclusions can be drawn from Soviet research (Gazenko et al., 1980), in which an increased calcium excretion is attributed to weightlessness.

Recovery of lost calcium begins soon after return to 1 G, with urine calcium content dropping below preflight baselines by the 10th day postflight, but fecal calcium content remained elevated even 20 days postflight. Though the markedly negative calcium balance also had not returned to zero by the 20th day, studies indicate that after several weeks or months a positive calcium balance would be reached. However, Rambaut and Johnston (1979) note the possibility that calcium balance might return to zero before the space flight loss has been made up, resulting in irreversible damage to the skeleton.

Bone mineral losses apparently occur only in weight-bearing bones during space flight (Nicogossian and Parker, 1982). Mineral loss from the os calcis increased in rough proportion to

the increase in mission length, until extensive exercise counter-measures began to be employed. Percentage reductions seen after 6-month Soviet flights then decreased to approximately the 3.2-8.3% level seen after 3-month flights (Gazenko et al., 1981). This affects postflight readaptation as well, since recovery of the skeletal mass is gradual and appears to take about the same length of time as the loss (Vogel and Whittle, 1976).

Skylab calcium balance studies suggest that the losses in bone mineral from the os calcis contribute relatively little to the overall calcium loss. The 4% loss observed in the os calcis after the 84-day mission would represent a loss of only about 100 mg of calcium, while overall calcium losses for this mission averaged 25 g. Thus it appears that other weight-bearing skeletal sites account for the major portion of the depleted mineral (Nicogossian and Parker, 1982).

Calcium supplementation as a means of increasing calcium balance seems to be a controversial issue among reputable scientific researchers. Some scientists contend that much of the increased balance shown with increased calcium intake is an artifact of increased recovery. Even if the supplemental calcium is absorbed, it does not necessarily reflect skeletal utilization (Mazess et al., 1985). Others point to the correlation of low fracture rate with high calcium intake as noted among the people of Finland (Recker, 1985), and response of periodontal disease to supplemental calcium (Krook et al., 1972; Lutwak et al., 1971). Nordin et al. (1979) have speculated that the availability of sunlight improves vitamin D status, thereby increasing calcium absorption efficiency and reducing calcium requirements. Reviews on the effects of dietary factors on skeletal integrity (Chinn, 1981) and of certain vitamins and minerals on calcium and phosphorus homeostasis (Anderson, 1982) are available as Life Sciences Research Office reports.

In a bed rest study to reduce urinary excretion of calcium and loss of calcium from bone, Hulley et al. (1971) supplemented dietary phosphorus with 1.3 g potassium phosphate per day, but with no effect on calcium losses. However, the combined ingestion of 1.2 g calcium and 1.3 g phosphate daily, in addition to the usual dietary intake, resulted in a positive calcium balance for the first 12 weeks of bed rest even though the second 12 weeks showed a mean negative balance (Hulley et al., 1971; Whedon et al., 1974; Hantman et al., 1973).

Schneider et al., (1981) found that urinary calcium excretion varied with protein intake. Ambulatory subjects consuming 69 g protein per day had a lowered urinary calcium excretion resulting in a positive calcium balance, whereas those whose protein intake was 156 g/day showed increased urinary calcium excretion.

Other bed rest studies have employed pharmacological procedures in an attempt to stem calcium and phosphorus losses. Calcitonin, a polypeptide hormone known to inhibit bone resorption (Hantman et al., 1973), and disodium ethane-1-hydroxy-1, 1-diphosphonate, a synthetic compound structurally related to pyrophosphate and shown to inhibit soft tissue calcification as well as bone resorption (Fleisch et al., 1969; Francis et al., 1969) were not effective in preventing negative calcium balance. However, another diphosphonate, clodronate, seemed to be more effective in inhibiting bone resorption without causing an accumulation of osteoid tissue. It produced a positive calcium balance for about 2 months during bed rest with decreased hydroxyproline excretion (indicative of skeletal turnover and breakdown) and phosphorus balance (Landenson and Bowers, 1973). However, since renal failure occurs in patients treated with clodronate, it is not a suitable prophylactic agent (Bounameaux et al., 1983).

The major countermeasures being explored to reduce the effects of space flight on the skeleton are the use of various weight-loading exercises or artificial gravity regimens that counteract the loss of gravitational and muscular stress, and nutritional and pharmacological manipulations. The six members of the Skylab 3 and 4 crews exercised heavily inflight but despite this, three showed substantial mineral losses, which casts doubt on the effectiveness of exercise as a countermeasure (Smith et al., 1977). However, later Soviet findings using different exercise modalities have been somewhat more positive regarding the effect of inflight exercise (Gazenko et al., 1981). Nutritional supplements of calcium and phosphorus, and drugs such as newer diphosphonates, show some promise as countermeasures for the effects of bed rest on the skeleton and may be effective for space flight (Rambaut et al., 1977b). Also, artificial light sources that emit a spectrum similar to that of natural outdoor light have been proposed as a possible countermeasure for the bony demineralization seen in space (Wurtman et al., 1985).

For a more complete evaluation of the problems related to bone demineralization and proposed solutions, see Anderson and Cohn (1983).

## 2. Muscle Atrophy

Analyses of blood, urine, and fecal samples from Skylab astronauts have supported the hypothesis that space flight is associated with substantial changes in muscle tissue (Nicogossian and Parker, 1982). Of particular relevance to the state of muscle tissue are the inflight increases in plasma calcium, phosphorus, potassium, and creatinine, and the postflight elevation of plasma creatine phosphokinase levels. Urine analyses have revealed changes in a number of substances that are considered indices of muscle condition, including increases in inflight excretion of calcium, sodium, potassium,

creatinine, phosphates, magnesium, total hydroxylysine, 3-methylhistidine, and almost all amino acids (Gazenko et al., 1980; Leach and Rambaut, 1977; Leach et al., 1976). This biochemical pattern strongly points to muscle breakdown in flight. According to Gazenko et al. (1980), fluid losses on long-term flights are largely attributable to a decrease of intracellular fluid due to muscle atrophy. The ratio of sodium/fluid in the urine is restored to normal more rapidly after short flights than after long flights.

Inflight exercise is considered the primary countermeasure against muscle atrophy (Nicogossian and Parker, 1982). Thornton and Rummel (1977) concluded that bicycle ergometry alone was insufficient for the maintenance of muscle mass and strength. A device that permitted walking and running under forces equivalent to gravity was viewed as ideal for the prevention of muscle deconditioning. A simulated treadmill was installed on Skylab 4 and its use may have accounted for the superior muscular condition of the crew members when compared with those on the previous Skylab missions. On the 175-day Salyut-6 flight, the 2.5 hour daily exercise regimen included walking and running on a treadmill that produced a load of approximately 50 kg along the longitudinal axis of the body for a total distance of 3.9-4.3 km (Yegorov, 1981). As an added countermeasure to muscle atrophy, the cosmonauts wore the "penguin" suit for 12-16 hours per day, which produced a load on the support-motor system to compensate for the lack of gravity on the antigravitational parts of the musculoskeletal system in the trunk and lower extremities (Nicogossian and Parker, 1982; Yegorov, 1981).

During the Skylab missions, there was a pronounced increase in urinary excretion of nitrogen and phosphorus (Whedon et al., 1977). The mean shift in nitrogen balance from preflight to inflight for the six astronauts on Skylab 2 and 3 was 4 g/day, with a similar excretory increase on Skylab 4. This biochemical evidence reflected substantial loss of muscle tissue, which was clearly observed in the legs of the crew members. Countermeasures must be developed before space flights of 1.5-3.0 years can be considered. Arm muscle tissue and strength were maintained or actually increased during the Skylab missions as compared with the legs (Thornton and Rummel, 1977). This is not unexpected considering that the legs under weightless conditions receive no effective loading, whereas the arms are provided with relatively far greater work loads in addition to the stressing associated with controlling locomotion.

Food, too, is a countermeasure that deserves consideration in the maintenance of muscular fitness. During the Salyut-6 mission, the food unit was substantially improved and the caloric value of the food ration increased to 3150 kcal (Yegorov, 1981). A nutritional regimen of four meals/day, consumed at approximate intervals of 4 hours, was established; it was considered an important element in maintenance of good health and high performance. After the Salyut missions, examination of blood

plasma revealed a decrease in most amino acids, particularly the essential amino acids. Given the fact that muscle is 20% protein, a loss of 200 g muscle protein would constitute a loss of 1000 g muscle tissue. Therefore, it was concluded that the diet of the cosmonauts should be supplemented preflight with methionine and aspartic acid, and inflight and postflight with the seven essential amino acids plus cystine, arginine, proline, and aspartic acid (Popov and Latskevich, 1984).

In a 1 G chamber test simulation of space flight conditions using subjects chosen to be as equivalent to the astronaut population as possible, Vanderveen and Allen (1972) deliberately reduced the caloric intake and found that the metabolic loss was almost all or completely muscle. From this, the conclusion can be reached that whether in space or on Earth, muscle that is properly nourished and exercised at reasonable load levels will probably maintain its function (Thornton and Rummel, 1977).

