Space Biology and Medicine

Joint U.S./Russian Publication in Five Volumes

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Dedication

This book is dedicated in loving memory to Abraham Moiseevich Genin (1922–1999) and Lawrence F. Dietlein, M.D. (1928–2002). Both made vast contributions to all four volumes of the U.S.-Russian publication *Space Biology and Medicine*. As members of the joint editorial board for this publication, they authored several chapters. Dr. A. Genin was a leader and fervent proponent of scientific cooperation among scientists throughout the world and of joint efforts within the scope of working groups, which would promote space exploration for peaceful purposes. He was distinguished by his great intellect, multifaceted erudition, charming wit, and deep wisdom in his dealings with colleagues, friends, and family. Dr. Dietlein was truly one of the pioneers of space medicine and space and life sciences. His brilliant career in America's space program spanned 4 decades, during which he set the standards by which both American and foreign space programs conduct their clinical and basic research. His contributions are innumerable, from protecting the health of astronauts to teaching new scientists the nuances of coping with the rigors imposed by the unique environment of space. He leaves a legacy and a void that is irreplaceable in America's scientific community. His intellect will be missed by all of those who had the privilege of knowing and working with him.

Editorial Board

Series Preface

The appearance of this work has an entire history behind it. As early as the mid-1960s Hugh L. Dryden and Dr. Anatoliy Arkadevich Blagonravov signed a number of agreements on collaboration in space research between the National Aeronautics and Space Administration of the U.S. and the U.S.S.R. Academy of Sciences. One of them was an agreement to publish a joint scientific work—"Foundations of Space Biology and Medicine"—in both Russian and English.

The material in that book, published in 1975, was based on the results of observations and research that had been conducted mainly on short-term flights of approximately 50 manned spacecraft carrying more than 70 crewmembers, and also dozens of space flight experiments conducted on dedicated biosatellites or "hitch-hiking" on unmanned spacecraft. The 1975 edition was generally well received by readers and reviewers, and for some time satisfied the need for information in space biology and medicine.

However, since that time, human space flight has made extensive use of space shuttle systems and long-term orbital space stations. New empirical data—the results of numerous, often unique flight and simulation experiments—have accumulated rapidly. The scope of biological experiments in space has expanded significantly. Thus by the mid-1980s it had become clear that it was time to summarize and analyze the knowledge we have gleaned in this area.

In 1987, a new intergovernmental agreement, Concerning Cooperation in the Exploration and Use of Outer Space for Peaceful Purposes, was signed (the first one was signed in 1971). Item 16 of the Addendum to this Agreement stipulated publication of a new edition of the joint U.S./U.S.S.R. scientific work, "Foundations of Space Biology and Medicine." A joint editorial board was formed to implement this project within the framework of the U.S./U.S.S.R. Joint Working Group on Space Biology and Medicine.

After considering the complexity of preparing and publishing a work covering the knowledge and experience acquired by both countries, the editorial board concluded that given the enormous amount of new material, and the new set of authors who would be preparing the chapters, the new edition would not simply be an updated version of the 1975 book, but in essence a whole new work. The goal of this new work would be to provide access for specialists, physicians, biologists, and engineers involved in space flight planning and management and the general scientific community to concise and systematic information about space biology and medicine that has accumulated during the last 25–30 years.

The five-volume work will be published in authenticated Russian and English versions. The editors of Volume I, *Space and Its Exploration*, are Dr. J. D. Rummel of the U.S. and Academicians V. A. Kotelnikov and M. V. Ivanov of the Russian Federation. This volume covers the history of space exploration, the space environment, life in the universe, and spacecraft technology.

Volume II, *Life Support and Habitability*, has two parts: Part 1—The Spacecraft Environment, and Part 2—Life Support Systems. The editors are Dr. F. M. Sulzman of the U.S. and A. M. Genin of the Russian Federation. This volume addresses major issues and requirements for safe habitability and work beyond the Earth's atmosphere.

Volume III, *Humans in Spaceflight*, is edited by Dr. C. S. Leach Huntoon of the U.S. and Professor V. V. Antipov and corresponding member of the Academy of Sciences, A. I. Grigoriev of the Russian Federation. This volume has two books, which provide in-depth discussions of physiological adaptation to the space environment.

Volume IV, *Health, Performance, and Safety of Space Crews*, is edited by Dr. L. F. Dietlein of the U.S. and Professor I. D. Pestov of the Russian Federation. This volume presents a concise description of systems and preventive measures necessary to assure crew health.

Volume V, *Reference Material*, is edited by Professor S. R. Mohler of the U.S. and Dr. A. A. Gurjian of the Russian Federation. This volume includes extensive reference material relevant to the major topics discussed in the previous volumes.

With only a few exceptions, volumes are being written by chapter authors who did not contribute to the 1975 version, and the editors had to devote considerable effort to ensure the consistent organization of the book as a whole, avoid contradictions, and link individual chapters. Nevertheless, we are aware that in spite of all our efforts, we have not been able to produce a work that is homogenous with respect to consistency of presentation, being written by scientists of two countries.

Thus, this five-volume edition represents another successful completion of a collaborative project between the Russian Academy of Sciences and the U.S. National Aeronautics and Space Administration in the area of space biology and medicine. We hope that this work will be a useful reference to the reader. We would like to officially express our gratitude for the efforts of the Joint Editorial Board and the many individuals who provided invaluable help in the preparation of this work for publication.

In addition, on behalf of the Joint Editorial Board we wish to express our sincere appreciation to the publication staff.

Arnauld E. Nicogossian, U.S.
Oleg G. Gazenko, R.F.
Editors-in-Chief

Foreword

One of the most important developments of the 20th century has been the introduction of humans into space. For the first time, humans were studied in an environment free of the effects of Earth's gravity. Inspired by the Russian theoretician Konstantin Eduardovich Tsiolkovskiy, Robert Goddard in 1926 launched the first rocket; in 1957 Sputnik I was launched; and in 1961 the first human was launched into space. Since that historic flight, scientists around the world have steadily and steadfastly realized the possibilities of space exploration. One of the major goals of space exploration is the establishment of permanent human presence in space, and the focus of researchers has evolved into understanding how biological systems, particularly humans, adapt and perform in the microgravity conditions of space. This greater understanding, put into practice, not only increases mission success, but also ensures the health of human explorers.

This volume brings together noted researchers from both Russia and the United States and the work they have accomplished in the last 40 years of studying humans in space, and provides a forum for them to present the research and factors involved in the health, performance, and safety of crews in space. Part I of the volume describes the selection and training of astronauts and cosmonauts. Part II discusses pre-, in-, and postflight medical monitoring of crewmembers. Part III regards illness and injury in space and their diagnosis and treatment. Part IV outlines protective or preventive measures provided against the hazards of space flight. Part V considers ergonomic and psychological support aspects of crew activities. Part VI discusses safety issues in human space flight. Finally, Part VII presents the benefits of space exploration for humans on Earth as well as concluding remarks.

This collaborative work is the result of many years of cooperation and friendship between the two editors. Through this collaboration, the foundations have been established for future international endeavors and for permanent human presence in space.

РОССИЙСКАЯ АКАДЕМИЯ НАУК

НАЦИОНАЛЬНОЕ УПРАВЛЕНИЕ ПО АЭРОНАВТИКЕ И ИССЛЕДОВАНИЮ КОСМИЧЕСКОГО ПРОСТРАНСТВА

ТОМ IV

ЗДОРОВЬЕ
РАБОТОСПОСОБНОСТЬ
БЕЗОПАСНОСТЬ
КОСМИЧЕСКИХ ЭКИПАЖЕЙ

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Москва
“Наука”
Год

National Aeronautics and Space Administration

Russian Academy of Sciences

Volume IV

Health, Performance, and Safety of Space Crews

Editors

Lawrence F. Dietlein (U.S.) and Igor D. Pestov (Russia)

Acknowledgments

The authors and editors of this volume would like to thank the many U.S. and Russian scientists who have dedicated their careers to the advancement of knowledge in human health and performance in space flight. Thanks are also extended to TechTrans International, Inc., and the talented individuals who translated English chapters into Russian and Russian chapters into English. Their expertise facilitated the flow of information between authors and ultimately the publication of this volume.

Special thanks go to Chris Wogan, Nancy House, and Hai Nguyen of NASA Johnson Space Center and to Eleanora Panchenkova* and Tatania Kasatkina of the Space Council of the Russian Academy of Sciences for their fastidiousness in editing this work. Their close collaboration with the series editors, authors, and translators has greatly increased the quality of the volume's content.

Lawrence F. Dietlein and Igor D. Pestov

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*deceased

Introduction

Volume IV is devoted to examining the medical and associated organizational measures used to maintain the health of space crews and to support their performance before, during, and after space flight. These measures, collectively known as the medical flight support system, are important contributors to the safety and success of space flight. The contributions of space hardware and the spacecraft environment to flight safety and mission success are covered in previous volumes of the *Space Biology and Medicine* series. In Volume IV, we address means of improving the reliability of people who are required to function in the unfamiliar environment of space flight as well as the importance of those who support the crew. Please note that the extensive collaboration between Russian and American teams for this volume of work resulted in a timeframe of publication longer than originally anticipated. Therefore, new research or insights may have emerged since the authors composed their chapters and references. This volume includes a list of authors' names and addresses should readers seek specifics on new information.

At least three groups of factors act to perturb human physiological homeostasis during space flight. All have significant influence on health, psychological, and emotional status, tolerance, and work capacity. The first and most important of these factors is weightlessness, the most specific and radical change in the ambient environment; it causes a variety of functional and structural changes in human physiology. The second group of factors includes the constraints associated with living in the sealed, confined environment of spacecraft. Although these factors are not unique to space flight, the limitations they entail in terms of an uncomfortable environment can diminish the well-being and performance of crewmembers in space. The third group of factors includes the occupational and social factors associated with the difficult, critical nature of the crewmembers' work: the risks involved in space flight, changes in circadian rhythms, and intragroup interactions. The physical and emotional stress and fatigue that develop under these conditions also can disturb human health and performance.

In addition to these factors, the risk also exists that crewmembers will develop various illnesses during flight. The risk of illness is no less during space flight than on Earth, and may actually be greater for some classes of diseases.

The overall goals of the medical flight support system are to minimize the physiological effects of destabilizing factors, to maintain crew health and performance, and to solve problems regarding medical flight safety. Although the forms in which medical support programs are organized may differ between Russia and the United States, both countries involve groups of medical specialists working toward the common goals of medical support before, during, and after space flights. This volume discusses these goals, which are achieved by ensuring that:

- the initial health status of the crewmembers conforms with accepted medical standards (via selection and training);
- cosmonaut and astronaut health is maintained throughout the preflight period (via medical monitoring, prophylaxis, and diagnosis and treatment of diseases);
- crewmember health status is stabilized during flight (via operational medical monitoring, in-depth examinations, medical aid, prophylactic intervention, psychological support);
- optimal working conditions and schedules are provided (via well-designed work stations, work/rest schedules, and performance monitoring);
- crews can be rescued in emergency situations (e.g., safety rules, rescue devices and techniques); and
- crewmember health is restored during the postflight period (via medical monitoring, rehabilitative procedures).

This set of medical support measures was designed to maintain human health and performance capacity, and thereby contribute to flight safety and success. The goals of this system can be attained only through the systematic use of such measures. The constituent elements of the approaches used in the Russian and U.S. programs are the subject of this volume.

Chapter 1 discusses the medical selection process through which applicants are selected to become astronauts and cosmonauts. The differences between the U.S. and Russian selection processes can be viewed in terms of objectives. For example, while the American process selects to exclude those with significant health risks during space flight, the Russian selection approach identifies those who will perform best in and adapt quickly to space flight conditions.

Although differing approaches also exist between Russian and American approaches to crew-training systems, they share many fundamental concepts and practices. Because of their basic similarities, Chapter 2 discusses mainly the Russian experiences with crew training.

Next are comprehensive discussions of methods of monitoring the health of crewmembers. Because of the high level of physical fitness in the astronaut and cosmonaut population (through the selection process), physiological adaptations that develop in the course of flight may mask any negative conditions in medical evaluations made without consideration of individual baselines. Therefore, both Russian and American systems have adopted the principle of continuous monitoring rather than periodic health checks. Chapter 3 discusses monitoring before flight to establish the baseline health status of each crewmember; these data are used for monitoring during and after flight. Chapter 4 discusses the continuous monitoring which takes place during flight to track any negative trends in each individual's health.

In order to preserve the health and performance of the crew in space, scientists seek to understand the etiology of diseases or injuries that occur. Chapter 5 presents a brief overview of which kinds of factors could be expected to contribute to functional disorders in flight and in other analogous situations, goes on to describe actual episodes of in-flight diseases and injuries, and finally underscores the importance of a comprehensive set of countermeasures to prevent—or at least minimize the complications of—in-flight medical problems.

Chapter 6 is devoted to explaining the principles and diagnosis of medical treatment in space flight. To prevent and minimize negative impacts to the mission, the programs must consider the infrastructure and facilities to keep crewmembers in optimal health, as well as have well-defined and -characterized risks of medical events occurring in flight. Past, present, and future capabilities for in-flight diagnosis and treatment are also discussed.

Chapter 7 outlines the importance of providing rehabilitation after flight is completed. Combined measures—medical, educational, social, and vocational—are used to train and reestablish a crewmember's full health and functionality, thus ensuring the long-term condition and longevity of the individual.

Chapter 8 discusses the physiological adaptations experienced in space flight in the context of countermeasures to them. Both Russian and American countermeasures aim to protect and condition crews for the unfamiliar environment of space flight and for optimal readaptation to Earth conditions upon return. The discussion also presents the different countermeasure protocols according to the length of the mission, as the degree of adaptation varies with this factor.

Chapter 9 details the psychological aspects within crew medical support. Described are the dynamics of psychological adaptation during the phases of the mission, as well as current measures to ensure the psychological well-being of the crew. The authors also share their experiences in providing support for Mir, as these long missions in space allowed the testing of various types and schedules of psychological support.

Chapter 10 covers general, yet critical, issues concerning the ergonomic design of workstations and crew performance technology—such as the controls, displays, and signals that present information to the crew—in addition to methods of evaluating the ergonomics of crew-spacecraft systems.

Chapter 11 discusses the analysis of crew performance in the unique conditions of space. The authors provide a review of results from psychological performance analyses of space crews conducted during the support of long missions on Skylab, Salyut, and Mir.

Chapter 12 details the safety requirements for environmental control systems on crewed spacecraft, as well as methods of analyzing flight safety, and criteria and techniques for safety assessments.

Chapter 13 summarizes the historical development of emergency systems in space flight and the mishaps that have occurred in crewed flight, outlines the rationale for escape systems and discusses the types of hazards and events that might prompt escape procedures, and discusses escape and rescue from low Earth orbit, emphasizing the Space Shuttle Program and the International Space Station. The author also reviews the international considerations of space rescue and briefly considers lunar and planetary escape-and-rescue scenarios.

Finally, Chapter 14 reviews how the principles used in designing equipment for the spacecraft environment can be beneficial for Earth-based settings, for example the many benefits accrued in the development of imaging, communications, and robotics technologies; materials science; and biotechnology. The authors also consider the potential commonalities between aging and space flight exposure in terms of bone loss and postural control. This discussion emphasizes the need to continue the exchange of emerging technologies between space research and commercial industries.

The experience accrued in organizing and implementing medical support of space flights already has been put to good use in solving humanitarian problems involving effective international collaboration, e.g., dealing with the consequences of natural disasters. Readers of Volume IV undoubtedly will find information useful for application in “non-space” arenas.

Lawrence F. Dietlein and Igor D. Pestov

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Space Biology and Medicine
Volume IV: Health, Performance, and Safety of Space Crews

Chapter 1

Astronaut and Cosmonaut Selection

Sam L. Pool, Yuri I. Voronkov, Christine F. Wogan, Pyotr L. Slepenkov,
John J. Uri

Human space flight is one of the most outstanding scientific accomplishments of the 20th century. Since the early days of space exploration in the 1950s, milestones such as the development of crewed spacecraft and orbital stations, the implementation of longer flights, moon landings, extravehicular activities, and locomotion in open space have significantly affected the medical requirements for astronauts and cosmonauts.

The United States and the former Soviet Union have independently developed medical procedures and standards for selecting astronauts and cosmonauts. Both countries began selecting their first candidates in 1959, and both have relied heavily on the tenets of aviation medicine, a discipline that already had an established, validated process for selecting flight crews.[1,2] In fact, the first candidates for the astronaut and cosmonaut corps were military jet pilots.[3]

In the 1950s and early 1960s, little information was available as to how humans would respond physiologically to space flight, although the U.S.S.R. had some experience with animal flights and Earth-based simulations of flight conditions. Given the largely unknown nature of the space flight environment at that time, both countries recognized the importance of ensuring that crews had some medical "margin of safety." Thus, early medical evaluations included almost every test that could be performed with normal, healthy individuals. The time and expense associated with space flight, as well as the risk of having to abort missions because of illnesses or defects overlooked in the screening process, heightened the importance of this process.[4–7]

Although the first sets of astronaut and cosmonaut candidates were ranked with regard to other candidates before the final selections, neither country had a specific set of "pass/fail" medical standards for space flight duty. The applicants were considered to be exceptionally well screened by virtue of their selection as military pilots and had maintained their physical qualifications for duty as high-performance jet pilots.

The U.S. developed the first specific set of "pass/fail" (inclusion/exclusion) medical criteria for astronaut selection in 1977; these criteria have been revised every 5 years to reflect experience with human space flight. The first set of Soviet/Russian medical selection procedures and standards were adopted in 1982 and revised in 1989.[8] The Russian approach involves in-depth clinical examinations that include a battery of stress tests, which together are thought to provide the most complete picture of the health and functional and reserve capacities of the individuals being tested.

The primary difference between U.S. and Russian selection philosophies is the predictive ability of the test battery. The U.S. medical selection process is designed to exclude ("select out") individuals who have significant health risks, but makes no attempt to include ("select in") those who will perform best, from a medical perspective, in the space flight environment.[8] In contrast, one of the main goals of the Russian medical selection process is to identify those individuals who can best tolerate space flight, adapt quickly to the physical factors associated with the spacecraft environment, and perform acceptably during flight. Russian standards for cosmonaut selection thus consider an individual's personality, psychophysiological traits, health status, functional capacities, and the rates at which adaptive skills and responses are learned and retained.[9–13]

This difference between American and Russian selection philosophies has engendered spirited debate that continues to the present. Russian space scientists maintain that their test battery allows them to predict who will perform well in space; U.S. scientists are less sure that the results of ground-based tests can be used to accurately predict how otherwise healthy individuals will adapt to the space flight environment. This chapter describes the similarities and differences in the evaluation processes used to select astronauts and cosmonauts, and the processes involved in certifying those that have been accepted for specific missions. (Training for specific flight programs and missions in the Russian space program is described in Chapter 2 of this volume.) The evolution of current selection procedures is reviewed, and current selection techniques, standards, and philosophies of the U.S. and Russian space programs are compared.

I. Historical Perspectives

A. The U.S. Astronaut Selection Process

The overall goal of NASA's selection process is to recruit people who can be trained to operate various spacecraft throughout normal flight phases and in emergency situations. These people also are expected to accomplish the scientific objectives of space flight.[14] The number of individuals chosen, and the periods in which selections are made, are planned so as to maintain an operational corps at all times.

In 1959, President Eisenhower declared that the first group of astronauts would be chosen from the military services, specifically test pilots. The first change in the astronaut selection process came in 1965, when NASA, working with the U.S. National Academy of Sciences, selected the first group of scientist-astronauts. This selection process evolved through extensive discussion and negotiation with the scientific community. The most substantial change in the U.S. selection process came in 1978, when the first set of specific exclusion/inclusion criteria were implemented, the category "astronaut" was subdivided into pilot astronaut and mission specialist, and women and minorities were selected for the Astronaut Corps.

Early examiners had little to guide them in developing selection criteria to match the requirements of the job, for little was known of the physical rigors associated with space flight. Speculation that space flight would degrade or make impossible basic body functions has been disproven. Nevertheless, humans do undergo substantial physiological changes in the course of adapting to the space flight environment (see Volume III of this series for extensive discussions of this topic).

Early methods used for medical selection were based initially on experience in aviation medicine, and reflected early expectations of what the duties of astronauts would be. The first astronaut candidates were all active military test pilots, graduates of test-pilot school with at least 1500 hours of experience flying high-performance jet aircraft. Of a group of 500 individuals from the U.S. Air Force, Navy, Marine Corps, and Army, 110 candidates met the basic requirements, and 69 from this group reported to Washington, D.C. under special military orders.

In Washington, these individuals were screened further through interviews with NASA project officials, psychiatric evaluations by two Air Force medical officers, reviews of their medical histories, and a battery of written tests. From these evaluations, 32 pilots were selected to undergo the next phase of screening.

These 32 finalists were screened with an extensive battery of medical and psychological tests, some of which were devised specifically for this purpose on the basis of the best medical judgment and state-of-the-art medical practices at that time. Candidates also underwent provocative physiological stress tests designed to simulate the combination of stresses an astronaut might encounter during a space mission. Tolerance was tested through use of a centrifuge, low-pressure chambers, an anechoic chamber, thermal-exposure units, and aircraft modified to fly Keplerian (parabolic) trajectories that produced brief periods of free fall. As a final step, peer ratings were obtained.

On April 2, 1959, NASA announced the selection of 7 men for Project Mercury (Fig. 1). This first group of astronauts ultimately was chosen because of their exceptional resistance to physical and psychological stresses and their particular scientific discipline or specialty. Since that time, 240 people have joined the U.S. Astronaut Corps, including 28 women (Table 1).

The first medical evaluations included practically every test known at the time (Table 2). The selection process has since become more focused, and some of the tests that had been used for screening candidates have been made part of the training process instead.

In 1977, using the medical standards of the Air Force, Navy, Department of Defense, and the Federal Aviation Administration, NASA developed a set of medical evaluation criteria for use in selecting astronauts.[16–19] These standards served as the basis for selections in 1978 and 1980, when 54 candidates (including 8 women) were approved to become pilot astronauts or mission specialists.

Standards have been revised regularly to reflect experience with human space flight, and the emergence of different categories of space traveler. Of the two career astronaut categories (i.e., pilot and mission specialist), standards for pilots, particularly vision standards, are more stringent than those for mission specialists. Standards for payload specialists and space flight participants are less stringent still, as described later in this chapter. Significant medical risk factors for acute and chronic diseases are weighed equally for all four classes.

Medical standards for career astronauts (pilot-astronauts and mission specialists) were modified in 1991 to include the potential effects of long flights aboard space stations.[19] Although this revision has not changed the standards substantially, it reflects careful consideration of individual health risks during longer flights. Particular attention is being paid to the possible effects of musculoskeletal and cardiovascular deconditioning, psychosocial issues, neurovestibular alterations, and exposure to radiation.

B. The Cosmonaut Selection Process

Medical evaluations for cosmonaut candidates have been—and continue to be—conducted in two stages. The first (outpatient) stage is conducted at aviation medicine departments in various hospitals. Medical documentation is compiled, and applicants undergo X-rays of the nasal sinuses (forward and side), fluoroscopic examination of the chest cavity, a 12-lead electrocardiogram (ECG), blood tests and urinalyses, and assessments of personality traits. Results of these assessments are evaluated by clinical specialists, each of whom establishes a diagnosis and recommends whether an applicant should continue the selection process. The medical certification board considers these recommendations and decides whether a particular candidate can proceed to the second stage of examination. For the second stages, military personnel are examined at the Central Scientific Research Aviation Hospital (CSRAH) and civilians at the Institute of Biomedical Problems (IBMP) State Scientific Center.

