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Assessment of Zero Gravity Effects on Space Worker Health and Safety

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November 1980

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U.S. Department of Energy

Office of Energy Research

Solar Power Satellite Project Division

Under Inter-Agency Agreement AI02-79CH10025

DOE/NASA

Satellite Power System

Concept Development

and

Evaluation Program

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NASA Johnson Space Center
Houston, Texas 77058
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U.S. Department of Energy
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Washington, D.C. 20585

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I. INTRODUCTION

This report has been prepared in response to a letter request from Margaret R. White of the Lawrence Berkeley Laboratory dated March 5, 1979 and an inter-agency agreement DOE IA #DE-A102-79CH10025 between the National Aeronautics and Space Administration (NASA) - Lyndon B. Johnson Space Center (JSC) and the U.S. Department of Energy (DOE). The report presents the results of a study performed by personnel within the NASA - JSC Life Sciences organization in conjunction with elements of The Boeing Company. In preparing this report, an effort has been made to respond to the letter and intent of the Statement of Work (SOW) included in the interagency agreement.

A. OBJECTIVES

One objective of the study is to assess the effects of all currently known deviations from normal of medical, physiological and biochemical parameters which appear to be due to zero gravity (zero-g) environment¹ and to acceleration and deceleration to be experienced, as outlined in the reference SPS design, by space workers. Study results are based on current knowledge and the current SPS Reference System Report, DOE/ER-0023, October 1978. These results include:

- a. Identification of possible health or safety effects on space workers - either immediate or delayed - due to the zero gravity environment and to acceleration and deceleration,
- b. Estimation of the probability that an individual will be adversely affected.

¹Although the SOW specified that only "the zero gravity environment and accelerations will be considered", NASA has taken the liberty of including potentially adverse effects/affects caused by other stresses of working in the space environment. This was done to provide relevant information which might otherwise have been excluded from consideration.

- c. Description of the possible consequence to work efficiently in persons adversely affected, and
- d. Description of the possible/probable consequences to immediate and future health of individuals exposed to this environment.

Another objective of this study is to prepare a research plan which addresses the uncertainties in current knowledge regarding the health and safety hazards to exposed SPS space workers. The plan is presented in section VI, Research Planning. It identifies current on-going research, proposed research to support a Space Operations Center (SOC) program, and research that will be recommended specifically to support an SPS program.

B. BACKGROUND

NASA has drawn heavily on the biomedical results from the Apollo and Skylab missions, and the Apollo-Soyuz Test Project (ASTP). Current knowledge of the effects of weightlessness and acceleration/deceleration is updated. Where appropriate, we have used the biomedical results of all prior manned missions flown by the United States as well as the groundbased experimentation done in conjunction with these flight programs. Information from Soviet Union space studies has been used where possible but is limited by credible sources of documentation containing sufficient supporting data.

Significant information used as a base is summarized in section IV and is included in matrix form in section III.

It is recognized that the sources of current knowledge are from prior programs that subjected crewmembers to situations and conditions not fully representative of the situations and conditions that future SPS space workers might encounter. To formulate their predictions of hazards, NASA and Boeing personnel assigned to this study have made a determined effort to identify and define the nature and magnitude of these differences. Factors involved in comparing past and future missions are shown in figure I-1. Some of the major differences in program requirements relating to the SPS space workers vs. the astronaut crews are shown in figure I-2.

CREW (SPACE WORKERS)

- o TYPE OF PERSONNEL
- o PREPARATION AND TRAINING
- o PRE-, IN-, POSTFLIGHT ACTIVITIES
- o REGIMENTATION AND DISCIPLINE
- o ETC.

MISSION FLIGHT PARAMETERS

- o ORBITS
- o ACCELERATIONS
- o SOLAR ACTIVITY PERIODS
- o ETC.

HABITAT

- o ENVIRONMENTS
- o SHIELDING
- o RECREATION AND REST
- o FOOD AND NUTRITION
- o PRIVACY
- o ETC.

CAREER*

- o TOTAL TIME IN SPACE
- o CUMULATIVE PSYCHOLOGICAL/
PHYSIOLOGICAL EFFECTS
- o JOB FATIGUE
- o SPACE TIME/GROUND TIME

*NOTES: DURING A 5-YEAR CAREER WITH A 90 DAY UP/90 DAY DOWN, A PERSON MAY SUFFER FROM SPACE ENVIRONMENT EFFECTS FOR 4 TO 5 MONTHS OUT OF EACH 6 MONTHS, RESULTING IN A CAREER SITUATION OF BEING IN A DEVIATE PHYSICAL CONDITION FOR 3 1/2 TO 4 YEARS TO THE 5 YEAR TOTAL.

AFTER THE 84 DAY SKYLAB MISSION, TWO CREWMEN HAD NOT REGAINED HEEL BONE CALCIUM BY DAY 95 POSTFLIGHT.

FIGURE I-1 Factors involved in comparing past and future missions.

1. THE TYPE OF PERSONNEL SELECTED:

- | <u>SPACE WORKERS</u> | | | <u>SKYLAB ASTRONAUTS</u> | |
|----------------------|---------------------------------|-----|--------------------------|-----------------------------------|
| o | MALE-FEMALE | VS. | o | ALL MALE |
| o | BROAD AGE RANGE | VS. | o | LIMITED RANGE |
| o | PHYSICALLY BASICALLY UNSCREENED | VS. | o | PHYSICALLY SCREENED AND DEVELOPED |
| o | LARGE CREWS | VS. | o | 3-MAN CREW |

2. THE EXTENT AND TYPE OF CREW PREPARATION FOR SPACE DUTIES:

- | <u>SPACE WORKERS</u> | | | <u>SKYLAB ASTRONAUTS</u> | |
|----------------------|---|--|--------------------------|---|
| o | SHORTER PREPARATION TIME AND TRAINING, LIMITED PRIMARILY TO JOB RELATED ACTIVITY, WITH MINIMUM SPACECRAFT PHYSICS & SYSTEMS, HABITABILITY, ETC. | | o | SEVERAL YEARS OF BROADBASED EDUCATION AND TRAINING IN ALL ASPECTS OF MISSION ACTIVITIES WITH EXTENSIVE EDUCATION IN FUNDAMENTALS OF ALL SCIENCES INVOLVED IN PROGRAM. |

3. THE NATURE OF THE MISSION ACTIVITY ASSIGNMENTS AND THE FREQUENCY AND DURATION OF FLIGHT TIME/GROUND TIME:

- | <u>SPACE WORKERS</u> | | | <u>SKYLAB ASTRONAUTS</u> | |
|----------------------|--|--|--------------------------|---|
| o | VARIETY OF SPECIALIZED SKILLS (WITH MINIMUM PROFESSIONAL ENGINEERING AND SCIENTIFIC SKILLS). | | o | EACH CREW MEMBER CAPABLE OF ALL SCIENTIFIC, TECHNICAL AND MANAGEMENT REQUIREMENTS. |
| o | WORK AT PEAK EFFICIENCY FOR MAXIMUM SAFE PERIOD DURING MISSION. RETURN TO SPACE IN SHORTEST SAFE AND PRACTICAL TIME. | | o | WORK AT HIGHLY MOTIVATING JOBS AT CAREFULLY SCHEDULED TIME LINES BASED ON METABOLIC AND EXPERIMENT REQUIREMENTS. MISSION DURATION BASED ON CREWS' CONDITION (CAREFULLY MONITORED). RETURN TO SPACE NOT A PRESSING ITEM. |

Figure 1-2 Major differences in program requirements relating to the space workers vs. astronaut crews.

C. APPROACH

The approach used by NASA in performing this study was to assign qualified and experienced scientists in various life sciences disciplines to identify and define the possible environmental effects on SPS space workers. The NASA participants worked closely with an aerospace contractor (The Boeing Company) who was responsible for coordination, compilation, collation and documentation of the information provided. NASA and Boeing participants drew extensively from documented research experiences and available expertise of prior manned space flight programs.

Sources of information includes:

- o Documented biomedical results from Skylab and other manned space missions. (Limited Soviet data were included from credible sources containing sufficient supporting data).
- o Documented results form ground-based biomedical research.
- o Documented results from ground-based tested and verified design and operational approaches.
- o Documented information from other programs involving isolated crew habitation and confined quarters, i.e., Arctic and Antarctic activities, off-shore oil operations, undersea programs (Tektite), submarine duty, etc.
- o Direct contact with designated NASA or contractor expert consultants.
- o Feedback from review meetings and comments on submitted reports.

The data base from these sources is comprehensive and includes:

- o Results from three major manned space flight programs of the United States. They are: seven Apollo flights, three Skylab missions and the Apollo-Soyuz project.

- o Results from extensive ground-based and flight research in all human body systems. (The subjects were predominantly male.)
- o Experiences gained from development of systems designed to support space flight. These systems are for health care, life support and protection, and environment and biological monitoring.
- o Results from extensive ground-based development and demonstration testing.

II. GENERAL SUMMARY AND CONCLUSIONS

Answers sought for the following critical questions, before commitment to build and operate an SPS are: How long can humans live safely and work efficiently in space? What is the maximum duration of an effective work schedule? What are the total number and frequency of missions to plan as a career in either low earth orbit (LEO) or geosynchronous earth orbit GEO?

To answer these and other questions for the Apollo program, NASA investigated the capability of astronauts to cope safely with the stresses associated with performing a vast battery of flight related tasks. During the Mercury and Gemini missions, we learned that man could withstand launch and reentry stresses, could perform complex mental and physical tasks for periods of up to 14 days, and could readapt to Earth gravity without adversely altering normal body functions. During Apollo missions, knowledge and confidence in man's ability to safely and effectively perform complex tasks in the lunar and space environments and readily adapt to changing environments was further expanded. During Skylab, emphasis was directed to man's ability to live and work in space by performing medical-oriented research experiments and by monitoring the inflight operation of several major body systems. In addition, dedicated research medical equipment was tested extensively.

The inflight experiments, designed to contribute to understanding the functioning of major body systems, included the cardiovascular musculoskeletal, hematologic, vestibular, metabolic, neurologic and endocrine systems. It was shown that a few body systems were not affected, the majority showed adaptive changes, and there were indications of progressive changes (e.g., bone demineralization, muscular atrophy, plasma volume and red blood cell loss.) These changes contraindicated long-term exposure to zero-g forces unless corrected.

In Skylab, major emphasis was directed to evaluating on-board life support systems. These included food, waste management, personal hygiene and inflight medical support. This data base will be valuable in planning future long-duration missions.

Evaluation of the medical experiments and the operational medical systems of the 84-day manned Skylab III mission provided a high degree of confidence in man's ability to work and live safely in a space environment for periods which may exceed 120 days.

Although most adverse affects experienced during space flight soon disappeared upon return to the Earth's environment, there remains a definite concern for the long-term effects to SPS space workers who might spend as much as half their time in space during a possible five-year career period. The proposed 90-day up/90-day down cycle, coupled with the fact that most of the effects of weightlessness may persist throughout the flight along with the realization that recovery may occupy much of the terrestrial stay, may keep the SPS workers in a deviant physical condition or state of flux for 60 to 100 percent of their five-year career. Further studies in effects/affects of sequential adaptation from one-g to zero-g, and reverse, will be necessary before a five-year career period can be evaluated properly.

The NASA and Boeing scientists involved in this study have concluded that there is substantial evidence to indicate that only preventable and corrective adverse effects will be experienced by SPS space workers. They further believe that, although additional potentially adverse effects may be identified prior to the early SPS missions, counteracting or ameliorating approaches can be developed contemporaneously to avoid any adverse effects to their health and safety.

This position should not be construed as having insufficient concern for the safety and health of the SPS space workers. It is based on the postulation that NASA/DOE will conduct adequate research and development to recognize potential threats and provide countermeasures to protect the workers. It further presumes that workers will be selected, trained, and motivated to make proper use of equipment, and approaches will be designed to make their careers in space healthy and safe.

The study did not include the effects of radiation.

There are several aspects of this study that deserve consideration if the conclusions presented are to be maintained in a proper perspective.

1. Conclusions based on "current knowledge" are derived from prior manned space flights where the type and condition of the crew and the mission conditions exposing the crew to adverse effects of the space environment are in many respects different from those anticipated for future SPS space workers.
2. The final definition of the role that man will play in space and the details of his living and working conditions will evolve during the next 15 to 20 years. We will gain additional experience through development and operations for precursor space projects detailed in the Space Transportation System (STS) and the SOC programs.
3. The NASA Life Sciences and Crew Systems organizations will gain an abundance of test data relating to the physiological and psychological stresses to be experienced by the SPS crews and their families. They are confident that the means to ameliorate or prevent any adverse effects due to these stresses will be developed. The information can be made available to the DOE at appropriated intervals during the developmental phases of the SPS program.
4. Although certain biomedical problems are known to exist in today's manned missions and complications are expected to occur when large numbers of people begin to make a career of working in space, our scientist and technical experts believe that these problems will be resolved and that humans will be able to live and work effectively in space without unusual degradation to their health, safety, and general well being.

III. INVENTORY OF HUMAN RESPONSES TO SPACE FLIGHT

This section presents a summary of known deviations from normal of human body systems in response to the space flight environments. It also includes methods of amelioration and a prognosis of impact on SPS space workers.

An encapsulated Inventory of Human Responses to Space Flight in matrix form, which follows, was derived from the American biomedical research programs in space. The major body systems/research entities in the order in which they appear are listed below. Detailed discussion of each entity starts on page 46.

- A. Musculoskeletal System
- B. Cardiovascular System, including B.1. Hemodynamics, B.2. Hematology, and B.3. Immunology
- C. Nervous System
- D. Neurophysiology, including D.1. Vestibular, D.2. Special Sense Organs, and D.3. Other Sensors
- E. Excretory System
- F. Digestive System
- G. Respiratory System
- H. Reproductive System
- I. Biochemistry
- J. Endocrine System
- K. Energy Metabolism
- L. Fluid Shifts
- M. Integumentary System
- N. Food and Nutrition
- O. Electrolyte Balance

INVENTORY OF HUMAN RESPONSES TO SPACE FLIGHT

SYSTEM/ COMPONENT	MEASUREMENT	GENERAL OBJECTIVE	PERTINENCE	RESULT	ONSET	DURATION	RECOVERY	DATA	REFERENCE	AMELIORATION	PROGNOSIS
A. MUSCULO-SKELETAL SYSTEM											
1. Skeleton	Heel bone demineralization pre, post-flight	Skeletal integrity	Measures local mineral loss and probably indicates loss of bone matrix	Loss of bone mineral	Not determined	Progressive	<84 days to >97 days post-flight	Skylab	Vogel 3	Exercise, artificial gravity, nutrition, parathormone, vitamin D, drugs, skeletal loading	Recovery time is protracted and uncertain. Since mineral loss continued unabated, this effect can limit space exposure.
	Urinary calcium excretion, pre, in, postflight	Skeletal integrity,	Measures mineral loss from all sources	Loss of bone mineral	Very early.	Constant loss	Uncertain	Skylab	Whedon 2	Exercise, artificial gravity, nutrition, parathormone, vitamin D, drugs, skeletal loading	Clear limit to space exposure without better countermeasures.
	Urinary hydroxyproline excretion, pre, in, postflight	Skeletal integrity	Measures skeletal degradation; probably chiefly from bone matrix but also from other connective tissue, esp. skin	Increased 33%	Very early	Not given	Not given	Skylab	Whedon 2	As above for skeleton	Same prognosis as other skeletal integrity measures
	Crew height, pre, in, postflight	Crew equipment fit	Direct measurement of height change	Up to 2.6 inch "growth" between day 6 and 9	N/A	N/A	Unknown	ASTP	Brown 28	N/A	Favorable; not a serious problem.
	Crew height, pre, in, postflight	Crew equipment fit	Direct measurement of height change	Up to 2.0 inch "growth" by 21st day	N/A	Throughout mission	By 3 days postflight	Skylab	Thornton 41	N/A	Favorable; not a serious problem.

¹ See listing of references beginning on p. 200

INVENTORY OF HUMAN RESPONSES TO SPACE FLIGHT

SYSTEM/ COMPONENT	MEASUREMENT	GENERAL OBJECTIVE	PERTINENCE	RESULT	ONSET	DURATION	RECOVERY	DATA	REFERENCE	AMELIORATION	PROGNOSIS
A. MUSCULO-SKELETAL SYSTEM											
2. Muscula- ture	Limb girth, pre, in, post flight	Holistic, organismic	Measures fluid shift & muscle atrophy together	Reduced leg girth	3 days	Through- out flight	<1 day postflight	Skylab	Thorn- ton 1	Exercise, especial- ly of anti-gravity muscles; artificial gravity, nutrition	Since force capa- bility of selected muscle groups was only slightly af- fected in parallel tests, prognosis is favorable.
	Urinary and fecal nitro- gen excretion, pre, in, post flight	Muscular atrophy	Measures muscular atrophy	Nitrogen loss	Very early	Through- out flight	Very early postflight	Skylab	Whedon 2	Exercise, artifi- cial gravity, nutrition	Guarded prognosis; safety for 6-9 months suggested.
	Exercise capability postflight	See "Energy	metabolism" below								
	Exercise capability inflight	See "Energy	metabolism" below								
	Force capability pre & post flight	Muscular atrophy	Measures decre- mental perform- ance	Slight decrease	Not de- termined	N/A	Not deter- mined	Skylab	Thorn- ton 1	Exercise, particu- larly of the muscles to be measured; nutri- tion	Favorable
	EMG analysis of skeletal muscle, pre and postflight	Neuro- muscular function	Measures excita- bility, fatiga- bility, electri- cal efficiency, and tension capability	Tension capability reduced. Super- excita- bility, increased fatiga- bility	N/A	N/A	Gracual	Skylab	LaFavers 21	None	Favorable. Other measurements show near-normal responses

INVENTORY OF HUMAN RESPONSES TO SPACE FLIGHT

SYSTEM/ COMPONENT	MEASUREMENT	GENERAL OBJECTIVE	PERTINENCE	RESULT	ONSET	DURATION	RECOVERY	DATA	REFERENCE	AMELIORATION	PROGNOSIS
A. MUSCULO-SKELETAL SYSTEM											
2. Musculature	EMG analysis of skeletal muscle, pre and postflight	Neuro muscular function	Measures excitability, fatigability, electrical efficiency, and tension capability	Increased excitability, decreased electrical efficiency of leg muscles. Increased electrical efficiency of arm muscles. Increased leg muscle fatigability.	N/A	N/A	Unknown	ASTP	LaFevers 22	None	Probably favorable. Other measurements show near-normal responses. Astronauts exposed to toxic gases during recovery.
	Stereometric analysis, pre and post flight	Muscular atrophy	Measures volume change	Loss of volume, 1.3 liters from legs; 300 ml ascribed to atrophy, the remainder to fluid shift.	N/A	Through-out flight	1/3 in one day, 2/3 in 3 days, complete by 30 days	Skylab	Whittle 40	Exercise	Favorable. There is no operational impact and the once-thought-important atrophy component has been reduced by exercise to a very low value. This entry to be updated upon receipt of data from ameliorative studies.

INVENTORY OF HUMAN RESPONSES TO SPACE FLIGHT

SYSTEM/ COMPONENT	MEASUREMENT	GENERAL OBJECTIVE	PERTINENCE	RESULT	ONSET	DURATION	RECOVERY	DATA	REFERENCE	AMELIORATION	PROGNOSIS
3. CARDIOVASCULAR SYSTEM											
1. Hemodynamics											
Heart	Echocardiography, pre, postflight	Cardiac structure & function	Direct measurements of cardiac performance	Small physical changes including ventricular and diastolic volume reduction, ventricular mass reduction, and stroke volume reduction.	N/A	Throughout	<30 days postflight	Skylab	Herry 6	None required that are not presently utilized (exercise, K+ supplement) nor are they proven appropriate	Favorable. Cardiac function was unimpaired. Small physical changes observed were reversible and non-limiting
Heart	Vectorcardiography, pre, in, and post flight with LBNP stress	Cardiac function in weightlessness	Direct measurements of cardiac electrical phenomena	Few changes between resting preflight & resting postflight. Many changes in flight and post-flight when LBNP stress added	<4 days	Generally throughout, except extreme response to LBNP in space abates in 5-7 weeks	No data	Skylab	Hoffler 7	Not required; control of autonomic nervous system by drugs, prevention of fluid shifts, and control of blood volume might prevent these adaptive responses.	Favorable. Changes are within normal range and are reversible.

INVENTORY OF HUMAN RESPONSES TO SPACE FLIGHT

SYSTEM/ COMPONENT	MEASUREMENT	GENERAL OBJECTIVE	PERTINENCE	RESULT	ONSET	DURATION	RECOVERY	DATA	REFERENCE	AMELIORATION	PROGNOSIS
S. CARDIOVAS- CULAR SYSTEM											
Heart	Vectorcardio- graphy, pre-, in-, and post- flight with ergometer stress	Cardiac function in weight- lessness	Direct measure- ments of cardiac electrical phenomena	Small changes except that QRS vector magnitude tends to increase during flight & heart rate response to exer- cise tends to be lower than preflight	<4 days	Throughout except that QRS vector magnitude tends to increase during flight and heart rate response to exercise tends to be lower than pre- flight.	Apparently less than 2 months. Upright exercise immediate- ly post- flight was not well tolerated.	Skylab	Smith 9	Not required. Necessity of K+ and exercise suggested to main- tain normal elec- trocardiographic response.	Favorable. Except for arrhythmias, no adverse changes could be attributed to stresses of extended space flight.
Heart	Cardiovascular electromech- anical properties, pre, and postflight	Determine systolic time intervals, and first heart sound amplitude	Direct measure- ment of cardio- vascular para- meters	Changes both resting & stress conditions	N/A	N/A	<31 days postflight	Skylab	Bergman 10	Measures to in- crease blood volume cardiac filling, & ventricular con- tractility, if in- dicated, could forestall part of the degradation measured. Neuro- humoral factors are possible. They could be maximized or minimized.	Favorable. Re- adaptation complete in 31 days on basis of this study. Capability for heavy exercise is depressed somewhat longer, perhaps 2 months.
Heart	Cardiac area by X-ray pre, and postflight	Determine heart size changes caused by zero-g	Could show less cardiac mass or deficit in blood return	Reduced dimensions	N/A	N/A	Quite variable	Skylab	Nicogossian 11	None indicated	Favorable. Recovery trends in 4-5 days.