For a more complete evaluation of the problems related to muscle atrophy and proposed solutions, see Herbison and Talbot (1984).

### 3. Body Fluid Changes

Common occurrences in weightlessness include a cephalad redistribution of blood, decrements in plasma volume, reduction in total body fluid, and a gradual progressive loss of electrolytes (Leonard, 1985; Nicogossian and Parker, 1982). Studies on the body's fluid and biochemical responses to space flight were conducted as part of the Mercury, Gemini, and Apollo missions, but only gross changes were noted pre- and postflight and inflight aberrations could only be inferred. However, the Skylab experiments were designed to study the most significant changes in greater detail.

Weight loss, determined from inflight body mass measurements, occurred primarily during the first few days of flight. About half of this loss was derived from lean body mass, which contains the most significant amounts of water and electrolytes, and the remainder from fat stores (Leach et al., 1979; Leonard, 1982). Rapid weight recovery postflight indicates that most of the loss can be attributed to fluid loss (Thornton and Ord, 1977). However, some of the weight loss related to adipose tissue loss results from insufficient caloric intake, although protein, mineral, and electrolyte loss seem to occur at a proportionately higher rate than can be accounted for on the basis of a hypocaloric regimen (Leach and Rambaut, 1977). The loss of fluids and potassium as a result of the vomiting that is sometimes associated with space motion sickness early in flight should not be ignored. No correlation exists between weight loss and mission length for flights up to 2 weeks, even though

loss diminished as Skylab flights increased in duration; this was probably the result of increased dietary caloric intake (Leonard, 1985).

There is an alteration in body fluid balance as indicated by the data obtained from Skylab. During the first 6 days inflight, all nine crew members decreased their water intake approximately 700 ml/day but their urine excretion decreased an average of only 400 ml/day, thus showing a net water loss (Leach and Rambaut, 1977). After this initial period, excreted urine volumes were similar to the preflight control values for each man. Although interstitial fluid volume did not appear to change appreciably postflight, there were significant decrements in the other extracellular fluid compartments and in intracellular fluid of 300 ml and 500 ml, respectively, as well as in blood volume of 600 ml which consisted of a combined loss of plasma volume and red cell mass (Leonard, 1985). Though plasma volume stabilized after the first few days, red cell mass loss continued throughout the mission (Johnson et al., 1977; Kimzey, 1977). Dunn et al. (1981), in reanalyzing Skylab data, found a significant correlation between red cell mass loss and changes in dietary intake, lean body mass, and exercise performed. They postulated that loss of red cell mass may be an adaptation to body weight loss and could be prevented by techniques that maintain lean body mass or increase tissue oxygen demands, such as exercise (Talbot and Fisher, 1985).

Red cell mass loss during the Gemini missions was about 17%; in Apollo, 10%; in Skylab, 8%, with the mean loss in Skylab 2, 3, and 4 being 9.4, 8.6, and 5.9%, respectively. These losses were apparently related to marrow suppression as there is little evidence to support increased cell destruction (Dietlein, 1977); however, the exact cause of the losses of red cell mass is unknown (Talbot and Fisher, 1985).

During the Gemini 7 mission, crew members exhibited a positive potassium balance pre- and post-flight, but a negative balance inflight accompanied by increased urinary aldosterone excretion (Lutwak et al., 1969). On Apollo flights 15, 16, and 17, potassium was found to be generally decreased postflight despite adequate potassium ingestion throughout these missions (Leach et al., 1975). During the Skylab missions, all of the electrolytes in urinary samples measured inflight were increased along with aldosterone, cortisol, and total 17-ketosteroids, whereas antidiuretic hormone, epinephrine, norepinephrine, and uric acid were decreased (Leach and Rambaut, 1977). Plasma sodium was generally decreased and urinary sodium increased throughout the flights and, though urinary potassium was more variable, in general it too was elevated. The nature of these changes tends to support the conclusion that they are transient and indicative of homeostatic adjustments, possibly mediated by atrial natriuretic factor released in response to pressure and volume changes in the circulation.

Soviet scientists assume that administration of vitamins, amino acids, and minerals promotes the retention of fluids and, thus, electrolytes. These preparations are administered in large doses just prior to reentry in order to facilitate the readaptation process (Yegorov, 1980). A low level of potassium in the diet has been implicated in the cardiac arrhythmias and long postflight recovery period observed on Apollo 15; potassium supplements may have prevented these problems on subsequent missions (Berry, 1981).

Countermeasures to be considered in ameliorating the effects of space flight on body fluid changes are provision of adequate caloric and nutrient content in the space diet to counteract electrolyte losses and maintain metabolic regulation (Nicogossian and Parker, 1982). Water and electrolyte replenishment, as well as vigorous isotonic and isometric exercise regimens, may partly alleviate the problem of reduced plasma volume and decreased orthostatic tolerance postflight even though they are unlikely to prevent the loss of red cell mass. Exercise appears to have multiple benefits as a countermeasure, and may diminish the loss of electrolytes associated with changes in muscle and bone and in mineral metabolism.

#### 4. Behavior and Performance

Except for vestibular dysfunction and the space motion sickness associated with it, the neurophysiological changes encountered during space flight do not compromise the performance of complex motor activities (Nicogossian and Parker, 1982). However, spatial illusions and disorientation of a transient nature occurred occasionally (Yuganov and Kopanov, 1975), sleep problems were encountered (Strughold and Hale, 1975), and initial inflight performance of a task generally took longer than the final preflight performance (Kubis et al., 1977). The latter was not attributable to exposure of long duration to the space environment, but rather to stress associated with last-minute flight preparations, change to a weightless environment, greater care and caution in task performance, and some measure of initial work overload.

The experiences related to behavior and performance in space are limited by the relatively small number of astronauts and cosmonauts involved, and the difficulties in conducting controlled experiments and engaging in expert inflight observation. Analogous experiences, however, are available on the effects of isolation or confinement on behavior in underwater habitats, submarines, isolated and remote work stations, and space flight simulation (Christensen and Talbot, 1985). As in space flights, these situations subject isolated groups of individuals in confined environments to long periods during which complex and routine tasks are performed. Under these circumstances, adverse effects have been observed, such as boredom, listlessness, fatigue, sleep disturbances, irritability, hostility,

depression, and personality deterioration. Despite these adverse factors, the ability of man to adjust and perform capably in the most trying environments has been amply demonstrated. A more complete review of human behavior and performance is available in a report by Christensen and Talbot (1985).

Over the past several years, evidence from animal studies and clinical trials has shown that foods and food constituents can affect behavior and performance (Fernstrom, 1981, 1985; Hartmann, 1983; Lieberman et al., 1983; Spring et al., 1983; Wurtman and Wurtman, 1985). Consumption of carbohydrate-rich meals alters the pattern of plasma amino acids, resulting in increased brain uptake of tryptophan. Subsequently, synthesis and release of the neurotransmitter, serotonin, is increased; consumption of protein-rich meals does not result in altered synthesis or release of brain serotonin (Fernstrom and Wurtman, 1971, 1972). These patterns of change in plasma and brain chemistry are more complex, as consumption of various foods affects levels of plasma large neutral amino acids, other than tryptophan, which compete for carrier sites necessary for transport to the brain (Fernstrom, 1985). In addition, there is some evidence that neurochemical changes in the brain occur; however, their influence on neuronal function is not well understood (Trulson, 1985). Furthermore, the serotonin content of food is variable (Feldman and Lee, 1985) and the influence of ingested serotonin itself on behavior is unclear. Finally, there is some fragmentary evidence of circadian patterns of response to ingested tryptophan (Ashley et al., 1985).

A number of studies have shown that observable changes in behavior of animals and human subjects occur after consumption of diets that are either rich in, or essentially devoid of, L-tryptophan. For example, oral doses of 1.0 g or more increased subjective appraisal of sleepiness and fatigue but did not affect sensorimotor performance (Hartmann et al., 1976; Lieberman et al., 1983, 1985). Consumption of a tryptophan-free diet altered sleep patterns (Moja et al., 1984).

Similarly, ingestion of dietary L-tyrosine and valine result in behavioral changes (Gelenberg et al., 1983; Lehnert et al., 1984; Lieberman et al., 1985). In general, oral administration of tyrosine or tyrosine-rich diets is thought to increase brain norepinephrine concentrations and alter blood tryptophan levels. Experimental administration of tyrosine has produced augmentation of antidepressant drug effectiveness and reduction in motor response to stressful stimuli. Valine administration with tyrosine eliminated observable responses to tyrosine.

Much of the research on dietary tryptophan, tyrosine, and related amino acids has been prompted by the intriguing possibilities for using dietary modification to substitute

or augment the effectiveness of pharmacologic agents used in treating brain and behavioral disorders. However, it is clear that consumption of foods with high levels of tryptophan produces a response in wakefulness that can be characterized as sedative to mildly hypnotic. Evidence of actual effects on motor or mental performance is conflicting. Lehnert et al. (1984) reported reduction in responses to stress in rats receiving tyrosine-rich diets.