The first group of cosmonaut candidates, all volunteers, were fighter pilots who were no older than 35 years, weighed no more than 70 kg, and were no taller than 175 cm. The several hundred members of this group were evaluated by a medical board consisting of leading specialists in aviation and clinical medicine. Of this group, 331 were recommended for further evaluation as inpatients at the CSRAH.

During the 6 weeks between the first evaluation and admission to the CSRAH, 197 individuals elected not to proceed with the evaluation process, citing family, job, or other circumstances, the uncertainty of the future, or concerns that the comprehensive medical examination would reveal conditions that might limit or terminate their professional careers. Thus, 134 candidates entered the CSRAH for the second stage of the selection process.

The second stage of evaluations, which typically takes 30 to 45 days, constitutes a series of clinical-physiological evaluations at either the CSRAH or the IBMP. These evaluations include X-rays of the stomach and duodenum; fibrogastroduodenoscopy; ultrasound study of the liver, gallbladder, pancreas, and kidneys; bicycle ergometric test; echocardiography; and analysis of stomach secretions and duodenal contents. Other tests, designed to assess functional reserve capacities and identify any latent health defects, include tolerance of moderate hypoxia (to 6000 m altitude for 15 minutes) with positive-pressure oxygen breathing, barometric pressure differentials, etc. Centrifugation is used to determine how long candidates can tolerate acceleration forces of +6, +7, and +8 G_z, as assessed by the severity of their emotional reactions, their quality of performance, and the rate at which their attention can be switched during these tests.

After the tests are completed, results from both outpatient and inpatient stages are presented to the medical certification board, which reviews the findings and issues a preliminary decision as to whether the candidate is fit to undergo the special training associated with assignment to a specific program or crew (as described in Chapter 2 of this volume). The final decision as to whether a cosmonaut candidate is medically fit for special training is made by the Chief Medical Certification Board, which consists of leading experts in clinical and space medicine from the U.S.S.R. Ministry of Defense and Ministry of Health.

From a group of about 40 finalists, 20 men were chosen as the first cosmonaut contingent in February 1960, and reported for their first training session the following month.[20] Not all of these candidates went on to complete space flights because of later problems with health or fitness. One candidate was diagnosed with signs of hemorrhagic purpura and excluded during his first year of training. Another developed ulcers during his eighth year in the cosmonaut corps; a third injured his back during his first year in the corps; and four others were disqualified due to lack of fitness. Fig. 2 shows the first cosmonauts to fly on the Vostok and Voskhod missions.

Several cycles of cosmonaut candidate selection have taken place from 1959 to date, but the structure of the original selection process remains essentially unchanged.[21] The 20 groups selected since 1960 have included pilots and flight engineers as well as physicians and women. Since 1976, non-Soviet candidates from other countries also have been selected, most of them military pilots.[20]

In 1982, a joint ordinance from the USSR Ministry of Defense and Ministry of Health established medical standards for the selection and retention of three classes of cosmonauts: pilots, flight engineers, and researchers. The ordinance was updated in 1989[8] and sets forth numerous exclusion criteria for use during standard medical examinations and stress tests. These criteria are discussed later in this chapter.

Undoubtedly, ongoing improvements in rocket engines and spacecraft will continue to add to the complexity of the cosmonauts' tasks and lead to expansion of the scientific, technological, and biomedical research performed in space. These factors in turn will affect the details of cosmonaut selection, as they have in the past. One example is the inclusion of flight engineers and researchers in spacecraft crews. The in-flight duties of these specialists, their professional qualifications, their lesser physical fitness (relative to that of fighter pilots), and the presence of certain health conditions has led to individualized approaches in determining the fitness of these specialists for flight.[12,22]

Summaries of the processes by which astronaut and cosmonaut candidates are selected are depicted in Fig. 3.

II. Tests Used to Screen Astronaut and Cosmonaut Candidates

The substantial investment in time and cost associated with selecting astronauts and cosmonauts, and then certifying them for specific flights, dictates that assessments of their health and functional reserves be as accurate as possible. The objectives of clinical examinations in both the Russian and U.S. programs are to rule out latent diseases and to evaluate physiological, functional, and reserve potential with respect to future flight performance. Both countries seek to evaluate applicants for their physical ability to adapt and work in the space environment, and to emphasize the detection and prevention of diseases that may disqualify them or interfere with their ability to perform.

The Russian evaluation takes this philosophy one step further, and assesses the "occupational performance capacity" of its cosmonaut candidates throughout the selection process. This assessment is based on information about the candidate's health, physical endurance, and psychophysiological traits, in combination with comprehensive clinical examinations and functional (stress) tests that are thought to simulate flight conditions.

The following sections offer a brief review and comparison of the tests given in the initial cosmonaut or astronaut selection process. A system-by-system comparison of the general tests given to astronaut and cosmonaut candidates is given in Table 3.

A. U.S. and Russian Selection Tests

With few exceptions, tests are similar in the U.S. and Russian selection processes. As noted above, the U.S. no longer uses provocative stress tests [e.g., vestibulometry, parabolic flight, lower-body negative pressure (LBNP)] in the selection process, nor is susceptibility to motion sickness used as a basis for selection. Many of the same tests are listed under different systems or categories in the two programs. For example, the Russian program requires evaluation of the visceral organs to rule out acute paroxysmal disruptions of consciousness and performance. Some of the tests that constitute this evaluation (e.g., ultrasound tomography of the abdominal organs; standard 12-lead electrocardiography at rest; echocardiography; 24-hour Holter monitoring; assessments of external respiration and gas exchange; and blood pressure measurements) are given in the U.S. program, albeit under different classifications. Other tests (e.g., endoscopy of the esophagus and gastrointestinal tract; X-rays of the stomach and duodenum; Dopplerography of the heart and major blood vessels) are unique to the Russian program.

In general, both programs emphasize thorough medical histories and detailed physical examinations. With regard to laboratory analyses, assessments of blood, urine, and fecal samples are similar in the two programs, but cosmonaut candidates also undergo assessment of gastric and intestinal secretions and a 2-hour glucose tolerance test. Both countries conduct extensive ultrasound evaluations of the internal sex organs, and both require mammography for women. Radiological evaluations (including dental views) are similar in the two programs, although not required routinely in the U.S. program. The Russian program, however, requires a complete set of spinal X-rays, and cosmonaut candidates also undergo excretory urography.

Otolaryngologic tests in both programs include sinus X-rays, audiometry, and tympanometry. The Russian program also includes endoscopic and exoscopic examinations as well as a battery of vestibular function tests (e.g., electronystagmography, caloric irrigation, rotation, optokinetics, and ocular tracking). Other vestibulometric tests assess vestibuloautonomic, vestibulosomatic, and vestibulosensory reactions. Susceptibility to motion sickness is tested in terms of tolerance of Coriolis acceleration [described further under "Russian Functional (Stress) Tests" below].

U.S. and Russian ophthalmologic evaluations are similar, and include tests of visual acuity, color and depth perception, phoria, tonometry, perimetry, fundoscopy, and retinal photography. The Russian program includes a color lacrimal-nasal test as well. Neurologic evaluations include electroencephalography (EEG) under various conditions, and, in the Russian program, Doppler assessments of cranial vessels and X-ray views of the skull.

Russian and American philosophies differ substantially with regard to the role of psychological testing in the selection process. Although both programs include psychiatric and psychological testing, the Russian program attempts to include those individuals who are best equipped psychologically for the rigors of space flight. The U.S. program, by contrast, seeks to exclude individuals with frank or latent pathology, but does not seek to determine which individuals are best suited for flight.

In the Russian program, psychological analysis is directed toward identifying latent psychopathological or neuropsychological deviations; determining the structure of each candidate’s personality (i.e., motivations and values); studying individual tolerance of stress, difficult living conditions, and interpersonal interactions; and evaluating the candidate’s learning ability with respect to operator tasks and the stability of learned skills. Candidates are evaluated through interviews and observation, reviews of their medical history, work, and professional records, and observations of behavior patterns and reactions during simulated space flight tasks and in group interactions. The latter assessments of personality are thought to allow an objective evaluation of psychological development, character traits, and temperament. This information is used to develop individualized plans for special (mission-specific) training (see Chapter 2 of this volume). Assessment of a candidate’s psychological performance capacity and readiness to perform operator tasks encompasses stability, concentration, allocation of attention, visual and auditory memory, thinking, spatial and temporal orientation (ability), sensorimotor coordination, ability to work under time pressure, and psychological performance during sleep deprivation.[23] Conclusions are drawn from qualitative analyses that yield a composite numerical indicator, and from evaluations of behavior patterns and reactions in group situations.

B. Russian Functional (Stress) Tests

Another substantial difference between the Russian and U.S. selection processes is the use of stress tests to assess the candidates’ tolerance of conditions that either mimic those of space flight or produce physiological reactions characteristic of the microgravity environment. As noted, such tests are an integral part of the Russian selection battery, but are used only for training in the U.S. program. Tests that constitute this assessment include exposure to tilt and LBNP, graded and submaximal physical exercise, hypobaric conditions mimicking high altitudes or explosive decompression, and $+G_z$ and $+G_x$ acceleration.

1. Tilt Test

For this test, subjects lie supine on a tilt table that is positioned sequentially as follows: 0° (horizontal) for 20 minutes; -15° (head-down) for 6 minutes, -30° (head-down) for 6 minutes; and finally 90° (head-up) for 20 minutes. ECGs (standard and chest leads), blood pressure measurements (via Korotkoff sounds), echocardiography (to compute systolic volume and cardiac output), and Dopplerography of the major cranial vessels are conducted during the tilt test. Tolerance of the head-down and head-up positions is rated as shown in Table 4 (head-up tilt) and Table 5 (head-down tilt).

2. LBNP Test

The Russian LBNP protocol exposes a horizontal subject in a vacuum chamber to stepwise increases in decompression as follows: -25 mm Hg for 2 minutes; -35 mm Hg for 3 minutes;-40 mm Hg for 5 minutes; and -50 mm Hg for 5 minutes. Physiological measurements during LBNP are the same as those during the tilt test; tolerance is rated from those measurements and from subjective observations as shown in Table 6.

3. Exercise Tests

Graded submaximal exercise tests (Table 7) involve physiological tolerance of exercise during continuously increasing physical loads on a bicycle ergometer; a treadmill can be used as well. ECG (12-lead), and gas-exchange and blood pressure measurements are recorded during these tests.

4. Hypobaric Tests

Cosmonaut candidates are exposed to moderate hypoxia (altitude 5000 m) in a barochamber for 30 minutes while ECG and blood pressure measurements are recorded. Physiological tolerance of hypoxia is considered diminished in the presence of grouped or polytopic extrasystoles, T-wave inversion, displacement of the ST interval, or drastic slowing of atrioventricular and intraventricular conductivity, regardless of the nature of changes in other markers (blood pressure, heart rate, external appearance, self-reported state).

The depressurization test involves breathing oxygen for 60 minutes followed by "ascent" in a barochamber to a 10,000 m equivalent for 15 minutes. Physiological tolerance to atmospheric depressurization is considered diminished in the presence of intense pain in the joints and muscles, "high-altitude cough," pain or itching below the breastbone or near the heart, high-altitude flatulence or marked abdominal distension accompanied by sharp pain; or collapse or syncope.

5. Acceleration Tests

A large-radius centrifuge is used to create +3–5 G_z and +4–6 G_x accelerations. Tolerance of $+G_z$ acceleration (5 G_z for 30 seconds) and $+G_x$ acceleration (6 G_x for 40 seconds) is considered diminished in the presence of poor subjective tolerance; collapse or loss of consciousness during or after acceleration; frequent monotopic, grouped, or polytopic extrasystoles, paroxysmal tachycardia, wandering pacemaker, or disrupted myocardial conductivity; decreases of more than 0.4 diopters in binocular visual acuity; increases of 1 second or more in the latency of conditioned motor reflexes to light signals; decreased blood pressure in head vessels to below 30 to 50 mm Hg; petechial bleeding; or proteinuria or other pathological changes more than 48 hours after acceleration. Marked tachycardia (pulse greater than 190 beats/minute), tachypnea (respiration rate greater than 40 cycles per minute), facial pallor, or hyperhidrosis during centrifugation require a second centrifuge test before certification.

C. Russian Motion Sickness Susceptibility Tests

Individual responses to intermittent and continuous Coriolis acceleration are thought by some to predict individual susceptibility to motion sickness in space. Protocols used to assess responses to these stimuli are described below.

1. Cumulative, Continuous Coriolis Acceleration (CCCA)

For this test, subjects sit with their eyes closed in an electrically rotated Barany chair (Fig. 4), positioned so the angle of rotation passes through the torso. The chair is rotated at a constant rate of 180 degrees per second (i.e., one rotation every 2 seconds). At the end of the fifth rotation, at the experimenter's command, the subject tilts his or her head from the right shoulder to the left (or vice versa) and back, at an angle of no less than 30 degrees to each side with respect to the vertical. The head is moved continuously and smoothly, without stopping at the extreme or central positions. Each movement takes 2 seconds from shoulder to shoulder, and is timed either with a metronome, or by saying "21 and 22, 21 and 22." Subjects are told before the test about any sensations that might occur, and are instructed to announce the presence of such sensations as they occur. Subjects are observed for signs of vestibuloautonomic disorders; any autonomic symptoms experienced during rotation are recorded along with the time of occurence.

2. Cumulative, Intermittent Coriolis Acceleration (CICA)

This test also involves subjects sitting with their eyes closed in a Barany chair, but positioned so the angle of the trunk is 90 degrees with respect to the axis of rotation. Again, the chair is rotated at a constant 180 degrees per second. At the end of the fifth rotation, the subject is instructed to straighten and then return to the starting position smoothly, taking 3 seconds for each movement cycle. Timing is maintained by having the subject say "21, 22, 23" aloud; movements are begun every 5 seconds in response to the experimenter's command. This test is continued for 60 seconds (4 bends and 5 straightenings), after which the investigator notes the severity of autonomic responses and asks about subjective sensations. After a 60-second rest, the chair is rotated in the opposite direction, and the test continues in the same order for another minute. The 60-second test period begins with the command to straighten, and thus only the time spent straightening and bending the torso is counted.

Coriolis tests are conducted during the first half of the day, at least 2 hours after eating. On the day of the test, the subject is not scheduled for any other loading tests (centrifugation, hypoxic tests, etc.). If meal or work-rest schedules have been disrupted or the candidate is ill, the test is rescheduled. Pronounced vestibuloautonomic symptoms (pallor, sweating, nausea, vomiting) during the test or immediately afterwards are considered threshold criteria for tolerance, i.e., candidates who show these symptoms typically are given negative predictions for occupational fitness.

III. Qualification/Disqualification Standards for Selection to the Astronaut or Cosmonaut Corps

In both the U.S. and Russian programs, differences in the responsibilities held by each class of crewmember (see Chapter 2, section IA) form the basis for establishing different selection criteria for these and other classes of space flight participants. Individuals who will become commanders or pilots must meet the most stringent health criteria (e.g., Table 8) and, in the Russian program, the highest psychophysiological standards as well. Less stringent requirements are imposed on mission or payload specialists (U.S.) and cosmonaut-researchers (Russia), who are not directly involved with spacecraft-control equipment or systems responsible for the lives of the crew. Individual factors considered important in evaluating candidates for cosmonaut-researchers include professional performance, reserve capacities, uniqueness in terms of the research program or investigational ability, and the ability to perform specific mission tasks.

An overall comparison of U.S. and Russian selection standards reveals that Russian exclusion criteria (Table 9) tend to be somewhat general. (The U.S. counterpart to Table 9 is 50 pages long, and lists 291 items, with many subclassifications.) However, Russian standards occasionally provide more detailed descriptions to be applied to individuals or individual conditions. If specific conditions or illnesses are not named as disqualifiers, then general statements such as the example given above are used to determine a particular candidate's fitness. Moreover, the sequelae of a particular condition, e.g., poor performance on an exercise test because of obesity, may be used as a disqualifier when the condition itself is not specified.[8]

A. General Causes for Exclusion

The most significant difference between the two countries is represented by the extensive functional (stress) tests in the Russian program. Applicants for any class of cosmonaut must undergo these tests, and must meet specific criteria for inclusion (see Tables 4–7). Astronaut candidates do not undergo this type of testing during selection, but do so after selection, during the training process.

In contrast, both programs exclude candidates who have temporary infections, injuries, contusions, or fractures that would interfere with space flight duties; malignancies; surgical procedures ([until recovery); presence of foreign bodies; history of heat stroke or vertigo; or allergies that could interfere with performance.

Radiation sickness or exposure is cause for rejection in both programs, but only the U.S. specifies exposure limits. Russian standards specify only the sequelae of past radiation exposure, in combination with fitness for special (mission-specific) training, the latter being decided by clinical and hematological evaluations over a period of not less than 6 months.

The U.S. rejects for chronic use of any medication, certain types of hepatitis, and HIV infection. The Russian process excludes individuals who take medication chronically for complications from certain types of illnesses, such as hepatitis, chronic infectious disease, or HIV infection.

B. Visceral Causes

1. Lungs and Chest

About 20 causes for rejection related to the lungs and chest are common to both selection programs. Pneumosclerosis is specified as cause for rejection in the Russian—but not the U.S.—program; 16 additional criteria are specified by the U.S.—but not the Russian—program. General standards in the Russian program are noted under *General and Visceral Causes* in Table 9.

With regard to cardiovascular function, both countries have similar examinations and rejection criteria. Exclusion criteria unique to the U.S. program include history of major congenital abnormalities, recurrent thrombophlebitis, severe varicose veins if associated with edema, and skin ulcerations or scars. The Russian process excludes candidates for disease or consequences of trauma to peripheral vessels, the presence of trophic disturbances, and circulatory disruption.

2. Abdominal and Gastrointestinal Causes

Only about half of the disqualifiers in this area are common to both programs. Both sides disqualify applicants with hernia, esophageal disease, chronic abdominal pain, ulcers, damage from GI surgery, neoplasm in any part of the GI system, malabsorption, colitis, chronic digestive disorders, diverticulitis, gall bladder or pancreatic disorders, hepatitis, spleen enlargement, and rectal or anal disease. The U.S. program also excludes candidates with chronic diarrhea or constipation, megacolon, GI bleeding, a history of cholecystectomy, cholelithiasis, splenectomy, gastrostomy, ileostomy, or colostomy, persistent enteric pathogens, wounds that interfere with function, sinus or fistula of the abdominal wall, a history of intestinal obstruction, and Crohn’s disease. The Russian program rejects candidates with chronic diseases of the digestive organs or consequences of damage or surgical intervention, particularly in cases of pronounced or persistent functional disruption with the tendency to become acute.

C. Anthropometric Causes

U.S. candidates must not be taller than 193 cm (76 in); minimum heights are different for pilot candidates (162.6 cm [64 in]) and for mission specialists (148.6 cm [58.5 in]). Weight ranges are specified for height and age. Russian requirements reflect the physical constraints of the Soyuz spacecraft; cosmonauts must not weigh more than 85 kg (187 lbs), nor be taller than 182 cm (72 in) while standing or 94 cm (37 in) while seated. Appropriate body mass ranges in the Russian program are calculated for each individual with a technique established at the Nutrition Institute of the Academy of Medical Sciences that depends on sex, age, and constitution. If an individual’s body mass is deemed either excessive or insufficient, the decision to admit that person for special training is based on his or her lipid, carbohydrate, and protein metabolism and ability to withstand functional physical loads.

D. Musculoskeletal Causes

Musculoskeletal causes for rejection are similar in both the U.S. and Russian selection programs; 37 of the 42 exclusion criteria are common to both programs. History of back pain, amputation, weak foot, hallus valgus, or bunions are causes for rejection in the U.S. but not the Russian program. General criteria for rejection in the Russian program include diseases or injury to peripheral nerves in the presence of persistent functional disruption or lasting pain; sequelae of damage to or disease of the bones or muscles with significant anatomical or functional changes; and foot deformities.

E. Head, Face, Neck; Ear, Nose, and Throat

Both programs reject candidates with deformities, congenital bone defects, and chronic joint disease. The U.S. program also rejects candidates with unrepaired cleft, chronic neck fistula, cervical lymphadenopathy, chronic spastic or nonspastic contraction of neck muscles, and symptomatic cervical ribs. Criteria regarding the nose, sinus, mouth, and throat are similar, although the wording and emphasis differ slightly. The U.S. specifies perforation or deviation of the nasal septum and extensive ranula as causes for rejection. Russian candidates are disqualified for rhinitis accompanied by dystrophic changes in the upper respiratory tract, mucosa, or spontaneous nasal hemorrhage. Congenital anomalies that cause permanent changes in the mouth cavity or tongue are causes for rejection. Except for mastoidectomy, both countries reject for similar ear problems, e.g., chronic ear diseases, perforated eardrum or disruption of ear pressure, or not meeting hearing standards.

F. Ophthalmic Causes

As would be expected, both countries emphasize extensive eye examinations and have about 33 causes for rejection in common. The Russian standards also reject for tearing from lachrymal duct disease, which is not specified in the American standards. The U.S. program includes 30 eye-related causes for candidate rejection that are not specified in the Russian program (Table 10).

G. Hematologic and Endocrine Causes

Comparing exclusion criteria in these areas is difficult because of differences in specificity between the two programs. For example, the Russian selection standards simply state that diseases of the blood and blood-creating organs are causes for rejection; U.S. standards list specific blood diseases (e.g., anemias, sickle cell, etc.). Russian standards specify that any degree of endocrine-gland disease is grounds for exclusion, but U.S. standards are more specific in terms of which gland and sometimes the degree of impairment. Both sides disqualify for metabolic disorders, but only the Russian program specifies enlargement of the thyroid gland with endocrine involvement.

H. Genitourinary Causes

Criteria regarding the genitourinary system are similar in the two countries; Russian standards are noted under both *Surgical and Excretory Causes* and *Gynecologic Causes* in Table 9. The U.S. program specifically rejects for neoplastic disorders; both reject for persistent menstrual abnormalities and obstetrical problems. Other causes specified by the U.S., but not the Russian program, include premenstrual syndrome that disrupts performance, requires medication, or causes medical absences, and chronic dermatologic conditions of the vulva.

I. Dermatologic Causes

Again, Russian standards regarding skin disorders are stated more broadly than U.S. standards, and include widespread skin diseases; sequelae of bone or muscle damage or disease entailing anatomical or functional changes; consequences of burns that limit joint movements or impede the use of footwear, clothing, or special apparel; connective-tissue disease; and large benign tumors.

J. Oral or Dental Causes

Dental reasons for rejection are virtually identical for astronaut and cosmonaut candidates, and include dental defects that interfere with clear speech or affect the ability to chew.