INVENTORY OF HUMAN RESPONSES TO SPACE FLIGHT

SYSTEM/ COMPONENT	MEASUREMENT	GENERAL OBJECTIVE	PERTINENCE	RESULT	ONSET	DURATION	RECOVERY	DATA	REFERENCE	AMELIORATION	PROGNOSIS
B. CARDIOVAS- CULAR SYSTEM											
Hemodynamics Vasculature	Compliance, pre, in, post flight	Vascular parameters	Somewhat contro- versal applica- tion to assess- ment of cardio- vascular adapta- bility	Increased compliance	Gradual over more than 10 days	Lessening throughout mission	Several days postflight	Skylab	Thornton 12	Perhaps exercise and tonus boosters (neurohumoral)	Although effect is maximal in time frame of Shuttle landing, prognosis is favorable in longer missions.
2. Hematology	Polymorpho- nuclear leucocyte response (phagocy- tosis) pre and post flight	Adequacy of phagocytic defense response	In vitro measure- ment of phago- cytic activity of leukocytes (migrate and phagocytize)	No signif- icant change in any step of the process	N/A	N/A	N/A	ASTP	Martin 9	N/A	Favorable. It is probable that zero-G exposure has no significant effect on phago- cytic capabilities. Data may have been compromised by in- advertent exposure of astronauts to toxic gases during recovery.
Hematology	Leucocyte counts pre and postflight	Adequacy of phagocytic defense response		Total count typically elevated	Unknown	Unknown	Quick re- covery (3 days or perhaps longer)	Skylab	Kimzey 14	None	Favorable. Firm evaluation of sig- nificance is not possible.
Hematology	Red cell shape changes, pre, in, post flight	Hematologi- cal re- sponse to weightless- ness	Direct measure of erythrocyte response of un- known etiology	Many dis- ordered cells peaking at 4 weeks	<3 days	Throughout	Not deter- mined. Im- provement was measured in flight. Abrupt change to normal up- on flight completion.	Skylab	Kimzey 14	None suggested.	Not grossly un- favorable. Cellular changes did not change in vitro performance or hamper human per- formance.
Hematology	Plasma volume pre, post- flight	Volume de- termination	Direct measure- ment	10% re- duction at recovery	N/A	N/A	About 2 weeks	Skylab	Johnson 13	Adaptation to zero- g results in pro- gressive loss of plasma volume, possibly counter- able by prodigious levels of exer- cise.	Not favorable. Pro- gressive loss of plasma volume causes handicap at recovery but not in flight, based on energy metabolism studies (Michel)

INVENTORY OF HUMAN RESPONSES TO SPACE FLIGHT

SYSTEM/ COMPONENT	MEASUREMENT	GENERAL OBJECTIVE	PERTINENCE	RESULT	ONSET	DURATION	RECOVERY	DATA	REFERENCE	AMELIORATION	PROGNOSIS
B. CARDIO- VASCULAR SYSTEM											
Hematology	Red cell mass, pre and post flight	Cell mass determination	Direct measurement of red cell mass	>11% reduction	N/A	N/A	30 to 60 days post flight	Skylab	Johnson 13	Amelioration not required physiologically. Erythropoietin release might be triggered if desired.	Favorable. Extrapolation of Skylab data to longer stays suggests preflight baseline recovery before 6 months in orbit.
Hematology	51 chromium red cell halftimes, pre and post flight	Measure of hematological parameters	Indirect measure of life span of erythrocytes	No change from baseline	N/A	N/A	N/A	Skylab	Johnson 13	None required	Favorable. No spaceflight decrement.
Hematology	14 carbon red cell life span, pre & postflight	Measure of hematological parameters	Direct measure of life span of erythrocytes	No change from baseline	N/A	N/A	N/A	Skylab	Johnson 13	None required	Favorable. No space flight decrement.
Hematology	Reticulocyte count, pre and postflight	Measure of hematological parameters	Direct measure of rate of regeneration of red cells	Depressed until post recovery	N/A	N/A	Recover in one week from 84-day mission & in 1 or 2 months from shorter missions	Skylab	Johnson 13	None required physiologically. Would be through erythropoietin release.	Favorable. No circulatory deficit; also correction in being during flight.
Hematology	Red cell mass pre and post flight	Cell mass determination	Direct measurement of red cell mass	Decreased 8%	N/A	N/A	< 28 days	ASTP	Kimzey 27	None	Favorable. Data may have been compromised by toxic gas inhalation during recovery.
Hematology	51 chromium half-times pre and post flight	Measure of hematological parameters	Indirect measurement of life span of erythrocytes	Decreased in one crewman	N/A	N/A	No data	ASTP	Kimzey 27	None	
Hematology	Plasma volume, pre and post flight	Volume determination	Direct measurement of plasma volume	Decreased 11%	N/A	N/A	<28 days	ASTP	Kimzey 27	None	

INVENTORY OF HUMAN RESPONSES TO SPACE FLIGHT

SYSTEM/ COMPONENT	MEASUREMENT	GENERAL OBJECTIVE	PERTINENCE	RESULT	ONSET	DURATION	RECOVERY	DATA	REFERENCE	AMELIORATION	PROGNOSIS
B. CARDIO- VASCULAR SYSTEM											
Hematology (Red Cell Metabolism)	Reduced glutathione pre, in, postflight	Red cell damage in flight	Measurement of metabolic factors in erythrocytes	Reduced in Skylab 3	Post flight only	2 weeks	2 weeks	Skylab	Mengel 15	None considered	Favorable. Response is reversed quickly.
	Adenosine triphosphate	"	"	Increased in Skylab 3	"	Unknown	2 weeks	"	"	"	Unknown. No threat recognized.
	Lipid peroxides	"	Measurement of damage to red cells	Absent	N/A	N/A	N/A	"	"	Not required.	Favorable.
	2,3 diphosphoglyceric acid	"	Measurement of metabolic factors in erythrocytes	Unchanged	N/A	N/A	N/A	"	"	"	Favorable
	Glucose 6 phosphate dehydrogenase	"	"	Reduced in Skylab 3 (1)	Post flight only	Unknown	2 weeks	"	"	None considered	Unknown. No threat recognized.
	Hexokinase	"	"	Increased in Skylab 2; decreased in Skylab 3	Inflight only	Unknown	Did not occur postflight	"	"	"	
	Phosphofructokinase	"	"	Reduced in Skylab 2,3,4 (2)	Post flight only in Skylab 2 Early in flight only in Skylab 4	Unknown	Unknown	"	"	"	
							Recovered in flight	Recovered in flight	"	"	"
	Glyceraldehyde phosphate dehydrogenase	"	"	Increased in Skylab 2; Decreased in Skylab 3	In flight only. 1 day		Did not occur postflight 1 day	"	"	"	

(1) Tabulated data shows postflight increase. Data summary shows decrease.

(2) Tabulated data shows post-flight reduction in Skylab 2 and an early inflight reduction in Skylab 4. Data summary adds a decrease in Skylab 3.

INVENTORY OF HUMAN RESPONSES TO SPACE FLIGHT

SYSTEM/ COMPONENT	MEASUREMENT	GENERAL OBJECTIVE	PERTINENCE	RESULT	ONSET	DURATION	RECOVERY	DATA	REFERENCE	AMELIORATION	PROGNOSIS	
B. CARDIO- VASCULAR SYSTEM	Hematology (Red Cell Metabolism)	Phospho- glyceric kinase	Red cell damage in flight	Measurement of metabolic fac- tors in erythro- cytes	Reduced in Skylab 3	Reduced inflight & splash down; elevated post- flight	Unknown	2 weeks	Skylab	Mengel 15	None considered.	Unknown. No threat recognized.
		Acetylcholine esterase	"	"	Unchanged (3)	Reduced in flt in Sky- lab 3 (3)	Unknown	Did not occur postflight	"	"	"	"
		Methemoglobin	"	"	Values to 28% in flight	Preflt through recovery	2 weeks	2 weeks	"	"	"	" (4)
		Adenosine triphospha- tase	"	"	Skylab 4 preflight data only	N/A	N/A	N/A	"	"	N/A	Data omitted
		Pyruvate kinase	"	"	Increased in Skylab 3	Inflt. only. Inflt. & post recovery	2 weeks	Elevated also in Skylab 4 post recovery	"	"	None considered.	Unknown. No threat recognized.
(3) Tabulated data shows in flight reduction; summary shows none. (4) These values are too high for long-term acceptance. Probable change in storage.												

INVENTORY OF HUMAN RESPONSES TO SPACE FLIGHT

SYSTEM/ COMPONENT	MEASUREMENT	GENERAL OBJECTIVE	PERTINENCE	RESLTT	ONSET	DURATION	RECOVERY	DATA	REFERENCE	AMELIORATION	PROGNOSIS
B. CARDIO- VASCULAR SYSTEM											
3. Immunology (Humoral Immunity)	<p>Serum proteins, pre- and post-flight</p> <p>Total protein, albumin A1, A2, B and C, Globulin, Transaminase Haptoglobin Ceruloplasmin A2 Macroglobulin A1 Glycoprotein A1 Anti-trypsin Complement Factor 3 IgG, IgA, IgM, IgD Immunoglobulins</p> <p>Immune factors, pre- and post-flight</p>	<p>Homeostasis and humoral immune factors</p> <p>Humoral immunity</p>	<p>Direct measurement of proteins and protein fractions, especially ones important in immunity.</p> <p>Measures presence of immune factors</p>	<p>One low albumin test out of 23 tests; LPH elevated on recovery; Haptoglobin elevated 3-4 days after recovery; low IgG in one crewman, days 1 & 2 after recovery; C-reactive protein positive 1 day after recovery</p> <p>No change in capacity to respond</p>	<p>N/A</p> <p>N/A</p>	<p>N/A</p> <p>N/A</p>	<p>N/A</p> <p>N/A</p>	<p>ASTP</p> <p>Skylab</p>	<p>Kimzey 27</p> <p>Kimzey 14</p>	<p>None</p> <p>Nutrition</p>	<p>Favorable (Test may have been compromised by toxic gas exposure)</p> <p>Favorable. Humoral immune system retains its capability.</p>

INVENTORY OF HUMAN RESPONSES TO SPACE FLIGHT

SYSTEM/ COMPONENT	MEASUREMENT	GENERAL OBJECTIVE	PERTINENCE	RESULT	ONSET	DURATION	RECOVERY	DATA	REFERENCE	AMELIORATION	PROGNOSIS
B. CARDIO- VASCULAR SYSTEM											
3. Immunology (Cellular Immunity)	Cellular im- mune system pre- and post- flight	Adequacy of immune response	In vitro test	Decrease in ability to react to foreign substances	N/A	N/A	By 8 days post re- covery	ASTP	Criswell 37	None	Questionable. Also no disease process appeared. Test may have been compromised by toxic gas exposure and cortisol therapy.
	Immune re- sponses, (in vitro) pre and post- flight	Cellular immunity (in vitro)	Measures capa- bility to re- spond to chal- lenges (in vitro)	Reduced response to PHA test; normal culture response	N/A	N/A	3-7 days	Skylab	Kimzey 14	Nutrition	Questionable response at splashdown, but normal responses recovered in days.
	Response of lymphocytes to in vitro chal- lenges pre- and post- flight	Integrity of cellular immune system	Relevance to im- mune response capability	Decreased response postflight to PHA challenge	Unknown	Unknown	3-7 days postflight	Skylab	Kimzey 14	None	Favorable. Firm evaluation of significance of these findings is not possible.
	Lymphocyte counts, pre & postflight	Integrity of cellular immune system	Relevance to im- mune response capability	Reduction in T-cells on re- covery	Unknown	Unknown	3 days postflight	Skylab	Kimzey 14	None	"
(Saliva Im- munology).	Capability of defense mechanisms	Adequacy of immunity	In vitro data	No demon- strable change in antibodies or lyso- zyme levels in serum and saliva(1)	N/A	N/A	N/A	ASTP	Taylor 29	N/A	Favorable. These data were in part taken after ex- posure of the crew to toxic gases and are partially questionable as zero-G related effects.
		1) Saliva level is thought to be representative of blood level of lysozyme									

INVENTORY OF HUMAN RESPONSES TO SPACE FLIGHT

SYSTEM/ COMPONENT	MEASUREMENT	GENERAL OBJECTIVE	PERTINENCE	RESULT	ONSET	DURATION	RECOVERY	DATA	REFERENCE	AMELIORATION	PROGNOSIS		
B. CARDIO- VASCULAR SYSTEM	Hematology and Immunology	Homeo- stasis and humer- al immuri- ty	Direct measure- ment of proteins and protein fractions, especially ones important in immunity	SkyLab 2 No sig- nificant changes in quan- tity or electro- phoretic patterns	N/A	N/A	N/A	SkyLab	Kimzey 14	Nutrition, exercise	Favorable. No changes in humoral immune system due to weightlessness nor changes in capacity to respond		
	Total proteins			SkyLab 2 No sig- nificant changes in immuno- globulins	N/A	N/A	N/A	SkyLab	Kimzey 14		"		
	Albumin			SkyLab 2 Slight decrease in C3 on recovery	Unknown	Unknown	2 weeks	SkyLab	Kimzey 14		"		
	Alpha 2- globulin			SkyLab 2 Increases in lyso- zyme post- flight	Post- flight	Unknown	2 weeks	SkyLab	Kimzey 14		"		
	Gamma- globulin			SkyLab 3 No sig- nificant changes in plasma proteins	N/A	N/A	N/A	SkyLab	Kimzey 14		"		
	Immuno- globulins (IgG, IgA, IgM, IgD, IgE)			SkyLab 4 No sig- nificant changes in plasma proteins	N/A	N/A	N/A	SkyLab	Kimzey 14		"		
	Prealbumin												
	Haptoglobin												
	Hemopexin												
	Transferrin												
Ceruloplasmin													
Alpha 1 - antitrypsin													
Inter-alpha- trypsin inhibitor													
Alpha 1 - antichymo- trypsin													
Alpha 2 - macroglobin													
Complement factors 3&4													
Alpha 1 - acid glyco- protein													
C-esterase inhibitor													
Lysozyme													
C-reactive protein													

INVENTORY OF HUMAN RESPONSES TO SPACE FLIGHT

SYSTEM/ COMPONENT	MEASUREMENT	GENERAL OBJECTIVE	PERTINENCE	RESULT	ONSET	DURATION	RECOVERY	DATA	REFERENCE	AMELIORATION	PROGNOSIS
B. CARDIO- VASCULAR SYSTEM Immunol- ogy (Reticu- lo-endo- thelial System)	None (not evaluated ex- cept as pos- sible source for immune factors and for removal of older and defective red cells)										No evaluation as such; no degrada- tion discovered.

INVENTORY OF HUMAN RESPONSES TO SPACE FLIGHT

SYSTEM/ COMPONENT	MEASUREMENT	GENERAL OBJECTIVE	PERTINENCE	RESULT	ONSET	DURATION	RECOVERY	DATA	REFERENCE	AMELIORATION	PROGNOSIS
<u>C. NERVOUS SYSTEM</u>											
Central	Task performance pre, in, postflight	Holistic	Evaluates behavioral performance	Baseline recalled after few trials	N/A	N/A	N/A	Skylab	Kubis 31	N/A	Favorable; performance continues to improve with time.
Central	Sleep types and adequacy by electroencephalogram	Holistic	Evaluates adequacy of sleep	Adequate	N/A	N/A	N/A	Skylab	Frost 35	None Required	Favorable; in post-flight period there is more REM sleep and it appears sooner
Peripheral	Achilles tendon reflexes pre, postflight	Reflex time measurement	Measures several elements including nerve conduction	Generally reduced time in Skylab 3 and 4	-	-	By 31 days post-recovery	Skylab	Baker 32	N/A	Reflex times lengthened during the month after recovery before becoming baseline. No suggested unfavorable prognosis.
Peripheral	Achilles tendon reflex periodic relaxation, pre and post flight	Reflex time measurement	Measures several elements including nerve conduction	Two men had shortened periods, the 3rd longer. There was a fine tremor.	N/A	N/A	Unknown	ASTP	Burchard 18	None (This measurement is related to thyroxine level)	Tremor may have been caused by toxic exposure. Other data as anticipated. Fair prognosis.
Autonomic	Pre, in, post flight heart rate	Holistic	Evaluates sympathetic activity	Accelerated rates		Throughout worst at 3 weeks (LB:NP)	Within 11 days	Skylab	Johnson 8 Hoffler 7	N/A	Favorable. Cardiovascular control mechanisms operative.
As a whole	Neuropsychological: tension, fatigue, circadian rhythm, stress responses	Behavior: capability in space, stress in space	Assessment of capability in weightless environment	No mission impairment (see also Endocrine System & Biochemistry)	N/A	N/A	N/A	General	Pestov 53	None	Favorable. Any disturbances such as Apollo 13 accident and new experiences such as space walking, docking, lunar landing and exploration, space construction (Skylab umbrella), and recovery from space were handled in exemplary fashion. Weightlessness has no apparent neuropsychological effect.

INVENTORY OF HUMAN RESPONSES TO SPACE FLIGHT

SYSTEM/ COMPONENT	MEASUREMENT	GENERAL OBJECTIVE	PERTINENCE	RESULT	ONSET	DURATION	RECOVERY	DATA	REFERENCE	AMELIORATION	PROGNOSIS
D. NEURO- PHYSIOLOGY											
1. Vestibular	Postural equilibrium postflight	Vestibular assessment	Evaluates vestibular function	Instability	N/A	N/A	Postflight measurement	Skylab	Hornick 34	None offered	Favorable. Neural reorganization is complete by 11 days post mission
2. Special Sense Organs (sight, hearing, smell, taste, touch)	No specific direct tests-pre and post flight only	Holistic	Holistic	No direct data	N/A	N/A	N/A	Skylab	Hordinsky 30	None required	Degradation apparently not discovered
	Function, usually qualitative	Holistic	Holistic	Generally normal	N/A	N/A	N/A	General	Pestov 53 Berry 54	N/A	Favorable; small changes but no changes in acuity.
3. Other Sensors	Blood pressure, hematocrit, blood volume, pH, pO ₂ , pCO ₂ , temperature, etc.	Performance of visceral sensors	Part of homeostatic control	Changes usually within normal range	Varied	Varied	Varied	General	Various	N/A	Favorable. It appears that the sensitivity of these sensors is adequate. (see plasma volume, however)

INVENTORY OF HUMAN RESPONSES TO SPACE FLIGHT

SYSTEM/ COMPONENT	MEASUREMENT	GENERAL OBJECTIVE	PERTINENCE	RESULT	ONSET	DURATION	RECOVERY	DATA	REFERENCE	AMELIORATION	PROGNOSIS
D. NEURO- PHYSIOLOGY	Vestibular Oculogyral illusion, pre, in, postflt.	Vestibular performance	Measures otol- ithic sensi- tivity	No loss of sensi- tivity	N/A	Throughout	N/A	Skylab	Graybiel 63	N/A	Favorable, no change in this parameter in zero-g.
	Blindfolded perception of direction and vertical- ity pre, in, postflight	Vestibular performance	Measures ability to orient while seated, blind- folded	Scattered points unless seat is in con- ventional orienta- tion	N/A	Throughout	N/A	Skylab	Graybiel 63	N/A	Favorable. Errors made while blind- folded did not occur without blindfolds.
	Motion sick- ness in flight	Incidence of motion sickness as result of provocative tests	Measures tenden- cy to become motion sick	Crews of Skylab 2, 3 & 4 did not be- come sick under test con- ditions which did not start until about 1 week in flight	N/A	Throughout	Immunity to motion sick- ness was lost after about one week post- flight	Skylab	Graybiel 63	Drugs	Acceptable; spontan- eous sickness occurred with 5 astronauts; recovery was spontan- eous in 3-5 days with one exception (7 days) Sickness susceptibil- ity was lost after 7 days or so in space, and was regained within one week post flight.
		And as a result of weightless exposure	"	Five astronauts became sick with- out pro- vocative tests	Imme- diate	3 to 7 days	By 7 days	Skylab	Graybiel 63	Drugs	↓
	Presence of illusions and false indications in flight	Vestibular performance	Reflex responses	Fre- quently exper- ienced	Imme- diate	Throughout	Postflight	Skylab	Graybiel 63	N/A	Favorable. The il- lusions of motion and false sense of turning or rotating are normal reflex phenomena which are not disabling.

INVENTORY OF HUMAN RESPONSES TO SPACE FLIGHT

SYSTEM/ COMPONENT	MEASUREMENT	GENERAL OBJECTIVE	PERTINENCE	RESULT	ONSET	DURATION	RECOVERY	DATA	REFERENCE	AMELIORATION	PROGNOSIS
E. EXCRETORY SYSTEM	Blood urea nitrogen, pre, in, post flight plasma concentration	Homeostatic	Plasma level constancy depends on excretion	Remained essentially constant but decreased post-recovery	N/A	N/A	>14 days postflight	Skylab	Leach 20	N/A	Favorable. Excretory system retains its capability
	Creatinine pre, post flight urine concentration	Homeostatic	24-hour excretion constancy depends on kidney	Constant	N/A	N/A	N/A	Skylab	Whedon 2	N/A	Excretory competence favorable. Urinary indicator competence favorable.
<p>See also the paragraphs entitled Biochemistry which reflect the responses of the excretory system in regulation of plasma constituents (blood samples), also water balance and electrolyte excretion (urine samples).</p>											

INVENTORY OF HUMAN RESPONSES TO SPACE FLIGHT

SYSTEM/ COMPONENT	MEASUREMENT	GENERAL OBJECTIVE	PERTINENCE	RESULT	ONSET	DURATION	RECOVERY	DATA	REFERENCE	AMELIORATION	PROGNOSIS
F. DIGESTIVE SYSTEM	Nutritional in-and-out balance plus medical evaluation	Holistic	Measurements chiefly of minerals; evalu- ation of well- being	Normal findings except occasion- al nausea & vomit- ing	Upon ir- sertior	Zero to 5 days	During flight	Skylab	Lordinsky 30	N/A	Favorable prognosis; recovery is sponta- neous. Problems are environment caused. Nitrogen, calcium and phosphorus changes are caused by non-nutritional factors.
	Glucose	Carbohy- drate metabolism	See Biochemistry						Leach 20		Hunger is normal. Weight is only slightly changed, usually decreased. No nutritional de- ficiency was detected
	Cholesterol	Fat metabolism	See Biochemistry								
	Triglycerides	Fat metabolism	See Biochemistry								
	BUN	Protein metabolism	See Biochemistry								
	Uric Acid	Nucleic acid and protein metabolism	See Biochemistry								

INVENTORY OF HUMAN RESPONSES TO SPACE FLIGHT

SYSTEM/ COMPONENT	MEASUREMENT	GENERAL OBJECTIVE	PERTINENCE	RESULT	ONSET	DURATION	RECOVERY	DATA	REFERENCE	AMELIORATION	PROGNOSIS
G. RESPIRA- TORY SYSTEM Pulmonary Function	Pre, in, post flight vital capacity	Pulmonary function	Direct measure- ment of lung parameters	Vital capacity decreased	Early	Throughout flight	<2 hours postflight	Skylab	Sawin 4	No countermeasure required provided high exercise level maintained in flights; per- haps no counter- measure required even without exercise.	Favorable. No physiologically significant decrement in pulmonary function occurred.
	Exercise capability in flight	Crew exercise capability in flight	Direct measure- ment of lung parameters	Normal crew exercise response	N/A	N/A	N/A	Skylab	Michel 5	N/A. Pulmonary function did not limit exercise capability in flight.	Favorable. Respiration does not pace exercise response in flight.
	Pulmonary efficiency *	Pulmonary function	Measures lung efficiency	Occasion- al in- creases	N/A	Mission average data given	N/A	Skylab	Michel 5	N/A. This pulmo- nary functional parameter is un- impaired.	Favorable.
	* V_E at $2LV_{O_2}$ (lung venti- lation neces- sary to pro- vide a cer- tain oxygen demand)										

INVENTORY OF HUMAN RESPONSES TO SPACE FLIGHT

SYSTEM/ COMPONENT	MEASUREMENT	GENERAL OBJECTIVE	PERTINENCE	RESULT	ONSET	DURATION	RECOVERY	DATA	REFERENCE	AMELIORATION	PROGNOSIS
H. REPRODUC- TIVE SYSTEM											
Male re- productive system	Pre, post flight physical examination	Holistic	Evaluation; no measurements except andros- terone	No data	N/A	N/A	N/A.	Skylab	Hordirsky 30	N/A	Apparently favorable; no findings given except congestive prostatitis and urethral irritation caused by constant- wear urinals in Gemini flights.
Female reproduc- tive system	None except bed-rest studies con- ducted to study possi- ble effects of weight- lessness on physiology with special reference to fluid reten- tion.								Sandler 55		

INVENTORY OF HUMAN RESPONSES TO SPACE FLIGHT

SYSTEM/ COMPONENT	MEASUREMENT	GENERAL OBJECTIVE	PERTINENCE	RESULT	ONSET	DURATION	RECOVERY	DATA	REFERENCE	AMELIORATION	PROGNOSIS	
I. BIOCHEMISTRY Blood	Plasma & serum, pre & post flight samples	CPK	Homeostatis	Increased after recovery	N/A	N/A	Unknown	Skylab	Leach 20	N/A	No threat posed.	
		LDH	Homeostatis	Decreased then increased	N/A	N/A	>2 weeks post recovery	Skylab	Leach 20	N/A	No threat posed.	
		Total bilirubin	Multiple, especially hemoglobin stability	Variable to decreased	N/A	N/A	Unknown	Skylab	Leach 20	N/A	No threat posed.	
		Sodium	Regulation of homeostatic adjustment	Electrolyte balance	Decreased	Early	Through recovery	Two weeks post recovery	Skylab	Leach 20	N/A	No threat posed.
		Potassium	Regulation of homeostatic adjustment	Electrolyte balance	Slightly elevated	Early	Through recovery	One blood sample past recovery	Skylab	Leach 20	Additives; nutrition	No threat posed.
		Calcium	Regulation of homeostatic adjustment; also bone demineralization	Electrolyte balance; also bone demineralization	Elevated	Early	Throughout	Several days post recovery	Skylab	Leach 20	Additives, nutrition; hormones	Guarded
		Chloride	Regulation of homeostatic adjustment	Electrolyte balance	Decreased	Early	Throughout	Two weeks post recovery	Skylab	Leach 20	N/A	No threat posed.
		Phosphorus	Regulation of homeostatic adjustment; also bone demineralization	Electrolyte balance; also bone demineralization	Elevated	Early	Throughout	Several days post recovery	Skylab	Leach 20	Nutrition; additives	Guarded

INVENTORY OF HUMAN RESPONSES TO SPACE FLIGHT

SYSTEM/ COMPONENT	MEASUREMENT	GENERAL OBJECTIVE	PERTINENCE	RESULT	ONSET	DURATION	RECOVERY	DATA	REFERENCE	AMELIORATION	PROGNOSIS
I. BIOCHEMISTRY Blood Plasma & serum, pre and post flight samples	Osmolality	Regulation of homeostatic adjustments; also fluid balance	Fluid balance	Reduced	Early	Throughout	Post recovery	Skylab	Leach 20	N/A	No threat posed.
	ACTH	Fluid and electrolyte balance	Regulator of adrenal activity	Decreased	Early	Throughout	Two weeks post recovery	Skylab	Leach 20	N/A	No threat posed.
	Cortisol	Adrenal function	Metabolite concentrations	Usually elevated	Early	Throughout	One blood sample post recovery	Skylab	Leach 20	N/A	No threat posed.
	Glucose	Carbohydrate metabolism		Increased at recovery	N/A	N/A	<2 weeks post recovery	Skylab	Leach 20	N/A	No threat posed.
	Albumin	Homeostasis		Decreased post recovery	N/A	N/A	>2 weeks unknown	Skylab	Leach 20	N/A	No threat posed.
	Magnesium	Homeostasis		Decreased	N/A	N/A	<2 weeks post recovery	Skylab	Leach 20	N/A	No threat posed.
	Cholesterol	Fat metabolism		Decreased except on recovery day	N/A	N/A	<2 weeks post recovery	Skylab	Leach 20	N/A	No threat posed.
	Triglycerides	Fat metabolism		Increased on recovery	N/A	N/A	<2 weeks post recovery	Skylab	Leach 20	N/A	No threat posed.
	Blood urea nitrogen	Hydration; liver and renal function; protein metabolism		Decreased post recovery	N/A	N/A	Unknown	Skylab	Leach 20	N/A	No threat posed.