There is little question that the weightless environment is stressful. Work/rest cycles can be expected to interfere with sleep patterns. Performance of scheduled or routine tasks may result in both anxiety and boredom. Because there is evidence that food constituents, particularly large neutral amino acids can alter behavior and possibly performance, their effects require further investigation. Although the influence of food constituents are subtle compared with many drugs, the potential effects of dietary patterns and composition of consumed foods on performance and behavior require careful consideration in planning for sustained activity in the weightless environment.

#### E. PAST RECOMMENDATIONS OF SCIENTIFIC ADVISORY GROUPS

Over the years, various advisory groups of scientific experts have provided NASA with recommendations on nutrition and metabolism in space. In the early and mid-60s, working groups and panels of the National Academy of Sciences -- National Research Council's (NAS-NRC) Space Science Board considered problems related to feeding and nutrition in space flights that are pertinent to missions of long duration.

The Working Group on Nutrition and Feeding Problems under the chairmanship of Chichester (1963) proposed investigations into (1) water requirements, (2) diet variation, (3) waste and flatus, (4) metabolic requirements related to nutrient and caloric intake, (5) nutritional requirements related to lean body mass and metabolic rates, (6) food production, and (7) food storage and accessibility.

The proposals of the 1963 group were refined by the Panel on Space Nutrition of the Life Sciences Committee (Chichester, 1965) in a report divided into three sections as follows:

A) General recommendations -- (1) strengthen and coordinate the NASA nutritional program, (2) form research advisory committees, (3) determine the scope and priorities of the nutrition program, (4) utilize currently planned flights to obtain data on nutrition, and (5) initiate NASA-sponsored conferences to obtain new approaches and aspects for solving problems under investigation.

B) Short-term flights of less than 90 days -- (1) determine water requirements, (2) carry out electrolyte balance studies, (3) study protein and mineral losses, (4) investigate effects of varying work loads, (5) study inflight metabolism, (6) precondition astronauts, (7) study effects of dietary deficiency states on performance, (8) determine the effect of diet on nutrient utilization, water requirements, and waste production, (9) study calcium metabolism and depletion, and (10) test effects of cabin atmospheres on food acceptability, spoilage, and flammability.

C) Long-term flights of more than 90 days -- (1) test effects of stress, (2) study the variability of food requirements, (3) determine effects of excessive and deficient mineral intake, (4) determine the adequacy of the RDAs for long-term flights, (5) study the long-term acceptability of monotonous diets, (6) study accumulation of nutrients in ecological systems, (7) investigate synthetic diets, (8) study aestivation, hibernation, and hypothermia as they relate to the space program, and (9) study the effects of diet on intestinal flora, motility, and flatus.

The 1966 Report of the Panel on Space Nutrition (Chichester, 1966) reviewed NASA's existing and projected nutrition program and offered specific comments on (1) dehydrated food and other relevant research, (2) minimal protein requirements, (3) protein synthesis in response to hormones and stress, (4) changes in the metabolism of fats and carbohydrates due to the effects of prolonged centrifugation, (5) metabolism and temperature regulation, as well as diet and performance of man in relation to his/her environment, (6) metabolic-carbohydrate interrelationship under stress conditions, (7) reactions of carbohydrates and amino acids, (8) closed ecological life support systems, (9) synthetic diets, (10) development and evaluation of foods for 30-day space flights, (11) human water metabolism in space environment, and (12) space gastroenterology and its relation to the space environment.

As part of this same report, the Panel commented on the proposed nutritional research programs of NASA's Ames Research Center which consisted of nutritional evaluation of (1) chemically synthesized foods, (2) biologically synthesized protein, (3) compounds produced by cell-free biochemical systems, (4) microchemical food synthesis systems, and (5) foodstuffs produced by a combination of the foregoing processes. Other aspects of these programs were the (6) determination of minimum requirements for amino acids and proteins, (7) development of high caloric density foods, (8) relationship between amino acid metabolism and water secretion, and (9) determination of factors responsible for appetite in humans.

In addition to these areas under investigation, the Panel recommended the following areas of interest in which work might be contemplated: (1) minimal requirements for essential

nutrients, rather than being confined to amino acids and proteins, (2) development of palatable formula diets, (3) analysis from a storage stability standpoint of available take-along foods, (4) study of changes in dietary appeal due to long confinement, (5) toxicological properties of foods which may be used, (6) effect of dietary regimens on waste production, (7) investigation of continued long-term consumption of unconventional food materials on intestinal flora and motility, (8) effect of diet on flatus, and (9) investigation of changes in metabolic balance under the stresses of flight.

In considering the future directions of the space program, the Life Sciences Advisory Committee of the NASA Advisory Council (Whedon, 1978) proposed that greater emphasis be placed on food technology, including (1) human nutritional requirements, (2) food and food-source selection criteria, (3) nutritional equivalency of various food sources, (4) physiological and psychological acceptability aspects of nonconventional diets and food sources, (5) new concepts for preparation, processing, storage, and distribution to reduce equipment and resources requirements, and (6) improved preservation and packaging of earth-produced foods.

Still another NAS-NRC study, this one by the Committee on Space Biology and Medicine of the Space Science Board (Bricker, 1979), considered dietary supplementation as a therapeutic approach to counteraction of physiological changes induced by weightlessness, the characterization of protein metabolism in space, the influence of gravity on mechanisms of protein catabolism, and the role of hormones in the development of negative nitrogen balance in space.

In a report presented to the NAS-NRC Space Science Board, seven working groups identified a series of life sciences experiments for a space station (Fabricant, 1983). Among the experiments proposed are two types for determining energy expenditure, both basal and that accompanying exercise: (1) measurement of gross body composition, i.e., protein, carbohydrate, and fat, after spending various amounts of time in space, and (2) determination of oxygen consumption and respiratory quotients under conditions of weightlessness. To determine if the regulatory signals and substrate fluxes in the body are normal or abnormal at zero gravity, the following broad experimental strategies were proposed in the Fabricant Report: (1) determine if the complement of anabolic processes associated with energy and substrate storage is normal in space, and (2) determine if catabolic responses associated with energy and substrate mobilization function normally at zero gravity. Also recommended are a series of experiments related to nitrogen balance, bone changes, muscle mass changes, fluid and electrolyte problems, and biological and psychological factors influencing performance.

The concerns of the various advisory groups outlined above were basically similar to those of the LSRO ad hoc Working Group whose opinions and conclusions (see Section IV) and research suggestions (see Section V) are described in this report.



#### IV. OPINIONS AND CONCLUSIONS OF THE WORKING GROUP

The members of the LSRO ad hoc Working Group represented broad expert investigative experience in areas pertinent to this study (see list of study participants in Section VII). In addition, several members had participated in NASA activities. The primary form of the discussions of the ad hoc Working Group was on the application of extant knowledge covering nutrition and metabolism to the needs of the Space Station program. Their observations were derived mainly from their experiences, knowledge of the pertinent literature, and presentations by the NASA staff.

##### A. ENERGY REQUIREMENTS AND EXPENDITURE

###### 1. Metabolic Measurements

A determination of the energy expended on various work-related activities in space is required in order to be able to plan a diet for long-term space missions. Up until now, the physical demands of the weightless environment have at no time exceeded known work capacity. If equivalent amounts of work are assumed, energy requirements inflight and on the ground are comparable. It is known that individuals work at certain averages, such as 30% of capacity averaged over time, or 45% of capacity at their "sustainable voluntary hard work level" for 3-4 hours, even though efficiency of utilization might differ (Evans et al., 1980; Hughes and Goldman, 1970). However, the question of metabolic expenditure over relatively long periods in space has not been fully resolved. A number of techniques are available for determining energy requirements. Examples are presented in the following paragraphs.

As a validating study for assumptions about the cost of work, indirect calorimetry could be used to measure energy expenditure on short-term flights. NASA should continue to monitor methods of body composition measurement that could be used periodically during space flights with equipment of moderate cost. There is substantial research to demonstrate that basal energy requirements can be estimated for an individual from lean body mass measurements, or by a factor of total body mass and anthropometric measurements. It is essential to obtain accurate daily mass measurements inflight because losses that were easily sustained on short missions cannot be tolerated on missions of long duration. Therefore, a body-mass measuring device should be on the Space Station for the purpose of determining caloric utilization.

Opportunities for developing techniques and equipment to measure either heat production or oxygen consumption while in the pressure suit should continue to be explored by NASA. For example, on 7- to 10-day Shuttle missions, the respiratory minute

volume could be determined perhaps by slipping a small device into the inlet airline of the space suit and doing a rotational count to provide an indicator of energy expenditure (Kreider et al., 1961). Such a direct measure of oxygen consumption is much better than the formerly used heart rate measurement to determine energy expenditure during activity.

Another cheaper, easier, but cruder method for determining energy expenditure is the Reported Perceived Exertion (RPE) scale in which the subjective perception of effort is related to an individual's maximum oxygen uptake (Borg and Lindblad, 1979). The subject's perception of exertion as reported on an open-ended numbered scale has a reasonable correlation with his/her actual oxygen consumption, thus providing an estimate of energy expenditure.

All of these measurements will help in determining energy needs in relation to food consumption. Preferably, these measurements should be made passively without implementation by the astronaut or anyone else. However, it should be remembered that metabolic measurements are modified if scopolamine or amphetamines are taken by the astronauts.