K. Neurologic Causes

Both countries reject candidates with disorders of the central or peripheral nervous systems and spinal cord, as well as CNS infections, convulsive disorders, craniotomy, and trauma to the head or CNS. The U.S. screens astronaut candidates for chronic headache, migraine, decompression sickness, abnormal EEG, congenital or developmental abnormalities of the nervous system, and neurological diseases of hereditary origin. The Russian program does not name these problems specifically, but instead lists such exclusion criteria as consequences of trauma, acute infections, CNS intoxication in the presence of stubborn residual symptoms, or other organic diseases of the CNS. The Russian program rejects candidates with diseases of the autonomic nervous system, but the U.S. system does not specify these disorders.

L. Psychiatric Causes

Rejection criteria for psychiatric causes are difficult to compare; however, both programs reject for psychosis, clinically significant neuroses, and personality disorders. The U.S. considers substance abuse (alcohol or drug abuse) to be psychiatric grounds for exclusion, but the Russian standards do not address this issue. Rather, substance abuse is regarded as a neurosis, and as such is included in the general category of all forms of neuroses and psychoses regardless of the etiology or mechanisms that caused their development, i.e., exogenic, organic, drug, alcohol, toxic psychosis, etc.

In summary, with the notable exception of the functional (stress) tests used in the Russian selection process, causes for rejecting astronaut and cosmonaut candidates are remarkably similar in both the U.S. and Russian selection processes. Recent emphasis on cooperative missions and free exchange of information between the U.S. and the former Soviet Union undoubtedly will continue to narrow any existing gaps between programs in terms of initial medical requirements for selection.

M. Types and Distribution of Disqualifying Conditions Found During the Selection Process

1. U.S. Causes

A summary of the numbers and distributions of disqualifying medical conditions found in applicants for the U.S. Astronaut Corps at selection is presented in Table 11.

2. Russian Causes

Of the 774 individuals (chiefly pilots) examined for cosmonaut selection between 1959 and 1985, 674 individuals were disqualified, 34% for visceral diseases or disorders; 26% for otolaryngologic problems; 15% for surgical or genitourinary problems; 12% for neurologic problems; 8% for dental problems; and 5% for visual (refraction) anomalies.

The most prevalent visceral problems were of cardiovascular (62%) or gastrointestinal origin (30%); the remainder (8%) were unspecified problems with blood or respiratory organs. Of the subgroup disqualified for cardiovascular disease, 36% had “cardiomyopathy of various etiologies,” 14% had “myocardosis/coronary sclerosis,” and 12% had neurocirculatory asthenia.

Most common among cardiovascular disorders were those that disrupted cardiac signal conduction, excitability, or automatism.[25] These parameters frequently were cause for exclusion from the Russian program during the first round of selections in the late 1950s and early 1960s. As diagnostic methods have improved, some individuals have been deemed fit to continue training who otherwise might have been excluded during the selection process. Improvements over the past 30 years in ability to assess cardiovascular function, reserve capacities, and compensatory capacities under ordinary and extreme conditions have compelled Russian and U.S. scientists to redefine “normal” ranges.

Of the group disqualified for gastrointestinal problems, 30% were disqualified for “visceral” problems, 16% for chronic gastritis or gastroduodenitis, 9% for liver or biliary disease or functional hyperbilirubinemia, and 5% for gastric or duodenal ulcers. Moderate changes in the mucous gastroduodenal tract combined with secretory and motor disorders, or a history of dyspeptic disorders, are considered sufficient reasons for rejection.

Of the 26% of candidates disqualified for ear, nose, and throat problems, 32% had surgically treated chronic tonsillitis, 30% had (untreated) chronic sinusitis and vasomotor rhinosinusopathy; 23% had “vestibular intolerance”; 7% had cochlear neuritis; and 8% had other diseases. (Slight vasomotor changes in the mucous membranes without nasal or barofunctional dysfunction are not disqualifying.) With regard to vestibular intolerance, observations of cosmonauts during professional training and flight have verified that otoconial reactions and Khilov swings are inadequate to assess resistance to space flight factors; centrifugation followed by Khilov swings also has failed to produce sufficient information. Tolerance of cumulative Coriolis acceleration using intermittent and continuous exposure is thought to hold more promise in terms of predicting individual susceptibility.

Surgical and excretory problems were the third most common causes of disqualification, accounting for 13% of the total number of candidates disqualified. Of this group, 29% had degenerative-dystrophic changes in the spine, 8% had developmental anomalies of the kidneys or urinary tract, and 10% had inflammatory changes of the kidney or urinary tract.

Among neurological disorders, the most common has been emotional-autonomic instability that becomes apparent during specific loading tests. For example, one indicator for terminating a test within the special selection program is the combination of emotional-autonomic instability and disruption of cardiac function. The psychological test results of individuals who show this combination of symptoms are evaluated with particular attention.

Excessive caries or periodontitis with alveolar atrophy have been the major dental/oral problems. Disqualifications associated with vision primarily reflect diminished visual acuity and refraction anomalies. Years of observing cosmonauts in action have allowed visual requirements for candidates and cosmonauts to be relaxed somewhat, depending on what their actual tasks will be during flight. Individuals who are not involved in controlling the spacecraft or using systems that require excellent vision can be deemed fit for special training even if they suffer from myopia of 0.5 in each eye. They may be advised to wear corrective glasses or contact lenses if the power of the corrective lens does not exceed ± 2.0 diopters.

IV. Qualification/Disqualification Standards after Selection

After individuals are selected to the U.S. Astronaut Corps (Fig. 3), they undergo medical evaluations yearly to continue their medical certification for space flight, as well as before and after each flight. Annual examinations emphasize early detection of latent pathological processes and determine physical suitability for short or long space flights. The tests given annually are similar but less extensive than the selection battery.

Disqualifying criteria for annual examinations are largely the same as those for selection, albeit with some latitude given for case-by-case consideration. Results of annual evaluations are used to classify astronauts into one of four groups: qualified with no restrictions, qualified with temporary or permanent waiver, temporarily disqualified, or permanently disqualified. After being selected, each individual undergoes a year-long training period before being assigned to a specific flight.

As noted, the Russian certification process is somewhat different (Fig. 3). After medical selection, candidates must be deemed medically qualified through a special program of inpatient examinations held at the CSRAH or IBMP. Candidates then are deemed fit or unfit for special training, i.e., activities such as parabolic flight, centrifuge testing, vestibular stimulation, barochamber testing, underwater practice sessions, and others. (Special training is described further in Chapter 2 of this volume.) Cosmonauts also undergo comprehensive medical examinations quarterly and before and after each flight.[8] When rare diseases or functional disorders are identified during any of these certification examinations, a cosmonaut's fitness for special training is determined by considering the following:

- The severity of disease and any functional sequelae;
- The extent to which pathological processes can be reversed;
- The amount of compensation for existing disorders;
- The status of compensatory mechanisms (measured during stress tests);
- Tolerance of acceleration;
- Level of training in the specialty;
- History of previous performance in the presence of health problems;
- The possibility that the disorder could worsen in response to training or space flight;
- The candidate's personality and motivation; and
- The duration of the scheduled flight and the nature of the work during that flight.

Cosmonauts are declared unfit if indications of any of the disorders listed in Table 9 become apparent. Cosmonauts also are rejected for "functional disorders" involving diminished tolerance of moderate hypoxia, sudden decompression, radial acceleration, changes in body position, physical exercise, or combinations of adverse conditions; diminished tolerance of parabolic-flight effects that does not improve with training; and "negative personality traits" (defined further in Chapter 2 of this volume).

A. Types and Distribution of Disqualifying Conditions Found After Selection

No one has been permanently disqualified from the U.S. Astronaut Corps for medical reasons during the U.S. Space Shuttle program. In the Soviet/Russian program, 39 selected cosmonauts were disqualified for medical reasons between 1959 and 1989. All of these individuals developed "acute" diseases that formed the basis for disqualification. The distribution of disqualifications on the basis of primary disease is shown in Table 12.

The most common cause of disqualification after selection (n = 9) was chronic gastroduodenal disease. Five of these individuals had moderate gastric hypersecretion or prolapse of the gastric mucosa into the duodenum. Of the 8 individuals who had duodenal ulcers, seven had foci on the posterior lower wall, and the eighth on the anterior upper wall. The ulcers bled in two individuals, and all nine became worse under stressful conditions.

The development of hemophilic blood-clotting disorder, purpura hemorrhagica, and second- or third-degree periodontitis (all disqualifiers during the first year in the Corps) led to the inclusion of blood coagulograms and pantomograms in the selection test battery. All 5 cosmonauts who were declared unfit because of kidney stones showed some evidence of this disease during preflight training. Since that time, several informative tests have been added to the compulsory selection battery to rule out similar errors in selection.

V. Summary and Future Issues

Requirements pertaining to the health status of candidates, as well as the methods and criteria for evaluating tolerance of provocative tests, are constantly being improved, refined, and supplemented. The most up-to-date approaches from clinical and aviation medicine, biochemistry, pharmacology, and other disciplines are used in this process.[13,26]

The U.S. space program has used retrospective analysis of astronaut health and changes in health status over time to identify those variables likely to be affected by age and exposure to the microgravity environment.[3] Specifically, exposure to space travel (i.e., microgravity, radiation, and ground-based training for space travel) is thought to be associated with increased risk of bone demineralization, muscle atrophy, thyroiditis, cataracts, cancer, renal stones, barotrauma, and infectious diseases. Prospective longitudinal studies were begun recently that aim to compare changes in astronaut health against changes in healthy control groups matched for age, sex, and body-mass index. Physiologic and lifestyle variables thought to constitute risk factors for chronic diseases will be measured annually and compared regularly between the test and control groups. Study results are expected to clarify the incidences of acute and chronic morbidity and mortality of astronauts; to describe the morbidity and mortality risks associated with the occupational exposures encountered by astronauts versus those of healthy control subjects; and to assess the lifetime and flight-time risk of specific diseases and disorders. This information will be helpful in modifying current medical standards for certification and in creating new standards as needed.

With the advent of extensive U.S.-Russian space missions in the 1990s, much effort has been put forth to develop a uniform, international set of medical standards for participation in space flight. These standards were still being debated as of 1996, but ongoing negotiations have considerably narrowed some of the gaps between the programs in preparation for international participation in building and staffing new generations of space stations.

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Figure Captions

Fig. 1 The first U.S. astronauts, selected for Project Mercury (NASA photo B59-0042). Standing, from left to right: Alan B. Shepard, Jr., Walter M. Schirra, Jr., John H. Glenn, Jr. Seated, from left to right: Virgil I. "Gus" Grissom, M. Scott Carpenter, Donald K. "Deke" Sleyton, and L. Gordon Cooper.

Fig. 2 The first Vostok and Voskhod cosmonauts, 1961–1965. Seated, from left to right: K. P. Feoktistov, V. N. Tereshkova, A. A. Leonov, A. G. Nikolayev, G. S. Titov. Standing, from left to right: Yu. A. Gagarin, V. A. Bykovskiy, B. B. Yegorov, P. I. Belyayev, P. R. Popovich, and V. M. Komarov.

Fig. 3 Diagram of the processes with which the U.S. and Russian space programs select astronauts and cosmonauts, respectively. FAA, Federal Aviation Administration; CSRAH, Central Scientific Research Aviation Hospital; IBMP, Institute of Biomedical Problems.

Fig. 4 Modified Barany chair used for vestibulometric testing.

Table 1 Chronology of U.S. astronaut selection from 1959 to 1995

Year	Category	# Finalists	# Selected Men	Women	Average age at selection, y
1959	Mercury Pilots	69	7	0	35
1962	Pilot-Astronaut	32	9	0	32
1963	Pilot-Astronaut	136	14	0	31
1965	Scientist-Astronaut	16	6	0	30
1966	Pilot-Astronaut	158	19	0	32
1967	Scientist-Astronaut	69	11	0	31
1969	Pilot-Astronaut	13	7	0	29
1978	Total	208			
	Pilot		15	0	34
	Mission Specialist		14	6	31
1980	Total	121			
	Pilot		8	0	34
	Mission Specialist		9	2	32
1984	Total	128			
	Pilot		7	0	36
	Mission Specialist		7	3	32
1985	Total	59			
	Pilot		6	0	33
	Mission Specialist		5	2	30
1987	Total	117			
	Pilot		7	0	34
	Mission Specialist		6	2	33
1990	Total	106			
	Pilot		6	1	34
	Mission Specialist		12	4	32
1992	Total	87			
	Pilot		4	0	34
	Mission Specialist		12	3	36
	International Mission Specialist		5	0	33
1995	Total	122			
	Pilot		8	2	36
	Mission Specialist		6	3	36
	International Mission Specialist		2	0	40
	Totals	1,441	212	28	33

Table 2 Medical and psychological tests given to U.S. astronaut candidates, 1962–1969 [Ref. 15]

Medical history and review of systems
Physical examination
Electrocardiographic examinations, including:
    routine electrocardiographic studies at rest, during hyperventilation, carotid massage, and breath-holding; a double Master exercise tolerance test, a cold pressure test, and a precordial map
Treadmill exercise tolerance test
Vectorcardiographic study
Phonocardiographic study
Tilt-table studies
Pulmonary function studies
Radiographic studies, including:
    cholecystograms, upper GI series, lumbosacral spine, chest, cervical spine, and skull films
Body composition study using tritium dilution
Laboratory examinations, including:
    complete hematology workup, urinalysis, serologic test, glucose tolerance test, acid and alkaline phosphatase, BUN, sodium, potassium, bicarbonate, cholide, calcium , phosphorus, magnesium, bilirubin (direct and indirect), thymol turbidity, cephalin flocculation, SGOT, SGPT, total protein with albumin and globulin, separate determination of Alpha 1, Alpha 2, β and γ globulins, protein-bound iodine, creatinine, cholesterol, total lipids and phospholipids, hydroxyproline, and red blood cell intracellular sodium and potassium. Stool specimens were examined for occult blood and microscopically for ova and parasites. Urine was cultured for bacterial growth, and a 24-hour specimen was analyzed for 17-ketosteroids and 17-hydroxycorticosteroids
Detailed examination of the sinuses, larynx, and Eustachian tubes
Vestibular studies
Diagnostic hearing tests
Visual fields and special eye examinations
General surgical evaluation
Proctosigmoidoscopy
Dental examination
Neurological examination
Psychological summary, including:
    Wechsler Adult Intelligence Test, Bender Visual-Motor Gestalt Test, Rorschach Test, Thematic Apperception Test, Draw-A-Person Test, Gordon Personal Profile, Edwards' Personal Preference Schedule, Miller Analogies Test, and performance testing
Electroencephalographic studies
Centrifuge testing

Table 3 Medical tests given to astronaut (1977–1992) and cosmonaut candidates [Refs. 8, 19]

Astronaut candidates	Cosmonaut candidates
Medical history	Medical history
NASA Medical Survey Questionnaire	includes surgical history and examination
Physical examination	Physical examination
includes rectal exam	includes rectal exam
pelvic exam and pap smear	pelvic exam and uterine ultrasound
proctosigmoidoscopy	
Cardiopulmonary evaluation	Cardiopulmonary evaluation
includes history and examination	includes history and examination
pulmonary function tests	pulmonary function tests
exercise stress test	exercise stress test
blood pressure	blood pressure
resting and 24-hour ECG	resting and 24-hour ECG
echocardiogram	echocardiogram
	phono- and mechanocardiography
	cardiac cycle analysis
Musculoskeletal evaluation	Musculoskeletal examination
muscle mass, anthropometry	anthropometry
Radiographic evaluation[a]	Radiographic evaluation
chest films (PA and lateral)	chest films (abdominal flat plate)
sinus films	cranium, spine, renal, and urologic X-rays
mammography	abdominal and urogenital ultrasounds
interview with radiation safety officer	radioisotope liver test
review medical radiation exposure history	excretory urogram and urofluorometry
Laboratory examinations	Laboratory examinations
complete blood workup	complete blood workup
(clinical biochemistry; hematology; immunology; serology; endocrinology)	(clinical biochemistry; hematology; immunology; serology
urinalyses, including 24-hour urine chemistry, renal stone profile, and urine endocrinology	urinalyses, including 24-hour urine chemistry and renal stone profile
stool analysis for occult blood, ova, and parasites	stool analysis for ova and parasites
	analysis of duodenal and intestinal secretions
Otorhinolaryngological (ENT) evaluation	Otorhinolaryngological (ENT) evaluation
includes history and examination	includes history and examination
audiometry	sinus X-ray
tympanometry	audiometry
	tympanometry
	exo- and endoscopy
	vestibular function
	optokinetic stimulation
Ophthalmologic evaluation	Ophthalmologic evaluation
includes visual acuity, refraction, and accommodation	includes visual acuity, refraction, and accommodation
color and depth perception	color and depth perception
phorias	night vision
tonometry	tonometry
perimetry	extraocular muscles
funduscopic examination with retinal photographs	slit-lamp examination and ophthalmoscopy

Table 3, continued

Astronaut candidates	Cosmonaut candidates
Dental examination	Dental examination
includes “panorex” and full dental X-rays within prior two years	orthopantomography
	electroodontodiagnosis
	vacuum test
Neurological evaluation	Neurological evaluation
includes history and examination	includes history and examination
EEG at rest	Doppler study of cranial vessels
EEG with photic stimulation	EEG with photic stimulation
EEG during hyperventilation, Valsalva maneuver, and sleep	autonomic reflexes
	skin thermometry
Psychiatric and psychological evaluation	Psychiatric and psychophysiologic evaluation
psychiatric interview	psychiatric interview
psychological tests	psychometric testing
	personality inventory
	sleep monitoring
Other tests	Functional tests
drug screen	decompression and hypoxia
PPD skin test	centrifugation (G_z and G_x)
microbiological, fungal, and viral tests	postural tests
pregnancy test	lower body negative pressure
screen for sexually transmitted disease	ergometry
abdominal ultrasound	thermal testing
	parabolic flight

[a] A pregnancy test is given to all female applicants before radiographic testing

Table 4 Ratings for tolerance of head-up tilt

Characteristics	Ratings	Description of ratings
General state	Good	Quite good
	Satisfactory	General state good, may be complaints of mild fatigue or weakness
	Poor	Complaints of marked weakness, vertigo, sensation of heat moving in waves in the body; may have convulsions or lose consciousness
General appearance	Good	Normal, sometimes slight cyanosis of the hands
	Satisfactory	Hyperhidrosis of the face, armpits, palms; perhaps facial pallor; may remain normal
	Poor	Facial pallor, hyperhidrosis of the head, chest, and palms; marked decrease in muscle tone
Respiration	Good	Unchanged or slight change in either direction
	Satisfactory	Unchanged or slight change in either direction
	Poor	Dyspnea; isolated deep respiratory movements
End systolic pressure	Good	Typically decreases somewhat, remaining in normal range; occasionally increases
	Satisfactory	Decreases moderately, less frequently remains at baseline
	Poor	Decreases markedly
Pulse pressure	Good	Decreases somewhat but remains relatively high (> 30 mm Hg)
	Satisfactory	Decreases to 20-25 mm Hg; can be high when diastolic pressure drops
	Poor	Decreases markedly (to < 20 mm Hg); can be quite high when diastolic pressure drops
Systolic volume	Good	Decreases by up to 30% of baseline, not less than 30 mL
	Satisfactory	Decreases by up to 50% of baseline, not less than 20 mL
	Poor	Decreases by more than 50% of baseline, less than 20 mL
Cardiac output	Good	Decreases by up to 30% of baseline
	Satisfactory	Decreases by up to 50% of baseline
	Poor	Decreases by more than 50% of baseline
ECG	Good	Regular rhythm, moderation respiratory cardiac arrhythmia
	Satisfactory	Regular, marked respiratory arrhythmia, wandering pacemaker; isolated extrasystoles
	Poor	Frequent atrial and rare ventricular extrasystoles, grouped extrasystoles, allorhythmia, etc.
T wave	Good	Amplitude diminishes by up to 30% of baseline
	Satisfactory	Amplitude diminished by up to 50% of baseline, slight deformation of the T wave in leads I–III
	Poor	Significant decrease in amplitude up to the isoelectrical level, appearance of double waves, double phases and inversion
ST segment	Good	Unchanged
	Satisfactory	Depression by up to 1.0 mm
	Poor	Depression by more than 1.0 mm

Table 5 Ratings for tolerance of head-down tilt

Characteristics	Ratings	Description of ratings
General state	Good	Slight sensation of rush of blood to head, pulsing in temples
	Satisfactory	Some signs of discomfort, marked sensation of rush of blood to head, heat, pulsation in temples
	Poor	Marked discomfort, throbbing and heaviness in head, headache
General appearance	Good	Reddening of face and sclera
	Satisfactory	Slight cyanosis of face and lips
	Poor	Marked cyanosis of face and lips

Table 6 Ratings for tolerance of lower body negative pressure (LBNP)

Characteristics	Ratings	Description of ratings
General state	Good	Good
	Satisfactory	Good
	Poor	Complaints of general weakness, dimming of vision, vertigo, nausea, perspiration, sensation of heat; development of state of collapse, convulsions, loss of consciousness
General appearance	Good	Normal, possibly moderate pallor of the facial triangle
	Satisfactory	Moderate facial pallor
	Poor	Marked facial pallor, cyanosis of the lips, local or general hyperhidrosis
Pulse pressure	Good	Decreases somewhat, remains 25 mm Hg or higher
	Satisfactory	Decreases to 15 mm Hg
	Poor	Below 15 mm Hg, marked sinusoidal fluctuations
ECG rhythm	Good	Regular, heart rate increases by up to 15 beats/minute
	Satisfactory	Heart rate increases by more than 15 beats/minute
	Poor	Tachycardia, alternating with bradycardia, extrasystoles, disruption of intracardiac conductivity
T wave	Good	Decreases by up to 30% of baseline
	Satisfactory	Decreases by up to 50% of baseline, slight deformation of the T wave in leads I–III
	Poor	Significant decreases, diffuse deformation of T wave, slight decrease in one T segment
Systolic volume	Good	Decreases by up to 30% of baseline
	Satisfactory	Decreases by up to 50% of baseline
	Poor	Decreases by more than 50% of baseline

Table 7 Ratings for tolerance of graded exercise

Characteristics	Ratings	Description of ratings
General state	Good	Good
	Satisfactory	General state is rather good, there may be complaints of slight fatigue
	Poor	Complaints of general weakness, fatigue, loss of consciousness
External appearance	Good	Normal, sometimes slight hyperhidrosis
	Satisfactory	Moderate hyperhidrosis
	Poor	Significant hyperhidrosis of skin, head, chest, palms; marked facial pallor; tendency to faint
Respiration	Good	Appropriate
	Satisfactory	Strained, with use of auxiliary musculature
	Poor	Frequent (rapid) labored respiration, dyspnea
Gas exchange	Good	Parallel between increase in loading and magnitude of pulmonary ventilation, oxygen consumption and heart rate; oxygen consumption at the peak of loading is no less than 30 ml/kg min
	Satisfactory	Oxygen consumption no less than 25 ml/kg min
	Poor	Oxygen consumption 25 ml/kg and less
Oxygen pulse	Good	Greater than 13 ml/beat
	Satisfactory	10–13 ml/beat
	Poor	Less than 10 ml/beat
Systolic pressure	Good	Increases to 200 mm Hg
	Satisfactory	Increases to 220 mm Hg
	Poor	Exceeds 230 mm Hg or decreases sharply as loading increases
Diastolic pressure	Good	Unchanged or changes within ± 10 mm Hg from baseline
	Satisfactory	Increases to 110 mm Hg
	Poor	Increases to more than 120 mm Hg
ECG rhythm	Good	Sinus
	Satisfactory	Sinus, monotopic extrasystoles (no more than 5% of heart rate per minute)
	Poor	Sinus, frequent monotopic systoles (more than 5% of heart rate per minute); grouped, polytopic allorhythmia [3 or more], paroxysmal tachycardia; fibrillation or palpitation of the aurical, auricular-ventricular blockade; blockade of the branches of the His bundles, shortening of the P-Q interval
T wave	Good	Slight change (by up to 50% of baseline)
	Satisfactory	Significant increases or decreases, sometimes the decrease is accompanied by flattening; moderate (by up to 75% of baseline) changes in the position of the amplitude axis
	Poor	Becomes biphase or is inverted; in some cases, huge decreases or significant increases in amplitude (by more than 75% baseline)
ST segment	Good	Unchanged
	Satisfactory	Decrease in horizontal or rising diagonal not greater than 0.75 mm
	Poor	Decrease in horizontal or decreasing diagonal of greater than 1.5 mm; in rising diagonal by more than 2.5 mm, if the absolute duration is not less than 0.8 seconds