INVENTORY OF HUMAN RESPONSES TO SPACE FLIGHT

SYSTEM/ COMPONENT	MEASUREMENT	GENERAL OBJECTIVE	PERTINENCE	RESULT	ONSET	DURATION	RECOVERY	DATA	REFERENCE	AMELIORATION	PROGNOSIS			
I. BIOCHEM- ISTRY	Blood Plasma & serum, pre and post flight samples	Uric acid		Renal function, protein & purine metabolism			Decreased post recovery	N/A	N/A	<2 weeks post recovery	Skylab Leach 20	N/A	No threat posed.	
		Total protein		Homeostasis			Increased on re- covery	N/A	N/A	1 or 2 days post recovery	Skylab Leach 20	N/A	No threat posed.	
		Alkaline phosphatase		Homeostasis			Reduced post recovery	N/A	N/A	<2 weeks post re- covery	Skylab Leach 20	N/A	No threat posed.	
		SGOT		Homeostasis			No change	N/A	N/A	N/A	Skylab Leach 20	N/A	No threat posed.	
	Blood serum pre and post flight	Lactic de- hydrogenase		Stress; injury	Evaluation of well-being			Increased in three crewmembers	N/A		>28 days	ASTP Leach 26	None	Uncertain prognosis; Results may have been compromised by inadvertent exposure of astronauts to toxic gases during recovery.
		Osmolarity		Homeostasis	Evaluation of well-being			Decreased in two crewmembers	N/A		<28 days	ASTP Leach 26	None	
		Sodium		Homeostasis	Evaluation of well-being			Decreased in three crewmembers	N/A		>28 days	ASTP Leach 26	None	
		Potassium		Homeostasis	Evaluation of well-being			Increased in two crewmembers	N/A		<28 days	ASTP Leach 26	None	
		Chloride		Homeostasis	Evaluation of well-being			Increased in two crewmembers	N/A		>28 days	ASTP Leach 26	None	
		Triglycerides		Fat meta- bolism	Evaluation of well-being			Decreased in two crewmembers	N/A		>28 days	ASTP Leach 26	None	
		Glucose		Carbohy- drate metabolism	Evaluation of well-being			Decreased in two crewmembers	N/A		<28 days	ASTP Leach 26	None	

INVENTORY OF HUMAN RESPONSES TO SPACE FLIGHT

SYSTEM/ COMPONENT	MEASUREMENT	GENERAL OBJECTIVE	PERTINENCE	RESULT	ONSET	DURATION	RECOVERY	DATA	REFERENCE	AMELIORATION	PROGNOSIS
I. BIOCHEM- ISTRY Blood serum pre and post flight	Cholesterol	Fat metabo- lism	Evaluation of well-being	Decreased in three crewmembers	N/A		<28 days	ASTP	Leach 26	None	Uncertain prognosis; results may have been compromised by inadvertent exposure of astronauts to toxic gases during recovery.
	Serum Gluta- mic Oxalace- tic Trans- aminase	Protein metabolism; stress; injury	Evaluation of well-being	Increased in three crewmembers	N/A		>28 days	ASTP	Leach 26	None	
	Serum Gluta- mic Pyruvic Transaminase	Protein metabolism; injury (liver)	Evaluation of well-being	Increased in three crewmembers	N/A		>28 days	ASTP	Leach 26	None	
	Blood Urea Nitrogen	Protein metabolism	Evaluation of well-being	Increased in three crewmembers	N/A		>28 days	ASTP	Leach 26	None	
	Uric Acid	Nucleic acid and protein metabolism	Evaluation of well-being	Decreased in two crewmembers	N/A		<28 days	ASTP	Leach 26	None	
	Alkaline Phosphatase	Stress; injury (liver)	Evaluation of well-being	Increased in two crewmembers	N/A		<28 days	ASTP	Leach 26	None	
	Calcium	Homeostasis (esp. bone)	Evaluation of well-being	Increased in two crewmembers	N/A		>28 days	ASTP	Leach 26	None	
	Magnesium	Homeostasis (esp. bone)	Evaluation of well-being	Decreased in one crewmember	N/A		<28 days	ASTP	Leach 26	None	
	Phosphate	Homeostasis (esp. bone)	Evaluation of well-being	Increased in one, decreased in one crewmember	N/A		<28 days	ASTP	Leach 26	None	
	Total Bilirubin	Hemoglobin destruction	Evaluation of well-being	Decreased in three crewmembers	N/A		>28 days	ASTP	Leach 26	None	

INVENTORY OF HUMAN RESPONSES TO SPACE FLIGHT

SYSTEM/ COMPONENT	MEASUREMENT	GENERAL OBJECTIVE	PERTINENCE	RESULT	ONSET	DURATION	RECOVERY	DATA	REFERENCE	AMELIORATION	PROGNOSIS	
I. BIOCHEM- ISTRY	Blood serum pre and post flight	Creatinine	Homeostasis protein metabolism	Evaluation of well-being	Increased in three crewmen	N/A		>28 days	ASTP	Leach 26	None	Uncertain prognosis; results may have been compromised by inadvertent exposure of astronauts to toxic tases during recovery.
		Creative Proosphokinase	Stress; injury	Evaluation of well-being	Decreased in two crewmen	N/A		<28 days	ASTP	Leach 26	None	
	24-hour urine analysis, pre, in, postflight samples	Volume	Homeostasis	Fluid balance	Decreased 5 or 6 days, then baseline	N/A	--	N/A	Skylab	Leach 20	None required	Favorable
		Sodium	Homeostasis	Electrolyte balance	Elevated except for 60 days postflight	Early	Throughout	>18 days	Skylab	Leach 20	None required	Favorable
		Potassium	Homeostasis	Electrolyte balance; muscle function	↓	Early	Throughout	>18 days	Skylab	Leach 20	None required	Favorable
		Chloride	Homeostasis	↓	↓	Early	Throughout	>13 days	Skylab	Leach 20	None required	Favorable
		Osmolality	Homeostasis	Fluid balance	Increased; postflight decreased	Early	Throughout	Immediate	Skylab	Leach 20	None required	Favorable
		Calcium	Homeostasis	Electrolyte balance; muscle function; bone demineralization	Increased	Early	Throughout	> 6 days	Skylab	Leach 20	See skeleton	See skeleton
		Phosphate	Homeostasis	Bone deminera- lization	Increased; postflight decreased	Early	Throughout	> 6 days	Skylab	Leach 20	See skeleton	See skeleton
		Magnesium	Homeostasis	Electrolyte balance	Increased; postflight decreased	Early	60 days of flight	>6 days (postflight decrease)	Skylab	Leach 20	None required	Favorable
Creatinine	Homeostasis	Kidney function; protein metabo- lism; tracer	Slight elevation N-S	Early	Throughout	At recovery	Skylab	Leach 20	None required	Favorable		

INVENTORY OF HUMAN RESPONSES TO SPACE FLIGHT

SYSTEM/COMPONENT	MEASUREMENT	GENERAL OBJECTIVE	PERTINENCE	RESULT	ONSET	DURATION	RECOVERY	DATA	REFERENCE	AMELIORATION	PROGNOSIS							
I. BIOCHEMISTRY 24-hour urine analysis, pre, in, postflight samples	Uric Acid	Homeostasis	Renal function purine metabolism	Reduced; in and post-flight	Early	Throughout	> 6 days	SkyLab	Leach 20	None required	Favorable							
	Hydroxylysine	Collagen stability	Protein degradation	Increased in flight reduced post-flight														
	24-hour volume	Homeostasis	Direct measurement of maintenance of homeostasis	Decreased in one; increased in one crewman	N/A	N/A	-	ASTP	Leach 2E	None	Uncertain prognosis; results may have been compromised by inadvertent exposure of astronauts to toxic gases during recovery.							
	Sp Gr	Homeostasis	↓	↓	↓	↓	-	↓	↓	↓								
	Osmolality																	
	Sodium											Decreased in two crewmen	< 28 days					
	Potassium											↓	↓	↓	↓	↓	↓	↓
	Chloride																	
	Calcium																	
	Magnesium											Direct measurement of maintenance of homeostasis	Decreased in one, increased in one crewman	↓	↓	↓	↓	↓
Phosphate	"											(Decalcification)	Decreased in two crewmen	↓	↓	Uncertain	↓	↓

INVENTORY OF HUMAN RESPONSES TO SPACE FLIGHT

SYSTEM/ COMPONENT	MEASUREMENT	GENERAL OBJECTIVE	PERTINENCE	RESULT	ONSET	DURATION	RECOVERY	DATA	REFERENCE	AMELIORATION	PROGNOSIS
I. BIOCHEM- ISTRY 24-hour urine analysis, pre, in, postflight samples	Uric Acid	Homeostasis	Direct measure- ment of mainte- nance of homeo- stasis	Decreased	N/A	N/A	> 28 days	ASTP	Leach 26	None	Uncertain prognosis; results may have been compromised by inadvertent exposure of astronauts to toxic gases during recovery.
	Creatinine										
	Hydroxypro- line		Indicator of collagen acti- vity	Increased in two crewmn			Uncertain				
	Hydrogen ion		Direct measure- ment of mainte- nance of homeo- stasis	Increased in two crewmn			> 28 days				
	Hydroxylysine		Indicator of collagen activity	Increased in three crewmn			< 28 days				

INVENTORY OF HUMAN RESPONSES TO SPACE FLIGHT

SYSTEM/ COMPONENT	MEASUREMENT	GENERAL OBJECTIVE	PERTINENCE	RESULT	ONSET	DURATION	RECOVERY	DATA	REFERENCE	AMELIORATION	PROGNOSIS	
J. ENDOCRINE SYSTEM	Blood plasma and serum, pre and post- flight samples	Human growth hormone	Homeostasis (metabolism)	Variable, elevated early in recovery	N/A	N/A	< 2 weeks postflight	Skylab	Leach 20	N/A	No threat posed.	
		Thyroxine	Homeostasis	Increased	N/A	N/A	< 2 weeks postflight	Skylab	Leach 20	N/A	No threat posed.	
		TSH	Homeostasis		Increased	N/A	N/A	Unknown	Skylab	Leach 20	N/A	No threat posed.
		Testosterone	Homeostasis		No data	N/A	N/A	Unknown	Skylab	Leach 20	N/A	No threat posed.
		Calcitonin	Calcium metabolism		Not detected	N/A	N/A	Unknown	Skylab	Leach 20	N/A	No threat posed.
		Vitamin D	Calcium metabolism		Generally unchanged	N/A	N/A	N/A	Skylab	Leach 20	N/A	No threat posed.
		Carbon dioxide	Homeostasis		Increased	N/A	N/A	Unknown > 2 weeks	Skylab	Leach 20	N/A	No threat posed.
	Blood plasma and serum, in flight samples	Angiotensin I	Fluid and electrolyte balance	Regulator of adrenal activity	Usually elevated	Early	Throughout	Several	Skylab	Leach 20	N/A	No threat posed.
		Aldosterone	Homeostasis	Adrenal function (sodium reten- tion)	Decreased; increased postflt.	Two weeks	Throughout	Two weeks post re- covery	Skylab	Leach 20	N/A	No threat posed.
		Glucose	Homeostasis	Metabolite concentrations	Decreased; increased postflt.	4 weeks	Throughout	Two weeks post re- covery	Skylab	Leach 20	N/A	No threat posed.
		Insulin	Homeostasis	Metabolite concentrations	Decreased; increased postflt.	3 weeks	Throughout	Two weeks post re- covery	Skylab	Leach 20	N/A	No threat posed.
		Creatinine	Kidney function	Kidney function	Slightly elevated	Early	Throughout	One blood sample post re- covery	Skylab	Leach 20	N/A	No threat posed.
		Parathormone	Calcium metabolism		Variable	Incon- clusive	Throughout	One blood sample post re- covery	Skylab	Leach 20	N/A	No threat posed.

INVENTORY OF HUMAN RESPONSES TO SPACE FLIGHT

SYSTEM/ COMPONENT	MEASUREMENT	GENERAL OBJECTIVE	PERTINENCE	RESULT	ONSET	DURATION	RECOVERY	DATA	REFERENCE	AMELIORATION	PROGNOSIS	
J. ENDOCRINE SYSTEM	Blood plasma and serum, in flight samples	Human growth hormone	Metabolic regulation	Metabolite concentrations	Elevated early in flight & early in recovery	Early	Short	Two weeks post recovery	Skylab	Leach 20	N/A	No threat posed.
	Blood plasma pre and postflight	Angiotensin I	Homeostasis	Direct measurement of endocrine levels	Increased in three crewmen	N/A		28 days	ASTP	Leach 26	None	Uncertain prognosis. Results may have been compromised by inadvertent exposure of astronauts to toxic gases during recovery.
		Cortisol		"	Increased in two crewmen		1 day					
		Aldosterone		"	"		8 days					
		Insulin		"	"		28 days					
		Diabetogenic Hormone		"	Decreased in two crewmen		1 day					
		T3 Uptake		Direct measurement of endocrine involvement	No data		-					
		T4		Direct measurement of endocrine levels	No data		-					
		Thyroid Stimulating Hormone		"	No change		-					
Human Growth Hormone	"	Increased in two crewmen		28 days								

INVENTORY OF HUMAN RESPONSES TO SPACE FLIGHT

SYSTEM/ COMPONENT	MEASUREMENT	GENERAL OBJECTIVE	PERTINENCE	RESULT	ONSET	DURATION	RECOVERY	DATA	REFERENCE	AMELIORATION	PROGNOSIS
J. ENDOCRINE SYSTEM	24-hour urine analysis	Homeostasis ↓	Direct measure- ment of endo- crine levels ↓	Decreased in one; increased in one crewman	N/A	N/A		ASTP	Leach 25	None	Uncertain prognosis; results may have been compromised by inadvertent exposure of astronauts to toxic gases during recovery. ↓
	Cortisol			Increased in three crewmen			< 28 days				
	Epinephrine			Increased in two; decreased in one crewman			> 28 days				
	Norepinephrine			Decreased in two; increased in one crewman			"				
	Aldosterone			Increased in three crewmen			< 28 days				
	Antidiuretic hormone			Decreased in two; increased in one crewman	↓	↓	↓	↓	↓	↓	
24-hour urine analysis, pre, in, postflight samples	Cortisol	Homeostasis ↓	Adrenal activity ↓	Increased in and postflt.	Early	Throughout	> 18 days	Skylab	Leach 20	None required	Favorable
	Epinephrine			Decreased in flight; slight elevation post, N-S	N/A	N/A	Unknown				
	Norepinephrine			Decreased in flight; postflt. elevation	Post-	18 days	> 18 days	↓	↓	↓	↓

INVENTORY OF HUMAN RESPONSES TO SPACE FLIGHT

SYSTEM/ COMPONENT	MEASUREMENT	GENERAL OBJECTIVE	PERTINENCE	RESULT	ONSET	DURATION	RECOVERY	DATA	REFERENCE	AMELIORATION	PROGNOSIS
J. ENDOCRINE SYSTEM	24-hour urine analysis, pre, in, postflight samples	Homeostasis ↓	Adrena activity (cortisone)	Reduced postflt.	Post flight	Through postflight	> 18 days	Skylab	Leach 20	None required	Favorable.
	Total 17- hydroxy cort- icosteroids		Androsterone	Increased	Early	Throughout	Postflight				
	Anti diuretic hormone		Fluid balance	Reduced in flight; reduced late post flight	28 days	After 28 days	At recovery, then re- duced >18 days				
	Aldosterone		Electrolyte, fluid balance	Increased in flight and 6 days post	Early	Throughout	>6 days postflight				

INVENTORY OF HUMAN RESPONSES TO SPACE FLIGHT

SYSTEM/ COMPONENT	MEASUREMENT	GENERAL OBJECTIVE	PERTINENCE	RESULT	ONSET	DURATION	RECOVERY	DATA	REFERENCE	AMELIORATION	PROGNOSIS
K. ENERGY METABOLISM											
Energy Production	Oxygen consumption, heart rate, blood pressure others, pre, in, post- flight	Energy production	Measures physical parameters in energy production	Good in-flight performance; altered post-flight performance	Post-flight	N/A	31 days postflight	Skylab	Michel 36	Augmentation of the circulating volume	Chief problems were reduced cardiac output and reduced stroke volume; near recovery in 31 days. Favorable prognosis.
Nutrition	(See entries on digestive system)										

INVENTORY OF HUMAN RESPONSES TO SPACE FLIGHT

SYSTEM/ COMPONENT	MEASUREMENT	GENERAL OBJECTIVE	PERTINENCE	RESULT	ONSET	DURATION	RECOVERY	DATA	REFERENCE	AMELIORATION	PROGNOSIS
L. FLUID SHIFTS	Leg girth	Fluid shift	Direct measurement	Leg volume reduction	<6 hours highest rate within 24 hrs.	Continuous	Start 1.5 hours post recovery; full 4 days	ASTP	Hoffler 24	None	Favorable. (Recovery portion of these data may have been compromised by toxic gas exposure during flight recovery.)
	Girth of body segments	Fluid shift	Direct measurement of girth	Shifts from legs and waist	Before day 3	Throughout mission	1 day	Skylab	Thornton 41	None	Favorable except for possible vestibular effect.
	Symptoms	Fluid shift	Symptoms probably related to fluid shift	Head fullness; headache	1 day or so	Slow taper off over 2 weeks	-	Skylab	Gibson 39	None	Favorable.
	Symptoms	Well-being	Symptoms probably related to fluid shifts	Head fullness; like a "cold"; nasal voices; puffiness	Not given	Not given	Not given	Skylab	Kerwin 38	None	Favorable
	Stereometric analysis	Body form	Measures changes in body form in zero-g and tracks fluid shifts	Large losses from legs and trunk	N/A	N/A	4 days for most; 30 days for full recovery	Skylab	Whittle 40	Exercise	Favorable. Effects are not disabling.
	Symptoms	Fluid shift evaluation	Well-being	Mild head fullness; no other symptom	Immediate upon orbit	Not given	Not given	ASTP	Nicogossian 16	None	Favorable. No interference with performance. (These data not compromised by toxic gas exposure)

INVENTORY OF HUMAN RESPONSES TO SPACE FLIGHT

SYSTEM/ COMPONENT	MEASUREMENT	GENERAL OBJECTIVE	PERTINENCE	RESULT	ONSET	DURATION	RECOVERY	DATA	REFERENCE	AMELIORATION	PROGNOSIS
M. INTEGUMENTARY SYSTEM	Skin barrier effectiveness and rate of healing	Occurrence of infections	Measurement of resistance to infection and healing response	Occasional rash and skin infection	Varied	Varied	Before end of mission	Skylab	Hordinsky 30 Taylor 33	None suggested	Favorable; no time lost; all healed promptly
(Microbiological)	Crew microbial measurement	Well-being	Measurement of immunity	No disease events	N/A	N/A	N/A	ASTP	Taylor 25	None	Favorable. No disease events. This data is based on performance before toxic gas exposure of ASTP astronauts, hence is not compromised by that event.

INVENTORY OF HUMAN RESPONSES TO SPACE FLIGHT

SYSTEM/ COMPONENT	MEASUREMENT	GENERAL OBJECTIVE	PERTINENCE	RESULT	ONSET	DURATION	RECOVERY	DATA	REFERENCE	AMELIORATION	PROGNOSIS	
N. FOOD AND NUTRITION	Food	Caloric requirement	Zero-g caloric requirement	Direct measure- ment	2900 C+ intake; 49C per Kg/day require- ment	N/A	N/A	N/A	ASTP	Smith 17	None	Favorable. (These data independent of toxic gas exposure incident.)
		Introspective	Adequacy	Hedonistic	Adequate	N/A	N/A	N/A	Skylab	Gibson 39	Prefer open pantry	Favorable.