At the Johnson Space Center in Houston, a computer-modeling procedure is being tested for recording the amount of energy used by the astronaut in a space suit for each task. The sum of the tasks can then be used to determine the total energy expended, and indicate the energy required to move an arm, move an object, or impart an acceleration. Also, it should be possible to use the space suit cooling system to measure the amount of cooling needed. The use of direct calorimetry for measuring the efficiency with which astronauts oxidize fats, carbohydrates, and proteins is not feasible in a spacecraft because of the errors that might occur, including losses from the pressure suit.

The possible need for insuit energy supplies adds to the complexity of this issue. If astronauts are expected to perform vigorous physical operations in space suits for extended periods, provision will need to be made for an insuit food supply. This will impact on how much food should be put on the Space Station. The composition of an insuit food supply should take into account the evidence that some individuals may be sensitive to the somnifacient effect of high carbohydrate foods.

Another promising method for determining energy expenditure is the doubly-labeled water ( $2\text{H}_2^{18}\text{O}$ ) method because it is both highly accurate and requires no dedicated hardware on the spacecraft. The method was initially developed by Lifson and McClintock (1966) and applied to man by Schoeller and van Santen (1982). The labeled water can be given orally; it mixes with the body water pool in about 3-4 hours. The two isotopes are then excreted from the body at different rates --  $2\text{H}$  as water, mainly in the urine with some in the sweat and exhaled breath, whereas,

$^{18}\text{O}$  is excreted both as water and exhaled  $\text{CO}_2$ . Therefore, the difference between  $^{18}\text{O}$  and  $^2\text{H}$  loss rates is directly proportional to the rate of  $\text{CO}_2$  production from which the energy expenditure rate can be calculated. The method has been validated against whole body calorimetry for periods of 7-14 days and the concordance is within 2%. This method has the potential of detecting small differences for periods as short as a day and has the added advantage of providing body composition data (Schoeller, 1983; Stein et al., 1986).

A number of biochemical parameters that are very useful as metabolic/nutritional indicators could be applied short-term to serve as a reference in helping design future long-term studies. For example, much could be learned from a 7-day study in which data are obtained for lactic acid levels, and nonessential amino acid levels which decline in blood. The methodology for determining energy expenditure, using deuterium heavy water ( $^2\text{H}_2^{18}\text{O}$ ), could be tested on a 7-day mission. With the growing numbers of individuals on the Shuttle missions, body composition studies could be verified and food record methodology tested during short missions; in general, short missions should be used to validate and collect baseline information.

## 2. Energy and Water Balance

Previous U.S. and Soviet space flight studies have shown that complete food records -- consumption, inventory, waste -- can be kept with minimal interference with crew activities. These data are needed to predict ranges of energy balance among crew members. For long-term space flights, such data will be needed for extended periods as the metabolic demands of physical activities span several days' duration. Development of the diets required to meet these metabolic needs should be based on metabolic-period calculations rather than 24-hour calculations. Therefore, seven times the RDAs, or recommended allowances developed by a group of experts for NASA, should be provided in the food made available for every 7 days of flight.

The regulation of energy expenditure and energy balance on space missions may be dependent on the quality of the carbohydrates ingested and the effect they might have on behavior (Fernstrom, 1981). Fats must be a concern also now that studies on primates indicate that omega-3 fatty acids have beneficial influences on the ability of cells in the retina to be stimulated for the purpose of maintaining sharp vision (Patlak, 1985). In addition, clinical studies revealed that omega-3 fatty acids may help prevent hardening of the arteries by lowering blood levels of cholesterol and triglycerides, and may retard the formation of platelet blood clots. The possibility that these fatty acids affect the stimulation of brain cells involved in learning and behavior is under investigation.

During the early missions, there was a negative water balance, but now water is available ad lib and water balance studies reveal that the intake is adequate. If the urine excretion or the evaporative water loss is high one day, the water intake is increased the next day to bring the body into balance. Whereas, NASA plans to recycle water from urine or waste water, the Soviets recycle 2 liters of water per day from the atmosphere. During EVAs, water is available from a bag in the space suit that can be increased to hold more water as EVA time is increased. The suit is supplied with 100% oxygen, and is air conditioned to decrease evaporative loss of water during EVAs. In the Space Station, water will be produced from a regenerative system if potability can be achieved; whether it will be available ad lib has not been determined. However, judging from studies under heat stress, thirst is not a reliable guide for ensuring adequate water replacement (Adolph, 1947). Therefore, NASA must make available potable, sterile water to meet all water balance requirements under all anticipated work and stress states throughout a mission.

### 3. Exercise and Work

Exercise consists of well-defined activities designed to prevent or ameliorate certain changes. Exercises may be both physiologically and psychologically beneficial, which may be why space crews insist on doing them even though they may not be necessary on a 7-day mission. Exercise is not forced on the astronauts, but it seems to be a part of the life style of the group.

If exercise is to be standardized to provide minimal, optimal, and maximal levels for each astronaut, the standard will have to be developed preflight and will depend on knowing the amount of exercise performed on the ground. Whatever exercise regimen is established on the ground will probably have to be maintained in space so that disuse of the muscles involved does not occur. In addition, the caloric requirement will be higher than that of the individual who has not been exercising. As a consequence, the best conditioned person is theoretically subject to the greatest deconditioning in space. It has been shown that the somewhat sedentary person who is not highly trained physically tolerates centrifuge G-forces better than his/her highly trained counterpart after a period of bed rest.

Except for energy expenditures related to EVAs on the moon, few data are available on energy cost of work required to achieve necessary tasks on the spacecraft. During the EVAs, a predominance of arm and hand work as compared with leg work has been reported, which is not true of customary activities on the ground (Gazenko et al., 1980). However, recent anecdotal information about maintaining body positions in EVAs with the Shuttle suggests substantial work by the lower extremities also.

Sixty years ago, Collett and Liljestrand (1924) reported that, at the same metabolic rate, greater physiological strain resulted from arm exercise than from leg exercise. At a given submaximal power output, oxygen uptake is greater for arm exercise than for leg exercise. Therefore, when working or exercising at a given power output, both the absolute (oxygen uptake), as well as the relative (percent of peak oxygen uptake), intensities are greater during arm activity (Sawka, 1986). Therefore, differences in nutrient requirements may exist depending on whether arm or leg activity is involved.

## B. NOURISHMENT

### 1. Space Diets and Nutrient Requirements

The Recommended Dietary Allowances (National Research Council, 1980) have been generated on the basis of limited biochemical and clinical measurements without any reference assumptions to behavior. They are meant to be met over a period of time rather than on a daily basis, and to provide a reasonable excess over the known nutritional requirements of most stable, healthy Earth-bound individuals.

The RDA guidelines have been used for developing space diets, but long-term adequacy of such diets in a space environment remains to be established. Meeting only the known nutritional requirements for vitamins, minerals, and essential fatty acids could create nutritional problems in astronauts on 90-day missions. For several micronutrients considered to be essential, RDAs have not been determined yet. Also, inflight lactic acid, cholesterol, and folic acid status of the astronauts is presently unknown. Therefore, should the RDAs continue to be used as guidelines, some incremental increase should be considered for various nutrients, particularly calcium, essential fatty acids, micronutrients, folate, and protein quality. In addition, carbohydrate:amino acid ratio changes may be desirable during long periods in space; for example, to accommodate adaptive changes in muscle metabolism. Though the specifications for space nutrition are needed, they should not be more rigid than necessary.

The data required for determining a 90-day-mission diet may be insufficient because the astronauts are under physiological and psychological stresses different from those of Earth-bound individuals. Therefore, their diets may have to be designed to meet those different needs. The Department of Defense has conducted considerable research on military personnel under various stressful conditions (Hirsch et al., 1984; Nesheim, 1985; U.S. Departments of the Army, the Navy, and the Air Force, 1985). This body of knowledge should be consulted for possible relevance to NASA's needs in nutrition and metabolism.

The assessment of appropriate nutrient requirements may be influenced further by transient digestive disturbances associated with space sickness such as anorexia, nausea, and vomiting, and the use of anti-motion sickness drugs, as well as by a greater than expected energy demand for performing tasks in space. Therefore, data should be collected during Shuttle missions on the nature and duration of possible digestive disturbances to determine whether a significant net effect on nutritional balance may result. In addition, experiments should be designed to determine whether space flight interferes with the absorption of micronutrients from the gastrointestinal tract.

The concept of pre-mission nutritional or pharmacological treatment to prevent or retard some deconditioning effects of space flight was discussed. An example might be dietary supplements of calcium, phosphorus, fluoride, and vitamin D metabolites to retard inflight bone demineralization. The practicality of this approach is unknown; however, it merits consideration for both ground-based and inflight studies. Dietary intervention during flight is another possible control measure; however, the scientific data base for such is lacking.