Table 8 Differences in medical standards for U.S. space flight participants [Refs. 19, 24]

Item	Pilots (Class I)	Mission Specialist (Class II)	Payload Specialist (Class III)	Participants (Class IV)
Distant vision	20/50 or better uncorrected; correctable to 20/20 each eye	20/150 uncorrected; correctable to 20/20 each eye	correctable to 20/40 best eye	same as Class III
Near vision	uncorrected < 20/20 each eye	same as Class I	not specified	not specified
Refraction/Astigmatism	specified	specified	not specified	not specified
Contraction of visual field	15°	15°	30°	not specified
Phorias	ESO > 15; EXO > 8 Hyper > 2	ESO > 15; EXO > 8 Hyper > 2	not specified	not specified
Depth perception	no errors in 16 presentations of the Verhoeff stereopter test	same as Class I	not specified	not specified
Color vision	pass Farnsworth lantern test	same as Class I	not specified	not specified
Hearing loss	each ear: 30 db @ 500 Hz 25 db @ 1000 Hz 25 db @ 2000 Hz 50 db @ 4000 Hz	same as Class I	better ear: 35 db @ 500 Hz 30 db @ 1000 Hz 30 db @ 2000 Hz	must hear whispered voice at 3 ft. (hearing aid allowed)
Height	64–76 inches	60–76 inches	not specified	not specified
Blood pressure	140/90	same as Class I	150/90; Rx allowed	150/90; Rx allowed
Radiation exposure	< 5 rem/year	same as Class I	not specified	not specified

Table 9 Russian exclusion criteria for cosmonaut candidates [Ref. 8]

General and visceral causes
Chronic infectious diseases
All forms of pulmonary tuberculosis
Diseases of the endocrine system and metabolism
Diseases of the blood or blood-forming organs, including chronic allergic diseases
Chronic respiratory diseases of nontubercular origin or sequelae entailing disorders of external respiration
All stages and forms of essential hypertension
Organic disease of the cardiac muscle, coronary artery, aorta, or valves, with circulatory insufficiency
Chronic disease of the digestive organs (or sequelae of injury or surgery) with persistent or acute disorders
Chronic kidney diseases
Chronic joint disorders of infectious, metabolic, or endocrine origin

Surgical and excretory causes
Thyroid gland enlargement, degree III or IV
Specific damage to the lymph nodes, bones, joints, genitourinary area, or other organs
Malignant tumors
Large benign tumors that impede movement or require special clothing
Sequelae of burns or frostbite entailing trophic disorders or ulcerating scars
Sequelae of injuries, diseases, or congenital defects of bones, cartilage, muscles, tendons, or joints with functional disruption or anatomical changes
Degenerative or dystrophic diseases of the spinal cord or sequelae of injuries with functional disorders or pain
Absence, cramping, or immobility of two or more fingers on one hand
Platypodia (degree III), with inflexibility
Diseases or sequelae of peripheral-nerve injury entailing trophic disorders or disrupted circulation
Hiatal, diaphragmatic, lumbar, obturator, sciatic, or postsurgical hernias
Chronic rectal-wall prolapse, complicated hemorrhoids
Pronounced enlargement of spermatic cord veins, with nodal conglomerates or pain
Urolithiasis
Nephroptosis (degree II or III)
Developmental anomalies of the genitourinary system

Otolaryngological causes
Chronic diseases of the middle and outer ear
Persistent hearing loss (unilateral to 1.5 m, bilateral 2–4 m)
Persistent barofunction disruption of the ears and sinuses
Diminished tolerance of vestibular stimulation
Lacrimal duct disease leading to tearing
Anosmia
Chronic rhinitis
Chronic nasal sinus disease, suppurative with polyps
Chronic laryngeal disease, with persistent loss of voice
Speech defects (stuttering or ankyloglossia)
Sequelae of disease or ENT injury that disrupt breathing, speech, swallowing, or impede use of special equipment

Ophthalmic causes
Blepharodiastasis, entropion or ectropion, blepharoptosis, blepharosynechia with disruption of vision
Chronic blepharal or conjuctival disease, when acute or resistant to treatment
Lacrimal duct disease leading to tearing
Chronic inflammatory or degenerative disease of the sclera, retinal detachment, glaucoma, optic nerve atrophy, decline in dark adaptation
Paralysis or persistent paresis of the oculomotor nerves, concomitant squint of over 10°, nystagmus
Decreased visual acuity[a]
Refraction anomalies (myopia, hyperopia, astigmatism)
Presbyopia
Dichromatism or type A or B anomalous trichromatism

Gynecologic causes
Severe fibrocystic breast disease
Genitourinary or enterovaginal fistulae
Prolapse of the female sex organs
Developmental defects of the female sex organs with functional disorders
Adhesions or endometriosis with functional disorders
Pelvic inflammatory disease
Persistent menstrual disorders

Oral diseases
Caries in 10 or more teeth
Recurrent periodontal disease with degree III atrophy
Chronic recurring disease of the oral mucous membranes
Abnormal occlusion
Chronic salivary gland disease with functional disruption

Skin and venereal causes
Widespread dermal disease not amenable to treatment
Syphilis

Psychiatric or neurologic causes
Psychotic disorders, regardless of duration
Neurotic disorders
Epilepsy
Sequelae of brain or spinal cord injury (due to infection or intoxication)
Organic CNS disease
Persistent, severe autonomic function disorders
Diseases and sequelae of peripheral-nerve injury with persistent functional disorders or chronic pain

[a] (> 0.5 diopters for mission specialists, and > 0.8 diopters for payload specialists).
CNS, central nervous system; ENT, ear nose and throat

Table 10 Disqualifying eye conditions for astronaut and cosmonaut selection

U.S. criteria[a]	Russian criteria
Xerophthalmia	Chronic inflammatory or degenerative disease of the membranes of the globe
Keratitis	Separation of the retina
Corneal ulcers	Glaucoma
Corneal dystrophy	Atrophy of the optic nerve
Uveal tract inflammation	Persistent decrease of adaptation to darkness
Orthokeratology	Consequences of acute illness, trauma, or surgical intervention
Photokeratorefractive laser surgery	Congenital changes of the membranes of globe, lens, or vitreous body with sufficient retention of visual function
Retina degeneration	Refractive anomaly
Retinitis	Impaired ability to adjust the lens for accommodation
Other inflammatory conditions of the retina	Chronic diseases of the eyelid and conjunctiva
Chorioretinitis	Malignant tumors
Optic neuritis	Benign tumors
Eye or orbit tumors	Other organic disorders of the CNS
Exophthalmus	
Loss of normal pupillary reflexes	
Pathological pupillary asymmetry	
Anophthalmos	
Interfering changes in the visual field	
Scotoma	
Esophoria	
Exophoria	
Heterotropia	
Failure on Verhoeff depth perception test	
Unsatisfactory night vision	
Preglaucoma	
Mandatory use of contact lenses	

[a] Not specified in Russian standards

Table 11 Disqualifying medical conditions found during the U.S. astronaut selection process

Year *No. Examined*	1959–67 480	1977 208	1980 121	1984 128	1985 59	1987 117	1990 106	1992 87	1995 122
Disqualifying standard									
Visual	49	28	9	5	3	5	17	10	14
Surgical	13	4	7	0	0	0	0	0	0
Neurological	13	3	7	1	0	0	0	0	2
Cardiovascular	14	13	5	1	1	5	6	1	1
Hematological	3	1	3	0	0	0	2	1	0
Otolaryngological	17	1	3	2	0	0	0	0	2
Metabolic/Endocrine	9	4	3	2	0	0	0	2	0
Gastrointestinal	11	1	0	1	0	1	1	3	0
Genitourinary	12	2	1	0	0	0	0	1	1
Pulmonary	2	1	0	0	2	0	0	0	2
Dental	1	0	0	0	0	0	0	0	0
Psychiatric	6	1	13	4	0	1	2	0	0
General	0	0	0	0	0	0	0	2	0

Table 12 Disqualifying medical conditions found after cosmonaut selection

Primary disease	No. of individuals	Years in corps before disqualification
Duodenal ulcer	8	2,3,8,8,9,11,19,20
Chronic gastritis	1	7
Hepatitis	2	9,12
Heart muscle diseases	5	1,2,3,6,8
Hypertension	2	2,16
Purpura haemorrhagica	1	1
Clotting disorder	1	1
Periodontitis (second and third degrees)	1	4
Deforming spinal spondylosis	2	2,8
Trauma and sequelae	2	1,5
Kidney stones	5	1,3,8,8,9
Autonomic/vascular dystonia	4	1,3,3,4
Asthenoneurotic state	2	3,15
Cervicobrachial radiculitis	1	21
Bilateral cochlear neuritis	1	8
Diminished tolerance to change in body position	1	3

Space Biology and Medicine
Volume IV: Health, Performance, and Safety of Space Crews

Chapter 2

Cosmonaut Training

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This chapter is a synthesis of Soviet (Russian) and U.S. experience in training crews for piloted space flights. Specialists in both countries advocate similar methodological approaches to the development of crew-training systems and use similar methods and types of training.[1–11] More than 30 years of experience with piloted space flights has defined crew training as a continuous, goal-oriented process by which practical skills can be acquired and maintained, and occupationally significant psychological and physical traits can be developed, for effective performance during flight.

An overview of the current crew-training system is illustrated in Fig. 1. The training process consists of three phases—general crew training, specific program training, and team training; the team-training phase includes technical, space flight, biomedical, and scientific issues. Important components of the space flight training are training flights; simulator, parachute, and high-altitude training; and escape and survival training. Biomedical training involves lectures, physical and psychological training, and special training on the effects of space flight factors. Given the basic similarity between the principles of crew training used in Russia and the U.S., the authors focus their discussion on Russian experiences.

I. Concepts, History, Stages, Evolution, and Trends

Early concepts of crew training were based on the assumption that space flight would be similar to stratospheric flight. Space crewmembers, like pilots, are considered operators who must function in unfamiliar environments. Thus the first cosmonauts and astronauts were selected from among the healthiest fighter pilots, who were considered better suited to be space crewmembers by virtue of their training and their experience flying one-person aircraft.

In the Soviet Union, the underlying concept of crew training was to prepare cosmonauts for flight not only as operators who control the functioning of the spacecraft systems, but also as biological subjects with individual psychophysiological traits and abilities.[1,3–6] Accordingly, crew training in the Soviet space program has emphasized mastering occupational skills and improving physiological and psychological tolerance to space flight factors.

Preparations for the first piloted space flights included much emphasis on medical issues; 50% of the total training time was allotted to biomedical training, which was aimed at increasing physiological tolerance to many space flight-related stress factors. During that early period, biomedical training focused on the use of dynamic tests (e.g., centrifuges, vestibular-test devices, experimental aircraft), and devoted little time to physical training.

As space flights became longer, the training philosophy evolved and became more diverse. Its emphasis shifted to the in-depth study of human capacities and the development of techniques to use those capacities, and to the use of countermeasures designed to ensure high levels of performance and occupational longevity. Individualized training became important, with programs tailored to each cosmonaut and each crew, and focused on identifying and considering individual psychological traits. Another feature of this stage in the evolution of crew training was technical training, which involved studying spacecraft design and training in spacecraft simulators. Skill mastery focused on preparing cosmonauts to perform critical tasks such as:

- monitoring the operation of onboard systems (automatic control mode);
- controlling the spacecraft by using onboard systems as a source of reference information (semiautomatic control mode);
- manually controlling onboard systems and flight operations; and
- dealing with contingency situations, including technical failures of onboard spacecraft systems.

This emphasis naturally led to the increased use of training simulators; during this phase, the time spent in simulators represented 70 to 80% of total cosmonaut training time. Simulator training also offers another advantage, namely the opportunity to establish and observe interactions among crewmembers and between the crews and the flight controllers. From psychological and instructional perspectives, training in a simulator is a good way to observe the behavior and performance of crewmembers, to identify conditions that require sessions to be terminated or modified, or to diagnose exhaustion, asthenic states, monotony, and diminished performance.

Training for the first American astronauts had much in common with the Russian concepts just described.[3,7–11] A major concern in training for early U.S. space flights was how the flight environment would affect crew performance, so astronauts were trained extensively under simulated flight conditions.[3] After it became clear that the flight environment itself did not adversely affect crew performance, the emphasis shifted to performing complex flight operations in the simulators.[7,8] The chief objective of U.S. biomedical crew training is to familiarize crewmembers with the unique features of the space environment, especially weightlessness, and to prepare them to manage unforeseen medical events such as illness or injury during missions.[11] The distinguishing features of the current crew-training systems in both the U.S. and Russian programs include the capacity to differentiate among individuals and the many available training methods and countermeasures that can be used to counter the adverse effects of weightlessness.

A. Crewmember Roles

The growing numbers and complexities of scientific research programs, and the expansion of space technology, have mandated that each crewmember be trained to perform different tasks and to hold different types of responsibility. Some differences exist between the Russian and the U.S. programs as to the responsibilities of each class of crewmember (commander, flight engineer, and cosmonaut-researcher in the Russian system; and commander/pilot, mission specialist, and payload specialist in the U.S. system). As noted in Chapter 1, the medical selection standards in both programs also differ among class of crewmember, being the most stringent for commanders/pilots, and progressively less so for the other types of crewmembers. In general, the types of tasks to be carried out by mission specialists, payload specialists, and cosmonaut-researchers tend to depend on the goals of a particular mission.

In both the Russian and U.S. programs, the commander is responsible for carrying out the flight plan, for leading the participants in the flight, and for ensuring the safety of the crew and the integrity of the vehicle. In the U.S. program, every mission also has a pilot, who acts as the commander’s “understudy” and is trained to do all of the same tasks. Both manage orbiter systems and standard payload support systems, such as Spacelabs; both participate in experiments and on-orbit operations, but neither can participate in EVAs. In contrast, mission specialists manage payload support systems that are specific to that mission; they coordinate payload operations and are responsible for carrying out scientific objectives. For missions to which no payload specialist is assigned, the mission specialists operate experiments. Payload specialists manage and operate assigned experiments or other payloads; they are cross-trained to assist mission specialists or other payload specialists in conducting experiments. Payload specialists also operate certain orbiter systems, such as the hatches and the food and hygiene systems, and are trained in normal and emergency procedures for crew safety.

In the Russian system, crews consist of a commander, a flight engineer, and sometimes a cosmonaut-researcher. The commander’s responsibilities are similar to those in the U.S. system. The flight engineer is responsible for ensuring proper functioning of the crewed vehicle’s onboard systems and for making decisions on the operation of those systems, in both nominal and off-nominal situations. When no flight engineer is present, the commander assumes responsibility for the correct and timely recognition of deviations in the onboard systems. Cosmonaut-researchers operate the onboard systems (under the direction of the commander), independently conduct communication sessions, and operate the individual life support systems, in both nominal and off-nominal situations. Cosmonaut-researchers are responsible for conducting planned experiments and research using the scientific equipment on board; they also service and repair the scientific instruments, refine observation and measurement techniques, document research results, devise new research techniques, and seek novel or rare natural phenomena. In addition, cosmonaut-researchers conduct observational studies of Earth’s surface and oceans, as well as objects and phenomena in the atmosphere and surrounding space.

With regard to training, assignments to a particular mission are made in accordance with each crewmember’s previous experience. The commonality of some training requirements allows some form of general curriculum, but individualized training also is necessary. For example, Russian commanders are responsible for the operations that control the spacecraft; flight engineers operate the onboard systems. When a crew consists of two individuals, scientific experiments are divided between them. When a cosmonaut-researcher is present, he or she bears the major responsibility for experiments and participates minimally in the operation of onboard systems.

The presence of a physician onboard is of particular interest with regard to biomedical training. Having a physician present frees the other crewmembers from the need to learn extensive medical-monitoring and first-aid tasks, and allows self-treatment and mutual rendering of first aid to be replaced by qualified medical treatment of prepathological and pathological conditions. The potential for conducting scientific medical experiments onboard is expanded. Numerous tasks related to maintenance of the life support system, onboard nutrition and fluid consumption, and the hygienic status of the spacecraft also can be assumed by an onboard physician.

II. Preparing Crewmembers for the First Crewed Space Flights

Training programs for the first cosmonauts and astronauts were aimed at maintaining good health, developing the potential for physiological adaptation to space, and imparting the skills and knowledge needed to perform professional duties. Crewmembers were required to learn concepts of astronomy; space and upper-atmospheric physics; meteorology; flight dynamics; guidance, navigation, and communication systems; rocket technology; and design of spacecraft and spacecraft systems. Crewmembers also had to be able to control the spacecraft and use its systems properly.

The fundamental principles and specific methods of early crew training were developed from results of biomedical experiments carried out on early orbital spacecraft, and later from assessments of how the space environment affected human crews. Exposure to acceleration, microgravity, vibration, noise, emotional stress, and other adverse space factors made it necessary for crewmembers to undergo special training to increase their physiological tolerance of these factors. Two training methods were selected, namely repeated exposure to a given factor (tolerance or endurance training) and more nonspecific training methods.

Endurance training was based on the concept of functional adaptation to specific stimuli, applied repeatedly and with gradually increasing intensity. The intensity of the stimulus and the duration of exposure were selected for each individual on the basis of that individual's physiological condition and the objectives of the intended mission. Endurance training involved tests in isolation chambers, thermal chambers at various temperatures, parabolic flights, and centrifuges; vibration-endurance tests; flight and parachute training; vestibular training; physical training; and trials in spacecraft mock-ups.[3,4,6,12–19] Training also included mastering the necessary skills associated with controlling and operating the spacecraft.

A. Training for Vostok and Voskhod Missions

1. Confinement in Isolation Chambers

Early in the human space program, the isolation and sensory deprivation of space flight were thought to be major stressors that might evoke serious psychological disorders. Accordingly, cosmonauts were confined for 10 days in isolation chambers so that their neuropsychological status and physiological reactions could be evaluated. Psychological changes under these conditions were limited to irritability, worsened mood, some degree of emotional stress, and diminished performance capacity. Sensory deprivation in a monotonous environment led to declines in overall and psychological performance capacity; development of drowsiness, apathy, boredom, and loss of interest; and sometimes heightened irritability, impaired thinking, illusions, and pseudohallucinations. As multiperson spacecraft were developed and flown, isolation studies were no longer mandatory; however, they still have some value for evaluating emotional stability.

2. Thermal Chamber

Early training programs that involved exposing cosmonauts to heat loads in thermal chambers sought to increase tolerance of possible temperature increases in the cabin or space suit. Sessions were conducted while the cosmonauts were at relative rest and dressed in street clothes. Chamber sessions consisted of several stages, the first of which involved identifying the length of time a subject could tolerate being exposed to 70^{o}C at 80% relative humidity (air flow 1.5 m/s). [The criteria for terminating exposure were reports of malaise, heart rate increasing to 120 to 130 beats per minute, and body temperature (measured sublingually) increasing by 2.5 to 3.5^{o}C.] After the maximum tolerable exposure time was determined in two separate tests, the exposure times were prolonged gradually to 30 to 70 minutes, with 2- to 3-day intervals between exposures. Finally, the period cosmonauts could tolerate after this training was assessed again for comparison with the initial measures. Later, while cosmonauts were being trained for the Soyuz flights, this complex, time-consuming protocol was replaced with two sessions involving only exposure to high air temperatures.

3. Parabolic Flight

The possibility of using the brief periods of free fall (near-weightlessness) created in parabolic aircraft flights for training space crews was investigated by American and Russian scientists in the late 1950s.[3,12,15] Individual responses to these flights were found to vary, with most subjects belonging to one of three broad groups: (1) those who felt well, could tolerate flight conditions easily, and did not exhibit any notable impairments; (2) those who experienced illusions and exhibited mild symptoms of motion sickness; and (3) those who had difficulty adapting and developed autonomic reactions such as weakness, pallor, sweating, nausea, and vomiting. Most members of the second and third groups could adapt upon repeated parabolic flights. This ability to adapt served as the basis for developing parabolic-flight training, which was—and still is—conducted while the trainee is either restrained or floating freely. This type of training is useful for learning how to function and move about in microgravity, and also has been used to train crewmembers to perform specific operations in microgravity.

4. Centrifuge Training

Large-radius centrifuges have been used to familiarize space crewmembers with the accelerations that take place during launch and staging. Acceleration amplitude and duration can be increased gradually to reach the loads anticipated during space flight. Test sessions familiarized the cosmonauts with sustained transverse acceleration and provided data on the effect of such acceleration on physiological functions. Centrifugation also has been used as a way of developing skills for controlling spacecraft systems during acceleration.

5. Vibration Training

All cosmonauts tested were able to adapt quickly to vibration, within certain limits, and that tolerance was found to be durable. Changes in physiological functions during the adaptation process generally were mild and transient.

6. Flight and Parachute Training

The objective of flight training, considered one of the basic components of cosmonaut training, is to foster quick thinking, emotional stability, and the psychological readiness to accept the complexities of space flight. Through flight training, cosmonauts acquire the skills needed for piloting, orienting themselves in space, conducting radio communications, and making evaluations and decisions under time pressure. Flight training also improves physiological tolerance of acceleration, weightlessness, noise, and vibration.

Parachute training is another important aspect of general crew training. Skills associated with parachute jumping include separating from the aircraft, controlling one’s body during free fall, calculating the time at which to deploy the parachute, controlling the parachute during descent, selecting a landing site, and correcting the landing. Jumping can take place during the day, at twilight, and at night; over different terrain (land vs. water); and with different types of clothing (flight suits, space suits, etc.). Parachute training also is considered beneficial for developing determination and perseverance.

7. Vestibular Training

The purpose of vestibular training is to develop physiological tolerance of vestibular stimulation. This type of training also can improve coordination, sharpen spatial perception, and improve equilibrium. The training program is tailored to each individual, but generally is based on biological principles of physiological adaptation to repeated exposures to acceleration and the effects of several nonlabyrinthine factors.

Vestibular training sessions can be active or passive. Active training takes place during physical training that involves bending, turning, jumping, exercising on treadmills or trampolines, or weightlifting. Passive training methods are used to supplement active training, and include rotating in a special chair that can be made to wobble, swinging on the “Khilov” swing, training with an optokinetic-stimulation drum, rotating in a chair while making head and torso movements, and balancing in a chair with an unstable base. Strict monitoring of vestibular and central nervous system functions during such protocols ensures the utility and reliability of the training.