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INVENTORY OF HUMAN RESPONSES TO SPACE FLIGHT

SYSTEM/ COMPONENT	MEASUREMENT	GENERAL OBJECTIVE	PERTINENCE	RESULT	ONSET	DURATION	RECOVERY	DATA	REFERENCE	AMELIORATION	PROGNOSIS
0. ELECTRO- LYTE BALANCE	Electrolyte and fluid balance, pre & post flight by nuclear studies to support fluid balance; electrolyte balance & hematologic studies	Homeostasis ↓	Direct measurement of adaptation or homeostatic control ↓	Crewmen lost 7% and 15% respectively	N/A ↓	N/A ↓	Unknown ↓	ASTP ↓	Leach 26 ↓	None ↓	Uncertain prognosis; results may have been compromised by inadvertent exposure of astronauts to toxic gases during recovery. ↓
	Total body water			Crewmen lost 2% each							
	Extracellular fluid			Crewmen lost 3% each							
	Exchangeable potassium			Crewmen lost 18% and 7% respectively							
	Plasma volume			Crewmen lost 12.5% average							
	Total body water			Crewmen lost 1.7% average							
Extracellular fluid	Crewmen lost 1.9% average										
Exchangeable potassium	Crewmen lost 8.2% average	Nutrition; K supplement; hormone therapy	Guarded because potassium depletion causes "irritability" changes in heart, nerve and muscle.								
							2 weeks usually	Skylab	Johnson 13	None	Guarded if data is reliable.
							Unknown	Skylab	Leach 20	None	Favorable
							Unknown	Skylab	Leach 20	None	
							Unknown	Skylab	Leach 20	Nutrition, K + supplement; hormone therapy	

IV. DISCUSSION OF HUMAN RESPONSES TO SPACE FLIGHT

This section contains discussions relating to the responses of humans to weightlessness, acceleration/deceleration and other elements of space flight which may affect the health and safety of SPS space workers.

A. WEIGHTLESSNESS

The weightless environment of space flight has been available for scientific investigation only since the early 1960's. The ability or inability of the human physiological system to adapt to this unique environment and subsequently to readapt to a one-g environment may ultimately limit the duration of manned space flights. This section contains a description of the general physiological effects of weightlessness, with emphasis on the physiological effects that could limit mission durations in the absence of effective countermeasures and with special reference to mission operations. Whenever morphological changes follow their physiological counterparts, the implications are discussed.

Research programs at NASA are carried out by many teams of investigators who utilize different approaches and methods in studying facets of the overall problems. Whenever possible, this section will attempt to unify the various research results and to present a composite picture or status of test results for each organ system or physiological function.

Definition

When the inertial forces of an orbiting body exactly balance the gravitational forces, the resultant forces impinging on the body have a magnitude of zero. This state is referred zero-g, null gravity, or weightlessness.

It is only during space flight that weightlessness is produced for any extended period. However, the zero-g state can be produced for brief periods within the Earth's atmosphere. Aircraft flying a Keplerian parabolic trajectory have produced periods of weightlessness for as long as 60 seconds (54). These brief periods of zero-g have limited usefulness for investigations of

the physiological effects of weightlessness; they are most useful for developing and evaluating space-flight hardware and procedures. Other available methods by which certain effects of the weightless environment on living systems can be simulated more or less realistically depend on the phenomenon being observed. Bed rest and liquid immersion have been used for many years to simulate the effects of space flight on the human musculoskeletal, cardiovascular, fluid, hormonal and electrolyte control systems. These analogs of weightlessness provide an opportunity to test hypotheses, explore mechanisms, and evaluate countermeasures in areas where physiological effects similar to those observed in zero-g are known to occur.

Weightlessness is known to affect several physiological systems including musculoskeletal, cardiovascular, humoral, vestibular, hormonal and electrolyte control. Many of the changes are not fully realized until return to the one-g environment.

Gravitational forces have been present in the evolutionary development of every species of land animal and plant. The anatomical placement and mass of the skeleton and musculature of land animals have subsequently evolved to maintain posture and provide locomotion against these gravitational forces.

To enable man and other animals to acquire and maintain posture and body orientation in normal gravity, the central nervous system interprets visual, kinesthetic, vestibular, and statokinetic signals to produce the "appropriate" gravity-dependent sensorimotor response. Both the mechanoreceptors within the body and the learned central nervous system interpretations are tuned to the terrestrial weight/force relationship. Further, the cardiovascular system of man and of other animals have evolved anatomical structures and physiological mechanisms (e.g., carotid sinus reflex) to overcome changes or orientation with respect to gravitational forces.

In essence, the "stress" of weightlessness is the removal of forces to which the body is adapted and for which the body is genetically designed to counteract. Adaptation to the weightless environment involves disuse or modified use of these structures and mechanisms. Rapid and complete adaptation to a weightless environment is desirable for enhanced performance during space

flight. However, the degree of adaptation during weightless exposure may affect the severity of problems encountered upon return and readaptation to the one-g environment.

The weightlessness of the space environment applies predictable stresses in selective modes to human subjects and results in fairly predictable responses. A number of these responses appear to be either deleterious to the continued health and well-being of anyone while in space, particularly over protracted periods, or somewhat prejudicial or disabling to anyone during and immediately after return to a gravity-based earth existence. At least one response, loss of structural integrity of bone, may not be fully reversed for several months.

The organ systems and functions recognized as sensitive to the changes to and from weightlessness are the musculoskeletal system, the cardiovascular system, the immune system, the endocrine system (secondarily), and bioenergetic control.

The organ systems that have suffered minimal or no measurable functional changes during space exposure include:

- Reproductive

- Digestive

- Respiratory (in zero acceleration)

- Lymphatic

- Nervous (especially psychomotor, behavior, judgement, problem-solving ability)

- Excretory

- Sensory (except vestibular)

Responses are classified as gross-level effects and less important effects.

Gross-Level Effects

Antigravity muscle mass loss, is probably comprised of fluid surrounding the muscle fibers and protein from the muscle fibers themselves. Other skeletal muscles exhibit these losses to a lesser degree. There is a small, reversible loss of strength and ability to perform work at maximal levels.

Skeletal integrity is compromised by slow losses of the protein matrix of bone as well as of bone mineral, leading toward osteoporosis. Recovery is known to require a protracted period.

There is a fluid shift, particularly from the legs to the head and upper torso, and some fluid is lost, probably from the blood plasma primarily with some contribution of interstitial fluids from leg musculature. The fluid shift to the upper regions causes engorgement of veins, puffiness of distensible regions of the face and neck, and sinus and oropharyngeal congestion. These changes possibly contribute to the development of untoward vestibular responses including nausea and vomiting.

Cardiovascular adaptability or competence (orthostatic tolerance) is compromised by weightlessness. This finding is demonstrated by stress tests including lower body negative pressure (LBNP) upon return to an erect posture in normogravity following space exposure.

Less Important Effects

Less obvious changes that may be secondary or tertiary level effects include:

Skin infections which might be a result of defense system change or depression, inadequacy of provisions for maintaining hygiene, increased virulence of microbial invaders, or other cause.

A loss of red cell mass, probably related to depression of hemopoietic capabilities.

Changes in neuroendocrine activity as measured in blood and urine specimens, with especial reference to electrolyte and water balance, electrolyte losses and plasma volume loss.

Physical injury produced by an inflexible or poorly fitting space garment after the subject has experienced spinal elongation on other anthropometric changes in null gravity.

Reduced sensory acuity or discrimination have been reported by some Apollo and Skylab astronauts. These have been manifest as a reported inability to taste spices in foods. Diminution in ability to smell due to engorgement of mucous membranes in the head and/or the lack of normal convection currents may contribute to this condition.

A catch-all category that produces the readout that bioenergetic control has been compromised; maximal work performance capability is reduced and the calibratable responses among energy output, heart rate and oxygen uptake lose their quantitative interdependence.

Musculoskeletal System

Reduction of external forces acting on the weight-bearing structure of the body results in loss of calcium and other minerals important to bone integrity. Animals reared on a centrifuge where they are exposed to elevated g loadings develop enlarged skeletal members. Human inactivity such as bed rest causes some members of the skeleton to lose mineral and leads to decreased density and increased brittleness of bone. The skeletal response applied load is described by Wolff's law as a linear one, hence there is assurance that a program to stress the skeleton should prevent demineralization. Also a host of factors that influence mineralization can be manipulated; e.g., vitamin D, calcitonin, parathormone, calcium, phosphorus, and nutritional requirements. Androgenic hormones might also be involved. However, means that have been tested in bed rest and in space have met with little success - calcium loss has continued throughout the longest space missions to date, 175 days (Soviet data).

Three of the Skylab crewmen exhibited loss of *os calcis* (heel bone) material, and none showed an loss from the arm skeleton. One had regained bone loss by the 87th day postflight, and the other two had not regained their losses by the 95th day. Losses were correlated with urinary hydroxyproline excretion which is thought to be an indication of bone matrix (protein) loss.

Urinary calcium excretion was high in all Skylab crewmen. As expected, fecal calcium excretion was greater than urinary calcium. The rate did not subside. Of particular note is the observation that whereas excretion of calcium in

urine reached a plateau (twice or more than normal at 1-G), the amount of calcium in the feces continued to increase for the full 84 days in all three astronauts of the SL-4 mission. The average loss from the heel bone was about 3.9% per month. Phosphorus loss was similar. Urinary calcium and phosphorus excretion had returned to normal in less than one week postflight, but bone structure had not been rebuilt. As noted above, upwards of three months were required for bone resynthesis. The loss was of no immediate concern, but it has a great deal of potential significance for long duration missions because the loss of total body calcium was about 0.4% per month.

Skeletal stress is normally produced by the action of gravity and by muscular force. In space, without apparent gravity, exercise from 30 minutes per day on Skylab 2 to 90 minutes per day on Skylab 4 did not prevent calcium excretion and bone demineralization. Soviet experience on Salyut 6 which involved exercise for periods of up to 150 minutes per day on flights to 175 days was similar in that bone loss continued. There is reason to expect that a novel exercise program can be synthesized that will more nearly duplicate the natural loads on the skeleton and maintain skeletal integrity, perhaps when augmented by nutritional factors, drugs, longitudinal compression of skeletal members, or other techniques short of providing artificial gravity.

Intractability of the demineralization phenomenon suggests that a part of the causation has not been considered. Perhaps a sensor is causing inappropriate decalcification, mobilizing calcium to meet an electrolyte balance requirement, while another part of the control system is causing the calcium to be excreted. If this is true, then loading calcium in the intake should suppress demineralization and urinary calcium. However, in bed rest studies loading calcium does not suppress urinary calcium; it appears to suppress demineralization for a time (up to 3 months) but then decreased intestinal absorption becomes so great that balance goes negative.

Without remedial measures, missions of 8 to 9 months would not be precluded, based on our present understanding of skeletal dynamics in weightlessness. Very lengthy missions would be precluded because of our belief that serious degradation to trabecular bone represents a morphological change that cannot be corrected.

During hypodynamic conditions such as bed rest, muscle size and strength are reduced. The resulting atrophy can be followed by measurement of excess nitrogenous compounds in the urine and by reduction in muscle volume. The musculature most affected is that involved in countering gravity, primarily in the legs. The most significant way to maintain musculature (tonus, strength, endurance) is to maintain a level of exercise which will prevent any loss of or change on the physiological properties of muscle. It is generally assumed that a properly designed exercise program will also result in sufficient skeletal stress to maintain the skeleton in prime condition, but the results from bed rest and space tests have thus far been disappointing.

The loss of nitrogen, both in increase in urinary nitrogen and by balance study (which takes into account the dietary protein intake) was significant; distinctly greater than previously noted in any bed rest study, and it continued for the full length of the Skylab flights.

In Skylab, there was no loss in work capacity. Muscular strength was slightly reduced. During postflight testing, work capacity was severely reduced, but the reduction was attributed to reduced cardiac output.

There was loss of nitrogen, indicating a loss in muscle mass which was also confirmed by measuring limb girth and by biostereometrics. The degree of atrophy is speculative as the fluid shift adds uncertainty to the interpretation of volume measurements. One investigator suggested the figure of 300 ml for muscle atrophy in Skylab astronauts, based on recovery kinetics.

Calculations of muscle tissue loss from nitrogen balance data indicated much greater muscle atrophy. These data indicate a mean muscle tissue loss among the three Skylab-4 astronauts of 1.9 kg. In recovery on Earth, there was a sharp drop in urinary nitrogen, to well below pre-flight levels, consistent with rebuilding of muscle tissue.

Postflight electromyographic studies on Skylab and the ASTP program showed muscle superexcitability and increased fatigability along with reduced tension capability. The ASTP data also showed increased electrical efficiency of arm muscles and decreased electrical efficiency of leg muscles.

Changes in size and electromyographic properties of muscle after prolonged space flight indicate that absolute muscular integrity has not been achieved by exercise. The experience of Skylab-4 indicated that there should be no concern for operational performance in stays of 90 days; from the continuation of increased urinary nitrogen excretion throughout flight, however, the duration of "no concern" beyond 90 days is uncertain, even with an exercise program.

Cardiovascular System

Hemodynamics

The normal or customary human tolerance to the stress of upright posture in one-g (orthostatic tolerance) is temporarily reduced after space flight. This is manifested subjectively by symptoms presaging syncope (faint-headedness, dizziness, weakness, transient instability upon standing) and objectively by test signs and cardiovascular measurements (increased heart rate, decreased pulse pressure, presyncope). The fairly consistent finding of a 10% loss in plasma volume after space flight may be a contributory factor in the development of orthostatic intolerance. Signs and symptoms may persist for up to one to two weeks after flight without a discrete mission duration dependency. A special concern arises when accelerative (decelerative) forces upon the long axis of the body ($+G_z$) are applied during crucial tasks, e.g., on reentry. To prevent tolerance from being exceeded, a cardiovascular counter pressure garment was worn to provide mechanical counterpressure to the lower extremities to reduce the postural hypotension of effects following landing and operations under one-g conditions.

No specific inflight operational problems are known that have a cardiovascular origin. A headward fluid shift may degrade performance, at least early upon attaining orbit, by virtue of reported feeling of malaise, headache, sinus congestion, and a sensation of head fullness.

Exercise capacity is moderately and transiently reduced postflight but appears well maintained inflight. The current hypothesis relates this postflight decrement in exercise capacity causally to the same mechanisms involved in reduced orthostatic tolerance.

Blood and fluid redistributions such that the heart does not fill normally seem to be at the core of the total phenomenon of orthostatic intolerance. It is conceivable that early inflight space sickness may be causally related. Alterations observed in inflight electrocardiograms are also probably directly related to cephalad fluid shifts.

Measurement of electromechanical properties of the heart postflight against a preflight baseline in both resting and stress condition revealed changes in systolic time intervals and reduced amplitude of the first heart sound. Recovery to preflight baseline required less than 31 days postflight, but the capability for maximum levels of exercise was depressed for perhaps two months.

Measurement of cardiac electrical parameters by vectorcardiography, and pre-, in- and postflight with ergometer and LBNP stress, revealed minor changes between resting values, pre- and postflight. Lower body negative pressure stress added to the changes. The most unfavorable responses to the LBNP stress diminished after five to seven weeks of flight. There were small changes except at recovery when low cardiac output compromised exercise capability. The changes during flight included increased QRS vector magnitude and reduced heart rate and response to exercise compared to preflight. The unfavorable responses to LBNP inflight and to exercise postflight were presyncopal in nature and of sufficient severity to cause early termination of test protocols. It should be noted that these failed protocols stem from inadequate venous return and consequent reduced cardiac output; the heart itself is not necessarily implicated.

The effect of the reappearance of hydrostatic forces due to reentry accelerations may accentuate the effects of an inadequate circulating blood volume after even a few days in space. Skylab experience indicates that adequate protection against orthostatic hypotension during reentry and during the first few hours after flight can be provided by a counterpressure garment. This countermeasure is indicated during any significant exposure to +Gz accelerations, as will be experienced by SPS crewmen¹. Recumbency can be of further

¹The effects of acceleration/deceleration is discussed in section B.

benefit during the first few hours after flight in cushioning the cardiovascular effects of return to one-g by preventing large shifts of intravascular fluids to the lower extremity vessels and extravascular compartments.

X-ray determinations of the cardiac area showed reduced dimensions postflight, attributed to either a loss of cardiac mass or a deficit in volume return to the heart. Recovery trends were noted in four or five days.

Measurements of heart parameters by echocardiography showed that the myocardium has lost mass in postflight measurements when compared with the preflight baseline. There was a reduction in ventricular end diastolic volume, and a reduction in stroke volume. These parameters returned to baseline in less than 30 days postflight. The investigators concluded that impairments of cardiac function as a result of space flight was relatively minor and recovery of function after flight was relatively rapid.

The only physical test of vascular parameters (other than venous pressure) was of compliance; the property of vessels to expand with increases in pressure. It was found that compliance of leg vessels increased for the first several days of flight, then lessened, and returned to baseline in several days after recovery. This would appear to be a small but significant complication to other factors causing cardiovascular embarrassment upon recovery.

Hematology

Blood studies performed in the space program included cell counts, red cell mass determinations, hemoglobins, hematocrits, plasma volume determinations, cytologies, and studies directed to immunological competence.

Plasma volume reduction averaged 8.4 percent in Skylab 2, 13.1 percent in Skylab 3 and 15.9 percent in Skylab 4 (see figure IV-1). The plasma volume loss may be attributed to operation of the Gauer-Henry reflex. An apparent overload of fluid causes atrial distension which causes the antidiuretic hormone (ADH) level to fall. Circulating fluid is then lost by diuresis or reduction in intake, or both (see figure IV-2). Discussion of the endocrinology depicted in figure IV-2 will be found in the sub-section entitled Endocrinology. It required approximately four weeks for plasma volume recovery after Skylab 2, two weeks after Skylab 3, and one week after Skylab 4.

Red cell mass appears to be some 15 percent reduced at about 40 days from launch (see figure IV-1). The red cell mass was apparently depleted by a splenic process. After 30 to 60 days in space, it appears that regeneration of the red cell mass had been initiated, and that regeneration was nearly complete after 84 days. The kinetics of recovery were identical whether or not the subject remained in flight, and complete recovery appeared at about day 100.

When the curves for red cell mass loss and plasma volume loss are superposed, as seen in figure IV-1, the kinetics of production of the effects and recovery are not matched; cell mass is normal while plasma volume is at near maximum reduction. This leads to rather high hematocrit values unless it is sensed and corrected.

Examination of erythrocyte shape showed that a significant fraction (about 7 percent) of the erythrocytes had undergone shape transformations to echinocytes near the end of Skylab 4. The echinocyte stage is the end stage in a series of recognizable changes from the disc-shaped red cell to a spheroid with protuberances. Within two hours after recovery, the echinocyte level had returned to the baseline value. Shape changes were without apparent significance or handicap to the crewmember.

Polymorphonuclear leucocyte ability to adhere, migrate and phagocytize was normal. This is a defense and clean-up process.

Immunity

Immunity entails a demonstrable level of defense against microbiological agents. Qualitative and quantitative tests are almost always performed outside the body, i.e., in vitro, with standardized reagents to show that the capability exists to repel an invader.

The only systems tested were humoral immunity which involved modified globulins, complement factors, several protein fractions, and B (bursa) lymphocytes which are carried in body fluids, especially the blood plasma; and cellular immunity which involves both T (thymus-dependent) lymphocytes and macrophages. Lymphocytes can engulf and neutralize microbiological agents. (Macrophage function is less specific and was not tested.)

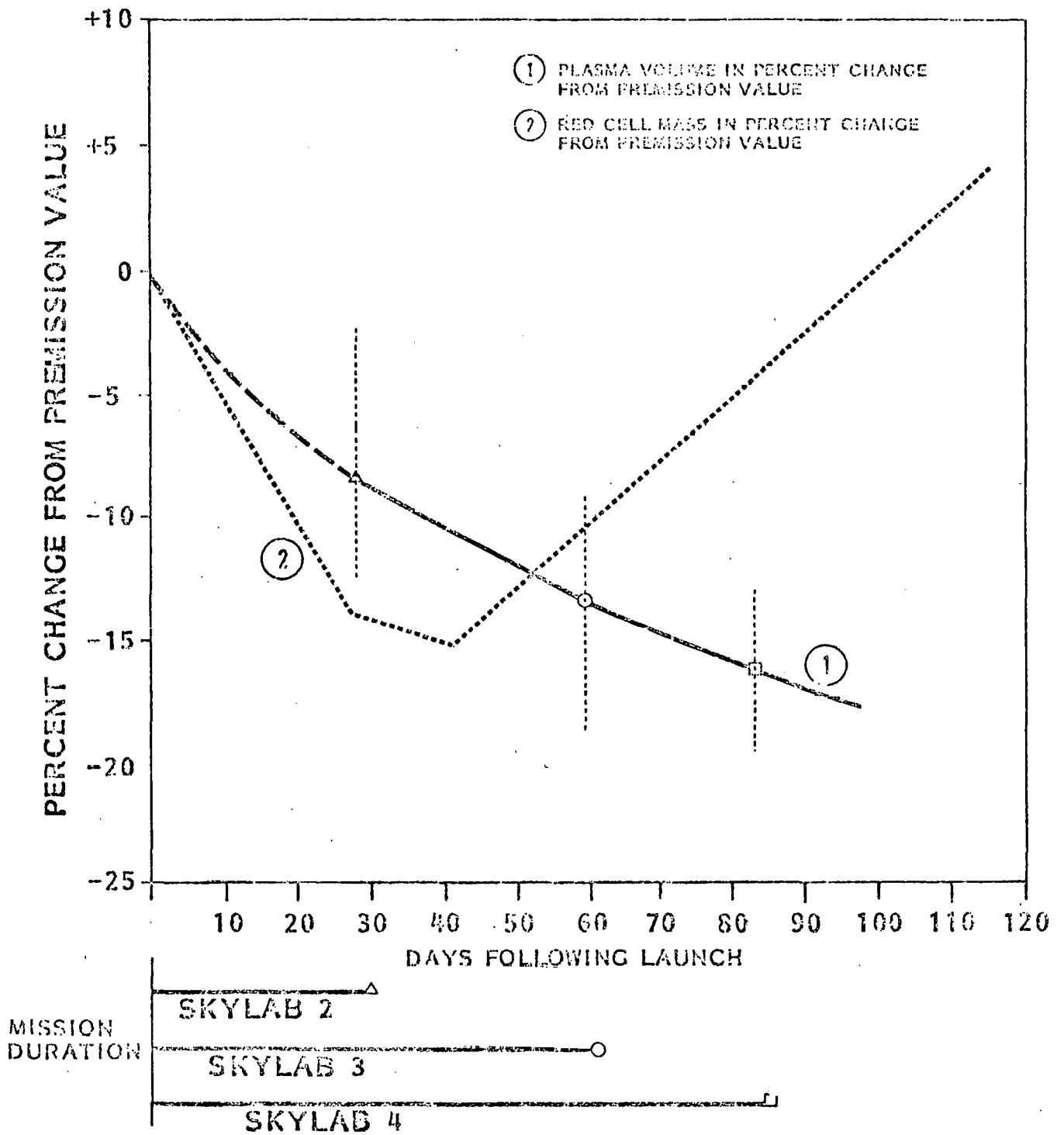


Figure IV-1. Blood volume changes in Skylab.