Chemically-defined diets are not being considered for the Space Station but in the event that they ultimately might be desirable for space crews, the RDAs are an inadequate basis for the development of such diets. A chemically defined diet, designed on the basis of current estimates of amino acid requirements, might result in deficiencies in a matter of weeks. Similarly, if current formulas for parenteral nutrition were taken as a model, difficulties could occur because RDAs for certain trace elements and other essential nutrients have not yet been defined. Such data might become limiting on a long-term flight. Even though the information necessary to develop a chemically defined diet is not available, nutritional models have been proposed (Dufour, 1984).

## 2. Nutrients and Their Interactions

Interactions among nutrients would not be crucial on a 7-day Shuttle mission, but on a long-term flight, trace element interactions, especially, could be of great importance because micronutrient metabolism influences energy needs and central nervous system function. For example, iron, copper, zinc, and manganese are known to compete for binding sites during intestinal absorption. Also important are carbohydrate/amino acid interactions, as well as calcium, essential fatty acids, and total calories. Therefore, more has to be known about optimal levels for inclusion of trace elements and other nutrients in the astronaut diet. For example, vitamin B<sub>12</sub>, zinc, and folic acid needs and interactions in space require more research. To obtain the necessary measurements of various nutrients, blood can be drawn pre- and postflight and each astronaut can serve as his/her own control. Red cell mass

might serve as a broader nutritional indicator. If a sub-committee is formed to develop RDAs for NASA, it should consider upper, as well as lower, limits of nutrients.

To determine the possible utility of dietary intervention against bone demineralization, not only must the interactions between nutrients be considered, but also the interactions of diet and exercise (Weiser, 1984). Of equal importance are the factors that enhance calcium absorption (vitamin D, lysine, arginine, lactose and other simple sugars) or inhibit its absorption (oxalate, fiber, phytic acid, other phosphate compounds of inositol, food with high phosphate content), as well as the source/type and amount of calcium. Additionally, since 1,25-dihydroxyvitamin D<sub>3</sub> is critical in the control of calcium absorption and metabolism, further consideration should be given to the provision of artificial sunlight exposure during missions of several years' duration (MacLaughlin et al., 1982). Also, it should be noted that riboflavin is particularly sensitive to the fluorescent lighting used in spacecraft, and despite the manufacture of some riboflavin by intestinal bacteria, it may not be sufficient to meet conventional nutritional needs.

The absence of dietary bulk or fiber on a long-term flight might produce changes in gut flora and subsequent changes in the nutritional requirements of the gut bacteria. On a refined diet, the density would be small and the change in mass on the gut flora must be considered. Gut wall changes may produce certain food sensitivities never manifested before.

### 3. Calories and Physical Activity

There is very little information available when considering sustained performance on mental, behavioral, and physical levels for periods up to 90 days. However, in terms of meeting metabolic needs, the extent of physical activity must be known if estimates of the energy required are to be made. Though workloads determine the required calories, they may predict the amino acid requirements as well (Young and Torun, 1981). In any event, experience has indicated that a space diet must contain no fewer calories than are appropriate for similar activity on the ground (Nicogossian and Parker, 1982). After the first month or two of space flight, there is a statistically significant increase in the need for calories to meet increased energy demands (Leonard, 1982). After 2 months, trying to do the same amount of work with a smaller, qualitatively different muscle mass may involve a change in expenditure of energy.

A study by Inoue et al. (1973) demonstrated that nitrogen balance is influenced by energy intake. Young men, consuming maintenance level calories ( $45 \pm 2$  kcal/kg), required an average of 0.65 g protein/kg, whereas, the men given a surplus of calories ( $57 \pm 2$  kcal/kg), required only 0.46 g protein/kg to

maintain nitrogen equilibrium. Whether or not the same or a similar equation applies in weightlessness is unknown. Such data, however, would be valuable in determining the diet and exercise prescriptions necessary for retarding loss of lean body mass during space missions.

Pre- and postflight in vivo neutron activation analysis (IVNAA) measurements could provide the needed basis for relating individual food intakes and exercise programs to the preservation of body composition (Beddoe and Hill, 1985). Such an assessment is necessary to take advantage of the proposed record-keeping of individual nutrient intakes and for the development of improved nutrition guidelines for future flights. A portable chemical source of neutrons, suitable for IVNAA (such as a 20 Ci  $^{238}\text{Pu}$ -Be source), can be used to activate carbon, hydrogen, and nitrogen for measurement. Other elements such as calcium, phosphorus, chlorine, and magnesium can also be determined, but appear to require other types of neutron sources. The potassium content can be obtained by measuring the naturally occurring  $^{40}\text{K}$  using the same detection instrumentation. Data on total body water derived from  $^2\text{H}_2^{18}\text{O}$  measurements may be of value when the "hydrogen to nitrogen ratio" is used to reduce errors resulting from differences in "body habitus." The outcome of pre- and postflight IVNAA measurements during Shuttle and space-platform expeditions would allow a judgment to be made on the desirability of placing IVNAA instrumentation on board, for the long space flights of the future.

## C. PROVISIONS

### 1. Food Packaging and Storage

Although fresh foods aboard the Space Station would be preferable because they are more palatable than other food types, weight and volume restrictions will probably limit their use. The food supply should be as light as possible, and items requiring refrigeration should be avoided. Foods preserved by irradiation are not practical because bound water in the food system must be minimized. An exception might be irradiated bread as a desirable "fresh" item considering its rather low water content.

Though some water may be transported to the Space Station by resupply missions, most of it will be recycled on board. Therefore, in all probability, rehydratable foods will be used primarily, and food packaging for the Space Station and longer missions is likely to be the same as that used in the Space Transportation System Shuttle Program (Sauer and Rapp, 1983). This type of biopackaging is capable of being hermetically sealed to maintain the dehydration status of the food. Despite the practical aspects of such food packaging, in the past the astronauts have been annoyed because rehydration is time-consuming. Even if hot water, heated on a forced convection

oven, is available for reconstituting food, it usually becomes cold by the time the food is ready to be eaten. Perhaps, a greater variety of more palatable rehydratable foods can be considered, as well as the means for keeping them warm until ingested.

In formulating food management and packaging systems, NASA has relied on the work done by the Department of Defense and private industry. However, in determining Space Station food requirements, it could be beneficial to develop greater collaboration on a broad scale between NASA and groups committed to food-science research, such as the Natick Research and Development Center, the J.B. Pierce Laboratories, and the University of Vermont Clinical Research Unit.

Data on the nutrient content of long-time stored food are not available readily, although Finot (1983) and his colleagues (Ford et al., 1983; Hurrell et al., 1983; Nielsen et al., 1985) have done studies on the effects of long-term storage on nutrients. The shelf life of foods on extended space flights can be a problem because of the vulnerability of certain nutrients to long-time storage. For U.S. Army rations, shelf life is considered to be 5 or 6 years but some rations seem to remain palatable even after 20 years. The shelf life of freeze-dried foods should be considered also. Color changes, such as the browning reaction, may be of concern over periods exceeding 90 days.

## 2. Food Records

Fully computerized nutritional surveillance activity should be incorporated into the routine of each mission of the Shuttle, as well as the Space Station, and should include determination of food intake, as well as biochemical analyses of urine and plasma. The 7-day Shuttle missions could provide indications of what should be looked for on the 90-day Space Station missions. Also, the 7-day missions can provide information on problems existing in the test protocol, screen out what will not work, indicate the equipment needs and the auxiliary data items necessary for interpretation of the food or other records. Observational data would provide for better protocol design and testing of the null hypothesis. Operational data are needed, from mission to mission, so that limited information can be obtained on an increased number of people.

After EVAs, astronauts are given the option of eating additional food to replenish expended energy. Better data on eating behavior are needed for crews in space without putting too many constraints on the astronauts whose cooperation is necessary in the maintenance of food records. The Soviet space diet is similar to that of the United States, but cosmonauts, as well as U.S. submariners and athletes, all eat four or five meals

per day whereas, our astronauts eat only three meals per day. Snacks could be the equivalent of another meal for U.S. astronauts, and their consumption should be recorded in the same manner as regular meals. Individuals seldom remember what they eat for meals and even fewer recall what they eat for snacks though some may consume as much as 1000 calories from snacks alone.

In the past, nutrient intake was estimated from the energy in the food items consumed aboard the spacecraft, but the only way of accounting for the waste or food not eaten was to determine the energy content of the garbage and divide the value by the number of astronauts on board to obtain an average. This unreliable estimate should be replaced by a system in which food is coded so the intake of each astronaut, identified by a code number, can be recorded by a computer to indicate what is eaten, at what time of day, and on which day of the flight. By means of a scanner similar to the one used in supermarkets, a record would be available of the number of calories and nutrients consumed on any given day.

### 3. Food Acceptability and Palatability

Food items that rate high on the hedonic scale are not necessarily consumed at a 100% level (Vanderveen et al., 1970). Individuals tend to select foods with which they have had previous experience; generally, taste for new foods has to be acquired. Foods differ in the frequency with which they can be consumed with the same measure of acceptance, and can lose acceptance if fed too frequently. Therefore, each astronaut's food preferences must be considered when the diet is planned (O'Hara et al., 1967) for the Space Station. On past space flights, NASA has a history of providing individualized food preferences selected from standardized menus, but there is a potential problem of imbalance in astronauts sharing food or trading one item for another. However, on a 90-day flight, serious metabolic consequences are not likely to occur. Also, experience indicates that after flights become routine, complaints about the food tend to increase. Of course, this differs from crew to crew with some even being complimentary. Perhaps complaints can be reduced by having astronauts eat the food they will be getting inflight for a considerable period of time preflight. Food judgments could be very different based on long-term consumption as compared with short-term.