8. Physical Training

Physical fitness is an important aspect of improving tolerance of adverse space flight factors. Much time is allotted for physical training, which has the goals of improving general health, speed, alertness, motor coordination, and spatial orientation, and fostering determination and emotional stability. The Soviet/Russian physical training program has three phases, the first aimed at raising the general fitness level, second at maintaining general fitness and training specific capacities, and the third at achieving high general fitness and specific conditioning. A comprehensive physical fitness program is thought to facilitate the acquisition of work-related skills and abilities.

9. Training in Spacecraft Simulators

Training sessions in spacecraft mock-ups take place during the final preparations for flight. In these sessions, flight programs are simulated with standard flight systems for life support, nutrition, clothing, and spacecraft control, although flight dynamics cannot be duplicated. Simulator training allows mission tasks to be defined accurately, space foods to be tested, and the quality and readiness of clothing and other personal equipment to be verified.

B. Specific Training for Soyuz Missions

Early Vostok flights proved that humans could go beyond merely surviving in space flight to conducting many types of work onboard the spacecraft. As flights became longer and more complex, the training program became more extensive, with many hours devoted to mastering technical and flight skills related to spacecraft control, operation of scientific equipment and life support systems, extravehicular activity, and repair and assembly work. Cosmonauts also studied specialized subjects such as the principles of celestial mechanics, aerodynamics, ballistics, astronomy, space and upper-atmospheric physics, bioastronautics, meteorology, and oceanography. Tasks that the cosmonauts would have to perform in space were learned with the aid of simulators, test stands, parabolic flights, water tanks, and centrifuges. The most complex and critical training phase, constituting 60% of total training time, was integrated crew training, i.e., training the entire crew in a special simulator.

At this stage, cosmonaut training involved both specific and nonspecific components. The specific component involved training on the centrifuge, parabolic flights, and high-altitude training. The nonspecific component emphasized physical fitness. Special attention also was paid to developing greater tolerance of moderately high altitudes (1500 to 2500 m).[16] Underwater training proved to be useful for simulating certain effects of weightlessness (translation and orientation under free-floating conditions, simulation of work operations, etc.). Moreover, the unaccustomed surroundings, dependence on a suit, and constant monitoring of the equipment, environment, and cosmonauts' physiological state were thought to foster development of determination, emotional stability, and self-discipline.

The curriculum for flight engineers focused on structuring and using work time efficiently, and organizing daily activities and meals. The curriculum also included general and specialized physical training, vestibular training, fundamentals of space biology and medicine, flight and parachute training, and other specialized training.

Physical training included daily morning exercises and special training sessions three times a week. The goals of specialized physical training were to improve tolerance of vestibular stimulation, acceleration, and hypoxia; to develop motor coordination in free-floating conditions; and to foster determination, emotional stability, alertness, and the ability to communicate concisely and accurately.

Vestibular training was tailored to each individual, and included both active and passive vestibular stimulation. Active stimulation involved making voluntary movements, including those that had a training effect on individual vestibular organs and the vestibular system as a whole. Passive methods involved complex, graded, specific, and nonspecific stimulation on special test stands. The goal of these techniques was to improve the tolerance of the vestibular system and the other systems that interact with it (visual and proprioceptive systems, interoceptors, etc.). Loading was increased gradually to prevent regulatory mechanisms from becoming overloaded.

Overall, this training program was successful in producing the required levels of physical fitness and vestibular tolerance for cosmonaut candidates. Scheduling the work/rest cycles and structuring the exercise sessions during training, and adapting protocols to individuals, had positive effects and fostered the development of compensatory and adaptive reactions to various environments and stimuli.

The inclusion of payload specialists in crews for Soyuz program brought different dimensions to the training process. These individuals often had more health problems, were less physically fit, or were less able to tolerate vestibular stimulation than were commanders or flight engineers. Special preventive procedures used with payload specialists included the use of drugs or surgical intervention; regulation of work/rest schedules, nutrition, and physical fitness; endurance training; and exercising in pools or saunas.

Three examples of medical interventions used in training payload specialists are described here. One cosmonaut periodically showed mild albuminuria and microhematuria after physical exertion or heat exposure. Surgical removal of his tonsils eliminated all signs of these conditions; moreover, after this cosmonaut completed an orbital flight, physical examinations revealed neither pathological conditions nor significant abnormalities in urinalysis. Another cosmonaut was found during the initial selection process to have low tolerance of vestibular stimulation and unstable pulse and arterial pressure both at rest and during physical exertion. This cosmonaut also had chronic compensated tonsillitis. Because associations between these abnormalities and a focal infection could not be ruled out, a tonsillectomy was performed, from which the cosmonaut recovered without complications. With further training, this person's vestibular tolerance improved, and his pulse and arterial pressure responses also became more stable. This cosmonaut adapted quickly to weightlessness and showed good endurance during an 8-day orbital flight. Finally, mild autonomic intolerance during an initial examination in a third cosmonaut disappeared after training, and this person tolerated a 5-day orbital flight well. In summary, although some payload specialists had health problems during preflight training, all successfully completed their training and missions, and none had reactions to space flight factors that exceeded acceptable physiological limits.

III. The Current Russian Training Program

As noted earlier in this chapter, the team-training segment of the Russian cosmonaut training program encompasses four areas: technical, space flight, biomedical, and scientific (see Fig. 1). Aspects of these four areas are described in detail below.

A. Technical Training

Technical training focuses on studying the design and operating principles of spacecraft and their systems. During the general crew-training phase, cosmonauts study some of the major structural components of spacecraft and general principles of space technology. During specific-program training, they study the particular spacecraft for that program, i.e., its construction, its systems operation, possible failure modes, corrective actions, and so on. During the final team-training phase, they study the specific vehicle on which they will work. The overall objective of technical training is to acquire knowledge in specific areas and to develop the requisite technical skills. The scope of the studies required during technical training encompasses the theory of space flight; spacecraft control systems; space navigation; principles of computer technology; booster rocket, transport, and space station technology; observing Earth from space; implementing experiments during space flight; the use of onboard systems for crewed spacecraft and space stations; and launch complexes.[20]

B. Space Flight Training

This type of training includes lectures and practical training pertaining to flight conditions, control of the spacecraft, use of its systems and equipment, and the various operations required by the flight program. The objective of space flight training is to develop the sensory, cognitive, and motor components of piloting skills.[3,4,20]

1. Flight Training

Flight training is conducted with the cosmonaut being the third member of transport-aircraft and helicopter crews. The goal of this type of training is for cosmonauts to develop a spectrum of psychophysiological characteristics that will ensure high tolerance of the extreme conditions of space flight. Psychophysiological tolerance, important but somewhat subsidiary for aircraft pilots, takes on special significance for cosmonauts. Aircraft and helicopter flights are thought to be the most appropriate models for this kind of training, because they help develop psychological and functional tolerance of the exposure to multiple, extreme environmental factors in the presence of emotional stress. Development of tolerance is evaluated on the basis of two factors, the performance level and the stability of physiological reactions.[21,22]

Some of the characteristics developed and perfected during flight training include flexible, automatic motor-coordination skills and oculomotor reactions appropriate to flight conditions. Other abilities honed include operating under time pressure, monotonous conditions, and with simulated instrument data; orienting directly and indirectly in the presence of rapid change in spatial position; conceptualizing and planning sets of operator tasks; attending to several tasks simultaneously, and switching attention appropriately; maintaining emotional stability under extreme conditions; and working with minimal or delayed feedback.

Another important aspect of this type of training is the development of adaptive physiological mechanisms through exposure to angular, linear, and Coriolis accelerations; temperature changes; variations in atmospheric and partial gas pressure; physical exertion; weightlessness; and reduced or alternating values of gravitational loads. On long aircraft flights, cosmonauts can experience the effects of biological-rhythm shifts. Finally, flight training also offers opportunities for cosmonauts to develop skills and knowledge relevant to testing and scientific research in space.

2. Simulator Training

Cosmonauts acquire the skills necessary to perform their flight duties in phases through the use of simulators. Simulator training involves practicing work tasks on functional, specialized, and integrated mission simulators. Functional simulators are used to teach the skills necessary to operate specific pieces of equipment or spacecraft systems; specialized simulators are used to train the crew in specific flight tasks like docking; and integrated mission simulators are used for training the crew as a whole (e.g., prelaunch preparations, orbital insertion, orbital flight, preparations for atmospheric entry and descent). In addition to skills pertaining to standard flight routines, simulator training focuses on developing the expertise to deal with special or unique flight situations, technology failure, and task integration.[20,23,24]

Spacecraft simulators are crucial for preparing crews for flight. The use of actual space flights for training purposes is neither cost-effective nor safe, but the use of simulators creates training opportunities in which the perception and motor responses of the cosmonaut are identical to those of actual flight. Training simulators generally model physical factors of the space flight environment (except for weightlessness), which further enhances the realism. The simulator cabin is equipped with actual instruments, displays, and controls so that conditions are as realistic as possible. Mathematical models are used to mimic spacecraft motion and the functioning of major systems during each phase of flight. Parameters generated by the model are displayed on various instruments and the simulator console; a simulated visual environment is displayed simultaneously by optical sensors in the windows. Cosmonauts' control actions give rise in real time to simulations of situations that would occur in actual space flight.

The effectiveness of the simulators in preparing cosmonauts for impending flights not only depends on the realism of the simulated conditions, but also on the method of instruction and the skill of the crew instructor. The curriculum must cover complex, critical situations requiring skills that cannot be acquired in the course of an actual flight. Simulators also allow instructors to alter situations and introduce new or additional conditions to increase the difficulty of spacecraft control, so the cosmonauts gradually develop control skills of increasing complexity. Cosmonauts practice complex elements of spacecraft control repeatedly; those skills involving rapid sequences of control actions are mastered first at slower-than-normal rates, followed by training at the actual required speed.

The final simulator-training phase involves the use of special-purpose simulators to form an overall mental representation of tasks that will be needed on forthcoming missions. Psychologists and instructors are tasked with using the simulators to create appropriate flight images in the minds of the trainees. The training schedule, crucial in this task, is based on a sequence of stages associated with the mastering the individual components of complex job skills.

Cosmonauts take an active role in the simulator-training process to develop the skills needed for specific operations or various flight modes, and to acquire general ideas of how to solve problems under nominal, contingency, and emergency conditions. The resulting high level of technical competence is achieved through training both individuals and the crew as a whole.

3. Parachute Training

Cosmonaut training and testing cannot simulate one crucial aspect of flight—the element of risk that compels cosmonauts to maintain constant vigilance and readiness for emergency action. Such risk can be modeled to some extent through parachute training.[14,25–28] The stressful nature of parachute jumping makes it an effective tool for learning to perform under extreme environmental conditions. Repeated parachute jumps are accompanied by gradual decreases in emotional stress and adverse physiological reactions, improved overall performance, and increased psychophysiological tolerance to the extreme factors associated with jumping.

4. Escape and Survival Training

The goal of escape and survival training is to enhance the ability to take effective, decisive, and rational actions in extreme situations after emergency escape from a spacecraft. Survival training teaches cosmonauts how to protect themselves against natural factors by the effective use of individual and group survival equipment, emergency clothing, means at hand, and natural resources. It also teaches ways of preventing and treating injuries or diseases caused by adverse flight factors, natural conditions, or the foregoing spacecraft emergency.

Survival in emergency situations is largely a function of the psychophysiological traits of the individual, e.g., determination, decisiveness, presence of mind, resourcefulness, endurance, and physical fitness. The main premise of survival training is that cosmonauts can and will retain their health and survive under the severest physical and geographic conditions if they can make use of everything nature makes available. However, in order to do this, cosmonauts must have both some theoretical knowledge and practical skills. The objective of survival training is to provide that knowledge and skills, and to psychologically prepare cosmonauts to overcome possible emergency situations by increasing their sense of determination and teaching them to evaluate situations effectively and act accordingly.

The conditions of survival training must resemble actual conditions as much as possible so that cosmonauts can understand and internalize the idea that they can preserve life and health through the use of knowledge, skill, and psychological stability. The critical areas for human survival must be identified, and all possible safety measures must be taken to ensure the safe outcome of the training exercise. Presumably, individuals taught to survive the most hostile climates and geographical circumstances will have less difficulty in less dangerous areas. Examples of the most difficult and hazardous areas in which to survive are the equatorial zones, oceans (Fig. 2), deserts (both in winter and in summer), the Arctic, the steppes in winter, massive forests (such as the Taiga), jungles, and mountains.[29]

Survival training in diverse terrain and climates is valuable not only for training purposes, but also for assessing psychological qualities, personality traits, and intragroup interactions. Group survival training enhances psychological tolerance of difficult living conditions and strengthens interpersonal relationships between crewmembers.

5. High-Altitude Training

Altitude training involves exposure to high-altitude equivalents in barochambers in order to develop skills in using individual and collective preventive measures, controlling the life support system and airlock, and tolerating moderate and extreme hypoxia and decreases in barometric pressure. Currently, this training includes classroom and practical instruction in the fundamentals of high-altitude physiology; flight-certification testing at 5,000 and 10,000 m equivalents; practice in donning launch, rescue, and EVA suits at 35,000 to 80,000 m equivalents; and physical exercise at 1,500 to 2,000 m equivalents, with brief ascents to 2,300 m, to increase nonspecific resistance to space flight factors.[30–36]

A schedule of high-altitude training in mountainous areas also has been developed. In order to prolong the positive effect of high-altitude acclimatization, this program is combined with special exercise, underwater swimming, and barochamber training.[37] Mountain training also is used for medical conditioning, mountain-survival training, evaluation of physiological reactions to stress, and for assessing individual personality traits and psychological compatibility.

C. Biomedical Training

Another important component of cosmonaut training, biomedical training seeks to prepare cosmonauts physiologically to function successfully in the unaccustomed conditions of space flight, provide them with medical knowledge, and impart the skills needed to live and work productively in space. The main objectives of biomedical training are to maintain health; maintain or improve conditioning and tolerance of space flight factors; learn to use the medical, monitoring, and research equipment provided in flight; learn to use countermeasures and self-monitoring techniques; learn to diagnose hazardous conditions; and learn to render first aid to oneself and one's crewmembers with the onboard medical kit or other available means.[3,6,38]

The specific content of biomedical training may vary from one phase of flight training to another, but safeguarding crew health and maintaining physical fitness are essential components of every phase. This objective is ensured through dynamic medical monitoring and observation, periodic clinical examinations, use of medical countermeasures, and physical training.

During the general crew-training phase (see Fig. 1), cosmonauts are introduced to the fundamentals of general and aerospace medicine and physiology, and they learn how to render first aid in case of injury or acute illness and how to perform therapeutic massage on themselves and other crewmembers. They also learn self-monitoring and ways of controlling their own psychophysiological states. Training for specific flight programs also involves physical training, and is structured to meet the goals of the upcoming flight and the individual characteristics of the participating cosmonauts. Crewmembers master the principles of maintaining physical fitness in flight and learn about the onboard medical equipment. During the final, team-training phase, cosmonauts study the equipment aboard their specific vehicle and are trained in procedures for performing specific biomedical experiments. Vestibular training and acclimation to fluid redistribution (using orthostatic and antiorthostatic stimulation) are used as necessary. Physical training and work/rest schedules are organized to ensure that the cosmonauts remain in good condition for the flight. Throughout the entire biomedical-training period, the cosmonauts' individual traits, current status, and ability to work as members of a group under various stressful conditions are studied.

1. Classroom (Theoretical) Instruction

Classroom lectures and readings are provided to familiarize cosmonauts with the fundamentals of space medicine and biology. Topics covered include the physiological effects of space and space flight factors on humans; methods of physiological preparation for life onboard spacecraft; preventing motion sickness during flight; using countermeasures against adverse flight effects and techniques to maintain high performance during flight; ways of assessing psychophysiological status and giving first aid; ways of maintaining personal hygiene, radiation safety, and life support onboard the spacecraft; and ways of ensuring safe return to Earth, accomplishing search and rescue, and readapting to Earth's gravity.

2. Physical Training

The objectives of the current Russian physical-training program are to develop and improve basic aspects of motor performance, e.g., endurance, strength, speed, and agility (general training); to improve physiological tolerance of the adverse effects of space flight factors (specific training); to improve health and endurance; and to develop enhanced psychological stability. Cosmonauts are trained in the use of onboard exercise equipment to prevent deconditioning, muscle atrophy, and bone demineralization during flight.

Physical training consists of daily 30-minute calisthenics in the mornings and 90-minute training sessions 2 to 3 times a week. The devices and activities used in preflight training include short- and long-distance running; swimming; cross-country skiing; cycling; team sports such as volleyball, basketball, tennis, and soccer; gymnastics and acrobatics; and use of exercise equipment such as treadmills, trampolines, inclined planes, ergometers, and others. Although some investigators[39–41] believe that intense physical training causes specific morphological and functional changes in the body that increase tolerance to space flight effects, others[42] find the data inconclusive. Additional information is needed in order to make recommendations regarding the intensity of physical training needed before and during flight.

3. Psychological Training

Psychological training, in the Russian program, is a balanced, systematic set of diagnostic and preventive measures used during all phases of training to improve the efficiency of crew performance. The goals of this training are as follows: to mobilize and foster the harmonious development of requisite psychophysiological and psychological traits; to improve self-evaluation and self-monitoring abilities; and to begin developing realistic mental representations of living and working conditions on upcoming flights.[20] The ultimate goal of psychological training is to produce strong, active, goal-oriented individuals who are morally and psychologically tolerant of adverse occupational factors and possess the necessary intellect and skills to accomplish space flight objectives.

The development of psychological stability (stress tolerance), optimum self-control, and group interaction skills are thought to be fostered by:

- observing cosmonauts' performance during all phases of training and space flight, and recommending ways to improve individual task-performance style;
- testing tolerance of psychological stress during tests and under field conditions;
- teaching principles of intragroup interactions and methods of self-regulation; and
- using psychological support measures.

Table 1 describes the scope and contents of the practical and psychological measures used to assess and improve cosmonaut personality traits during selection and preflight training. Specific means by which personality traits are identified and modified as needed are described below.

Classroom training involves lectures on the psychological aspects of space flight and group interaction. Helping individuals understand their own particular psychological traits, revealed through previous testing, is thought to allow them to develop appropriate systems of self-evaluation and self-criticism as well as realistic ideas of their present and potential capabilities. Cosmonauts are given visual representations of their psychological traits in order to enhance understanding and to allow them the chance to watch changes in various psychological parameters. Specific recommendations concerning self-actualization and further improvement of particular psychological functions, traits, and characteristics are a necessary part of this training method.

Specific techniques used to reach the goals of psychological training include behavior modification, problem solving, and autogenic feedback. Behavior modification involves the presentation of logical arguments that certain personality traits and qualities are conducive to the successful performance of certain tasks. Elements of emotional persuasion, suggestion, and instructional techniques also are used to foster optimism and confidence in one's ability to overcome shortcomings. First, the fundamental causes (personality traits) responsible for negative attitudes, misinterpretations, or conflicts between an individual and that individual's milieu are identified and discussed. Next, plans are developed and implemented to improve self-knowledge, resolve conflicts, and maintain the desired results.

Problem-solving techniques aim to teach ways of surmounting shortcomings in cognitive functions (attention, memory, reasoning, and imagination), and fostering intellectual development and comprehension. Analyses of the characteristics of an individual's cognitive functions are used to design a set of tasks to improve functioning. These tasks can involve perception, attention, imagination, memory, reasoning, and others. A new approach to problem solving, which fosters the activation of cognitive functions during task performance and the internalization of beneficial information-processing skills, involves collaborative problem solving by a group of cosmonauts dealing with unstructured materials (e.g., Rorschach ink blots, pictures from the Thematic Apperception Test, and fragments of the Associative-Projective Logic Test).

Skills of conscious self-regulation are taught by means of autogenic-feedback training. The nature and history of this type of training, its psychological and physiological principles, and its uses are described in classroom instruction. Practical sessions then are used to teach crewmembers how to control: muscle tone in the arms, legs, and internal organs; vascular reactions of the extremities; breathing rhythm; heartbeat; and sleep and wakefulness. The need for such training is assessed from the severity of autonomic responses to psychological stress and the amount of anxiety experienced during various tests.

Additional medical and psychological training is conducted over a 7- to 10-day period in a special test facility, during which selective, differential improvement of personal traits or qualities is sought while cosmonauts perform tasks like psychophysiological tests, operator tasks, compensatory tracking, reacting to a moving object, detecting signals, estimating time intervals, assessing homeostatic interactions, providing verbal associations, etc. The goals of this training are to improve efficiency in performing various simulated tasks while living in difficult environments and using standard means of life support. The success of this type of training depends on the availability of feedback to the cosmonaut regarding the quality of his or her performance. When implemented well, this type of intensive training has the aspect of a game or competition, which tends to increase its effectiveness. (Effectiveness is evaluated in terms of cosmonaut productivity, positive group dynamics within the crew, stable and positive mood, and expression of "desirable personal traits.")

The results of psychological crew training are evaluated by periodic psychological examinations and by data obtained during other forms of training. Results from psychological evaluations conducted at the end of the general training phase may indicate that some cosmonauts are not suited for later training phases. Nevertheless, the psychological preparedness of cosmonauts tends to differ at different stages of training; as training progresses, improvements are seen in cognitive function (attention, perception, memory, imagination, reasoning); emotional tolerance of stressors; cognitive efficiency; personality traits and qualities, interests, values, and personal attitudes; and motivational traits that determine self-criticism, determination, persistence, general discipline, and responsibility.

Team training. Team-oriented psychological training is not an independent training phase; group components are present throughout the preflight team-training process. The basic goals of this type of training are to increase cooperation and mutual understanding among crewmembers; to improve crew cohesiveness; to develop optimal interaction and management styles; to develop a back-up system and appropriate mental images of forthcoming activities; and to gather and analyze data needed to develop further psychological training.

Training and developing cohesive crews involve several phases, the first being selection of specific crews for specific missions. [The selection component is present in all phases of crew training in the Russian program, since final decisions about participating in a particular crew are made only after comprehensive psychological analysis of the crew as a whole (Table 2).] The ultimate objective of psychological team training is to increase crew professionalism and performance as an integrated unit. The scope and content of the measures used to achieve these ends are presented in Table 3.

The duration of joint training is a significant factor in increasing compatibility and cooperation within crews. Crews preparing for short, 1- to 2-week flights undergo joint training for at least 6 months. Optimal joint training takes about 1 year for flights lasting 1 to 2 months, and from 1.5 to 2.5 years for 2- to 12-month flights. The duration of joint training can be curtailed if a crew is composed of cosmonauts with previous space flight experience, especially if the crew commander has substantial experience.

4. Special Training

Special training, which is aimed at improving tolerance of and adaptability to space flight factors, is conducted during all phases of the cosmonaut training process. This type of training encompasses a variety of different conditions and training methods, including parabolic aircraft flight, centrifuge testing, vestibular stimulation, barochamber testing, underwater activities, and others.

Parabolic flight. As mentioned earlier under Section IIA3, the free-fall periods experienced during parabolic flight can be useful for practicing occupational skills (Fig. 3). Aircraft for these flights are equipped with technical, training, and scientific equipment, recording instruments, and other devices that allow crewmembers to practice microgravity operations. Subjects also become accustomed to shifting between hypergravitational and hypogravitational conditions.