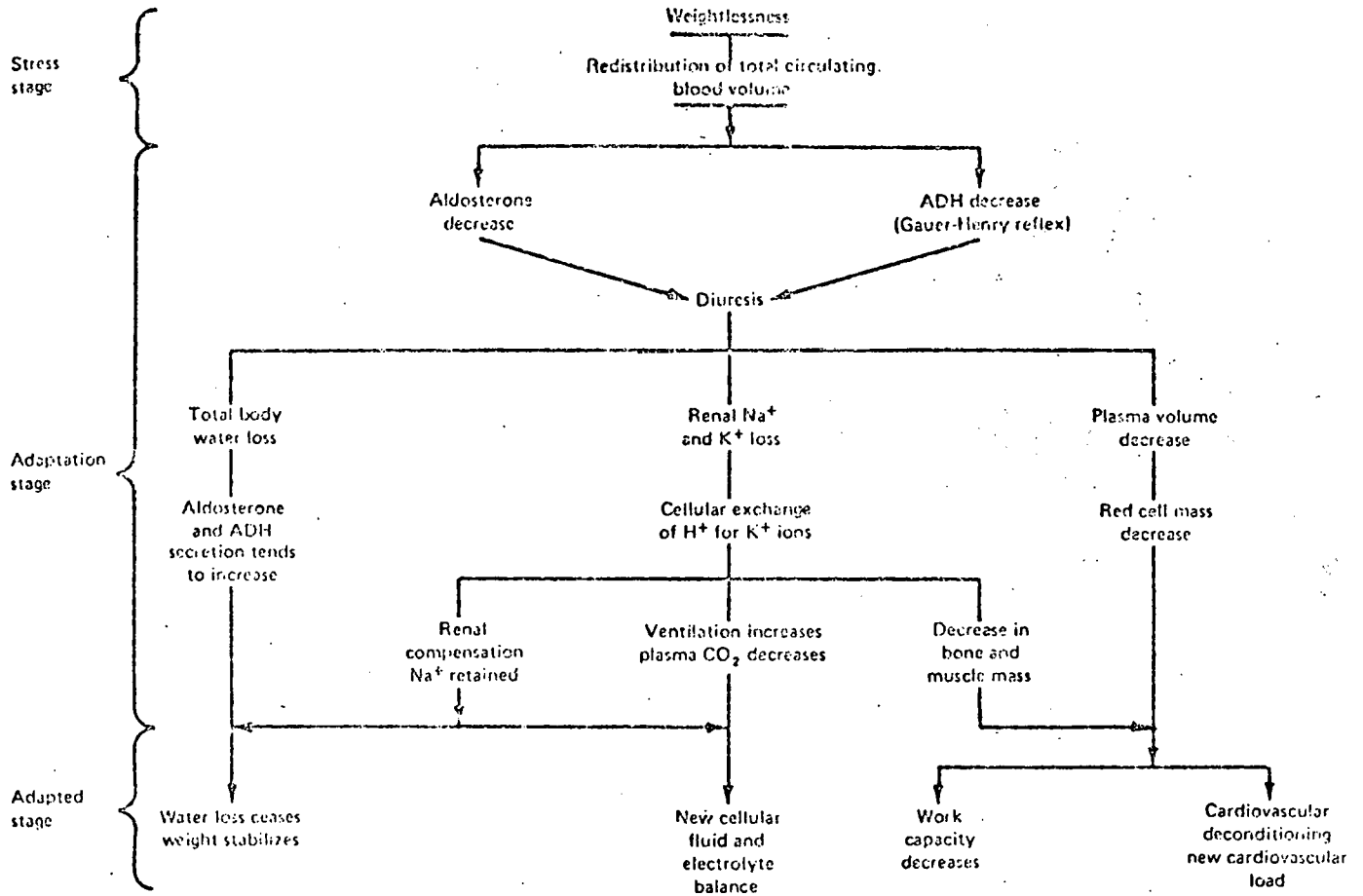


Figure IV-2. Adaptive fluid and electrolyte response to weightlessness (preSkylab hypothesis).

The capacity of the humoral system can be demonstrated by enumeration and quantification of immunoglobulins and other protein fractions.

The capability of the cellular system can be estimated by determining whether lymphocytes, when stimulated by a reagent, will synthesize additional nucleic acid, change shape (blastoid transformation) and subsequently engulf bacteria.

Another method of determining immune and defense status is by qualitative and quantitative estimation of microflora on astronaut's skin, mucous membranes and in their waste products pre-, in-, and postflight.

A final data source regarding immune status is the incidence of infectious disease during zero-g exposure and postflight. In Skylab, postflight infections included a sty, a boil, and a presumed fungal infection.

Principal Skylab findings of the cardiovascular system which might impact missions lasting longer than six months and which need further definition are:

- o Fluid redistribution in flight,
- o Plasma volume decrease contributing to orthostatic intolerance,
- o Red blood cell mass decrease, and
- o A potential for a significant breakdown in the capability of the immune system. A depressed or changed immune system, a self-contained environment, and decreased attention to cleanliness are conditions favorable to rapid multiplication of microbes.

Nervous System

The central nervous system has not been evaluated by quantitative tests in space, but many facets of its performance, homeostasis¹, registering of senses (sight, hearing, etc.), cognitive functions, problem solving, and sleep have been carried out with no hint of decrement.

¹Homeostasis is the state of equilibrium in the living body with respect to various functions and to the chemical compositions of the fluids and tissues, e.g., temperature, heart rate, blood pressure, water content, blood sugar, etc.

The peripheral nervous system is not known to be affected by weightlessness. However, weightless effects on other systems, e.g., altered calcium-potassium ratios, could significantly affect nerve thresholds and recovery and thus produce alterations in nerve function.

In Skylab, task performance in zero-g equaled ground baseline efforts after a few trials, and performance continued to improve with time.

Heart rates were usually elevated inflight in the U.S. programs, particularly before stress tests. There were also reported fluctuations in heart rate in the Soviet Union programs.

Sleep was found to be adequate in quality and duration. In the postflight period, REM sleep appeared earlier in the night (reduced latency) and was increased in quantity.

The Achilles tendon reflex time was generally shortened for more than four days postflight. However, for Skylab 3 there was a lengthening which returned to baseline by 29 days postflight. For Skylab 4, after the initial shortening, there was a lengthening and a return to baseline by 30 days postflight.

Postflight, muscle electrical activity-time shortened similarly on three crewmen and increased on one other. Two crewmen showed lengthening for less than a week and two showed shortening for a similar period before approaching baseline in the 30 days. A part of these changes is attributable to muscle reaction as well as to nerve conduction.

Neurophysiology

Vestibular responses in zero-g had been the subject of considerable speculation preflight because one of the sensors, the otolith, is a gravity (verticality) sensor. Ground-based tests showed it would be able to detect accelerations and decelerations occurring in zero-g, but would lose its usual one-g stimulus; the remainder of the vestibular apparatus would function in zero-g identically to the way it functions in normal gravity. Orientation with respect to gravity in zero-g would, therefore, depend on visual and tactile cues. Any misfits in the input of information were expected to result in illusions and confusion.

In Skylab there was a variety of symptoms. Illustrations include sensations of rotation, nystagmus, dizziness, vertigo, and postural illusions.

Neurophysiological response by the vestibular and autonomic nervous systems to zero-g resulted in motion sickness symptoms. Signs included pallor, cold sweating, nausea and vomiting. Five of the nine Skylab astronauts were affected, although not always to the vomiting stage. Inflight, complete recovery from symptoms typically occurred within three to five days. After this initial period of adaptation, crewmen were virtually free of motion sickness symptoms.

Upon return to one-g, there were several days of unsteadiness while visual proprioceptive, motion, and gravity cues were readjusted.

Organs of Special Sense

Flight data for these sensory modalities were not quantitated on Skylab but a number of phenomena, produced by acceleration, did involve the eyes reflexly. Some visual experiences in zero-g including ocular counterrolling, oculogyric illusion and oculogravic illusion represent reflex activity of the vestibular apparatus. None is abnormal, unpleasant, or incapacitating. Nystagmus, on the other hand, has the same genesis but is mildly unpleasant and temporarily interferes with vision. It is probable that all of these phenomena were experienced in Skylab but only nystagmus was reported.

Other Sensors

Homeostasis, the process through which body equilibrium is maintained, is achieved through sensors. Since the environment to which the body and its processes must adjust is altered in weightlessness, there is concern over the adequacy of these responses. In some cases, the adjustment involves a physiological change. For these changes to be acceptable, they must be beneficial or at least not harmful, and they must be reversible upon recovery. If these criteria are not met, NASA will seek to prevent or correct the adjustments by some ameliorative technique. A first step is to determine that the sensors are functioning in a purposeful manner.

The associated matrix in section III entitled, *Inventory of Human Responses to Space Flight* lists data from Skylab experiments and the associated responses. Interpretations are frequently not clear and more detailed studies will be

needed to provide suitable solutions to the problems of altered hemostasis in the weightless environment.

It appears that the nervous system has maintained its stability in the transition to zero-g, while in zero-g, in the transition to one-g, and during the body's recovery in one-g conditions. Excellent mental, behavioral and physical performance was noted both inflight and postflight. While permitting some detailed changes in the various organ systems which are adaptive in nature and, in the main, help attune the transition or an organ to a challenge, there are exceptions which the medical and scientific communities regard with caution, e.g., potassium loss, reduction in immune competence, demineralization, muscle atrophy and vestibular performance pattern changes. These may be desirable adaptations to the new environment; when they aren't, it may be that the sensors which supply information to the central nervous system (such as pO_2 , pCO_2 , blood volume, posture) are at fault rather than the nervous system itself.

Motion sickness is likely to occur soon after entering zero-g, and the malaise lasts for about three days. Nevertheless, duties can be accomplished during this period. Physical accommodation plus drugs may limit or prevent motion sickness. Preflight screening may be necessary to eliminate sensitive individuals.

Current experience indicates vestibular responses would not be a limiting factor to extended periods in zero-g. Visual acuity, hearing, smell, taste and touch appear to be normal in zero-gravity and upon recovery, thus they are not considered to be limiting factors for STS missions.

More detailed studies will be needed to provide the background to judge the adequacy of the sensors and the systems in which they perform. In this way the enigmas of potassium and calcium loss can be solved - how sensors are involved and whether the losses are related to efforts to correct untoward electrolyte imbalances caused by weightlessness.

The parameters of homeostatic control and the adequacy of the sensors that serve the system for adaptations to weightlessness are largely unknown. This

is an important area for research because calcium, potassium, water and nitrogen balances are involved. The results will be important inputs to planning for STS missions.

Excretory System

The very large body of data on homostasis, hematology, food and nutrition, endocrinology, metabolism, and biochemistry in space owes its cohesiveness to the controls governing mineral and fluid balance and excretion. The principal functional unit in carrying out the operations that result in homeostasis is the kidney; it excretes excess water and, selectively, electrolytes in the proper ratio in order to maintain the necessary balance and pH. Other materials excreted are generally waste products. The intestine, lungs and skin also play important roles in removing products that aid in achieving homeostasis.

Functioning of the control system and the normality of creatinine excretion prove the intactness of the excretory function in zero-gravity.

There was, however, a slight increase in plasma creatinine in both Skylab and ASTP. There was nothing to suggest the risk of urolithiasis (formation of kidney stones), for which some concern has been expressed from the increased calcium excretion experienced in bed rest simulations and actual space flight; maintenance of adequate urine volumes will be obviate such risk.

Although there were no specific challenging tests of the excretory system in space such as were performed on the respiratory and circulatory systems and musculature, nothing was found that indicates any limit to stays in space based on decrements in renal performance.

Digestive System

Foods of known composition have been tested during simulations at reduced atmospheric pressures and pre- and postflight during U.S. space missions. Data from these tests have been used to establish baseline norms and postflight differences for each astronaut.

Essentially, the digestive system has functioned in a normal, predictable manner. Foods in the Apollo Program, caused soft stools, pre-, in-, and

postflight. Flatulence, when present, was worsened in reduced environmental pressures, in simulations and inflight. Astronauts occasionally took an anticholinergic drug (Lomotil) to control bowel activity.

There was one case of a flu-like upper respiratory condition which was accompanied by nausea and vomiting. Also there have been cases of nausea and vomiting which were attributed to motion sickness and which lasted from one to five days.

Departures from anticipated in-and-out nitrogen and electrolyte balances were caused by muscle atrophy, bone demineralization, and excretion of more potassium than was ingested.

Future food tests will be conducted at standard atmospheric pressure; excessive flatulence should not recur, and no aspect of digestive system function should limit orbital stay times.

Respiratory System

Since the lung is a highly elastic structure with air and fluid-filled regions, it is sensitive to influence that restrict its expansion or contraction and displace or augment its fluid component, e.g., accelerations.

Very sophisticated inflight determinations of pulmonary function of Skylab showed no decrement in the ability of the respiratory system to support exercise. A loss in vital capacity attributed to fluid shift to the lung circulation offered an obstacle to achieving the deepest inspiration. This loss of vital capacity did not appear in postflight tests.

Pulmonary function suffers little or no decrement in zero-g. If there is any decrement, it is constant and not progressive. In healthy subjects, pulmonary function does not limit exercise capability. The limiting factors are usually muscular fatigue or circulatory competence, depending on the condition of the individual.

Reproductive System

There have been no special tests performed to determine the effect of zero-g on the male reproductive system. Reported occurrences of congestive prostatitis and irritated urethras were caused by wearing a urinal during early space flights. Space flight has had no demonstrable affect on the male reproductive system.

A female cosmonaut (Soviet) is reported to have had normal children several years after her flight in space. While the U.S. has not used female astronauts, space simulation studies do not preclude them from taking part in future space missions.

Biochemistry

By quantitative chemical analyses, changes in the intracellular and interstitial body fluids can be monitored. Examples of these body fluids are plasma, lymph and cerebrospinal fluids, parotid secretion and urine.

Analyses for nutritive components (metabolites) in plasma such as amino acids, nitrogenous compounds, glucose, cholesterol and triglycerides indicate the normality or abnormality of protein, carbohydrate and fat metabolism during space flight.

As the space program matured, a battery of tests of increasing complexity carried out on plasma serum and urine, showed a number of changes. Many of these changes were similar to the effects observed in bed rest. These changes are regarded as an adaptation response to the weightless condition.

Inflight excretions of sodium, potassium, chloride, calcium, phosphate, and nitrogen were elevated. Inflight plasma sodium and chloride were reduced and plasma calcium, phosphate and potassium were elevated. Exchangeable potassium was reduced postflight, indicating potassium depletion through the reduction in muscle tissue mass.

Metabolic processes were found to be qualitatively unaffected by weightlessness. Quantitative changes were indicated by: reduction in insulin and glucose during flight, loss in fat stores, altered levels of metabolites of

protein origin in the plasma suggesting a catabolic process, and losses in body water and body weight. The known changes are regarded as posing no threat as they are within normal ranges and are quickly reversible postflight.

Endocrine System

The physiological relationships of the endocrine system influence and regulate body functions such as excretion, metabolic and neurohumoral controls to maintain homeostatic balance as the body adapts to weightlessness. Endocrinological data are obtained from electronic monitoring of the cardiovascular, muscular, and possibly the neurological body systems, and from a detailed analyses of blood and urine specimens for levels of hormones and the substances they cause to be mobilized, excreted, metabolized, or stored. For example, cardiovascular monitoring can detect changes in heart rate and blood pressure. Electromyography detects changes in muscular physiology. Discrete levels of hormones acting on tissues are detected by blood analyses, and activity levels, which are longer lasting, are found as traces in urine. These and other data collected from fluid shifts, energy metabolism, and hematology are vital adjuncts to assessment of endocrine function and homeostatic adjustments.

In Skylab, levels of the following hormones were estimated in plasma (serum) or urine, or both; adrenocorticotrophic hormone (ACTH), cortisol, angiotensin I, aldosterone, insulin, human growth hormone, thyroxine, thyroid stimulating hormone, testosterone (andosterone), parathormone, calcitonin, antidiuretic hormone, epinephrine, norepinephrine, total 17-hydroxcorticosteroids and total 17-ketosteroids. Of these, cortisol, epinephrine and norepinephrine are usually associated with physical and emotional stress.

Significant changes were observed, which varied in magnitude and direction. They all disappeared shortly after return to Earth. The changes are for the most part indicative of a successful adaptation by the body to the combined stresses of weightlessness and flight. It is evident that a new, stable level of homeostasis is achieved in space and the safe exposure times of crewmen to the weightless environment is not limited.

The neurohumorally controlled changes predicted to occur in the process of adaptation to weightlessness are diagramed in figure IV-2. The predictions were borne out in well over half the areas which were highlighted. The remainder are areas in which predictions were borne out equivocally, or negatively demonstrate that there are unknown mechanisms or that the mechanisms have as yet been imperfectly described.

Energy Metabolism (Metabolic Activity, Work Capacity, Exercise Tolerance)

In normogravity, weight and friction induced by gravity usually suffices to maintain a person's stance at a chosen place.

Coversely, maintaining one's stance at a chosen place in zero-g requires means for restraining or stabilizing oneself so that one can exert forces without being displaced, and preferably without having to use muscular energy.

In the space program, early efforts were centered on devices involving thrusters to aid mobility and restraint. In the Gemini program, mobility did not suffer but extravehicular (EVA) activities were compromised by lack of restraints to the extent that seemingly simple tasks caused overwork and produced more metabolic heat than the space suits could handle. These findings caused a shift of emphasis from mobility devices to stabilizing and restraint devices.

In Skylab, it was found that the isotonic task of riding a cycle ergometer offered no more of a challenge than in one-g, and, in time, astronauts became more efficient in zero-g. This test was not carried to a maximum effort, however, but was at a high level, 230-286 watts, roughly 1/3 horsepower.

Maximum-effort arm and leg flexion and extension showed small decrements when tested postflight against a dynamometer. With increasing allied exercise on a zero-g treadmill and other exercise devices, the decrements became less than 0.1% per day in leg extension maximum effort.

Somewhat similar measurements were made postflight in Skylab and ASTP with an isometric task, while electromyography (EMG) was employed. In this case, it was noted that EMG changed during holding of less than maximum effort forces, fatigability was enhanced, and efficiency was degraded.

Postflight, the Skylab astronauts showed severe decrements in work capacity on a stationary cycle ergometer. It became apparent that the cardiac output was too low to support the levels of exercise that were used preflight and inflight, hence the problem was in readapting the one-g conditions.

Recovery to baseline capability required, usually, less than a month, but there were decrements in strenuous whole body exercise capability, such as running, for approximately two months. Astronaut reported experiences are parallel. They feel that the appropriate period for rehabilitation following space flight is three months.

The physiological responses to exercise inflight showed differences that can not be generalized for all crewmen. These included decreased recovery heart rate, decreased systolic blood pressure, decreased diastolic blood pressure, increased resting respiratory minute volume, increased pulmonary ventilation, decreased or increased oxygen consumption and carbon dioxide production, decreased pulmonary efficiency (lung ventilation necessary to provide a certain oxygen consumption), and decreased mechanical efficiency (oxygen consumption necessary to provide a certain level of energy output). These changes did not degrade the capability to perform submaximal exercise but did show that the quantitative relationships among cardiovascular, respiratory and musculoskeletal parameters that were obtained during preflight testing were not maintained in flight.

Flight menus were designed to meet comparable individual energy requirements under normal gravity conditions, specified nutrient levels, and crew-selected preferred foods. Energy requirements calculated for each Skylab crewman averaged 45.68 kilocalories (Kcal) per kilogram (kg) of body weight per day with a standard deviation of 4.50 Kcal/kg/day. Based on inflight changes in total body weight, muscle mass, and body volume, they lost weight.

The estimated energy required to maintain a crewman during the ASTP mission was approximately 39 Kcal per kg of body weight per day. This estimate was based upon preflight measurement of lean body mass and adjustments for inflight activity levels. Although this lesser amount was thought to be adequate because of the brevity of the ASTP mission and the failure to achieve metabolic stabilization, these crewmen lost weight also.

An awareness of the true energy demands should be kept in mind for an understanding of the degree of metabolic energy needed for productive work in flight and without loss of body weight.

The cycle ergometer is regarded as an excellent testing tool but inadequate for maximal stress to the individual and not suited to an important musculoskeletal parameter, maintenance of bone and muscle integrity, and particularly of antigravity muscles and weight-bearing bones.

It was found that exercise tolerance was maintained quite well in zero-g by a program that supplemented ergometry with exercise devices which employed the anti-gravity muscles and weight-bearing long bones. The most pertinent device resembles a functional treadmill.

It is apparent that work can be done efficiently in a weightless environment if tasks are properly designed. Man's capability of living and working for long periods of time in zero-g do not appear to be limited by bioenergetic considerations.

Physiological Limits

Definitive limits have not as yet been established for continuous or cumulative exposures to the weightlessness of space flight. Several physiological effects mentioned in the previous discussion could ultimately impose limits on zero-g exposure. Bone demineralization is the most apparent effect of weightlessness that could limit flight durations in the SPS program. Degeneration of gravity receptors is another potential limiting factor for space-flight duration; however, the nature and time course for the development of this effect remain speculative. Both of these effects are only realized with reappearance of gravitational or other external forces. Other physiological effects of weightlessness, such as cardiovascular deconditioning, loss of plasma volume, and immunosuppression, may not be current limiting factors to space-flight duration but will require monitoring and deployment of appropriate countermeasures.

Motion sickness appears to be a time-limited annoyance that interferes with performance. The fluid shift and spinal lengthening that interferes with

fitting and wearing of emergency equipment and with physical comfort at work station equipment can be remedied by forethought and application of better bioengineering designs.

Exposure limits must be derived through further experimentation and/or progressively increased exposures to zero-g. When established, these limits will likely be a function of the availability of effective countermeasures. Moreover, with sufficient progress in these countermeasures, weightlessness, as such, may not be the most critical factor for limiting long-duration space flight.

Space experience in the U.S. to date has shown that man can live and work in space for periods of as long as 84 days. It has also shown that the most deleterious effects of zero-g exposure may not be realized until return to one-g and subsequent readaptation. From physiological evidence amassed through extensive experimentation in cardiovascular, hematological, endocrinological, vestibular, and musculoskeletal systems, it can be stated that the tentatively allowable exposure period to zero-g can be safely extended to 6 months. This may not apply to reexposure to zero-g after a recovery period in one-g; a cumulative problem of more seriousness than an initial exposure to weightlessness may appear.

Physiological measurements and performance parameters should be carefully monitored during these extended missions to detect debilitating changes that might occur. This approach of systematically increasing exposure times can be continued until physiological limits are approached or until operational goals are realized.

B. EFFECTS OF ACCELERATION/DECELERATION

Physical forces act on the body to cause acceleration and displacement of the whole or some part of the body. The extent and the circumstances of the response of the body to force may result in a range of physiological responses from a level at which no effect can be perceived or measured to a level resulting in massive tissue destruction. This section represents an attempt to differentiate and define the types of forces that may act on the body, to

identify the physiologic effects, to present limits for these forces, to present the rationale for these limits, and to identify areas in which additional research is required. For the purposes of this section, the forces will be divided into those resulting in sustained linear acceleration and in angular acceleration.

NASA has very limited information on the effects of acceleration/deceleration in space flight and will be unable to provide substantial information regarding these environments until further research is accomplished.

The results compiled by NASA of extensive studies involving "ground-based" testing on subjects who have resided in a one-g environment is presented here.

The reader is advised to use care in the application of the information presented here. Although very limited quantitative analyses and test results exist, it is known that the nature of the response of the body to linear and angular accelerations is altered when in the weightless environment and upon return to one-g after a space flight. The duration of exposure to weightlessness is known to influence the extent to which the response of the body to acceleration is altered and also the length of time to readjust to normal pre-flight response characteristics.

Sustained Linear Acceleration

Definition and Description

Sustained linear acceleration can be defined as the response of an object or a body to a net directional force applied over a duration of 0.2 seconds or more.

Linear acceleration occurs whenever there is a change in velocity of the spacecraft (e.g., during spacecraft launches and entries). The nature of the response of the body to linear acceleration depends on a number of characteristics of the force and resultant acceleration.

The magnitude of the force acting on the body and the mass of the body determine the magnitude of the acceleration. The duration of the acceleration is a significant factor in the response of the body, particularly at the shorter

duration exposures approaching impact (duration < 0.2 second). Also significant are the direction of the force vector, the resultant direction of acceleration with respect to the orientation of the body, and the specific body position. The restraint and support systems for the human body in an accelerating vehicle determine the manner in which forces are transmitted from the vehicle to the body and thereby strongly influence the physiological response to the acceleration.

The symbol g_0 (g_0 or g) represents a unit of acceleration equal to 980.665 cm/s^2 and equal to the acceleration resulting from the unopposed force of gravity at sea level. The symbol G is used to denote a nondimensional, relative measure of either acceleration expressed in multiples of g_0 or a force field expressed in multiples of the force of gravity. The unit G is used to represent acceleration in describing the physiological stresses in response to acceleration and is sometimes referred to as a unit of physiological acceleration.