Palatability remains an issue and should be addressed. A satisfactory scientific approach to palatability determinations has never been developed. Perhaps, experts in palatability should meet with nutritionists at institutions, such as the Natick Research and Development Center, the J.B. Pierce Laboratories, the University of Vermont Clinical Research Unit, and the Monell Chemical Senses Center at the University of Pennsylvania,

to determine if more has been learned about the subject. If this is not practical, a review of the literature may serve as a useful alternative.

A total of 54 individuals are slated to participate in Space Station assignments with six on board at any one time. They will be resupplied with food every 90 days, and to ensure that the necessary nutrients are consumed, the astronauts may be required to eat the food prescribed. Also, if the astronauts could be depended on to take vitamin-mineral supplements, some of the problems associated with vitamin content of the food might be alleviated. The stability of vitamin-mineral supplements might be easier to measure than the stability of the food itself (Food and Drug Administration, 1979). The supplements could serve as a precaution against certain deficiencies, but care would have to be taken to avoid toxic excesses.

During periods of stress, the eating pattern may be quite different because of the variability among groups and among individuals within groups as to what, when, and how much is eaten. Astronauts should not be required to eat the same food, the same amount, or at the same time before EVAs; it should remain an individual matter. The Farnborough Army Personnel Research Establishment in the United Kingdom has vast experience analyzing what soldiers will eat, portion sizes, what is left over, and the like (French, 1975). These data could provide background information for deciding what foods should be stored on the Space Station.

A classification of desirable, as well as undesirable, foods should be created. Though certain undesirable foods may constitute no problem in the short-term, it may not be true in the long-term. Heavy metals, such as lead, mercury, cadmium, and cesium tend to have a cumulative effect and foods containing relatively high contents should be avoided. At one time, foods such as asparagus, cabbage, broccoli, mixed Italian vegetables, and others that promote formation of flatus in the intestine were banned. All of the gas-producing taboos require a new examination to determine which vegetables should be eliminated from the Space Station diet because most of the foods in this category provide valuable sources of fiber.

#### 4. Microbiological Safety

On commercial airliners, the low humidity and the recirculation of air through the compressor, which is very hot, tend to kill microbial organisms, but in the closed environmental system of spacecraft, microbes are more likely to present a problem. If prepared food is not eaten promptly, it should be discarded to prevent bacterial contamination. However, it is important that food waste be individually identified so records can be maintained of what each astronaut did not eat. On the

Shuttle there is the problem of being unable to dispose of uneaten food in space, so it must be held for return to the ground. If the food waste spoils in such a closed environment, widespread microbial contamination could ensue, which may not only be harmful but may produce unpleasant odors that could create an olfactory fatigue problem. However, 8-hydroxyquinoline sulfate should not be used to deodorize food waste because it is toxic, it has a penetrating odor that may cause nausea, and its quinone structure may adversely affect hemoglobin formation. The waste management system for the Space Station should be simple to use and should not require extensive training.

It is known that the water supply on the spacecraft is not sterile and may contaminate the food during the rehydration process. Even though the water is in storage tanks, the filters can be sources of bacteria. Such contamination can be reduced by having ultraviolet light directed at the filters. Auxiliary devices, such as ovens, that are used during the preparation of meals may be responsible for contamination also. There is some information available on bacterial contamination that occurred on previous space flights. However, data on viruses are limited mainly to identification of viral forms in pre- and postflight nose, throat, and fecal specimens obtained from the Apollo astronauts. Undoubtedly, one of the engineering concerns for the Space Station must be the elimination or control of microbiological contamination.

#### D. SPACE-RELATED CHANGES

##### 1. Bone Calcium

Some members of the Working Group were of the opinion that astronauts exercise during space flights because they are convinced it is useful as a countermeasure to bone demineralization and muscle atrophy, and the medical personnel within the astronaut corps are convinced also that exercise is useful. Space medical experts point out that in bed rest studies, losses in the untreated calcaneus were 45%, whereas, in the 211-day Salyut flight in which crew members exercised approximately 3 hours per day, there was very little loss. The mainstay of Soviet countermeasures is a prescribed diet high in calories, exercise on a bicycle ergometer and a treadmill, and use of a penguin compression suit that covers crew members from the top of the shoulders to the bottom of the feet (Yegorov, 1979). These measures have been considered effective in countering bone changes on the long-term Salyut missions. However, metabolic balance data have not been obtained from the Soviets, nor have data on the reversibility of bone demineralization.

On Skylab, two astronauts lost 7% of the heel-bone calcium, which was not recovered even 90-days postflight. Based on the maximal negative calcium balance of 200 mg/day

in the normal healthy skeleton, this translates into 18 g in 90 days (Rambaut and Johnston, 1979). Without more information on the effects of vitamin D, calcitonin, and parathyroid hormone on bone homeostasis, it is not possible to know whether the previously well-conditioned person may show greater bone loss than the person who does not exercise preflight. On the ground, excessive training does not seem to be more effective in preventing bone loss than does normal activity. Also, there is no way of knowing which, if any, of the measures used in the Soviet flights were effective in prevention of bone loss. Because the loss is primarily from trabecular bone, the possibility of fracture is increased (Anderson and Cohn, 1983). The jaw is also composed of trabecular bone and, therefore, should be examined in astronauts to determine if losses occur only in the weight-bearing bones (Lutwak et al., 1971).

If exercise is required to minimize bone demineralization, it will add another expenditure load relative to nutrition. More energy will be required, and some modification of the diet may be necessary in terms of vitamin D or calcium consumption, as well as other dietary components. Bone density studies should be done on astronauts who participate in six or more Shuttle flights; a single exposure does not produce significant change but several might. More sensitive methods of measuring changes in bone mass, especially trabecular bone mass of vertebrae, with a dual photon computer-aided tomography (CAT) scanner, are being developed.

A safe range of exogenous vitamin D intake on long-term flights has not been established. Unless there is full-spectrum light on the spacecraft or it has quartz windows similar to those in the Salyut spacecraft to permit penetration of the sun's ultraviolet rays, there may be insufficient endogenous production of vitamin D. As the primary regulator of intestinal calcium absorption (DeLuca, 1985), vitamin D has special importance in the space environment. Therefore, the amount of vitamin D required to alleviate insufficiency should be determined and toxic levels should be considered.

The 800 mg of calcium per day given astronauts on the Shuttle flights may be insufficient as evidenced by information in the literature (Krook et al., 1972; Lutwak et al., 1971; National Research Council, 1980). Astronauts may need 1200-1500 mg calcium/day in foods or supplied in supplements; 1500 mg is a plateau beyond which additional calcium usually is not absorbed. If, for 2 weeks prior to a Shuttle flight, astronauts were fed a particular dietary combination, which was continued during the 7-day flight, urinary calcium could be measured postflight to determine what portion of the calcium was being excreted. Feces would have to be measured also to determine calcium absorption. Such a dietary study would be worthwhile in indicating the effectiveness of 1500 mg calcium as a means of decreasing bone loss inflight. In this connection, phosphate intake would have to be standardized at a constant

level because excesses deplete calcium, sodium, and zinc. However, an experimental study on the actual requirement for calcium, phosphorus, and vitamin D in relation to bone metabolism could be useful.

Consideration of 1200-1500 mg/day calcium intake by astronauts during space flights raises concerns about excess calcium in the diet leading to possible hypercalciuria. In turn, the hypercalciuria can give rise to renal stone formation. This problem forced the premature termination of a recent space flight, but excess calcium intake may not have been the cause of the problem. Metastatic calcification studies done on humans show that the calcium comes from the preexisting skeleton and not from the diet. In this regard, the toxic effects of calcium would be easy to screen. Calcium can stimulate the production of calcitonin which might mitigate bone demineralization (Krook et al., 1971). Calcitonin stimulates bone formation and prevents bone resorption with very little effect on the gut or kidneys. However, it is much easier to take additional calcium than it is to inject calcitonin.

Pharmacologic intervention to ameliorate bone loss should be considered, such as the possible use of some diphosphonates, provided that a nontoxic form can be identified. If animal studies on bone are conducted, the rat should not be used because its bone remodeling system is so different from that of humans, whereas, the monkey and dog are good models for such studies (Krook et al., 1971). To gain data, it might be useful to hold primates on the Space Station for a number of years for the purpose of obtaining biopsies of bone, muscle, and other tissues for examination at several intervals over an extended period of time.

## 2. Muscle Mass

Consideration of eicosanoid (twenty-carbon fatty acid) biology and prostaglandin balance might provide opportunities for developing countermeasures to muscle atrophy (Palmer et al., 1983; Rodemann et al., 1982). Prostaglandins play an important role in maintaining protein balance across muscles. Therefore, the use of drugs that influence prostaglandin metabolism, such as salicylic acid, indomethacin, or mepacrine, may deserve evaluation as possible countermeasures to muscle wasting. It is known that nutrition is an effective modulator of metabolism, and that there is a cost to adaptation. A prescription for what is necessary to prevent changes in muscle mass on the Space Station is being sought, but has not been found yet.