Centrifuge training. Centrifuge training was used in the U.S. only during the Mercury and Gemini programs, and was dropped from the training program when the Apollo program began.[11] The Russian space program involves extensive training sessions in large centrifuges, which are thought to familiarize cosmonauts with conditions that simulate the direction, magnitude, and duration of accelerations experienced during space flight. Tolerance to sustained longitudinal acceleration (G_z) is evaluated annually; cosmonauts must demonstrate good tolerance of 5 G_z for 30 seconds before they can be admitted to flight training. If their tolerance is satisfactory, diminished, or poor but they have no other health problems, they undergo centrifuge training sessions and are re-evaluated. Tolerance of sustained transverse acceleration (G_x) is evaluated after cosmonauts have been accepted into the team-training phase. Experience has shown that good tolerance of transverse accelerations of up to +8 G_x for 40 seconds predicts good tolerance of accelerations associated with flight on Soyuz spacecraft.

About 1 to 2 months before prelaunch training, cosmonauts undergo centrifuge sessions that simulate launch and landing acceleration profiles while they practice actual spacecraft control operations. These sessions are intended to reinforce skills and behavior during exposure to accelerations that are characteristic of the flight environment.

Vestibular conditioning. The objective of this type of training is to minimize unpleasant vestibular effects during the acute period of adaptation to weightlessness and to maintain effective crew performance during that time. Conditioning is based on experimental results that suggest that individual tolerance of vestibular stimuli can be increased, even in space motion sickness. Increased tolerance of vestibular stimuli is thought to result from vestibular adaptation, which is defined as the diminution of vestibular reactions resulting from repeated stimulation of the labyrinth.

After being selected, cosmonauts undergo passive vestibular conditioning to familiarize themselves with the required level of conditioning and to allow individualization of the conditioning process. Rotating chairs, the Khilov swing, and an optokinetic stimulation drum are used for conditioning. Later, vestibular tolerance, particularly tolerance of cumulative Coriolis acceleration,[43] is evaluated annually. During the preflight training phase, vestibular conditioning begins 2 to 2.5 months before launch and continues until the day before launch.

Susceptibility to motion sickness is evaluated during all phases of cosmonaut training, from the results of vestibulometric testing and conditioning sessions. The accuracy with which susceptibility can be predicted increases during training, reaching about 90% by the end of the training period.[44] The vestibular conditioning methods used at the Yu. A. Gagarin Cosmonaut Training Center are 52 to 60% effective in preventing space motion sickness in susceptible individuals.

Development of vestibular habituation is of particular interest. Three stages in this process have been distinguished, i.e., acquisition, retention, and transfer. Acquisition takes the form of progressive decreases in the intensity of responses to repeated labyrinthine stimulation. Habituation seems to be different for vestibulosensory, vestibulosomatic, and vestibuloautonomic reactions; vestibular conditioning generally leads to extinction of the vestibuloautonomic reaction. Another feature of habituation is that the diminished response is retained for certain periods; the extent to which habituation is retained is proportional to the time elapsed since the last conditioning session. Loss of habituation is greatest when 8 or more weeks elapse since the last conditioning session[45]; if only one conditioning session has been completed, habituation is lost after only 10 days.[46,47] For this reason, vestibular conditioning is performed at least once a week and typically is terminated just before launch.

High-temperature training. Physiological tolerance of high ambient temperatures is tested to determine whether cosmonaut candidates can tolerate hyperthermia. Testing takes place in a thermal chamber in which the air temperature is 60^{o}C, the relative humidity is 30±5%, and the rate of air flow is about 1 m/s. Physiological tolerance is determined in terms of the time needed in the thermal chamber to raise the subject's oral temperature by 2.0 ± 0.1^{o}C, and in terms of the subject's cardiovascular and urinary responses.[48] Individuals whose tolerance is less than optimal are exposed to the thermal regimen described in section IIA2, and then undergo special physical conditioning procedures that involve physical exercise accompanied by overheating. During the final training just before flight, conditioning is targeted to a specific EVA program.

Underwater training. Underwater mock-ups of space stations or Space Shuttle components are used to train cosmonauts or astronauts to conduct microgravity procedures in unpressurized modules or on spacecraft exteriors. The Russian "Hydrolab" facility is cylindrical, 23 m in diameter and 12 m deep, and is equipped with portholes. A full-size mock-up of the space station and orbital complex rests on a platform that can be raised or submerged as needed. The high-fidelity station mock-up fully simulates the station interior and exterior volumes, interior design elements, interior passages, and modes of egress. Additional exits are provided for safety. The mock-up is illuminated by spotlights aimed through the portholes, so that activities taking place within can be observed and filmed.

The Hydrolab is equipped with a multipurpose telemetry system that picks up and transmits physiological and hygienic information about the subjects inside their space suits, as well as providing a voice link. Information is processed by a special-purpose computer and is output to magnetic tape recorders, printers, and visual displays located at the control center. A hoist is used to lower and raise cosmonauts, who wear space suits similar to those worn in flight. Neutral buoyancy is achieved and the suits balanced by appropriate placement of lead weights. Suits are pressurized to 0.4 atmospheres above water pressure to mimic the space-related rigidity. Thermal control in the pressurized suits is maintained by water-cooled inner garments.

Because underwater activities present some degree of danger, those who work in pressurized suits (cosmonauts and investigators) are accompanied by several scuba divers. Both the investigators and the divers must be licensed for underwater work and must undergo a special medical checkup and safety briefing before every experiment. These individuals also are monitored medically during and after each experiment.

Crews undergo about 30 to 50 hours of intensive training in the Hydrolab. Training involves mastering the work station configuration; using various fixating equipment and tools skillfully; learning to move efficiently on the station exterior, and to move and work smoothly and symmetrically with other team members; learning to transport and transfer cargo; learning to maneuver in the suit, particularly with regard to keeping the visor from colliding with structural elements; and other safety measures. Considerable attention is devoted to instructions for emergency situations. Postflight analyses of crew activities on spacecraft and space stations have confirmed that cosmonauts who complete the entire underwater-training cycle can perform the most efficiently in space.

Head-down (antiorthostatic) conditioning. This type of conditioning is conducted to improve the power and efficiency of the regulatory mechanisms in the circulatory system, and thus improve orthostatic tolerance.[49–55] Conditioning sessions involve either low- or high-intensity stimuli, defined as follows. Low-intensity stimulation involves sleeping and undergoing bed rest in a -5^{o} head-down position. High-intensity stimulation is achieved by alternating between orthostatic (upright) and antiorthostatic (head-down) positions on a tilt table; the maximum head-down tilt angle ranges between -30^{o} to -45^{o}. Two training cycles generally are conducted, the first 4 to 6 months before flight and the second just before launch. The first cycle involves 8 to 10 sessions conducted 1 or 2 days apart; the second cycle covers 7 to 8 sessions. Crewmembers also are advised to sleep in a -5^{o} head-down position for 2 months before flight.

Head-down conditioning also precedes parabolic flight in the research aircraft. This preliminary conditioning of the body to headward blood redistribution is thought to improve the effectiveness of compensatory mechanisms during repeated exposure to hypogravity alternating with hypergravity.

D. Scientific Training

For technical reasons, scientists cannot always participate in space flight; therefore, crews must be prepared to conduct observations, tests, and experiments onboard the spacecraft. To ensure that the results obtained are correct, cosmonauts must understand the experiment’s design, know how to use the equipment properly, be able to evaluate and document results, and be able to send those results back to Earth for detailed analysis. Training in those and related procedures begins during the specific-program training phase, but is conducted mainly during the final, team-training phase, when the orbital characteristics, crew work schedule, and other issues pertaining to flight experiments have been established.

The successful participation of scientific experts in space flights has been a major step toward improving the quality and effectiveness of space flight research in several scientific disciplines.[56] The development of spacecraft that can house three or more crewmembers has allowed investigators who have no professional piloting experience to participate in space exploration.

IV. Proposed Additions to or Improvements in Training Methods

Many suggestions have been made to expand or improve traditional means of crew training. One such proposal[57] involved a nearly full-scale flight simulation, to be implemented with a ground-based training simulator linked via telemetry with a set of manual controls onboard the spacecraft and an information display system. This set-up creates a closed-loop system in which the cosmonaut, display, and controls are onboard a spacecraft, but the object of control (implemented through mathematical models and visual representations of the modeled environment) is on Earth. This system was first used to allow cosmonauts to practice docking with a space station, and significantly improved their performance and their psychological status within 4 or 5 practice trials. This method also is promising with regard to helping cosmonauts adapt psychologically to working conditions in space.

Methods of biomedical training that model the combined effects of several space flight factors are thought to facilitate the development of more appropriate compensatory and adaptive reactions during actual flights. One such method involved the use of a complex vestibulometric test device that combines head-down hypokinesia with optokinetic stimulation and Coriolis acceleration by rotating the head in the sagittal plane while the body is rotated about a vertical axis passing through the heart.[58,59] Another method involves using an anti-*g* suit (to create excess pressure on the lower body and increase blood pressure in the upper body) in combination with exposure to cumulative Coriolis acceleration every 3 hours in a Barany chair.[60] This latter method is used in combination with a posthypnotic suggestion that he or she will experience the feeling of diminished weight.

Another proposed modification[61] involves performing active translation motions during parabolic flight, so that subjects are exposed to linear and angular acceleration during 10 successive parabolas. This combination of free fall and movement by the subject reportedly resembles actual space flight conditions.

An experimental facility for simulating the dynamics of an entire space flight has been developed at the Yu. A. Gagarin Cosmonaut Training Center.[62,63] This facility combines a centrifuge with a cabin suspended on a gimbal mount and a device for creating excess pressure on the lower body. Headward redistribution of blood is simulated by the combination of lower-body pressure with horizontal-body orientation and cabin motion created by the centrifuge. A programmable control console is used to simulate the following sequence: the acceleration profile of orbital insertion; the transitional period between acceleration and weightlessness; the hemodynamic, sensory, and statokinetic effects of weightlessness; and the acceleration profile of descent. Cosmonauts perform spacecraft-control operations and other functions during this process by using instruments located on an operator’s console in the centrifuge.

Partial submersion in water (three submersions for 12 hours each during available free time) also has been proposed as a way to foster preliminary adaptation to weightlessness.[64,65] This method is believed to improve orthostatic capacity upon return to 1 *g*. Alternating between submerged and nonsubmerged conditions is thought to be the best way of increasing adaptive capacity.

Autogenic feedback has been recommended by many for improving psychosomatic status.[66–71] Results from a 3-day simulation experiment[66,72] suggest that autogenic training was instrumental in eliminating unpleasant sensations like vertigo, nausea, and feelings of heaviness in the head during the acute phase of adaptation. Subjects using autogenic procedures experienced a sensation of unusual physical lightness and maintained a high level of performance for an extended period. Subjects who used autogenic-feedback techniques performed 6 to 12% better than control subjects on spacecraft control, had a 4 to 5% greater probability of detecting signals in the communication and navigation system, and were able to detect these signals 3.5 times faster than control subjects. Yet another suggestion was to speed autogenic training by using instrument-assisted biofeedback.[69] Biofeedback can be combined with various autogenic-training exercises for conscious relaxation and training in both general and specialized self-regulation techniques.

Mastery of conscious self-regulation skills as a defense against extreme environmental conditions is considered by some to be one of the most important aspects of cosmonaut training.[70] One such method includes taking active measures to counteract nervous tension; developing a specific strategy to regulate behavior described as “relative freedom from personal problems” and “deactualization of many nonexisting problems”; and mastering psychophysiological self-regulation techniques (voluntary control of breathing, muscular and vascular tonus, and the functioning of cardiovascular and other systems of the body).

Preflight yoga exercises have been proposed as a way of improving coordination, promoting muscle relaxation during the dynamic phase of flight, and supplying substantial [physical] loads during the static phase.[73] Finally, ways of teaching self-treatment and first-aid techniques could be updated frequently to include the use of new methods as they become available.

A. Training for Interplanetary Space Flights

Because interplanetary missions will require long periods of weightlessness during which rapid return to Earth is not possible, the biomedical component of training for this type of mission should be expanded from its current form. The risks of psychological (anxiety, psychological disturbance) and somatic illnesses (cardiac arrhythmia, neurodermatitis, spastic colitis, ulcers, etc.) increase with the time spent in flight, especially in remote flights, as does the risk of medical problems associated with possible failure of the life support system and the consequences of harmful environmental factors (overheating, altered atmosphere, and high-energy particles, among others). It is difficult to imagine that crew safety and optimal performance—and thus successful completion of flight—could be ensured without a specially trained physician being part of the crew on such flights.

Some specific countermeasures against psychological complications on long-term interplanetary flights could include the use of role-playing and simulations to enhance resolution of conflicts, or learning constructive methods of managing interpersonal relationships through training in social psychology.

In addition to the medical and psychological risk factors associated with interplanetary flights, sensory deprivations (i.e., sensory adjustments made to the microgravity environment) could pose another form of risk, in that crews could experience spatial illusions and sensorimotor problems upon landing on Mars or other planets. Optical conditions in the Martian atmosphere also could affect cosmonaut efficiency. These issues suggest the need for specialized training devices and methods of in-flight sensory conditioning as well as the development of technology to improve or augment the crewmembers' sensory systems.

In summary, the idea, first proposed during the earliest space flights, that space crewmembers require occupational and biomedical training is still applicable today, although the emphasis on occupational training has increased, particularly with regard to simulators. As flight duration lengthens, as the complexity of flight systems increases, and as the scope of scientific flight programs expands, the crew-training system should include both a general component, for skills needed by all crewmembers, and an individualized component, based on crewmember experience, previous training, and specialization. Although the present system of crew training has amply demonstrated the ability to produce competent crews that can tolerate space flight factors, further improvements to the system are always possible.

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Figure Captions

Fig. 1 Components of the cosmonaut training process.

Fig. 2 Escape and survival training in a water immersion facility.

Fig. 3 Parabolic flight training.

Table 1 Psychological tests given during crew selection and preflight training [Ref. 20][a]

Type of test	Mode of administration
Psychophysiological tests	
Sensorimotor responses to sensory & verbal stimuli	computer
Timed tests of varying difficulty	computer
Physiological functions during task performance	computer
Sleep and diurnal physiological rhythm assessment	computer
Cognitive-function tests	
“Black and red table”	computer
Compass test	paper & pencil
Dial reading	paper & pencil
Recall of words, numbers, symbols, texts	paper & pencil
Copy-reading test	paper & pencil
Tangled lines	paper & pencil
Counting with attention switching	paper & pencil
Rule induction	paper & pencil
Free recall of assigned & impromptu subjects (given to individuals and groups)	computer
Operator tests	
Response to a moving object	computer
Tracking	computer
Recognition of instruments and spacecraft	computer
Work task simulations	computer
Detecting unexpected information against a background of noise[b]	computer
Task performance while sleep deprived for 64–72 hours (test given once)[b]	combined
Personality and projective tests	
Rorschach test (given to individuals and groups)	paper & pencil
Thematic Apperception Test (given to individuals and groups)	paper & pencil
Word association	paper & pencil
Eysenck questionnaire	paper & pencil
Minnesota Multiple Personality Inventory (MMPI)	paper & pencil
16 Personality Factor Questionnaire	paper & pencil
Rosenzweig’s frustration test	paper & pencil
Projective-associative test of perceived role	paper & pencil
Structured interview	computer
Projective musical test (given to individuals and groups)	computer
Fixed set method (given to individuals and groups)	paper & pencil
“You and the world” test	paper & pencil
Luscher’s color test (given to individuals and groups)	paper & pencil
Individual differences in social perception	paper & pencil
Ecological-psychological laboratory and field simulations	
Psychological stability in an isolation chamber (test given once)	lab
Simulations of docking or astro-orientation (given to individuals and groups)	lab & simulators
Centrifuge, pressure, thermal, and immersion tests (given to individuals and groups)	lab & simulators
Homeostat (given to groups only)	special equipment
Sports (given to groups only)	special equipment
Flight training (given to individuals and groups)	training
Parachute jumps (given to individuals and groups)	training
Survival in hostile climates and geographic areas in the desert, tundra, mountains, and at sea (in winter and in summer)	tests & training
In-flight personality assessments	
Physical examination and dynamic monitoring (before flight) (given to groups only)	combination
Psychological monitoring and support measures (during flight) (given to groups only)	combination
Physical exam and monitoring during readaptation, sociopsychological readaptation (given once to group only)	combination

[a] Tests are given several times to individuals unless otherwise noted.

[b] Test given in an isolation chamber.

Table 2 Indications and contraindications for spacecraft crew selection [Ref. 20]

Indications (inclusion criteria)	Contraindications (exclusion criteria)	
	Relative	*Absolute*
Commonality of values and goals	Similarity of values and goals, with some discrepancies	Multiple unfavorable value and goal characteristics (egocentrism, personal ambition, self-assertion, etc.)
Multiple attributes of objective & productive cognitive styles	Signs of subjective or combinations of unproductive styles	Multiple indicators of subjective & nonproductive styles
Normal personality structure	Presence of alternative forms of normal personality structure	Multiple alternative forms of personality structure in all crew members. Similarity of the most pronounced (negative) personal characteristics.
Positive emotional relations among the crew	Signs of negative attitudes of crew members to each other	Multiple negative interrelations among the crew
Willingness to work as a team; fast & efficient crew training	Signs of isolation & competition among crew members; relatively inefficient, slow crew training	Persistent isolation & competition among crew members; no improvement during training

Table 3 Scope and contents of psychological team training [Ref. 20]

Methods and types of team training	Duration, repetition, and timing of training	Comments
Psychological and therapeutic work with crewmembers	1 hour, repeated, while crew as a whole is trained	Performed as needed during training in crew cooperation
Simulation of group performance	5 to 7 days, once, during training of the crew as a whole	Used selectively depending on crew performance
Psychological support of special training (in hydrolab, centrifuge, during flight training, in various climatic and geographic locations)	no special time needed	Used selectively depending on crew readiness performance
Periodic crew briefings on results of the group psychological evaluations	no special time needed	Presentation method is determined by the relations among the crew members
Instructing flight commander in group-control skills	1 hour	Need for training is determined by degree of control in the crew

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Chapter 3

Medical Monitoring Before and After Flight

Roger D. Billica, Yuri Ivanovich Voronkov, Ashot E. Sargsyan, and Leonid Ivanovich Voronin

The continuing effort to provide appropriate health care for space crews has evolved into a robust program that encompasses all phases of crewed space missions, from the selection process through long-term follow-up after the completion of missions. Experience gained throughout the evolution of the crewed space program has verified that clinical medicine can be practiced in the space environment, given the availability of appropriate hardware, supplies, procedures, crew training, and ground support.[1–3]

Space medicine programs are based on the principles of preventive medicine. Strict medical standards applied during the selection of astronauts and cosmonauts (see Chapter 1) ensure that these populations are, at least initially, relatively healthy. Nonetheless, the working environment for astronauts and cosmonauts is quite different from occupational settings on Earth. As discussed throughout Volume III of the *Space Biology and Medicine* series, space flight conditions constitute a unique combination of factors to which living organisms have not been exposed during their evolution. The function or regulation of every body system is affected to some extent by the new conditions; moreover, the perturbations take place concurrently with intellectual and physical demands, exceptional responsibility, and worldwide visibility. Also, the growing diversity and complexity of space-based research has led to the inclusion of non-career astronauts (payload specialists) in space crews.[2,4] An aggressive health care program is needed to maintain crew health and performance, and to prevent adverse consequences to missions and to the long-term health of the participants.[5,6]

Both the U.S. and Russian programs consider health monitoring to be the cornerstone of medical practice in the space program setting. Despite some differences in the U.S. and Russian approaches to selection and training (see Chapters 1 and 2), both programs have adopted similar principles for monitoring health during flight (see Chapter 4) as well as on Earth. In the course of developing the International Space Station, the U.S. and Russian space agencies (NASA and the Russian Space Agency, respectively) have clarified the specific monitoring requirements that had been previously established by each program. The establishment of the International Space Station program, involving many international partners and full-fledged multinational cooperation in space medicine, will lead to a common set of monitoring requirements.[4,7]

Preflight and postflight medical monitoring activities are the focus of this chapter. In-flight monitoring activities are reviewed in Chapter 4.

I. Rationale and Definitions

In both the U.S. and Russian programs, the overall goals of space medicine are to maintain optimal health and fitness of the crewmembers; to manage the occupational hazards associated with physiological responses to the space flight environment (primarily weightlessness and confinement); and to deal with any injuries and illnesses that arise.

The strict selection process results in astronauts and cosmonauts being generally healthier and more physically fit than the general population. Hence, many of their physiological variables (e.g., stroke volume, spirometric measures, muscular strength, exercise tolerance, etc.) tend to fall in high-normal ranges or better. Thus, medical evaluations made without consideration of each individual’s baseline (preflight) condition can yield results that are technically normal for age and sex, which in turn can lead to underestimation of health deterioration while significant deconditioning may have taken place. Therefore, both agencies have adopted the principle of *monitoring,* rather than periodic checks of health status, to ensure timely detection of any negative trends in various health indicators.

Interpreting the results generated through monitoring is complicated by the pronounced variations in responses of individuals to same environmental exposures, especially during long flights.[8,9] For example, the extent of microgravity-induced bone calcium loss varies so greatly[10] that “normal” ranges have yet to be established. The same is true for many other variables; consequently, in the absence of distinct clinical norms, flight surgeons must rely heavily on the monitoring data so as to base risk assessment and other decisions on a large number of factors; conservative approaches generally are taken wherever possible.

The medical monitoring of astronauts and cosmonauts is not limited to tracking the ill effects of the space environment and the progress of further rehabilitation. Even healthy astronauts carry some chance of acquiring certain illnesses, such as appendicitis. Moreover, the chance of acquiring certain illnesses and injuries in space has shown to be somewhat higher than in normal Earth conditions. Therefore, medical prevention and monitoring activities must also take into account the timely detection of overt or apparent conventional illnesses, especially infectious diseases. One can easily imagine the potential magnitude of problems arising from a serious in-flight infection (see Health Stabilization Program below). Significant achievements in this area to date will serve as a baseline capability that will undergo further refinement and sophistication to meet challenges of the ISS and future programs.

Furthermore, individual exposures to environmental factors such as radiation, toxic substances, and infectious agents are also monitored both directly (e.g., individual dosimetry) and indirectly through continuous environmental monitoring (e.g., radiation monitors, microbiological sampling, and air/water quality monitoring).

A. Continuous Medical Monitoring

The need for “uninterrupted” monitoring data and scientifically valid conclusions and projections has mandated the recent development of medical databases in both the U.S. and Russian programs. In Russia, when flight research is conducted, when weightlessness is simulated on the ground, and when various population groups are examined, a vast amount of data is collected regarding the effect on the human body of real and simulated space flight factors, and regarding the prognosis of the effects’ anticipated consequences.[11-16] Monitoring in the U.S. program is a part of a larger medical risk management effort that includes studies of analogous populations and microgravity simulations. In the U.S. program, NASA also uses risk management endeavors to identify requirements for health care; to allocate program resources; to update medical standards; and to set priorities for operational research activities.[3]

As described in Chapter 4, the onboard capability for medical evaluation, on both U.S. and Russian spacecraft, is extremely limited. Although some medical data are available during flight, other crucial information cannot be obtained until the subject returns to Earth. For this reason, numerous attempts have been made to predict the extent of cardiovascular deconditioning, calcium loss, neurovestibular changes, orthostatic intolerance, etc. on the basis of all available data, including those derived from provocative tests, training procedures, and previous flights (if available).[17,18] Therefore, medical monitoring data are also acquired during many training activities to be stored for inclusion in individual databases for further analysis.