Acceleration is a vector quantity, and, in the literature on the effect of acceleration on mammalian subjects, the direction or vector of G , or the G load, is denoted by the North Atlantic Treaty Organization Advisory Group for Aeronautical Research and Development (AGARD) convention shown in figure IV-3.

The symbols G_x , G_y , and G_z are used as units to express inertial resultants to whole-body linear acceleration in the three orthogonal axes in multiples of the magnitude of the acceleration of gravity g . In this usage, G is the inertial force of the body resisting acceleration and the G vector is in the direction opposite that of the vehicle acceleration. The symbols R_x , R_y , and R_z denote angular acceleration about the three orthogonal axes as discussed in the section entitled "Angular Acceleration."

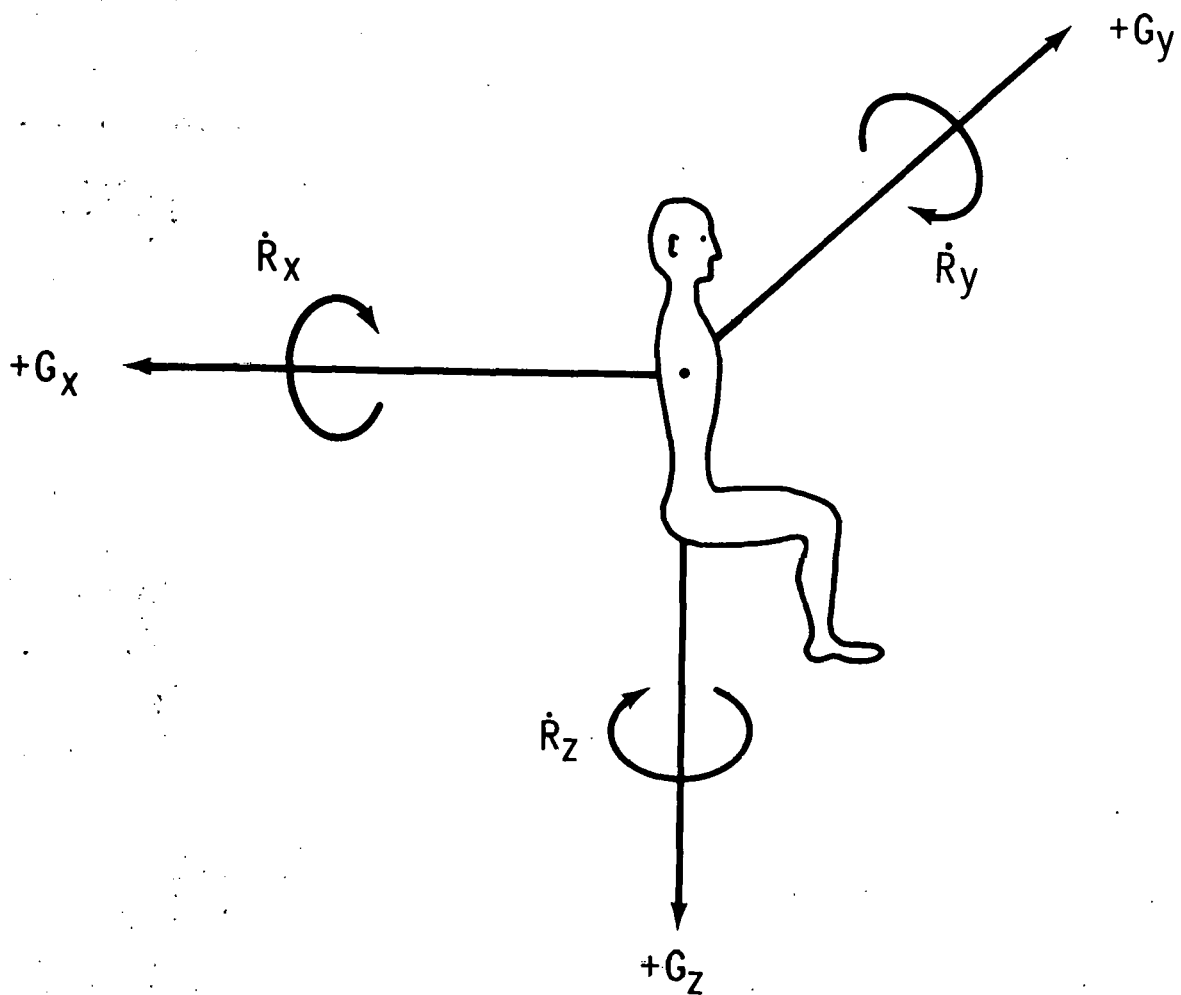


Figure IV-3. AGARD physiological acceleration system.

Physiological Effects

The physiological response to sustained linear acceleration is a response to the forces and pressures acting on the body to cause the acceleration. On the surface of the Earth, the force of gravity acts on every element of body mass. This force is directional toward the center of the Earth. When a body is stationary on the surface of the Earth, the force of gravity is countered by an equal force vector in the opposite direction. This force is effective at the points of contact of the body with the Earth but must be transmitted to each element of body mass if the acceleration of the element is to be prevented. The structure of the body has evolved under one-g conditions and is adapted to the transfer of forces supporting the body (resisting acceleration to the center of the Earth) for those body positions that are normally assumed on Earth.

When a space vehicle is accelerated at a given rate, the forces generating the acceleration must be transmitted from the rocket engines to all mass elements of the vehicle and to all mass elements of the passengers. The physiological effect of acceleration occurs when the structure of the body is not capable of transmitting applied forces to each element of the body with the result that relative movement of body elements occurs and relative pressures within the body are altered. These effects will be considered in the following paragraphs for different axes of acceleration as defined in figure IV-3 and for the physiological systems most limiting in each axis.

The cardiovascular effects of acceleration are generally the most significant. The force causing the acceleration of the body is transmitted to the blood. This transmittal of force is accomplished by the following sequence of events. Blood is displaced in the direction opposite the accelerative force. This displacement is resisted by the elastic tissues of the body so that a pressure gradient is created in the vector opposite that of the force causing the acceleration. Engorgement and pooling of blood occurs in the areas of the body that experience higher than normal blood pressure. Diminished blood flow rates and poor oxygenation of tissues result in those areas of the body that experience lower than normal blood pressure. The greatest changes in cardiovascular pressures occur when the acceleration vector is parallel to the course of the major blood vessels of the body (G_z). The effects are most severe when these pressures displace blood from the head ($+G_z$). Progressively reduced blood pressure in the head will result in loss of visual acuity, gray-out, blackout, and finally unconsciousness as the oxygenation of the eyes and the brain is progressively reduced.

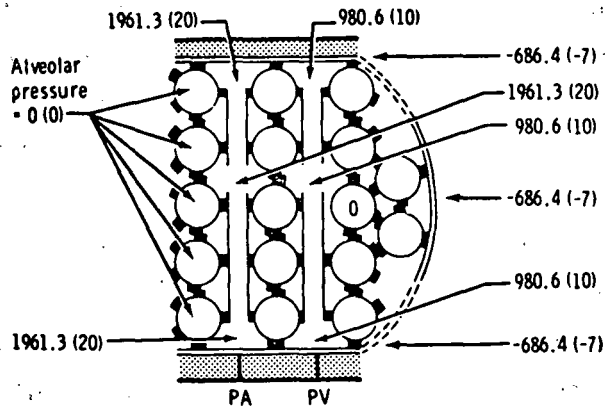
The respiratory effects of acceleration result from a change in relationship of pressure differentials, which, in a one-g environment, facilitate respiration and gas exchange. In a supine subject in a one-g environment (where the force of gravity is effective in the $+G_x$ orientation), there is normally a gradient in intrapleural pressure and in both arterial and venous pressures from dorsal to ventral chest walls (figure IV-4). These gradients do not interfere with inflation and deflation of the lungs or with perfusion. However, under severe G loading, the pressure differentials at the intrapleural

interface resulting from the acceleration become more significant. Modification of intrapleural pressure by exertion of respiratory musculature in the chest wall becomes insufficient to inflate the alveoli near the dorsal chest wall or to empty the alveoli near the ventral chest wall. In addition, the pressure gradients in the blood vessels reduce or eliminate perfusion of the alveoli near the ventral chest wall. Respiration is affected by acceleration in all axes but is affected most significantly by $+G_z$ acceleration. Respiratory effects are more likely to be the limiting factor in $+G_x$ acceleration, however, because there is greater tolerance to cardiovascular effects in that vector.

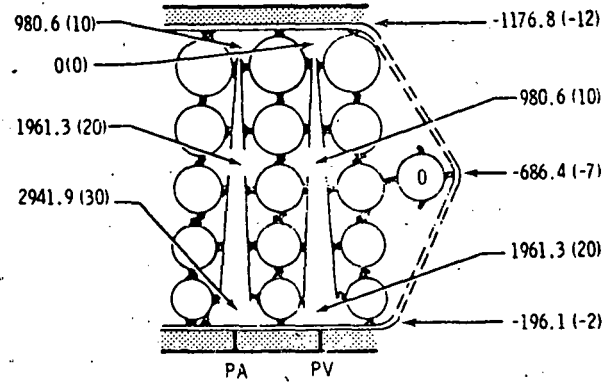
There are direct effects of forces due to acceleration on all the body organs and systems as well as effects secondary to the hypoxia that may result from the cardiovascular and respiratory alterations and to hormonal response to the general body stress. Figure IV-5 depicts some of the interrelationships that may occur at different functional levels.

Table IV-1 contains a listing of subjective effects of sustained acceleration in each of the possible vectors. These subjective effects derive from the physiologic effects that have been described previously and bear on the tolerance limits that will be discussed in the following paragraphs.

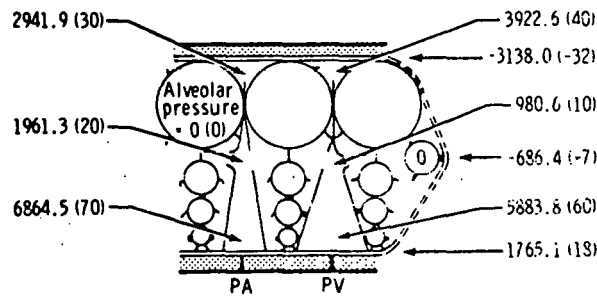
To date, NASA limits launch and landing accelerations to levels of 3-g or less.



(a) Null gravity.



(b) Normal gravity.



(c) Acceleration of 5G.

Figure IV-4. Influence of $+G_x$ accelerative stress on intrapleural pressure. The dorsoventral dimension of the lung is 20 centimeters; the ventral chest wall is at the top and the dorsal chest wall at the bottom. The single zeros denote atmospheric pressure in the central portion of the thorax in the plane of the heart. The values represent positive and negative intrapleural pressures (with directional arrows) and positive pulmonary pressures (i.e., PA = arterial pressure and PV - venous pressure) expressed in newtons per square meter (centimeters of water).

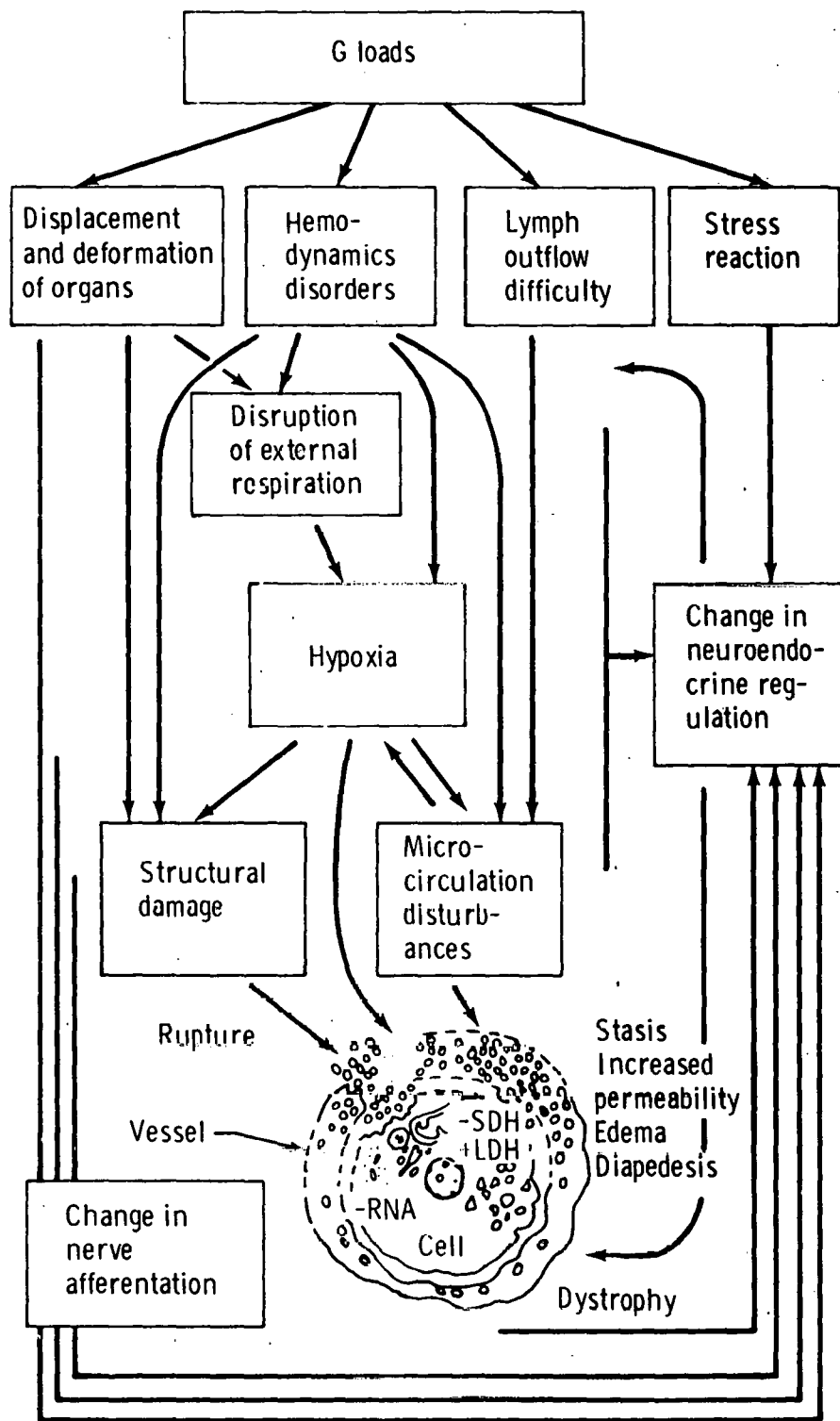


Figure IV-5. Basic mechanisms of accelerative action on an organism. Cell changes consist of increased activity of lactate dehydrogenase, (+LDH), reduced activity of succinate dehydrogenase (-SDH), and reduced quantity of ribonucleic acid (-RNA) in cytoplasm.

TABLE IV-1.- SUBJECTIVE EFFECTS OF ACCELERATION

Magnitude, G	Effects
Positive acceleration (+G _z)	
1	Equivalent to the erect or seated terrestrial posture.
2	Increase in weight, increased pressure on buttocks, drooping of face and soft body tissues.
2.5	Difficult to raise oneself.
3 to 4	Impossible to raise oneself, difficult to raise arms and legs, movement at right angles impossible; progressive dimming of vision after 3 to 4 sec, progressing to tunneling of vision.
4.5 to 6	Diminution of vision, progressive to blackout after approximately 5 sec; hearing and then consciousness lost if exposure continued; mild to severe convulsions in about 50 percent of subjects during or following unconsciousness, frequently with bizarre dreams; occasionally paresthesias, confused states and, rarely, gustatory sensations; no incontinence; pain not common, but tension and congestion of lower limbs with cramps and tingling; inspiration difficult; loss of orientation for time and space as long as 15 sec after acceleration.
Negative acceleration (-G _z)	
1	Unpleasant but tolerable facial suffusion and congestion.
2 to 3	Severe facial congestion, throbbing headache; progressive blurring, graying, or occasionally reddening of vision after 5 sec; congestion disappears slowly, may leave petechial hemorrhages, edematous eyelids.
5	Limit of tolerance, 5 sec; rarely reached by most subjects.

TABLE IV-1.- Continued

Magnitude, G	Effects
Forward acceleration (+G _x)	
2 to 3	Increased weight and abdominal pressure; progressive slight difficulty in focusing and slight spatial disorientation, each subsiding with experience; 2G _x tolerable at least to 24 hr, 4G _x for at least 60 min.
3 to 6	Progressive tightness in chest (6G _x , 5 min), chest pain, loss of peripheral vision; difficulty in breathing and speaking; blurring of vision; effort required to maintain focus.
6 to 9	Increased chest pain and pressure; breathing difficult, with shallow respiration from position of nearly full inspiration; further reduction in peripheral vision, increased blurring, occasional tunneling, great concentration to maintain focus; occasional lacrimation; body, legs, and arms cannot be lifted at 8G _x ; head cannot be lifted at 9G _x .
9 to 12	Breathing difficulty severe; increased chest pain; marked fatigue; loss of peripheral vision, diminution of central acuity; lacrimation.
15	Extreme difficulty in breathing and speaking; severe vise-like chest pain; loss of tactile sensation; recurrent complete loss of vision.
Backward acceleration (-G _x)	
--	Similar to effects of +G _x acceleration with modifications produced by reversal of force vector. Chest pressure reversed, hence breathing easier; pain and discomfort from outward pressure toward restraint harness manifest at approximately -8G _x ; with forward head tilt, cerebral hemodynamic effects manifest akin to -G _z ; distortion of vision at -6G _x to -8G _x ; feeling of insecurity from pressure against restraint.

TABLE IV-1.- Concluded

Magnitude, G	Effects
Lateral acceleration ($\pm G_y$) ^a	
3	Discomfort after 10 sec; pressure on restraint system, feeling of supporting entire weight on clavicle; inertial movement of hips and legs, yawing and rotation of head toward shoulder; petechiae and bruising; engorgement of dependent elbow with pain.
5	External hemorrhage; severe postural headache (14.5-sec duration).

^aLittle information available.

Physiological Limits

The accelerations that occur or are predicted during space flight can be quantified. However, the concentration of force and the relative displacement within the body which are the causative agents of the physiological effects are very difficult to quantify. The physiological effects are very difficult to quantify. The physiological limits are therefore most easily stated in terms of acceleration. Different empirically defined limits can be shown to apply under a variety of conditions of body support and restraint (figure IV-6). The effects of these supports are to distribute the force over the body and to restrict deformation and changes in volume of body segments. The most effective restraint is immersion in water. When the body is immersed in water, it becomes part of the liquid system in which it is immersed and there is good transfer of force without deformation. The air cavities in the body do allow some deformation that becomes limiting at higher G levels. Tolerance varies as a function of acceleration vector as shown in figure IV-7. During practical space operations, it is unlikely that an acceleration will be restricted to one vector. Since reduced tissue oxygenation and reduced respiratory ventilation are both likely to be effects of high levels of acceleration, it is not surprising that pressure breathing and enriched-oxygen

breathing mixtures have been shown to increase tolerance to acceleration. Figure IV-8 shows the upper limit of tolerance of a group of highly motivated test pilots suitably restrained without water immersion. It can be compared to the average tolerance values depicted in figure IV-6. The tolerance limits, therefore, must be stated in terms of the acceleration. The heavy solid line in figure IV-7 is a plot of required acceleration to achieve Earth orbit against the required duration of that acceleration. Plotted on the same graph are some nominal limits for acceleration. This plot illustrates the physiological trade-off that must be made between short-duration, high-G loads and much longer duration, lower G loads.

Because overall human tolerance to sustained linear acceleration in the transverse ($+G_x$) axis is effectively twice that in the vertical ($+G_z$) axis, all manned space vehicle launches and entries before the Space Shuttle have oriented thrust near the $+G_x$ axis. Maximal peak $+G_x$ forces for the Apollo spacecraft reached approximately six-g on entry with lesser values for launch and orbital maneuvers. Mercury and Gemini spacecraft operated at slightly higher values (figure IV-9). No acute operational problems, significant physiological deficits, or clinical sequelae related to the cardiovascular and musculo-skeletal systems are known to have resulted.

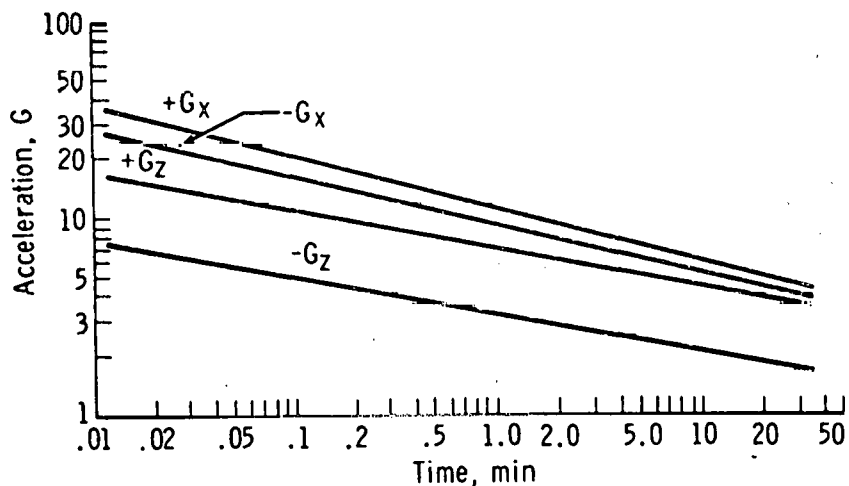


Figure IV-6. Comparison of average G tolerance in four vectors of sustained linear acceleration.

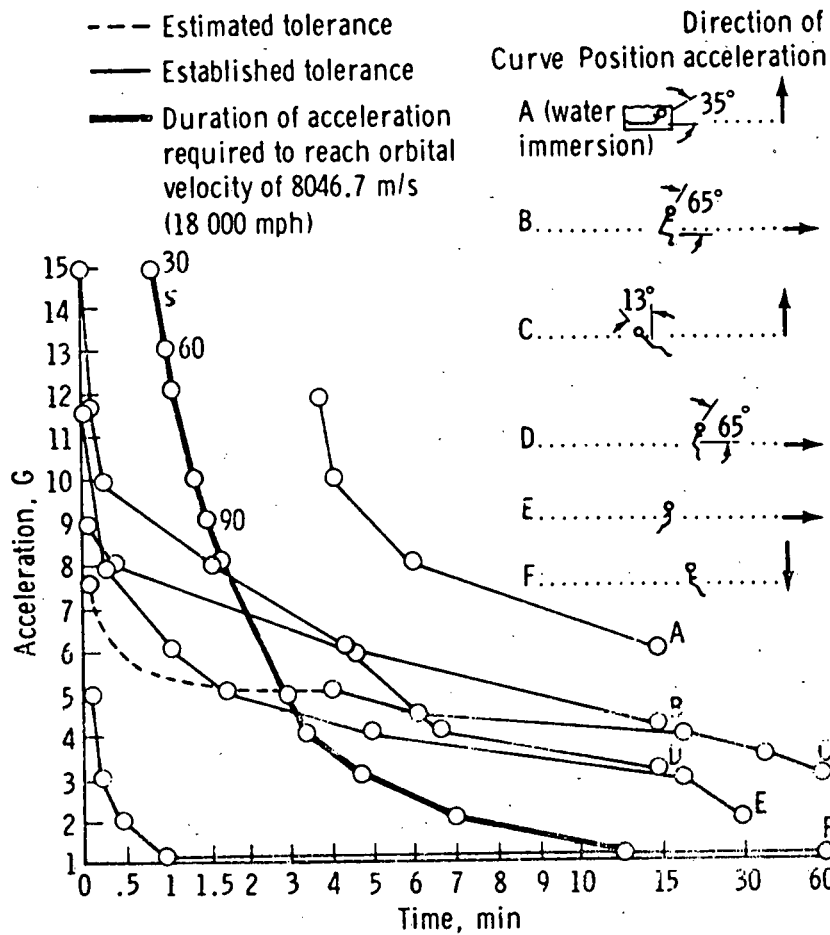


Figure IV-7. Effect of body position and posture on tolerance to acceleration. The time scale (abscissa) is linear but nonproportional.