There is evidence that lean individuals tend to lose protein more rapidly during total and partial food deprivation than individuals with a substantial body fat mass (Forbes,

1985a). The effects of total and partial starvation have been extensively studied in overweight and obese subjects because the acquired data are important in designing weight-reducing diets. However, there is a lack of precise data on the effects of different levels of caloric intake by lean individuals. Inasmuch as Space Station crew members are expected to be physically fit and lean, NASA should consider studying the effects of various caloric intakes in weightlessness. There is a need to relate the demands of physical performance in space with preservation of muscle mass.

The penguin suit, which is worn 16 hours/day by Soviet crews, applies compressional stress between the top of the shoulders and the iliac crest, from the iliac crest to the heels with bungee cords, and then a stirrup goes onto the ball of the foot. It applies stress on the gastrocnemius, which seems to be effective in preventing muscle atrophy (Yegorov, 1981). Rather than 16 hours in the penguin suit, 3 hours/day may be sufficient to achieve the same results.

### 3. Fluids and Electrolytes

Many of the changes seen in space may be adaptive and physiological; attempting to alter them may be counterproductive (Leach and Rambaut, 1977). For example, there might be no need for intervention when body fluids change at the beginning of a mission. However, toward the end of the mission, as has been done in some U.S. and Soviet flights, fluids might be prescribed with sufficient salt to ensure retention in preparation for return to 1G as an aid to restoring orthostatic competence. Except for partial repletion of water and salt shortly before reentry, means of intervention at this stage of a mission have not been identified. However, on every mission, pre- and postflight blood samples are drawn permitting numerous laboratory assays. To determine other possible means of intervention, it could be useful to obtain blood inflight and perform at least some of the same procedures.

During EVAs, electrolyte loss is highest during the first few minutes of sweating, but decreases substantially thereafter (Lutwak et al., 1969). Because of the water loss alone, an astronaut's weight can change as many as five times per day. As a result of the losses incurred during space flight, it is now required, as noted above, that 1 hour prior to reentry a partial fluid load of 32 ounces of water and extra salt be taken.

Significant inflight arrhythmias occurred during the Apollo 15 mission. The rhythm disturbances were believed to be caused by potassium deficits. Consequently, NASA prescribed supplemental dietary potassium, which appeared to alleviate the problems in subsequent flights (Hawkins and Zieglschmid,

1975). Though there is no RDA for potassium, or for sodium either, "safe and adequate" intake ranges are available. It is preferable anyway that a desirable range of specific nutrients should be indicated rather than a mean because of the variability among astronauts.

In a mission that involves a number of years, it may be necessary to allow adaptation to take place and then perhaps weeks or months prior to landing initiate measures to prepare the astronauts for the gravitational fields that will be experienced at either end of an Earth/Mars mission. However, to determine whether such an approach is feasible, more baseline data will be necessary.

#### 4. Glucose Metabolism

During Gemini, Apollo, and Skylab missions, there was a deterioration of glucose tolerance after 4-5 days inflight (Leach and Rambaut, 1977). On Apollo, postflight serum glucose increased 9.8% over preflight measurements, and on Skylab it was 4.2%, but during the first four Shuttle missions the increase was 24.3%. Individuals varied so much that differences were lost when only a mean value was given; therefore, in the future, data should be given for each individual rather than as a mean and range for the group. Each individual can serve as his/her own control.

#### 5. Brain Neurotransmitters

The metabolic changes that occur in space as a result of a lack of gravity may modify the effects of nutrient intake on circulating substrate levels, thereby modifying the availability of nutrients to the brain. It is conceivable that nutrient supplements might be used pharmacologically to produce changes in neuronal output as compensation for undesirable events occurring in space (Fernstrom, 1981).

Brain serotonin is increased when meals high in carbohydrates are ingested. As a result, individuals are less effective and responsive to their environments, and pain sensitivity is decreased. The brain makes 30-50 different neurotransmitters but at least six or more exhibit the property of having their synthesis rates coupled to the availability of a particular nutrient-precursor. Therefore, the rate at which the serotonin neuron makes and releases serotonin is dependent on the availability of tryptophan. The rate at which the dopamine and norepinephrine neuron and the adrenal medulla make epinephrine is dependent on the availability of tyrosine; acetylcholine is dependent on choline. Thus, nutrient availability becomes important, not only in preventing malnutrition,

but also in effecting the production and release of neurotransmitters (Wurtman and Wurtman, 1985). There may be a need for supplemental nutrients that are neurotransmitter precursors.

During space flight, a particular nutrient required by nerve cells to make their neurotransmitters, such as tyrosine required by sympathetic nerve endings, may be limited. For example, astronauts returning to Earth have experienced difficulty maintaining blood pressure, particularly when standing, which has been ascribed to cardiovascular deconditioning. However, it may or may not be related to a depletion of sympathetic neuronal epinephrine associated with adaptation to hypovolemia. Perhaps, giving the astronauts tyrosine before they land might alleviate the situation; obtaining relevant experimental data seems worthwhile. When neurons, such as those of the sympathetic nervous system or the locus coeruleus of the brain, release catecholamines, they use up more tyrosine than can be provided by the blood, unless tyrosine levels are increased.

Because choline is limiting in acetylcholine production and motor neurons function by releasing acetylcholine, lower than normal levels of choline could possibly interfere with neuromuscular transmission, as in a marathon where there is a 60% reduction in plasma choline levels among participants. Therefore, when space flight problems occur that may involve norepinephrine, L-dopamine, acetylcholine, or serotonin, it is not unreasonable to think of providing particular neurotransmitter precursors as a possible countermeasure.

## 6. Circadian Rhythms

Circadian rhythms have important effects on metabolism, physiology, and performance. They influence many important functions such as plasma concentrations of nutrients and hormones, sleepiness/wakefulness, and body temperature. When zeitgebers such as the light/darkness cycle are altered, individuals show much variability in their circadian adaptation. These factors could have major effects on metabolism and performance in space.

Astronauts are urged to eat at regular times to avoid perturbation of circadian rhythms. During space flights, the craft is darkened for 8 hours and, insofar as possible, the time schedule is maintained to conform with the one on Earth. Circadian rhythm changes can be noted by strapping a thermister around the wrists of crew members for 2 days and recording body temperatures, or by collecting samples of saliva and measuring melatonin levels. Melatonin is not only a very stable indicator of circadian rhythms, but is also responsive to environmental perturbations (Lewy, 1983).

The U.S. Army conducted an experiment with two full regiments of soldiers being flown from the United States to Germany (Knapp, 1970). One regiment was flown in conventional tourist fashion with a meal and movie on the plane; these men experienced the typical 3-4 day period during which circadian rhythms were altered. The other regiment was ordered to sleep as soon as the plane was boarded, the lights were turned off, and the time was moved purposely by 6 hours; reportedly these men experienced no problems and performed without disruption of their circadian rhythms. It is possible, therefore, that manipulation of circadian rhythms by altering light-dark and food schedules could have some behavioral consequences.

## V. RESEARCH SUGGESTIONS

Nutrition and metabolism should be considered over a broad spectrum in terms of extended periods in space. They should be considered in relation to mission duration requirements, that is, 90-day missions in the mid-1990s extending to missions of several years' duration at the turn of the century. Methodology, associated with nutritional and metabolic requirements, should be tested on Shuttle missions to provide protocols for the Space Station. Operational data should be obtained on each current mission for possible extrapolation to flights of extended duration.

Pre- and postflight data, as well as inflight data concerning nutrition and human metabolism under conditions faced in space, have been difficult to obtain in the past, and obtaining such data from crews who have been in space for 3 months will be even more difficult without careful advanced planning. Therefore, the earlier that study requirements can be established for eliciting the needed information, the better.

Though not a research suggestion, the point has been made that most NASA documents are internal reports that have not been peer reviewed, and are difficult for non-NASA scientists to obtain. It would be useful to have as many NASA reports as possible published in the open literature, where they could be indexed by the secondary services and easily accessible to those scientists interested in the work and findings of NASA.

### A. METABOLIC NEEDS

- Examine the field-feeding data-collection study techniques of the Defense Departments of the United States and United Kingdom to identify the most efficient study techniques and approaches, and to avoid repetition of research and development.
- Obtain data on each individual, as well as group averages, in the future. A more accurate picture can be obtained by focusing on individual data. Means can be published, but the analyses should be oriented toward individuals because of suspected substantial inter-individual variation in daily energy expenditure related to sex, body size, and composition, as well as exercise/task demands.
- Conduct a validating study on energy needs of astronauts and determine possible differences in metabolic efficiency in space and on the ground. The amounts and proportions of dietary fat, protein, and carbohydrate must be quantified to permit correlation with energy expenditure.