Longer exposure of crews to microgravity aboard space stations mandates a meticulous, individualized approach to preflight medical data monitoring and evaluation.[19] Both the habitability and the medical care capability of the International Space Station will improve throughout the assembly process, and by the “assembly-complete” stage will provide reasonable conditions for prevention, diagnosis, and treatment of space flight deconditioning and of many predictable injuries and illnesses.[20] All three components of the station’s crew health care system (CHeCS) (see Chapter 4), namely the Environmental Health System, the Countermeasures System and the Health Maintenance System, have been designed to improve the continuity of medical monitoring throughout long space flights.

The NASA Human Exploration and Development of Space program brings new challenges to the aerospace medicine community. Many aspects of crew-vehicle, crew-ground and crew-environment interactions are expected to change substantially in the long-term orbital and interplanetary missions of the future. In Russia, such programs were developed and implemented during training and execution of long-duration space flights on the Salyut and Mir Space Stations.[21] It is believed today that human maladaptation, illness, and injury rather than transportation system limitations will be the pace-limiting factors for such missions.[9,15,17] Medical support and monitoring of interplanetary mission crews will require even more sophisticated capabilities and will be more automated and self-sufficient than the current ISS crew health care system.

B. Definitions

The American Medical Association defines monitoring as the “maintenance of a constant watch on a patient's condition so that any change can be detected and appropriate treatment given.”[22] Stedman’s Medical Dictionary describes monitoring as “performance and analysis of routine measurements aimed at detecting a change in the environment or health status of a population.”[23]

In the space medicine setting, medical monitoring has been defined as "periodic physiological or clinical evaluations of health status to ensure that no increase in medical risk has occurred, and that preventive measures are instituted promptly."[24] This definition specifically emphasizes the preventive nature of astronaut health monitoring during short-term space missions. As the duration of exposure to space flight factors lengthens, however, it becomes necessary not only to detect and follow, but also to predict and prevent probable changes in the structure and function of human systems, organs, and tissues. Monitoring also must include environmental data and information about exposures to various physical and chemical factors. Furthermore, occult (or newly developed) pathology not immediately related to space flight can present itself before, during, or after flights, and this probability also must be accounted for. Therefore, perhaps a more comprehensive definition of medical monitoring in space medicine may be the "periodic physiological, clinical, and environmental evaluations to ensure that no unfavorable trends in the health status and medical risk of the astronauts have occurred, and that appropriate preventive, diagnostic, and therapeutic measures are instituted promptly so as to maintain the health, performance, and well-being of space crews."

In the Russian literature, measures taken to assess the current condition of the crew and the environment and to predict the future state are described as "medical monitoring," while the term "dynamic observation" is sometimes used in the same sense as the English word "monitoring." In this meaning, several varieties of medical monitoring are distinguished (real-time, periodic, phased, preflight or postflight, etc.). The Russian version of the term "monitoring" is used basically as a synonym for continuous monitoring of physiological functions or environmental parameters in real time, for example, when the heart rate, respiration, body temperature, pressure in the spacesuit, and other parameters are watched during extravehicular activities (EVA).[8]

II. Selection of Monitoring Modalities

Exposure to microgravity and the space environment has important medical and health implications, including bone loss (matrix and minerals), potential increases in risk of malignant tumors, neurovestibular changes, orthostatic hypotension, and others.[6,17,25] Because of the risks inherent in human space flight, the enormous value of space research and on-orbit experiments for human civilization, mission cost, as well as other factors, crewmembers must function at high performance levels at all times. Even the preflight training of astronauts is a set of very demanding mental and physical activities. Therefore, certain minimal requirements for crew performance exist. Crewmembers must remain physically and mentally healthy and physiologically capable of performing all mission tasks. The flight deck crew (for U.S. Shuttle missions) must be able to maintain orthostasis and perform the critical operations required to fly the Shuttle, while sitting upright, during entry. All crewmembers must be capable of unaided egress from the spacecraft in an emergency. In addition, astronauts must have some degree of career longevity, with recovery, rehabilitation, and repair capabilities available on their return from space flight. For these reasons, the capability must exist to monitor the health of the crew both on the ground and in flight. To that end, human performance and environmental effects are evaluated periodically by monitoring both the sustained physiological changes during space flight and the spacecraft environment. When necessary, appropriate treatment is administered and effective countermeasures are prescribed to prevent or ameliorate the adverse effects of exposure to microgravity.[4,24]

Selection of particular monitoring modalities is influenced by program-specific, mission-specific, and individual factors. The latter group can be divided further into factors associated with individual flight assignment and duties and those related to medical history and baseline medical data.

Each space program (e.g., Apollo, Space Shuttle, Salyut, or International Space Station) has an official list of medical evaluation requirements that stipulate the minimally required sets of pre-, in-, and postflight medical evaluations with respective timeframes. Comparison of such documents from various missions shows a clear evolution based on the knowledge and experience gained during previous space programs. In some complex programs these requirements partially depend on the duration of missions, with the range of screening and monitoring modalities increasing with flight duration. Besides nominal mission duration, program-specific requirements are also determined by the average EVA activity of the program, the nature of the missions (e.g., low Earth orbit versus interplanetary), availability of countermeasures, features of the vehicles such as radiation shielding and protection system performance, and other factors.[6–9,17,20]

Within a particular program, medical monitoring modalities can still largely vary depending on the features of the particular mission. For example, mission-specific pre- and postflight monitoring modalities can depend on mission duration, nature of mission tasks, EVA activity, as well as environmental factors such as solar activity or microbiological characteristics of the environment.

The individual pre- and postflight monitoring plan is composed by the crew surgeon on the basis of program-specific requirements, mission-specific factors, individual mission assignments as well as data on the individual's responses to the previous missions, particularities, and the speed of recovery and rehabilitation processes. Real-time corrections to the individual pre- and postflight monitoring program are also possible at any time to relieve any concerns of the crew surgeon.

A. Individual Baseline Databases

Health monitoring data collection is planned at fixed intervals in conjunction with the physical health evaluations at astronaut selection and before the first mission; they collectively establish a baseline normative database against which in-flight management and postflight recovery will be implemented. Prior experience has demonstrated significant diversity of individual physiological responses to space flight factors; in particular, it is believed important to establish a baseline profile for each crewmember in terms of metabolic and endocrine functions, and electrolyte and acid-base balance[19]; prior experience has demonstrated significant diversity of individual physiological responses to space flight factors.[3,19,20] During subsequent missions, depending on available information and the clinical judgment of the crew surgeons, only select protocols may be implemented if adequate baseline data already exist. The established baseline may be re-established periodically, as clinically indicated. In the postflight phase, guided by clinical manifestations and physical evaluation, only those protocols can be implemented that are required for diagnostic purposes or to guide the rehabilitation process and the return to flight duties.

III. Preflight Medical Evaluation and Monitoring Activities

Medical fitness for flight is determined by the crew surgeon, who conducts preflight medical evaluations of all crewmembers.

In Russia, data obtained from cosmonauts' physical examinations are reviewed by the Main Medical Board of the Ministry of Public Health and the Ministry of Defense of the Russian Federation 45 days before space flight. Depending on the nature and duration of the flight, there are minimum sets of tests/examinations required at certain intervals referenced to the launch or landing date. In the U.S. program, the current Astronaut Medical Evaluation Requirements Document regulates the frequency, composition, and other detail of medical evaluation procedures throughout all phases of training, missions, and rehabilitation. In Russia, this is conducted in accordance with regulations put into effect by an Order from the Minister of Public Health and the Minister of Defense (see Chapter 1).

The International Space Station Program has adopted most of the principles of preflight medical evaluation and monitoring that have been verified during various programs conducted by space, military, and civilian agencies in several countries, primarily the United States and Russia. Among these, the U.S. Skylab and Space Shuttle programs and the Russian long-duration space flight experience aboard the Salyut and Mir stations are the main sources of current knowledge in this area. Significant contribution to the knowledge base of space medicine monitoring has been made by ground-based experiments and simulations.

A. Preflight Medical Assessment and Certification

1. U.S. Program

Health care for U.S. astronauts begins with an extensive candidate selection examination, which is held every 2 years at NASA Johnson Space Center (JSC) in Houston, Texas. As described in Chapter 1, astronaut candidate finalists undergo thorough 5-day physical and laboratory exams, including a treadmill stress test; pulmonary function tests; sigmoidoscopic and imaging examinations; and exams conducted by specialists in ophthalmology, neurology, psychiatry, dentistry and otolaryngology. Each candidate's results are compiled and presented to the Space Medicine Board at JSC to be measured against NASA's medical standards. After selection, astronauts undergo yearly medical examinations to recertify their fitness for flight.

When U.S. crewmembers are assigned to specific flights, they begin a rigorous training schedule that covers a spectrum of medical issues particularly relevant to space flight. This training includes familiarization with the medical and physiological problems encountered in microgravity, including space motion sickness, cardiovascular deconditioning, reduced-pressure effects and decompression sickness, radiation, habitability and countermeasures, and use of in-flight medical equipment. Two crewmembers are designated crew medical officers and receive additional training in diagnosing and treating common medical problems, administering intramuscular and intravenous medications, and using onboard clean-up kits for decontamination and protection from potentially hazardous contaminants. For the ISS Program, they are also trained to conduct periodic in-flight medical evaluations, including monthly comprehensive physical examinations. Crew medical officers are equipped with a "medical checklist," a quick reference to common ambulatory and emergency medical problems and a complete description of all onboard medications and their side effects.

<u>Preflight examinations</u>. All crewmembers undergo extensive preflight medical examinations in addition to those associated with biomedical research and longitudinal data collection. Preflight exams, typically scheduled 10 days and again 2 days before launch, are conducted to detect any medical problems that might require attention and to provide baselines for postflight comparison. The final preflight examination, held immediately before launch, certifies U.S. crewmembers for flight and documents their physical status at the beginning of the mission. Results from these examinations are compared to those from two postflight sessions held the day of landing and three days thereafter.

In addition to the certification process, astronauts also undergo real-time medical monitoring during potentially hazardous activities, such as underwater and hypobaric-chamber training sessions and some forms of biomedical testing. Medical staff oversee all potentially hazardous activities as a means of ensuring safety and quality assurance.

2. Russian Program

Cosmonaut selection and training are considered to be an integrated, continuous process. The phases of the process, i.e., outpatient screening, inpatient examinations at the aviation hospital or the Institute for Biomedical Problems (IBMP) clinic, and flight training, are described in detail in Chapters 1 and 2 of this volume and are reviewed only briefly here.

The goal of the outpatient phase is to identify overt pathology and functional disorders that would represent absolute contraindications for space flight (Table 1). Examinations in the hospital are designed to identify latent (occult) pathology, incipient preclinical forms of disease, and slight deviations in the functional status of organs and systems, as well as to evaluate physiological functional reserves. Psychological examinations also are important during this stage. Candidate cosmonauts undergo comprehensive assessments by internists, surgeons, otolaryngologists, dentists, neuropathologists, and psychologists. Special provocative tests also are used to evaluate the "reserve potential" of the physiological system being tested. The results of these tests and evaluations, and those from tests conducted after cosmonauts are assigned to a crew (see below), are assessed by the Medical Certification Board, which declares individuals either qualified for special training, qualified with reservations, or not qualified (see Chapter 1). The qualification period lasts for 1 year. Qualification with reservations usually reflects the discovery, during the evaluation process, of a medical condition that requires treatment; such individuals are deemed temporarily unfit for special training for up to 6 months. Individuals who pass the inpatient testing stage subsequently undergo special training (see Chapter 2), the goals of which are to improve tolerance and induce adaptive physiological reactions to specific space flight factors, and to impart the skills needed to control spacecraft systems and equipment.

If a cosmonaut has a health problem that requires clarification or reassessment of the Board's recommendation, then a special examination and Board session are held. Other medical assessments conducted between regular Board meetings (during the training process) are observations during tests, physical training and daily life; interim medical examinations; and quarterly in-depth medical examinations.

Interim examinations (Table 2) are held before and after any training procedure that makes unusual demands on cosmonaut health (e.g., centrifugation training; barochamber, thermochamber or isolation chamber training; survival training in various climates and geographical areas; parabolic flights on research aircraft; and underwater training). Interim exams including analysis of blood and urine, and evaluations by internists, neuropathologists, and otolaryngologists (when tests involve barometric pressure changes). If the results of preliminary interim examination are positive, the cosmonaut is allowed to participate in further tests and training. Results of the last interim examinations are used to assess the effect of training on the cosmonaut's health and tolerance of the factors to which he or she has been exposed. Measures are taken as needed to improve physiological tolerance of particular factors.

In-depth examinations (also conducted as part of the outpatient selection process) take place quarterly (Table 3). These examinations include general clinical analyses of blood, urine, and feces; cosmonauts older than 40 years also undergo tests of blood sugar and cholesterol every 6 months. Functional tests consist of ECG at rest and during graded exercise on a bicycle ergometer (every 6 months), followed by Holter monitoring. Cosmonauts also are examined by specialists in internal medicine, neuropathology, surgery, otolaryngology, ophthalmology, and dentistry. Results from medical and psychological observations and from interim medical examinations during training also are considered during the in-depth examination.

Annual certification. After cosmonaut candidates pass the selection procedures, they are recertified annually at the IBMP clinic in-patient facility or at the Central Aviation Hospital (see Chapter 1). Tests for recertification closely resemble those of the inpatient selection phase (Tables 4 and 5).

Preflight examinations. Cosmonauts undergo additional clinical and physiological tests once before they are assigned to a prime or a back-up crew, again 30 to 60 days before launch, and again 5 to 7 days before launch. When an individual is assigned to a crew, results from the last regular inpatient certification can be used if the Board finds no reason to repeat any of the component tests. The tests constituting preflight examinations are similar to those of the annual recertification but include 24-hour Holter monitoring and assessments of tolerance of low atmospheric pressure and +4 to +8 Gx accelerations.

Tolerance of extreme decompression (breathing 100% oxygen at an altitude equivalent to 10,000 meters for 15 minutes [after prebreathing oxygen for 60 minutes]) is mandatory if the mission is to include EVAs. This test is not necessary if the mission does not call for EVA (e.g., flights on Soyuz-type spacecraft that do not involve transferring crewmembers to space stations).

The different acceleration profiles used for annual versus preflight certifications reflect the different goals of the two processes. The annual test (tolerance of +3 Gz and 5 Gz for 30 seconds each) seeks to evaluate general tolerance and allows cosmonauts to begin flight training. Preflight certification tests (tolerance of +4 to +8 Gz) seek to predict individual tolerance of acceleration profiles expected during actual space flights. Good tolerance of transverse (+Gx) acceleration (magnitude up to 8 G, duration up to 40 seconds) has been shown to predict good tolerance of acceleration during the active phases of flight on Soyuz-type spacecraft, including emergency ejection and descent from orbit.

When cosmonauts develop medical conditions, the type of treatment, i.e., outpatient or inpatient, is decided on a case-by-case basis. Conditions such as contusions (with limited tissue edema), minor cuts or bruises, limited 1st- or 2nd-degree burns or frostbite, single boils that are not associated with fever or do not affect the individual's general state, or acute infectious laryngitis and pharyngitis (without severe symptoms of toxicity) are generally treated on an outpatient basis. After either inpatient or outpatient treatment, a short period of rest (not longer than 15 days) may be prescribed, during which the cosmonaut cannot participate in training. When the recovery and rest periods are over, the cosmonaut resumes classroom work first and then special training.

The final preflight medical examination takes place 5 to 7 days before launch and again on the day of launch. The L–7 to L–5 examination includes comprehensive analysis of blood, urine, and feces, resting ECG, and evaluations by internists, neuropathologists, surgeons, otolaryngologists, ophthalmologists, and dentists. Launch-day evaluations are conducted by internists, neuropathologists, and otolaryngologists.

Experimental examinations. Scientific studies and experiments are conducted independent of the preflight medical evaluations. These studies are conducted in accordance with special programs developed before each flight, and theoretically can include experiments in any area of physiology, medicine, pharmacology, hygiene, or psychology. The results from such studies, like those from baseline medical monitoring, can be significant in the flight certification process, although they are not a mandatory part of the decision making.

3. Preflight Evaluation Procedure for U.S. Crewmembers of the ISS

For the U.S. astronauts in the ISS Program, preflight medical activities planning and crew medical monitoring begins 1 year before the launch date.[24] At this time, a crew surgeon, deputy crew surgeon, and biomedical mission manager are assigned to the mission. Further medical data reviews and monitoring activities become the responsibility of the crew surgeon. This individual schedules and arranges for every evaluation, assessment, data sampling, and other activities. The crew surgeon ensures that all existing monitoring and preparatory requirements are satisfied and that each individual crewmember's medical records precisely reflect all acquired information. The first full psychological/psychiatric evaluation is done at this time.

Six months before the scheduled launch date, the crew aeromedical summaries and drug sensitivity testing records are updated. Nutritional assessment and counseling, and radiation history reviews are required at this time, and individual exercise programs are initiated. Baseline physiological parameters are determined and recorded. One month before launch, the crew surgeon and deputy crew surgeon meet with the crew for medical examinations and preflight medical testing to include a full flight physical examination. For short missions (less than 30 days), this session replaces the medical evaluation held 10 days before launch. Microbiological assessments of the crew are begun at this time. A full psychiatric/psychological evaluation is repeated.

Further medical examinations fall into the category of "near-flight" exams (L–10 days or closer). These evaluations are conducted at the launch site or at the training site before crew transfer to the prelaunch crew quarters. Near-flight examinations are conducted to detect any medical problems that might require attention and to provide "fresh" baselines for postflight comparison.

A comprehensive preflight examination is performed 10 days (for short flights) or 7 days (for intermediate or long flights) before launch. Additional studies commensurate with the annual evaluation's requirements may be added so that this exam, if performed within 30 days of the crewmember's birthday, will substitute for the annual exam.

For short flights, this preflight medical evaluation consists of a full physical, otolaryngology and ophthalmology evaluation, cardiovascular/cardiopulmonary studies, a battery of laboratory tests, and microbiological assessments (Table 6). For long flights, nutritional assessment and repeated microbiological sampling are required.

For U.S. launches, the Health Stabilization Program, which includes partial isolation from potential infectious disease sources, and circadian shifting are initiated at this time at both the Johnson Space Center and Kennedy Space Center crew quarters. The final crew physical examinations are performed 2 days before launch. Findings are released on the crew's health status, and this is equivalent to confirming that the crew is flight-ready. On launch day, a brief medical evaluation (several minutes long) takes place on the launch site, which terminates the preflight medical evaluation and monitoring sequence. This examination, held immediately before launch, certifies U.S. crewmembers for flight and documents their physical status at the beginning of the mission. Results from these preflight examinations are later compared to those from the postflight sessions on the day of landing and three days thereafter. After "main engine cutoff," the crew surgeon and deputy crew surgeon return to the Johnson Space Center to begin the in-flight portion of crew medical monitoring.

For a launch from Russia, the procedures for examining the crews are in keeping with the "final preflight examinations" program described above in the "Russian Program" section.

B. Preflight Countermeasures

1. Russian Program

As noted earlier, the difference between medical assessment/certification and preflight countermeasures is somewhat blurred in the Russian space program, since training is considered an extension of the selection and assessment process. The primary goal of the general training is to improve cosmonauts' physiological tolerance of space flight factors as they acquire new occupational and professional skills. Traits revealed during training, such as speed and stability of an individual's adaptive responses, are important in evaluating a candidate's performance. For this reason, the provocative tests used during this phase simulate space flight factors as closely as possible. Special attention is given to cosmonaut-researchers (payload specialists) during this training so that their performance and abilities can be expanded as much as possible. Some means by which general conditioning is improved have included exercise training, endurance training, surgical intervention (as appropriate), therapeutic use of physical factors and temporary change of climate, and controlling diet and work-rest schedules.[27]

As the durations of space flight continue to increase, it becomes apparent that maintaining the adaptive capacities of crewmembers during those flights will necessitate the development of additional prophylactic countermeasures that can be used both during preflight training as well as during actual missions.

2. U.S. Program

Many preflight activities have been implemented to protect crew health before launch and to prevent medical problems that could delay or impair missions. Some of these activities, i.e., protocols for stabilizing crew health, shifting circadian rhythms, and others, are described briefly below.

Health stabilization program. The Health Stabilization Program was designed to minimize crew exposure to infectious disease before missions. The brevity of early Mercury and Gemini flights was such that the possibility of infectious diseases manifesting themselves during flight was not considered a concern. As the duration of the Gemini flights increased, the corresponding increase in risk of disease prompted reducing the number of people to whom the crews were exposed before launch. Although no serious episodes took place during flight, Gemini crews did experience minor illnesses such as colds and influenza during the period before launch.

During the Apollo program, concern increased over the possibility and consequences of infectious diseases, particularly with regard to the difficulty of completing a lunar landing should a crewmember become seriously ill during the mission. During preparations for Apollo-8, every crewmember suffered viral gastroenteritis during the preflight period. Treatment was successful, and the spacecraft was launched on schedule. However, the recurrence of the infection in one crewmember during flight[28] greatly increased awareness of the need for more stringent preflight measures to protect astronaut health during missions.

The Apollo-14 mission was the first to be conducted under a formal Health Stabilization Program for flight crews. The goal of this program was to eliminate in-flight health problems by minimizing or eliminating adverse alterations in the health of flight crews during the period immediately before launch. Combining key elements of clinical medicine, immunology, exposure prevention, and epidemiological surveillance, the essence of the program was to institute strict controls over locations to which flight crews had access and over the number of personal contacts during the 3-week period before launch. The health status of individuals who had to be in contact with the crewmembers also was monitored carefully.[28]

The effectiveness of the Health Stabilization Program in reducing the incidence of illness during all phases of early missions is reflected in Table 7.[29] Before institution of the program, 57% of prime crewmembers experienced some illness during the 21 days before launch, as well as during and after flight. These illnesses included upper respiratory infections, viral gastroenteritis, and one rubella exposure. After Apollo-13, the only illnesses observed during the Apollo and Skylab programs were minor skin infections, which were not believed to be related to preflight exposure.

Because extending the period of orbital flight increased the probability of in-flight illness, and because in-flight illness would have compromised the results of detailed biomedical experiments, the Health Stabilization Program was incorporated into the Skylab mission sequence as well. Additional 7-day isolation periods after landings were added to allow extensive medical observation, examinations, and documentation of recovery from the physiological changes noted during flight.

The inception of the Space Shuttle program presented new challenges for protecting crew health during the preflight period. The frequency of the flights meant that more flight crews would be under medical surveillance than ever before; also, the large numbers of people involved in launch preparations meant that crews would be exposed to many more people before flights.

In 1981, NASA identified three levels of preflight health screening. Level I, the least stringent, was a voluntary program based on health education and awareness for flight crewmembers and contact personnel. No special medical surveillance or examinations were involved except for a cursory screening completed 2 to 3 weeks before flight. Level II, which most resembles the current program, required limiting the number of contacts with flight crews and required those who must be in contact with the crews to undergo medical examination and surveillance. Level III, a true isolation (quarantine) program, provides the maximum amount of health protection. The appropriate level of health stabilization is determined for each mission by the Health Stabilization Board established at the NASA Johnson Space Center.