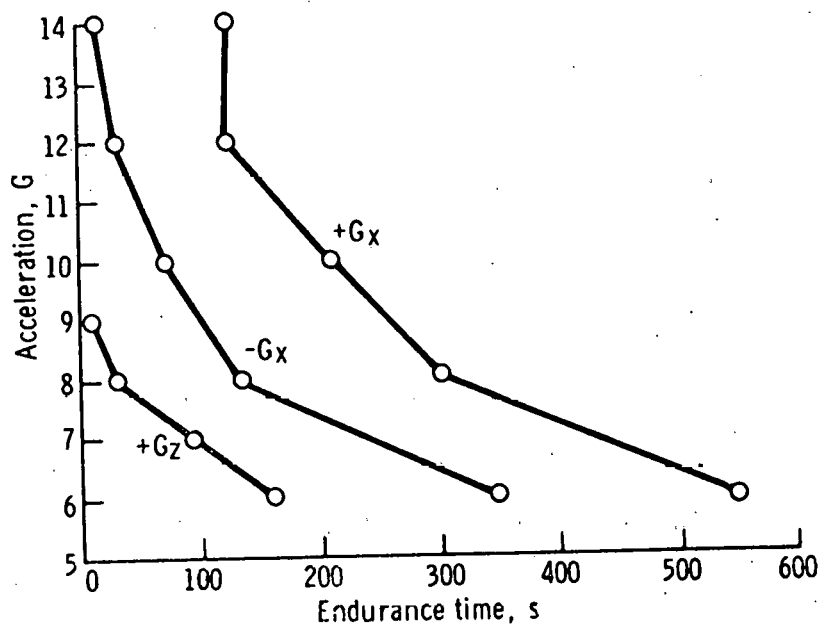


Figure IV-8. Voluntary endurance of acceleration by highly motivated test pilots.

The Space Shuttle vehicle will impose quite a different acceleration environment on the crew. The G loads will be lower but will have a longer duration (figure IV-10). Visibility requirements during landing necessitate an orientation of the crew couches that results in an acceleration during entry that is primarily in the $+G_z$ vector. A cardiovascular counterpressure garment covering the legs and lower torso is being made available for use during Space Shuttle Orbiter entries to reduce the effects of this acceleration.

Acceptable limits of acceleration for normal, healthy adults are in the range of 8G to 10G in the positive x-axis and 3G to 5G in the positive z-axis; this is dependent upon individual tolerance, required functions and performance, and use of restraining devices, and assumed relatively slow rise gradients and finite durations. The time magnitude interval is very important to overall tolerance.

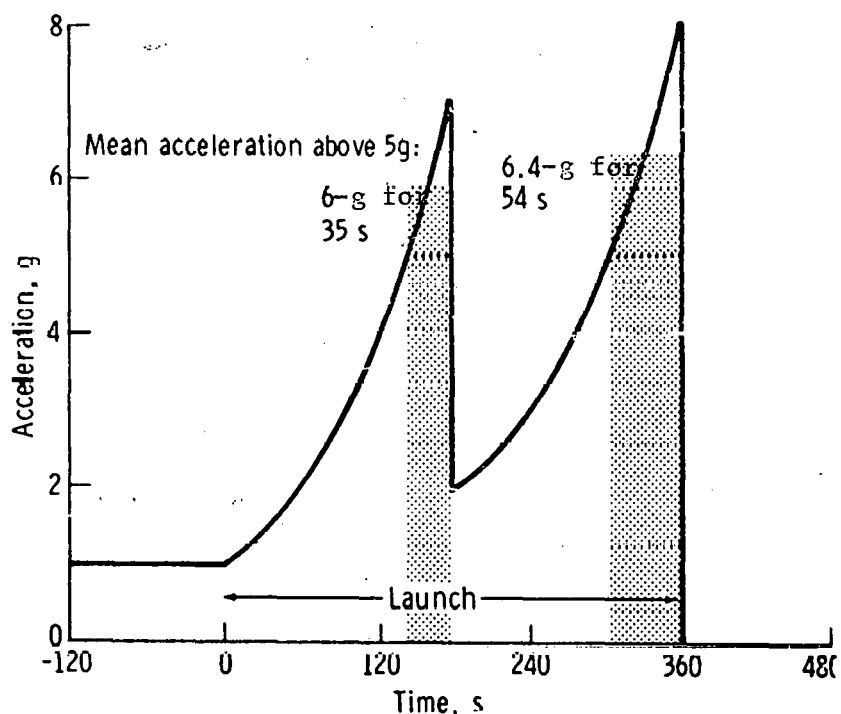
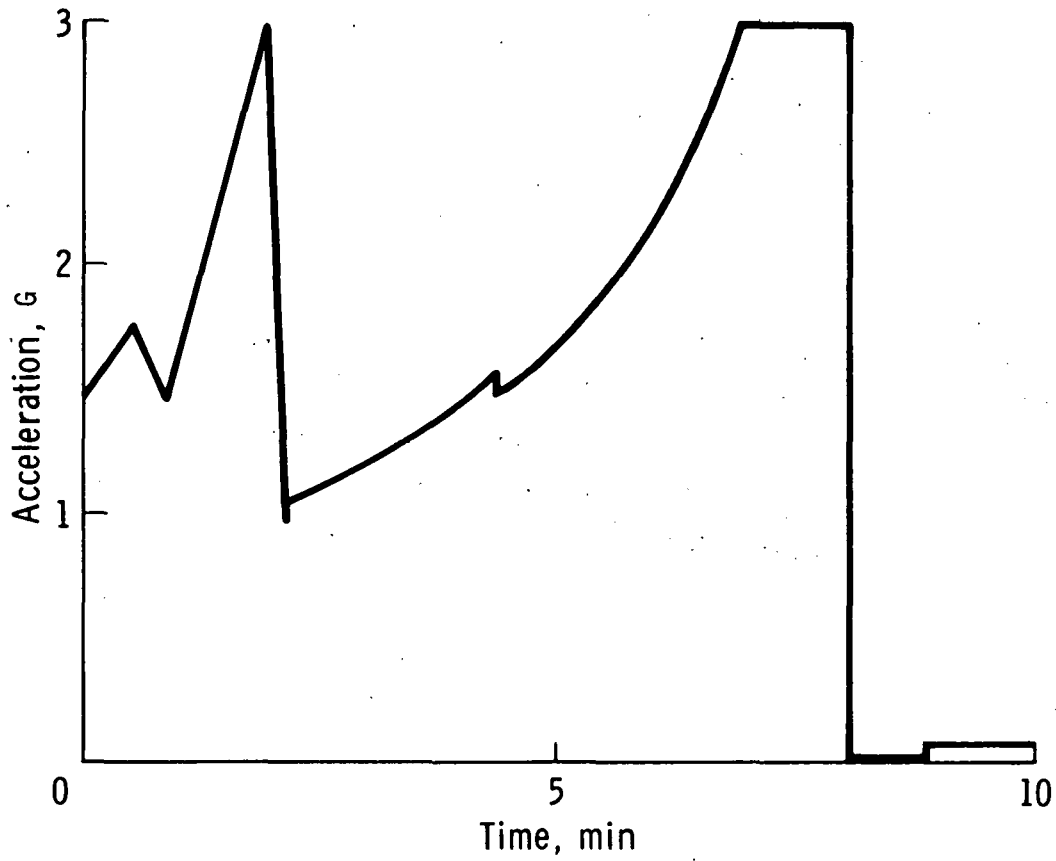
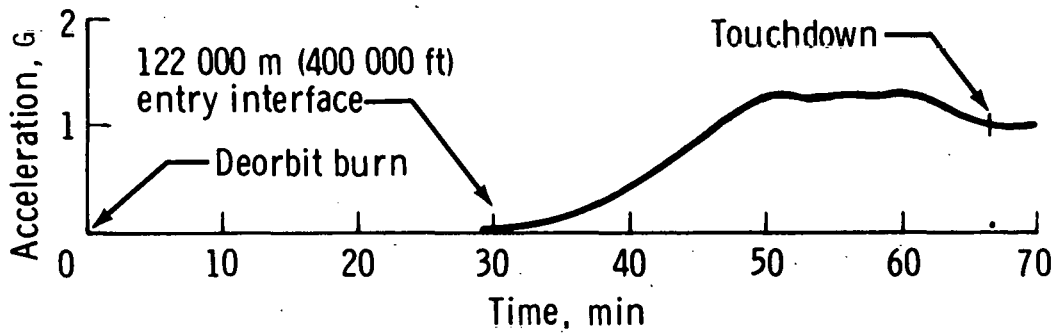


Figure IV-9. Acceleration profile of launch phase of the manned Mercury-Atlas 6 orbital flight. Striplled areas show periods of acceleration greater than 5-g.



(a) Launch.



(b) Entry and landing.

Figure IV-10. Acceleration profiles of the Space Shuttle vehicle as a function of time.

Interacting Environmental Parameters

Since the physiological effects of an acceleration force field are many, the potential for modification of these effects by a number of environmental factors should be considered. As stated previously, the primary limiting effects of high gravitational forces are a loss of oxygenation due to effects on the cardiovascular and the respiratory systems. Oxygen pressure is, therefore, a very important interacting variable. Temperature can be expected to interact when it results in vasodilation and decreased cardiac return. Any other environmental factor that might affect the cardiovascular or respiratory system would be expected to influence acceleration tolerance.

Effect of Individual Variation

Figures IV-6 (average tolerance curves) and IV-8 (maximum tolerance for test pilots) provide some indication of the effect of individual variation on tolerance to a force field. However, in Space Shuttle missions and in other future space missions, a much more diverse population may be exposed to force fields other than that due to gravity at sea level.

Research Needed to Further Define Spacecraft Limits

Research is needed to provide the following:

- o Definition of the effects of various durations in a null-gravity environment on subsequent tolerance to force fields in all axes.
- o Definition of the range of acceleration forces resulting in physiological effect and of tolerance in the population that may fly in space.
- o Optimization of countermeasures that may be used under high-force-field conditions.

Angular Acceleration

Definition and Description

Angular acceleration can be defined as the response of an object or a body to a combination of force vectors that results in a change in direction of motion of the object. Radial acceleration is angular acceleration that occurs during circular motion with the axis of rotation either within the body or outside the body. Rotary acceleration is radial acceleration for which the axis of rotation is within the body subjected to the acceleration.

The convention for describing orientations of angular acceleration is given in figure IV-3. The symbol $\underline{+R}_y$ refers to pitch, tumbling, or rotation around the y-axis; $\underline{+R}_x$ refers to rolling, spin, or rotation around the x-axis; and $\underline{+R}_z$ refers to yaw, yaw spin, or rotation around the z-axis.

Physiological Effects

The physiological effects of the force resulting in angular acceleration are in part similar to the effects of the forces resulting in linear acceleration. The forces acting on the body are a function of the radius of rotation and the velocity. As the axis of rotation increases in length relative to the size of the body, the physiological effects of the angular acceleration approach the effects of linear acceleration and the same types of cardiovascular and respiratory effects occur. As the radius of rotation being considered approaches the dimensions of a man, forces act in different directions in different parts of the body, and, since the force increases as the square of the distance from the center of rotation, the cardiovascular and respiratory responses are complicated. The $\underline{+R}_x$ rotation around an axis passing through the heart produces pooling blood in the feet similar to $+G_z$ acceleration and at the same time produces an increased hydrostatic pressure in the head similar to $-G_z$ linear acceleration. Movement of the center of rotation toward the feet increases the $-G_z$ effects. Conversely, movement of the center of rotation toward the head increases the $+G_z$ effects. The same types of considerations apply to $\underline{+R}_y$ and $\underline{+R}_z$ acceleration.

The other major effect of angular acceleration is in the vestibular system. The discussion of these vestibular effects will be very brief in this section, and the reader is referred to reference 58 for more detailed discussion. Each vestibular apparatus is made up of three semicircular canals and two otolith organs. These sensory organs provide information that aid in orientation and in eye, head, and body coordination. The otolith organs, the utricle and the saccule, act as detectors for linear acceleration, whereas the semicircular canals operate as detectors of angular acceleration. The vestibular system evolved under earth gravity conditions, in which acceleration is limited by the normal self-induced motions of the individual. When the vestibular system is exposed to much higher accelerations and combinations of forces, the effect can be motion sickness and/or sensory illusions resulting in disorientation.

These effects are likely to be limiting factors, at least in terms of performance, during rotational acceleration and in short-radius angular acceleration. If angular acceleration were to be used to integrate an artificial gravity in future space stations, vestibular disturbances (i.e., motion sickness and disorientation) would be a prime determinant of the minimum acceptable radius. The stimulus of the vestibular system in the absence of gravity in the Apollo and Skylab missions has been shown to produce a sequela of motion sickness of three to five days in some crewmen followed by a period of insensitivity to motion sickness in response to provocative tests.

Physiological Limits

Subjects without prior experience can usually tolerate rotation rates as large as 0.63 rad/s (6 r/min) in any axis or combination of axes. Most subjects cannot initially tolerate rotation rates in the region of 1.26 to 3.14 rad/s (12 to 30 r/min) and rapidly become sick and disoriented above 0.63 rad/s unless carefully prepared by a graduated program of exposure. On the other hand, rotation rates of 6.28 rad/s (60 r/min) for as long as 3 or 4 minutes around the y-axis (pitch) and around the z-axis (spin) have been described by some subjects as being not only tolerable but pleasant. Intolerability becomes manifest again at approximately 84.4 rad/s (80 r/min) in the pitch mode and at approximately 9.4 to 10.5 rad/s (90 to 100 r/min) in the spin mode. In the pitch axis, with the center of rotation at the heart level, symptoms of negative acceleration ($-G_z$) are demonstrated at approximately 8.4 rad/s (80 r/min) and are tolerable for only a few seconds. Some effects of positive acceleration ($+G_z$), namely numbness and pressure in the legs, are also observed but develop slowly, with pain being evident at approximately 9.4 rad/s (90 r/min). No confusion or loss of consciousness is found, but, in some subjects, disorientation, headache, nausea, or mental depression are noted for several minutes after a few minutes of exposure. With rotation in the spin mode, when the head and trunk are inclined forward out of the z-axis, rotation approaches tolerance limits at 6.28 rad/s (90 r/min). Except for unduly susceptible subjects, tolerance tends to improve with frequency of exposure. Long-duration runs in the pitch mode have been endured for as long as approximately 60 minutes at 0.63 rad/s (6 r/min) in selected subjects.

These extreme limits are not likely to be a consideration in design of spacecraft. They may set limits to survivability in contingency situations involving failure of spacecraft orientation control system.

In considering physiological limits to angular acceleration with long-radius components (such as high-speed aircraft turns), it is appropriate to use the acceleration limits defined for linear accelerations.

Interacting Environmental Parameters

The most significant interacting variable is the presence or absence of gravitational forces, particularly where the vestibular effects of radial acceleration are considered. Those environmental parameters previously mentioned which interact with linear acceleration also interact with radial acceleration.

Effect of Individual Variation

The space motion sickness syndrome that was noted in the Apollo and Skylab flights did not occur in all crewmen. Susceptibility of a crewman to motion sickness produced by provocative tests in one-g apparently had no corollary in weightlessness.

Research Needed to Further Define Spacecraft Limits

Research is needed to define the causative mechanism of the motion sickness syndrome under zero-g conditions and to establish preventive and/or ameliorative measures. Research is needed to define the effect of various durations of zero-g exposure on subsequent tolerance to angular accelerations in all axes.

C. EFFECTS OF OTHER FACTORS

Space workers may experience other potentially harmful effects other than the weightlessness of space or acceleration. These include habitat environments, life support systems in the habitat and work areas, health care, work area hazards, and altered biorhythms and diurnal cycles.

Habitat Environments

The various environments of the habitat area can present a broad spectrum of potentially adverse physiological or psychological effects. These potentially adverse environments influence habitat design or operational approaches at the cost of optimizing conditions for the space worker's well-being and almost always result in maximum costs and weight penalties. Many trade studies will be necessary to derive final habitat design of suitable environmental ranges. Elements of habitat environments include:

- o Atmospheric compositions and pressures
- o Temperature and humidity
- o Noise and vibration
- o Light
- o Odor
- o Bacteria and toxic elements
- o Circadian rhythm disruption
- o Particulates (ingestibles and inhalation)
- o Ionizing radiation (not treated in this document)

Life Support Systems in Habitat and Work Areas

To accommodate to the space worker's daily physiological and psychological health, safety and general well-being, the following items must be considered.

Food and Nutrition	Water (potable, cleansing, industrial)
Hygiene	Sleep
Rest and recreation	Exercise
Privacy	Waste and trash management
Clothing	Architectural design (space and layout)
Entertainment	

Health Care System

An efficacious space Health Care System will provide for prevention and treatment of medical contingencies, trained medical personnel, and proper medications and equipment. The elements of the Health Care System will include:

Prevention: Selection of healthy workers, periodic multiphasic screening, maintenance of health trend analyses, training and indoctrination of the space worker in important facets of space health, physical fitness programs, etc.

Treatment: Protocols for probable routine or emergency medical contingencies, and medical personnel - (paramedics, physician's assistants, physicians, and specialists consultants).

Medications and Equipment: Ready supplies of medication for known space complaints (motion sickness), contingency medications for common, ground-based complaints (toothache, headache, etc.) and drugs for emergency procedures. Equipment for monitoring day-to-day general health of the space workers as well as equipment to rescue, stabilize, transport and hospitalize a space worker in trouble.

Work Area Hazards

Construction will present many hazards. Workers will be exposed to heated surfaces, high electrical charges, mechanical dangers, brilliant light and complete darkness. Lack of references may present difficulties in judging distances and direction.

Altered Biorhythms and Diurnal Cycles

Space workers will be subject to several types of altered rhythms - from cellular and glandular internal body rhythms to daily habit routines. Some of these altered rhythms may be consequential enough to warrant identification and analysis, to determine their contribution to physiological or psychological problems, and to treat or correct.

V. AMELIORATION OF POTENTIALLY ADVERSE EFFECTS

The physical and social world of a space worker is subject to many dramatic alterations and without adequate preparation and conditioning, a worker may be physiologically or psychologically affected adversely. These adverse effects may be partially or totally prevented if appropriate preventive actions are taken. If adverse effects are experienced, the severity or duration of the effect may be reduced with appropriate treatment or corrective action.

These preventive or corrective actions will be discussed in this report briefly and in general terms.

A. PREVENTIVE ACTIONS

Preventive actions for amelioration of adverse effects include: selection, training and indoctrination of candidates, estimating and stimulating motivation, programming physical conditioning, and maintaining good living and working conditions.

Selection

Satellite Power System workers will be selected for long-term assignments. The prime consideration will be the worker's capability for maximum productivity over a five-year career span. To obtain maximum productivity a space worker must be in good physical condition, be resilient and adaptable to changing and stressful conditions, dedicated and purposeful in professional endeavors, and intelligent enough to understand not only the job requirements but the actions that must be taken to remain healthy in space. The exact criteria for selecting space workers and effective means for testing potential workers for the desired characteristics must be developed.

Training and Indoctrination

Data from past manned space missions show that extensive training and thorough indoctrination are strong contributing factors to adaptation in the space environment. Astronauts reported the importance of training which enabled them to continue their duties even though they were suffering from malaise of vestibular origin. Proper indoctrination in the importance of food, exercise,

hygiene and other health sustaining regimens were responsible for minimizing potentially adverse physiological effects of the space missions.

Space workers of the future will require extensive training and indoctrination prior to their initial space flight and sustained training and indoctrination throughout their career. The nature and extent of this effort must be defined and suitable programs developed prior to the early SPS missions; the STS and SOC programs of the 1980's will provide this early opportunity.

Motivation

A five year career as an SPS worker will place severe physiological and psychological stresses on the space worker, his or her family or associates. These stresses can lead to a very high personnel turnover.

Past experiences with various programs involving long-term assignments to remote and stressful environments have shown that good training and high salaries are not sufficient to maintain a steady work force. For example, offshore drilling companies are experiencing a 100% annual turnover in personnel who are extensively and expensively trained and highly paid. These companies are desperately seeking better methods for selecting, preparing and sustaining a dependable work force.

In contrast, the Skylab, Tektite, and our nuclear submarine programs found their crews to be highly motivated and productive.

It is hoped that careful studies of the effects of repeated missions for the STS crews and long duration (90 day) missions for the SOC crews will provide the answers for keeping SPS workers motivated and serving during an effective five year space career.

Physical Conditioning

Maintenance of the space worker's physical condition is a significant factor in the amelioration of adverse effects of the space environments. A good physical condition requires regimens of adequate nutrition, exercise, rest and hygiene coupled with an enticing food system, enjoyable recreation, and psychological support.

These requirements must be met between missions as well as during space flight and must be tailored to the needs of the individual. These needs will be dependent upon the character of the space worker, the quantity, quality and type of work to be done, and the levels of environmental stress involved.

The needs of U.S. astronauts and Soviet Union cosmonauts have been studied extensively at NASA. Although the knowledge derived from these past missions is extensive there is a great deal to be learned about the needs for the individuals we may expect to employ in the SPS program.

Some countermeasures, devices and exercises designed to maintain musculo-skeletal and cardiac condition in space, and to correct for reduced cardiac output upon reentry are listed here.

Lower Body Negative Pressure Device (LBNP) - LBNP is the application of a partial vacuum to the body from the waist downward. It increases the volume of the legs temporarily, stresses the cardiovascular system and its controls, and may provide for maintenance of tonus in vasculature of the legs.

Gradient Positive pressure - Gradient positive pressure is the concept, of applying pressure to the lower half of the body during the dynamic force of reentry and after recovery to prevent undue shift of body fluids as a result of vehicle accelerations and gravity. The pressure is applied in gradient fashion with the greatest pressures in the regions farthest from the heart.

A gradient positive pressure device, worn to resist the dynamic force of reentry, is the G-suit or cardiovascular counter pressure garment. It can be used to prevent the pooling of fluids in the body below the level of the heart during the acceleration force of reentry and thus forestall possible ortho-static hypotension.

A G-suit is a pair of tight fitting trousers containing built in air bladders that are inflated or deflated by a manually operated air valve.

Venous occlusion cuffs - Venous occlusion cuffs are blood pressure cuffs that, when rhythmically inflated and deflated, interfere with return of venous blood

to the heart. They may be used to stimulate the development of tonus in vasculature of the lower limbs.

Positive pressure breathing - Positive pressure breathing (PPB) is the application of a breathing system which pressurizes the air being inhaled or exhaled. By pressurizing the chest, it deters venous return to the heart, engorges veins, stresses the cardiovascular system and its controls, and is used to stimulate the development of tonus in vasculature.

Valsalva maneuver - The Valsalva maneuver is a method of pressurizing the chest by closing the glottis or obstructing the nostrils while attempting to exhale. Its effects are similar to those of positive pressure breathing.

Bone stress - Bone stress is achieved by using skeletal loading devices to forestall the effects of disuse in weightlessness. Several forms were tested, but in long-term bed rest studies (up to 17 weeks) no significant protection was afforded to the problem of bone loss.

Double trampoline - A double trampoline is a device composed of two trampoline heads between which a human can oscillate and receive sensory impacts which mimic the effects of gravitational acceleration on susceptible systems, including the cardiovascular system. (No studies yet conducted.)