- Consider determining CO<sub>2</sub> production with  $2\text{H}_2^{18}\text{O}$  as a measurement of energy expenditure. Alternative methods, such as respiratory minute volume, should also be evaluated. The latest, simple techniques for direct measurement by the astronauts of subcutaneous fat should be considered as well; for example, simple ultrasound techniques and serial skin-fold caliper measurements weekly, keeping in mind the possible distortion resulting from fluid shifts.
- Develop appropriate methods for determining body composition inflight to complement those now used and to permit comparison of measurements at various time intervals. One such method uses  $2\text{H}_2^{18}\text{O}$  to provide information on energy (CO<sub>2</sub> elimination) and water turnover; components of body composition can be calculated from total body water. Also, simple anthropometric procedures, such as lengths, girths, and skinfolds, should be employed, and the experimental use of total body impedance should be explored. Utilize a body-mass measuring device on a regular basis on the Space Station.
- Conduct neutron-activation studies of several elements, such as calcium, potassium, and nitrogen for body composition data. Transient activation is achieved with little radiation and may detect changes pre- and post-flight; perhaps such activation could be determined in long-duration flights. Neutron-activation measurements are of importance in complementing any balance studies that are conducted, or possibly they may be used in place of balance studies. In vivo studies of calcium and potassium have been shown to be valid estimates of body composition.
- Calculate the caloric requirement for exercise as a portion of the total energy expenditure.
- Tabulate and categorize the tasks to be performed as Space Station EVAs and their probable durations, the duties inside the craft, the exercise schedules, and the possible mix of functions so that work-related energy expenditure can be estimated. If such task analyses are available, nutrient needs can be predicted more accurately, and experiments can be planned to provide the data required.
- Quantitate energy expenditure with respect to EVAs, exercise regimens, and other activities for a determination or estimation of the calories required in different situations, as well as the changing energy needs as tasks are identified during progress of the missions. Without such information, it is difficult to know how much energy expenditure will occur and what provision for food needs to be made.

## B. NUTRIENT REQUIREMENTS

- Calculate nutrient and energy requirements on the basis of kilocalories per kilogram of body weight or lean body mass, or per square meter of body surface area, as well as kilocalories per day; give ranges and standard deviations, as well as means, because it is likely that inter-individual variability in nutritional needs will be relatively large.
- Collect computer-generated data on actual food consumption and nutrient intake by individual crew members on the future Shuttle flights if the hardware for doing so can be developed. Data on individual food intakes should include what is eaten at what time of day and the day of the flight. Once an appropriate data-collection system is selected, individual quantification of meal and snack consumption would be valuable. From such Shuttle food-consumption records, as well as body weight and composition changes, design criteria and test protocols could be generated and applied to a food system for the 90-day duration Space Station.
- Estimate the metabolic effects of a constant standard diet in long-term flights by reviewing what has been learned in long-term metabolic studies, including those dealing with long-term enteral and parenteral nutrition of patients.
- Establish an optimal mix of protein, fat, and carbohydrate, bearing in mind that an increased energy turnover may require more than 3000 kcal/day for some crew members.
- Determine the nutritional quality of the diet and the effect thereon of interactions among nutrients. It is essential to know not only the minimal daily calories needed for long missions, but requirements for adequate protein, amino acids, minerals, vitamins, and other essential single nutrients.
- Develop adjusted Recommended Dietary Allowances (RDAs) for space flight. The RDAs may be inadequate for determining a Space Station diet, but they provide a reasonable starting point as long as the nutrients for which RDAs do not exist are considered also; for example, essential fatty acids, and some of the trace elements, as well as dietary fiber. Whether or not the RDAs should be changed when the unique stresses of space flight are added should be evaluated for specific nutrients. The criteria for meeting the RDAs should be based on a weekly, rather than on a daily, assessment.

- Develop ranges for space flight dietary standards for all known or potential essential nutrients. These standards should include allowances for job performance and regular exercise. RDAs might serve as the basis for initial planning for future meals. These ranges can be modified based on experimental data from early missions.
- Explore the efficacy of a nutrient energy supply that could be accommodated in the space suit.
- Determine the necessity for multivitamin/mineral supplements, and determine whether their use should be made mandatory rather than discretionary. Also, consider the use of individual supplements (as in Skylab) to compensate for inadequate consumption of prescribed meals.
- Quantify the safe range of exogenous vitamin D intake for long-term space flight, and determine the dependence of vitamin D precursor activation on natural or ultra-violet light. The relation of the light spectrum to riboflavin, vitamin K, and biotin should also be examined. Based on good data, light spectra and intensities under which space flyers will be living should be chosen to simulate natural sunlight. These considerations may be important for prevention of bone mineral loss during space flight.
- Collect basic data on nutritional and metabolic variables that can be measured in serum or plasma preflight and immediately (1-2 hours) before and after landing.
- Consider the dietary accumulation of heavy metals, nucleic acids, and other undesirable toxic elements and compounds on long-term flights.

#### C. FOOD SYSTEM

- Review military studies on the nutritional quality of rehydrated food, and on the vitamin content of food stored for long periods under conditions likely to be utilized for storage in spacecraft.
- Determine food acceptability, palatability, and stability for the Space Station by such means as a review of military studies and consumption of foods for extended periods before flights by crew members. Consider changes in food taste and alteration in taste acuity, as well as perception of a persistent, unpleasant taste in the mouth, and gustatory and olfactory fatigue. Browning reaction may be an additional consideration.

- Obtain better data on feeding behavior by incorporating nutritional surveillance into the remaining Shuttle flights to determine if the quantities of nutrients consumed in the supplied dietary items are adequate for use in the Space Station missions.
- Improve food records by developing a computerized, noninvasive hardware and tracking system to determine food item consumption at various times of day by individual astronauts. Such food coding, perhaps using optical scanning techniques, would provide a detailed record of what is eaten and not eaten.
- Develop noninvasive collection and measurement procedures for analysis of trace compounds in saliva and respiratory gases.
- Evaluate whether production of flatus by crucifers and legumes, foods which are major sources of dietary fiber, is sufficiently deleterious to eliminate them from space diets.
- Deal with the microbiological hazards of space flight as they relate to potential contamination of food, water, and associated equipment.
- Address the engineering concerns related to contamination of food and water by the water injector. Improved water-injector hygiene is needed because a pure uncontaminated drinking water supply is essential. Food should be eaten immediately after preparation, and food waste should be microbiologically stabilized or sterilized. Also, the problem of microbially contaminated air filters and interior surfaces should be resolved. Any infectious illnesses suffered during a flight will markedly alter nutrient requirements and metabolic expenditures.

#### D. COUNTERMEASURES TO SPACE DECONDITIONING

- Obtain basic data on bone demineralization and skeletal muscle atrophy for the purpose of determining effective nutritional intervention. Explore the relationship between calcium intake and bone demineralization and remineralization in all future space missions. Mechanistic explanations are needed for bone demineralization and muscle protein catabolism.
- Conduct bone density studies using tomographic or absorptiometric techniques on astronauts who participate in multiple flights for the purpose of ascertaining possible cumulative patterns of bone demineralization.

- Supply approximately 1200-1500 mg calcium, preferably in food to ensure ingestion or as a supplement, as a countermeasure to bone demineralization. Limit phosphorus which reduces effective calcium utilization. If diphosphonates can be shown to be safe and effective, they should be tried also for the purpose of minimizing bone demineralization. Astronaut candidates should be prescreened to eliminate those with persistent hypercalciuria and an increased propensity for renal stone formation.
- Conduct studies on bone physiology related to the effectiveness of preflight loading with either diet supplements or drugs, and their utilization inflight; also consider use of the Soviet penguin suit as an aid to prevention of deconditioning with respect to both bone and skeletal muscle preservation.
- Collect pre- and postflight data on bone demineralization and body composition, as well as data on food and supplement consumption inflight. Attempt to determine if space flights cause unanticipated alterations in the metabolism of vitamins and trace nutrients.
- Determine the conditions under which persons with low body fat content lose lean body mass more rapidly than normal-weight or obese subjects. Determine the effects of insufficient calories, insufficient exercise, or weightlessness. Determine if nitrogen loss can be reduced by increasing the daily caloric intakes, or by adding high-quality protein.
- Estimate water balance because dehydration is a concern when EVAs are performed and dry 100% oxygen is breathed for as long as 6 hours. Since ad lib water may not be adequate, determine how much water from what other sources, including water in food, should be provided in the space suit. Evidence from previous ground-based studies indicates that normal thirst mechanisms may fail inflight.
- Determine the behavioral and performance responses of individuals to particular food constituents (carbohydrate vs. protein), so that those in flight can be told not to eat the "wrong" foods at certain times; for example, foods that make them sleepy when they have to do careful work. Determine whether performance can be improved specifically by supplemental tyrosine and/or other nutrients. Determine whether the stress of space flight causes changes in plasma nutrient levels, and/or in actual requirements for particular nutrients.

- Consider obtaining individual data by noninvasive means concerning circadian rhythms that can easily be measured. Study these data to determine if circadian changes are altered by space flight stress, by the duties of individual astronauts, or by light/darkness cycles under use. Determine if stable rhythms reemerge on long flights. Consider if any possible changes are likely to produce nutritional or performance effects and if more detailed investigations are needed.



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