Tumbling - Tumbling routines can be devised to simulate gravitational accelerations to members (arms and legs) at a distance from the body's center of gravity. (No studies yet conducted.)

Electrical stimulation of muscles - Electrical stimulation of muscles has been proposed to exercise muscles in weightlessness in order to prevent disuse atrophy and to provide skeletal stress. (No studies yet conducted.)

Exercise - Exercise coupled with another stressor (LBNP, cuffs, PPB or bone stress) has been proposed to produce effects that would be difficult to achieve singly in weightlessness. Particular reference is made to coupling exercise with a means of producing a simulated gravitational effect on cardiovascular or skeletal systems while providing muscular exercise. To

date, all studies have not afforded protection but the pregoing combination has not as yet been tested.

Hypoxia - Hypoxia is a powerful cardiovascular, respiratory and neurohumoral stressor which causes shifts in the electrolyte and acid-base balance and may counter the acidosis believed to occur in weightlessness. It may ameliorate disuse phenomena such as demineralization, but even so, it is doubtful that long periods of hypoxia would be feasible.

Medication - Medication has been proposed to counteract or ameliorate weightless responses, e.g., hormone therapy to curtail loss of potassium and calcium.

Centrifugation - Centrifugation is a technique for supplying artificial gravity to a space vehicle and as a stressor in studies of acceleration physiology.

The SOC program is expected to yield significant information in this area of interest.

Living and Working Conditions

The physical and psychological well being of the SPS space worker will be affected by environments that are controllable as well as those that are inherent in space flight. The living and working conditions of the space worker will need careful consideration if the long and repeated missions are to be made acceptable. Some of the more obvious controllable elements are:

- o Lighting
- o Temperature
- o Humidity
- o Breathing Environment (pressures and constituent gases)
- o Noise
- o Toxic and Noxious Elements
- o Architecture (space and layout)
- o Clothing
- o Social and Management Structure

B. TREATMENT AND CURATIVE ACTIONS

We must expect that with many hundreds of space workers involved, some will be adversely affected by the environments of the space missions. The adverse effects may vary in severity and duration. Curative action will be taken to exclude the cause and treatment will be administered to eliminate the effect. Some possible actions are discussed briefly below.

Task Reassignment or Schedule Modifications

The assigned work task of a person may be such that undue mental or physical stress results. A change of task may provide more healthful conditions by changing neurologic, metabolic, environmental, etc., stresses.

Schedule modifications may improve conditions affecting eating, sleeping and social activities.

Physical Conditioning

The physical conditioning needs will vary with individuals and may change with time. Where a worker is getting improper diet, rest, exercise, etc., some adverse effects are probable and the physical conditioning regimen must be adjusted to correct them. Frequently this may be a matter of personal discipline. If the worker is deliberately neglecting a healthful regimen, closer supervision may be involved in the corrective action.

Medical Treatment

In situations where the worker has experienced a medical contingency involving illness or injury due to any cause there must be adequate medical treatment available to stabilize or heal the victim.

Medical capability will include diagnostic and treatment systems with suitable support for rescue, transportation, and communications. These systems have been extensively defined, analyzed and evaluated in several developmental programs and tested during past manned space missions.

Altered Living Conditions

If some element of the space worker's living conditions causes an adverse effect or if a change in living conditions is held necessary during the treatment period, then these conditions can be modified. Such changes could range from moving the individual to a quiet area or to complete isolation.

VI. RESEARCH PLAN

A. GENERAL

The SOW, paragraph 5.1.2 Research Plan Preparation, requests that NASA prepare a research plan addressing the uncertainties in the knowledge regarding the health and safety effects of the zero gravity environment and acceleration/-deceleration and which, if carried out, will make future assessments more reliable and/or help to eliminate or ameliorate adverse health effects.

In responding to this SOW task, NASA again has taken the liberty of treating all the space environments except the radiation environment. We have also assumed that the period of time covered by the plan will extend from the present until just prior to the first SPS space mission (approximately 20 years).

It is anticipated that NASA-JSC will be conducting two major space programs in the 1980's and early 1990's - the Shuttle/Spacelab Space Research and the Space Operations Center. Our Life Sciences organizations will be conducting research in support of these programs. This research can be designed to yield information needed to identify potential adverse effects of the SPS-type space operations and suitable countermeasures.

Rather than present the research plan as a formalized planning document, we have chosen to provide information relating to the types of research that NASA scientists feel should be accomplished and indicate when the results of this research will be available. We have also provided information on which institutions and agencies are currently involved in the "NASA" research program and how DOE may become involved.

To describe the research plan to qualify humans for long periods in space as merely a NASA plan is an injustice because the people who aid in planning and conducting the research and validation are not exclusively NASA personnel; this program is international in scope.

The SPS program will introduce to NASA a new opportunity to extend and expand currently planned research. It will also provide an opportunity for DOE to participate in the planning, conduct and administration of the life sciences research activities.

B. RESEARCH AREAS

During the next few years NASA-JSC will be involved in research designed to support the general objectives of Life Sciences:

- o To determine effects of space environment on life systems.
- o To gain greater understanding of life processes and systems.
- o To extend crew health care capabilities for space utilization and exploration.
- o To develop improved life support and protection systems for people working and living in space.
- o To develop crew operations and equipment design to enhance crew/space-system integration.
- o To develop processes that exploit the advantages of space for bioprocessing.
- o To determine advantages of space to help support clinical research on Earth, and
- o To synthesize space technology to health care for people on Earth.

This research will be conducted in various laboratories throughout the nation and in space aboard the Shuttle/Spacelab.

The research will be directed to support general objectives of Life Sciences as well as the specific needs of NASA space programs. There are three specific programs that have some probability of being funded in this decade - the STS, SOC and SPS programs.

Bioresearch done for any one program will often benefit all programs, and for this reason we have chosen to include a general description of the potential research which may support the needs of the SPS program.

Currently On-Going Research

NASA-JSC is currently involved in over 100 ground-based experimental studies. These studies relate to medical and clinical protocols, space physiology, life support systems, extravehicular systems, health maintenance and crew selection. Documented records of these on-going studies are available at JSC. Some studies have been active for several years and others have been recently initiated to cover new research areas.

A partial listing of the major groups of experiments is shown in table VI-1. These Research and Technology Objectives and Plans (RTOP) may consist of from 2 to 15 individual studies. An example of one group is shown in table VI-2.

Shuttle/Spacelab Space Experiments

During the Shuttle/Spacelab missions, it is anticipated that approximately 100 Life Sciences experiments will be flown to explore the physiological/psychological effects of the space environment. Another 20 to 30 experiments will be performed to support the definition of requirements for health care, life support and protective systems (LS/LP) or habitability systems.

The Shuttle/Spacelab missions will be 7-day or 30-day missions and consequently will not provide an opportunity to perform experiments on long duration space exposure. Life Sciences at JSC has a responsibility for crew health maintenance and for assuring that crewmembers are selected to meet certain medical selection criteria. It is anticipated that some observations regarding physiological problems and fatigue build-up of crewmembers may provide information useful in the selection, training and indoctrination of future space workers.

TABLE VI-1. CURRENT RESEARCH

RTOP GROUP NO.	TITLE
199-10-11	Operational Laboratory Support
199-10-21	Medical Selection Criteria
199-10-31	Crew Health Maintenance
199-10-41	Systems Habitability Verification
199-20-11	Cardiovascular Deconditioning
199-20-21	Space Motion Sickness
199-20-31	Bone/Muscle Alterations (See table VI-2)
199-20-51	Blood Alterations
199-20-61	Fluid and Electrolyte Changes
199-20-71	Radiation Effects and Protection
199-20-91	General Research
199-60-11	Life Support Systems
199-60-21	Extravehicular Systems
199-60-31	Nutritional Requirements
199-60-41	Food Production
199-60-71	Man-Machine Systems
199-70-11	Program Definition

TABLE VI-2

TYPICAL RTOP: 199-20-31 Bone/Muscle Alterations

<u>Code</u>	<u>Task Title</u>
01	Long Term Bed Rest
03	Calcium and Bone Metabolism
04	Musculoskeletal Deterioration
05	Muscle Disuse Atrophy
07	Skeletal Muscle Disuse Atrophy
08	Systems/Calcium Metabolism
09	Bone Implant/Growth
10	Bone Density/Tomography
11	Calcium Metabolism Parameters
12	Vitamin D Metabolism
13	Vitamin D/Calcitonin/Parahormone

Research in Support of the SOC Program

In support of the OSC program, Life Sciences will conduct a number of studies relating to the systems definition of health care, LS/LP, and habitability systems. These SOC systems could serve as demonstration models to help formulate SPS design and operational approaches.

To illustrate the type of research involved in our planning, we have included a list of SOC research proposals submitted by NASA scientists. These are shown in table VI-3. Table VI-4 relates the research proposal to a particular biosystem or entity.

Brief forms of each proposal will be reviewed and those selected prioritized as a next step in the formulation of an SOC support plan. Further information about proposals listed are available through the Space and Life Sciences Directorate, JSC.

Of equal importance is the experience to be gained from the SOC operational activities. This program will involve from 4 to 16 space workers living in modular 4-man habitats for periods of 90 days. The space activities, work schedules and mission cycles will be similar to those described in the SPS reference report. For the first time crewmembers will be making repeated missions into space and working at "routine" jobs in the space environments. The long term and accumulative effects of repeated trips into space on the crewmembers and their families (or social contacts) will be explored. Because of crew size and length of mission the studies will be limited on the STS program and more extensive on the SOC program.

TABLE VI-3. SUGGESTED SOC RESEARCH PROPOSALS

1. To advance biochemistry studies (electrolyte levels and levels of steroid hormones).
2. To study physiological/biochemical aspects of bone demineralization (biochemical data; animal data; remedy development).
3. To study inflight clinical microbiology capability (contamination control; clinical lab; system improvements).
4. To study inflight clinical/research capability (health monitoring; broad banded).
5. To study infectious disease control (study populations, adjust balances).
6. To study SOC atmospheric monitoring (toxicology trace gas analysis).
7. To determine nutrient requirements under weightless conditions (develop requirements through surrogates).
8. To adapt recommended dietary allowances to long-duration space flight (determine nutritional requirements vis-a-vis stress, through humans and surrogates).
9. To study immune competence during long-duration space flight (determine immune responses of 500 subjects on 90-day flight).

TABLE VI.3 (Continued)

10. To study erythrokinetics during long-duration space flight missions (examine changes in red cell replacement in space flight; kinetics, mechanisms, chronic reexposure).
11. To study and develop methods to predict and treat myocardial infraction, particularly in space where fluid shifts, volume, endocrine, and excretory changes occur.
12. To plan and execute countermeasure development for bone demineralization.
13. To determine diagnostic and research equipment and radio-pharmaceuticals for inflight utilization; perform modifications for space use.
14. To prevent and correct cumulative atrophic effects on muscle.
15. To study particulate handling by pulmonary system.
16. To assess clothing considerations in a large space habitat (clothing selection, laundering and cleaning).
17. To study safety considerations in the space operations center regarding loss of pressure (pressure suits, emergency pressure system in vehicles, transfer sphere, pressure haven).
18. To develop non-invasive techniques to monitor subclinical bubbles in the tissues of space workers (develop instrumentation for research in gas embolus formation [bends]).
19. To develop and utilize a quantitative index of bends susceptibility (consider and evaluate susceptibility factors - age, exercise, body fat - in bends).
20. To determine limits of repetitive decompressions in space workers (evaluate limits of successive exposures).
21. To determine cabin and suit pressures for space operations center (develop cabin and suit pressures for operational and emergency use).
22. To determine humidity control in large spacecraft (determine engineering penalties of different options).
23. To determine temperature control in a large spacecraft (study of costs and benefits of various strategies).
24. To develop a proposal for a health maintenance facility for the Space Operations Center (develop a space clinic).
25. To study the effect of prolonged exposure to weightlessness on sensory system functions (effect on sensory system function; adaptation, and readaptation from one-g to weightless).

TABLE VI-3 (Continued)

26. To study the gravity receptor alterations during prolonged exposure to weightlessness (determine effects of long-term exposure to weightlessness such as morphological or functional alterations, which may or may not be appropriate for one-g; use humans and surrogates).
27. To study space motion sickness (develop predictors, countermeasures and operational procedures to minimize sickness effects).
28. To determine an advanced feeding system (define food system for SOC).
29. To determine reclaimed water quality requirements (develop standards for potable water; develop standards for non-potable water for hygiene; develop water quality monitoring devices).
30. To study and determine clothing/bedding provision (determine method or recycling or disposal).
31. To study and determine solid waste/refuse disposal (identify and quantify material; determine means of disposal).
32. To determine advanced metabolic waste management (develop a multi-use system).
33. To study metabolic waste sampling and monitoring (devise system for sampling human waste for scientific and clinical use).
34. To study personal hygiene (identify requirements for hygiene and develop equipment).
35. To study housekeeping methods (evaluate provisions for housekeeping and sanitation for SOC).
36. To provide for environmental control systems (develop hardware to close water and atmospheric loops).
37. To analyze volatile organic contaminants in the spacelab atmosphere (collect air samples and monitor spills).
38. To study inflight analysis of aqueous samples using the miniature fast analyzer (to qualify a laboratory chemical analyzer in zero-g to support research and clinical requirements).
39. To study body fluid and electrolyte loss during early space flight (examine fluid compartments and measure content of samples to chart circulatory and renal adaptation to zero-g).
40. To determine the effects of null gravity on the effectiveness of nitrogen washout (conduct nitrogen washout trials in null gravity prior to EVA's).

TABLE VI-3 (Continued)

41. To study the effect of zero-g on sweat (quantitate sweat rates, evaporation dynamics in zero-g).
42. To study basal metabolism in zero-g (measure effect of zero-g on metabolism and on postural muscles).
43. To study cell separations under microgravity conditions (space experiment to isolate kidney cells capable of producing urokinase).
44. To study tissue culture growth/fermentation in low-g (space environment where gravity-induced floating or sedimentation are reduced and culturing is optimized).
45. To study cell to cell interactions and biosynthesis dynamics in microgravity (space experiment to study cell physiology especially biosynthesis in zero-g).
46. To study laboratory animal for depression of CNS function produced by the combination of zero-g stresses and the intake of low levels of chemical compounds (in-flight toxicology to quantitate multistress and reevaluate space flight criteria [tolerances]).
47. To study coronary artery perfusion and systemic blood flow distribution (space experiment to quantify myocardial perfusion and systemic flow by radioisotopes).
48. To study pulmonary ventilation/perfusion and thoracic blood volume alterations in zero-g (space experiment to measure respiratory parameters in the presence of fluid shifts to the thorax).
49. To study in-flight saline ingestion as a countermeasure for reexposure to normal gravity (space experiment to forestall symptoms or orthostatic intolerance in the presence of reduced blood volume by supplying physiologically-acceptable fluid upon recovery).
50. To study electromechanical cardiac activity (monitoring of cardiac phenomena in flight for clinical and research use).
51. To determine aerobic and muscular strength exercise requirements for spaceflights (develop exercises to enhance muscle strength and aerobic capacity and to uplift or maintain physical work capacity and physical conditioning as well as to promote crew health).

52. To study physical performance in the space station (design counter-measures for reduced human physical performance, especially life support equipment, work stations, stabilization devices, locomotion aids, and exercise devices).

Research in Support of the SPS Program

Much of the biological and biosystems research scheduled for SOC will be applicable to SPS. There are, however, several characteristics of the SPS program that will require research directed specifically to SPS.

These features include:

- o A large number of people - hundreds in space simultaneously,
- o A large variety of tasks,
- o A large number of female workers,
- o Repeated long duration missions over a five year career span, and
- o Workers in GEO and LEO habitats and work area.

The significance of these unique features is that life support, protective, habitability and health care systems developed for previous programs would require scaling up or major redesign/replacement with a new system concept. In addition, the operational environments might introduce new psychological and sociological situations that may impact the worker and his family and earth-based associates. These projected situations will introduce new areas of research for NASA.

C. SCHEDULE

A schedule to provide information relating to the health and safety of SPS space workers has been formulated. Consideration is given to the "need" date for finalizing SPS workers' schedules (about 1995) and the currently anticipated manned space program preceding or concurrent with the SPS space missions. This schedule is shown in figure VI-1.

The period between now and the date when final SPS decisions will be made for such items as mission stay time, number of shifts, work schedules, and ground-based time between missions is currently estimated to be about 20 years.

There will be a number of milestones during that time period when NASA will be able to provide supplemental information for making the decisions involving SPS workers' health and safety. These milestones are indicated in figure VI-1. A brief summary of the information now available at each milestone is outlined below.

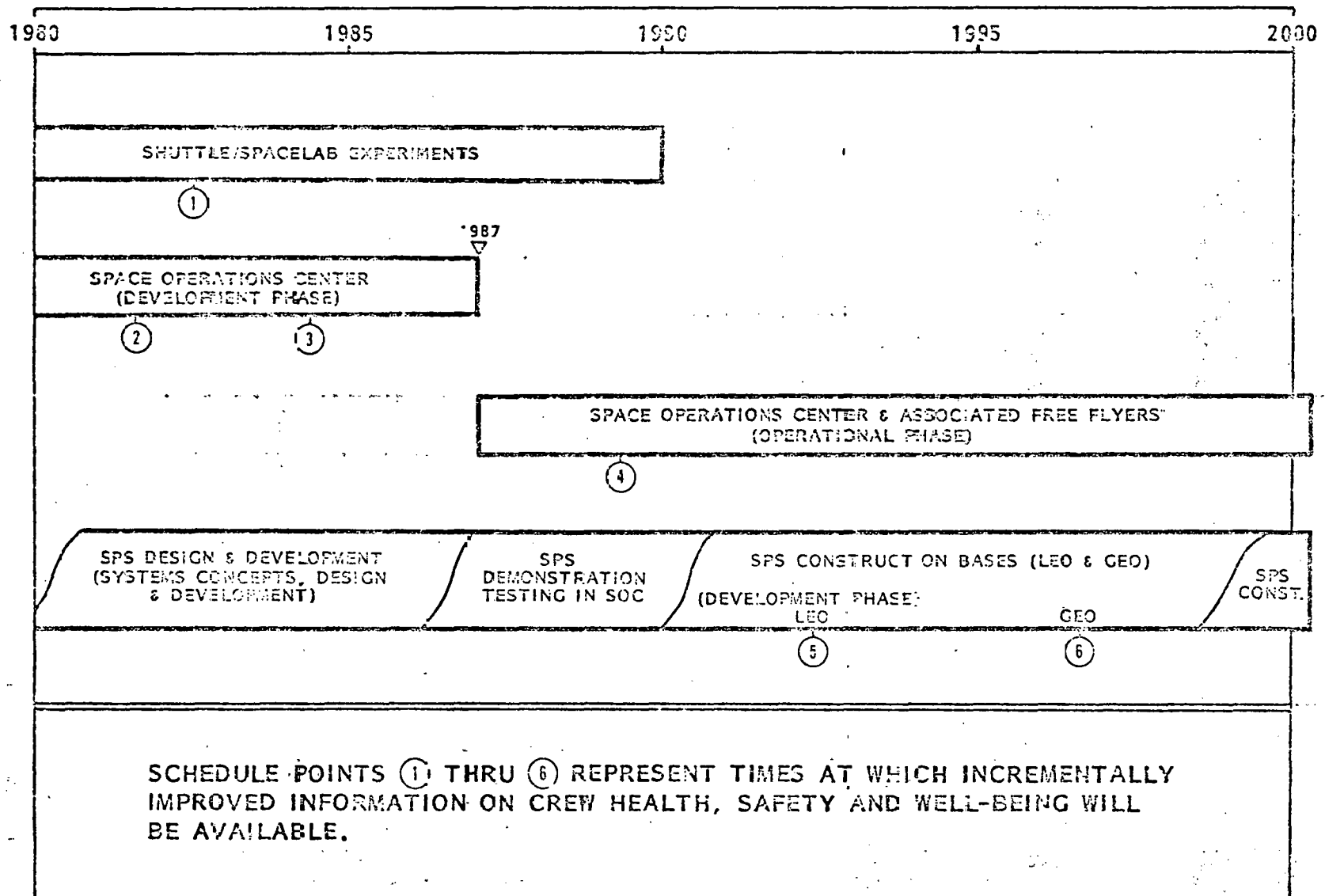


Figure VI-1. Comparative schedules for the Shuttle/Spacelab, SOC, and SPS programs.

1. After the first year of Shuttle missions, some crewmembers will have made repeated missions in LEO. These mission experiences will provide information regarding the trends in physiological and psychological responses of the crewmembers, and their families to this new life style.
2. As preparations for constructing a SOC get underway, extensive ground-based testing, crew training, and multiple mission simulations (demonstrations) will be conducted. Extensive information relating to crew health, safety and well-being, and to their relatives will be provided. In addition, this information is expected to indicate the type of life support and protective systems needed to enhance the morale and to provide living comfort for the space workers. It is during this period that many of the concepts of crew scheduling will evolve.

The ground-based training and mission simulations will duplicate the operational aspects of both flight and ground operations. It will also serve to highlight potential problem areas in the hardware system, the operational procedures and the human performance of flight and ground crews.

3. With construction of the SOC progressing during several mission periods (9 months to one year), NASA will again be in a position to offer a significant amount of additional information relative to the crew schedules, the physiological/psychological health and safety of the crew, morale factors, and crew-related systems design and operational approaches for SPS habitat and work stations. During this period the crewmembers and their families will have experienced all phases of premission, mission and intermission activities, and the repeated experiences of adjustment.

The experience of mission repetition will enable NASA to understand the cumulative effects of the zero-g, one-g, and the transitional phases relating to job effectiveness, worker and family morale, and the physiological/psychological condition of the crewmembers.

Additional information relating to working conditions, habitation suitability, number and type of medical contingencies, social structure tendencies, group dynamics, etc., will become available.

4. During SOC operations, NASA will continue to accumulate knowledge and experience while working with additional crewmembers, a greater variety of skills and intellectual levels, different social and organizational structures, and improved support systems, habitat configurations, operational procedures, etc.

- 5 & 6. As the time approaches to send large numbers of workers into space to build the SPS construction bases, NASA will have gained much experience in preventing or correcting any adverse effects of the space environment on space workers. In addition, they will have learned much about maintaining high work effectiveness through worker selection, training and motivation. Increasing numbers of space workers will be required as the SPS construction bases in LEO and GEO develop. Increased crew responses to the space environment, working conditions and crew support systems will permit NASA to make progressive evaluations based on the increased numbers, personalities and skills represented.

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APPENDIX A

ACRONYMS AND ABBREVIATIONS

ACTH	Adenocorticotrophic hormone
ADH	Antidiuretic hormone
AGARD	Avisory Group for Aeronautical Research and Development
ASTP	Apollo Soyuz Test Project
CNS	Central Nervous System
DOE	Department of Energy
EMG	Electromyography
EVA	Extravehicular activity
GEO	Geosynchronous Earth Orbit
h (hr)	hour(s)
JSC	Lyndon B. Johnson Space Center
LBNP	Lower Body Negative Pressure
LDH	Lactate dehydrogenase
LEO	Low Earth Orbit
LS/LP	Life Support and Life Protection
NASA	National Aeronautics and Space Administration
PPB	Positive pressure breathing
(r/min)	revolutions per minute
rpm	
rad	radian
REM	Rapid eye movement
RNA	Ribonucleic acid
RTOP	Research and Technology Objectives and Plans
s (sec)	second(s) (time)
SDH	Succinate dehydrogenase
SOC	Space Operations Center
SOW	Statement of Work
SPS	Satellite Power System
STS	Space Transportation System
Zero-g (or 0-g)	zero gravity

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