The first Space Shuttle mission, STS-1, included a level II program. Crew training facilities and work areas were secured; only those persons who had passed medical screening were allowed entry, and they were instructed to wear surgical masks when within 6 feet of crewmembers. Each person in contact with the crew voluntarily reported any illness to the NASA clinic. The number and location of those approved as primary contacts for the STS-1 crew are shown in Table 8. The rate of illness in this population during the program was 28 illnesses per 1,000 persons per week;[30] a summary of those illnesses is presented in Table 9. The STS-1 program effectively excluded 38 persons known to be ill from crew work areas, thereby preventing exposure and possible illness.

The Health Stabilization Program for the next mission, STS-2, was reduced from level II to level I.[31] Posters and signs were placed in crew work areas and information sheets were distributed to contacts. Special routes were established for crewmembers to prevent accidental exposures. Of 164 primary contacts during the 14-day period before launch, only 3 illnesses were reported. Crewmembers experienced no illness from infectious disease. However, illnesses noted on missions 51-B, 51-F, 61-C, and before D-1 were thought to arise from increased numbers of crew contacts before flight, as well as from reduced surveillance.

The Health Stabilization Program established for subsequent Shuttle missions is more stringent than the original level I and II designations, but falls short of formal quarantine. The work forces at Johnson Space Center and Kennedy Space Center are educated about limiting crew contact and exposure before each mission through the use of bulletins, videos, and posters. Those who must contact crewmembers are identified, medically screened, and badged. Crews live in restricted crew quarters beginning about 7 days before launch, after which contacts are restricted. Family members of the crews are also medically screened and monitored as part of this program. To date, only one flight, STS-36, has been delayed because of crewmember illness during the preflight period; however, minor illnesses still occur occasionally during that time.

Circadian rhythm shifting. Scheduling constraints and weather conditions often result in mission schedules that are out of cycle with normal workdays. Flight rules limit crews' launch duty day to 18 hours, including wake-up, suiting and preparation, time on the launch pad, and time on orbit before sleep, in an attempt to protect them from undue physiological stress. However, this demanding day could begin any time from very early morning to late evening, depending on the requirements of that mission. The resulting time shift, akin to "jet lag," has been associated with fatigue, disorientation, and diminished performance.

A sleep-shifting program has been implemented to aid crewmembers in avoiding the deleterious effects of time shifting. Beginning several days before launch, crewmembers use a combination of bright lights, a controlled environment, and programmed meal and exercise periods to adjust their own circadian rhythms to match the mission schedules. The response to this program, which is optional at present, has been positive both in terms of crewmember comments and according to physiological measurements of temperature cycles, melatonin and cortisol concentrations, and recordings of motor activity (actigraphic).

The Russian program provides similar principles and approaches to disease prevention among space flight crewmembers during the preflight period.

Other preflight countermeasures. Other preflight countermeasures are being used or considered. Some pharmacological agents are tested before launch to familiarize crewmembers with dose response, drug effectiveness, and potential side effects. All crewmembers are encouraged to maintain physical fitness between missions; a related program under development seeks to target specific in-flight physical tasks that require unique levels of strength, endurance, or flexibility (e.g., extravehicular activities) and provide a physical training program specific for those tasks.

Crews' nutritional status can be optimized before launch, particularly before long missions. Nutritional assessment is necessary to obtain baseline data for further ground-based and in-flight monitoring and planning as shown in several studies.[32,33] Nutrition will play an even greater role as the duration of missions increases in programs such as the ISS Program or planetary exploration.[34]

Other potential countermeasures are discussed throughout this volume.

C. Preflight Medical Interventions

Treatment for an acute illness or injury or an ongoing medical problem during the preflight period is provided under the direction of the NASA flight surgeons using resources of the clinics at Johnson Space Center and appropriate outside referrals. The goal of such intervention is to return the crewmember to full health and duty status. An active preventive medicine program also has been established for crewmembers and their families, with risk-factor analysis, follow-up counseling, and intervention provided as needed.

D. Preflight Psychosocial Support

Preflight psychosocial support for the current Space Shuttle program consists of activities designed to assist a designated crew with team-building activities, leadership and communication skills, and stress management techniques. Counseling and crisis management is available to individuals and families as needed. Future psychosocial support activities are targeted to assist the space program in selecting an optimal mix of crewmembers, especially for longer flights, on the basis of psychological profiles and behavioral and coping skills. Crew training in these areas will continue to play a vital role in flight preparation. These and other psychosocial issues are discussed in detail in Chapter 9.

E. Preflight Environmental Health

The safety of the Space Shuttle internal environment is maintained through a stringent program of preflight analysis, monitoring, and verification of water quality, atmospheric composition, and microbial status. Standards also exist regarding allowable levels of noise in the habitable volumes. All middeck or Spacelab payloads are evaluated by a safety review board for hazards such as electric shock, fire potential, sharp edges, and possible atmospheric contamination. Payloads that contain toxic material must be double- or triple-contained. Antidotes or other specific treatments are identified and flown in the Medical Accessory Kit, a component of the Shuttle Orbiter Medical System (see In-Flight Medical Care Systems, below). Toxicity analyses and treatment procedures are provided via database to flight surgeons at the Mission Control Center.

F. Radiation Dose Review and Projection

Medical monitoring of flight crews also includes controlling individual radiation exposures. Exposures from each mission and accumulated exposures are used for health risk assessment. Radiation dose for each individual crewmember is monitored during each flight and added to his/her radiation exposure history, an essential part of astronaut’s aeromedical summary (medical record). In the International Space Station program, these data are reviewed 6 months before launch. Five months before launch, radiological assessment of payloads is finalized. One month before launch, crew radiation exposure projections are planned including any planned EVA radiation exposure. In recognition of the cumulative effects of radiation, these are considered by the crew surgeon and radiation health officer in conjunction with the doses accumulated during the previous flights. Two to three weeks before launch, the solar flare activity report is provided to the crew surgeons. Seven days before launch for tours over 30 days in duration, radiation biodosimetry is conducted. Preflight samples of white blood cells are drawn. Using chromosomal analysis, dose response curves to controlled standardized radiation exposures are formulated on preflight samples for comparison with cells collected postflight. This concludes radiation-related preflight activities on the condition that projected doses do not exceed 30-day, annual, and career radiation limits set for the given gender and age group and/or do not lead to early termination of the astronaut’s career, which would adversely affect other planned flights in the near future.[26]

IV. Postflight Evaluation and Health Care

A. Medical Monitoring after Landing

Health care for astronauts and cosmonauts also continues after landing. Crews are supervised and monitored closely for several hours after landing by flight surgeons. Each crewmember undergoes a physical examination as well as participates in baseline data collection and biomedical investigations. A more complete physical is conducted 3 days after landing; the results of this exam often are sufficient to recertify the short-duration crewmember for flight status. Assistance is provided for returning crewmembers to re-establish their normal circadian rhythms, physical conditioning, or other health needs. Although postflight medical quarantine was a part of earlier space programs, it is no longer considered necessary. Environmental samples taken during the mission are analyzed in Earth laboratories after landing.

Both the U.S. and Russian space programs have provisions for emergency medical services (EMS). In the U.S., the services have been established through NASA, in cooperation with the Department of Defense, to provide medical support in the event of an emergency landing. EMS forces and equipment are based at strategic locations around the world during any Shuttle mission. These forces are prepared to participate in rescue and recovery operations, including medical triage and transport as needed to identified medical care facilities. Various modes of emergency landing or bailout followed by rescue and recovery operations are simulated and practiced routinely by EMS personnel and NASA flight surgeons.

In Russia, the prompt recovery, medical aid, and evacuation of crewmembers from the descent module at the touchdown (splashdown) site is achieved through collaboration among the search and rescue sections and medical services of the Russian Ministries of Defense and Health.

Medical support of crews at touchdown (splashdown) and during evacuation includes a set of administrative, therapeutic, prophylactic, sanitary, disinfection, transportation, and health maintenance measures directed at maintaining the life and health of crewmembers after completion of space flights. Several conditions are of major importance at the descent module landing site and during evacuation:

- Crewmembers must be carefully assisted out of the descent module in a way that will prevent injuries and problems with orthostatic intolerance;
- Vital signs must be used to identify the need for first aid or expert field care;
- Limited-isolation or quarantine measures must be directed at limiting contacts and protecting crewmembers from infectious diseases;
- Evacuation procedures must ensure the timely transport of crewmembers to the intermediate airport or, if necessary, to a treatment facility (military or civilian hospital) for interim specialized care; and
- The readiness of rescue and first aid equipment must be maintained at probable points of descent module landing.

B. The Russian Program for Postflight Medical Monitoring

Search and rescue operations, evacuation, dynamic medical monitoring, and remedial and rehabilitation measures performed on crews after completion of space flight are directed toward identifying functional changes or physiological shifts in the cosmonauts and restoring their health. The major objectives of dynamic medical monitoring and remedial and rehabilitation measures in the postflight period are:

- Clinical assessment of functional and physiological status
- Determination of the nature, content, scope, and tactics of rehabilitation and other measures during the postflight readaptation period
- When necessary, use of remedial and rehabilitation measures during rescue, en route, at the Cosmonaut Training Center, and at the rehabilitation sites
- Hygienic/disinfection measures in evacuation vehicles and at sites visited by the crew
- Investigation of the effects of space flight factors on human physiology
- Assessment of the efficacy of onboard countermeasures in order to improve them further
- Development of recommendations directed toward optimizing the restoration of the professional performance capacity of crewmembers after space flights
- Prediction of whether a crewmember will be able to participate in further space flights
- Development of recommendations to support effective training of crews for future space flights.

The ultimate objective of medical monitoring is determining the nature, scope, and schedules of remedial health measures during the various periods of readaptation. The measures used during the acute period of readaptation are directed at restoring health and treating problems, They include a light regimen of motor activity, prevention of orthostatic disorders (e.g., wearing anti-G suits), orthostatic training to support gradual recovery of tolerance to an upright position, a balanced diet with four meals per day, breathing and muscle toning exercises, immersion in tepid water, hygienic showers, relaxation massage, analgesic and sedative electric stimulation in order to foster normalization of sleep and dissipate emotional tension, sunbathing with graded ultraviolet exposure, electrical stimulation of leg muscles, and use of pharmaceuticals (as indicated). The measures used during the subsequent (subacute) period of readaptation include a light schedule of motor activity with gradual increase to a training schedule, a balanced diet with four meals per day, light morning gymnastics, controlled-pace walking, physical therapy, general and relaxing massages (daily), baths in water saturated with carbon dioxide, pool swimming /aquatic gymnastics, electrical stimulation of the leg muscles, drug therapy (as indicated), and psychological stress reduction.

Health-restoring measures used with the cosmonauts while they recuperate in the sanatorium[†] include a remedial-training schedule of physical activity, walking at a measured pace (short excursions), general massage, mud and mineral water bath procedures (as indicated), drug therapy (as indicated), and a balanced diet.[35]

The nature and schedule of remedial health measures used, and the points at which are utilized during evacuation and rehabilitation are prescribed on the basis of a crewmember's health status. Timelines for use of various measures are established on the basis of results of medical monitoring and are determined by the severity of the adverse changes induced by space flight factors, the state of health and performance capacity of a crewmember, the efficacy of in-flight prophylactic measures against deconditioning, and the conditions and efficacy of the readaptation measures used. The extent to which health and the functional and physical status of crewmembers is restored after use of rehabilitation measures is assessed from the results of a final clinical physiological examination, which is used to derive or adjust individualized plans for subsequent biomedical support.

Six months after completion of a space flight, cosmonauts undergo an inpatient medical examination to determine fitness for the next cycle of special training.

V. U.S. Medical Risk Management Program for Space Flight

NASA has established a medical risk-management program to supplement routine preventive-medicine activities in order to provide a truly comprehensive health-care program for astronauts. The purposes of this program are to identify space flight medical risks and their influence on crew health and mission success, to identify medical capabilities that are essential in providing optimal health care during space flight, and to identify the long-term consequences of space travel under specific conditions so that preventive measures can be investigated and instituted.

This multifaceted risk management includes elements such as collection and consolidation of medical data from astronauts, cosmonauts, and analogous populations; surveys of informed medical opinion, and comparison of risk-management methods used in other organizations. Subcomponents of this program include ground-based longitudinal studies of astronaut health. An epidemiological cohort study is underway to examine the incidence of acute and chronic morbidity and mortality in astronauts and in several control groups over time. A similar but more focused in-flight study to be conducted in parallel will track and analyze the incidence of illness and injury during space flight. Until sufficient medical data from space flight are collected to reach statistical confidence limits, data from various analog populations will continue to be evaluated for comparison and application to space-medicine models.

A more profound understanding of the medical risks associated with space flight confers several long-term benefits, among them the ability to apply that understanding to the allocation of program resources and mission planning, to the refinement of medical selection standards, and to the prioritization of biomedical investigations and development of preventive countermeasures.

VI. Automated Medical Monitoring and Database Development in the Russian space program

Advances in space medicine and associated progress in human performance in space have reached a level that seemed ambitious 30 years ago. However, further progress is difficult to achieve if radical changes are not made in

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[†] Transliteration from Russian "sanatorium"; health resort with enhanced and recreation facilities and personnel. The Russian space program uses several facilities of the Ministry of Health; particular resort is selected on an individual basis depending on the specifics of the rehabilitation tasks, time of the year and crew preferences.

the methods and technology for acquiring, storing, integrating, and processing biomedical information. The amounts of data previously obtained and the rate at which new data are being accumulated (including projections for the future) are so great that it is already difficult to handle them comprehensively. Furthermore, most data are received currently in forms that are unsuitable for integrated processing, complete analysis, and support of scientific conclusions.

In many cases, physiological and other data from various phases of training for crewed flights, during the flight itself, and during the postflight period, are obtained by different specialists in different locations. While generally true in the international setting, this situation is not uncommon even within particular space programs. In such conditions, same clinical or physiological parameters may be presented in different formats and units and may even have differing significance, and normal values due to different equipment and/or methods used to obtain them. When the data obtained by various organizations (services) is initially incompatible (e.g., due to different formats), information processing becomes extremely complicated and data reliability suffers.

The increase in demands made on hardware for collecting data and on results of information processing for immediate reliable assessment of physiological status to enable prediction of future state, especially on long-term flights, makes it important to perform integrated processing of physiological and medical data. These requirements compel development of techniques for more efficient extraction of information from dynamic parameters and for integrated processing of data taken at different times. An effective solution to these problems is the application of certain information processing methodologies and the development of concepts for a centralized computer database containing various parameters and descriptions relating to space flights.[36]

The role and place of a database in a system of medical monitoring and medical support of space flights will be determined by the importance and nature of the decisions made at various stages in the work of the medical service. Russia has had experience in developing databases applicable to the phases of training and direct medical support of space flights. The creation of a database on the results of training for and completion of long-term space flights onboard Russian space stations and future space stations is of particular importance. Such database will be able to support real-time medical monitoring, prediction of likely abnormalities in the health of crewmembers during various phases of training, during the space flight itself (including EVAs), and during the period of readaptation after long-term exposure to weightlessness. Some specialists believe that such a database will also allow to confirm early indications that a cosmonaut is failing to adapt or is under excessive stress and also of pathological deviations and diseases.

To find a solution for any of these problems, medical personnel turn to medical research data. In on-line medical monitoring, there must be compact (concise) representation of changes over time in a large number of parameters and any instance where one of them exceeds the normal limits must be indicated. Prediction will require a great amount of retrospective information which is processed and analyzed using appropriate algorithms from various prognostic models. For diagnosis, along with data obtained in flight, additional specific data is needed on each cosmonaut, such as his or her medical history, results of laboratory and other studies, and data on status and reactions during selection and training. Thus the database in the system of medical monitoring must support the solution of various problems and at the same time meet scientific needs. The two major scientific objectives are to establish new scientific facts and identify new scientific principles for obtaining new knowledge in the area of space medicine; and to improve the medical monitoring and medical support of space flight systems, using near-real-time analysis of information.

The concept of a centralized database developed by the IBMP (Moscow) involves input into a computer of all the medical and auxiliary information at various phases of training and medical support of space flight to be stored as a set of related information blocks (files) containing separate groupings of data.[37,38] The files will consist of records, each of which in its turn consists of information from a certain event (for example, the set of measurements of several parameters at a certain moment of time). The records are “time-linked” as well as associated with a particular cosmonaut, and to the specific conditions under which the data were obtained. The records consist of fields containing individual information elements (such as dates, times, parameter values, textual information, and service codes). Different files contain information related to different sets of measured parameters, such as the schedule of events on board, the personal data for each cosmonaut, and the conditions under which medical studies were performed (tests, loadings etc.) The database is a set of such files linked to each other through the content of their particular fields called “sort keys,” which might be date and time, a code for a particular cosmonaut, or a code for the conditions under which data was taken. Thus, it becomes possible to automate retrieval of specific information through programmable queries (period, cosmonaut, type of study, loading, etc.) from various files.

Aside from solving the problems listed above, a centralized database makes it possible to ensure a more detailed and thorough statistical analysis of the medical information obtained not only to enable on-line decisions, but also to identify patterns of physiological reactions to space flight conditions. In addition, this database can be used to support the derivation, implementation, and testing of mathematical models of physiological systems affected by space flight.

A. Russian Biomedical Training Information System

The information environment describing the results of biomedical training of cosmonauts for space flight contains approximately 6000 quantitative and qualitative variables, evaluations, conclusions, and curves obtained from approximately 100 types of medical studies, exposures to various factors, and training procedures. The information system is a means for providing automated information support of biomedical training. The main goal of information support of biomedical training is the timely provision of reliable information on all aspects of the state of health and psychophysiological readiness of a cosmonaut to perform the biomedical aspect of the program in an upcoming flight.

The biomedical training information system developed by the Institute of Mathematics of the Byelorussian Academy of Sciences uses the “Entry” database management system implemented on a minicomputer. The core of the system is the data stored on the minicomputer, and these data form the information environment describing various aspects of biomedical training. Information on the results of biomedical training is distributed among 13 fully independent bases, the information in which covers all aspects of biomedical training. The information system for biomedical training provides:

- A dictionary of 3000 terms (variables) has been developed;
- The structure, scope, and contents of the primary information stored has been formalized
- Primary information from keyboards and magnetic media can be keyed in the input format;
- An information pool of primary medical information can be stored and maintained;
- Data can be retrieved pertaining to an individual or group;
- Information can be presented in the format in which it is stored in the computer or in formats stipulated by the user; and
- The system allows for multiuser operation.

At the current level of development, the biomedical database can:

- Monitor data to check completeness and timeliness of use of medical monitoring measures;
- Compare actual values of parameters with a norm and with graphic depiction of dynamics of parameter changes;
- Statistically analyze arrays of parameter values to determine parameter norms for individuals; and
- Develop clinical physiological descriptions of cosmonauts based on analysis of results of preflight biomedical monitoring.

Each database contains primary medical information in the form of documents, which is the major unit of stored data. Each document is described by a schematic logic according to which the information is input into the database and consists of three parts: a retrieval mode (machine language), an executive summary, and quantitative and qualitative values of parameters (primary medical information). The database system is designed to store information for 100 cosmonauts for a period of 10 years. The approximate amount of peripheral memory required is 40 to 50 megabytes.

VII. The Future of Health Monitoring for Space Travelers

Space medicine has played a key role in the human ability to live and carry out complex tasks in space for several months and to readapt successfully upon return to Earth. However, it is also true that we do not have enough facts or scientific knowledge to reliably predict all long-term effects of space flight, especially after longer exposures to microgravity, cosmic radiation, confinement, and other factors. There are still many unknowns to be uncovered and many concerns to be addressed before living and working in space for extended periods will be recognized as safe and routinely achievable. The International Space Station will serve as a critical developmental test bed in these areas. Establishment of new clinical norms and the tools to practice medicine in space will be among most momentous products of ISS operation.

Medical care beyond the space station era will continue to require a comprehensive approach that allows incorporation of new philosophies and new technologies. Newer advanced ventures involving larger crews and more remote missions require further developments of medical support capabilities. As space missions become longer and farther from Earth, the epicenter of medical care will shift from ground-based mission controllers to independently functioning space-based medical units. In-flight preventive health and countermeasures activities will become established routines, and the skills and training provided to crew medical officers will be expanded to match the evolving levels of stand-alone medical functions. Advanced expert medical computer systems will assist in monitoring, diagnostic, and treatment protocols. Telemedicine conferences with two-way audio-video communication and multimedia computer support will replace the current private medical conferences. The ability to provide accurate diagnosis with definitive treatment in space, followed by long-term care and on-orbit recovery, will ultimately prevent the need to interrupt critical space missions because of medical contingencies.

As humans extend space missions still further to establish lunar colonies and explore other planets, the need to define the limits of human tolerance to microgravity will become more compelling. The importance of preflight, in-flight, and postflight medical monitoring and countermeasures will increase in order to protect the health and performance of crewmembers for longer periods in more remote locations. New wearable and implantable sensors will be built, tested, and routinely used for uninterrupted medical monitoring of critical physiological parameters by ground-based and on-board computers in all phases of space missions. Multi-analyte chemical and biological sensors connected to onboard computers will allow autonomous monitoring and control of the environment of space vehicles, thus saving the precious crew time and making the space tours safer and more efficient.

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Space Biology and Medicine
Volume IV: Health, Performance, and Safety of Space Crews

Chapter 4

In-Flight Medical Monitoring

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I. Introduction

Assuring the health of crewmembers has been an integral and essential goal of the U.S. and Russian human space programs. The space agencies of the U.S. and Russian Federation (R.F.) have developed methodologies, tools, and training that have been used to maintain the health, safety, and performance of orbiting crews (Fig.1). Throughout history, the need for medical surveillance and monitoring has existed when individuals were subjected to hostile environments. For example, the monitoring of the health of military personnel has been practiced since ancient times when the fighting efficiency of Roman soldiers was periodically tested. In addition to monitoring the soldiers' health, the importance of public health activities, such as separating living quarters in military camps from latrines and isolating the sick from the healthy, became apparent.[1,2]

While the origins of space medicine are traced to the practice of public health in the military, early balloon flights provided the opportunity to perform medical monitoring during exposure to extreme conditions of flight.[3] One of the pioneers in this field of aeromedical monitoring was the physicist J.A.C. Charles, who, in 1783, built and piloted a hydrogen gas-powered balloon to an altitude of 2,750 meters and provided the first descriptions of altitude sickness. Another pioneer in this field was the American, Dr. J. Jeffries, who collected samples of the upper atmosphere during balloon flights and measured his own body's reaction to this novel environment. He provided the first descriptions of motion sickness, disorientation, cardiovascular changes, and hypoxia at high altitudes. Thus, the specialty of altitude physiology and medicine, the precursor of space medicine, was born.[4]

In the 20th century, the developments in aviation and space technology expanded the frontiers of aerospace medical monitoring. In spite of the rapid evolution of aviation during World War I, there was little knowledge of the physiological reactions of the body to hypoxia, acceleration, and other stressors of flight. The first person to use a high-altitude suit to protect against the extreme environment of flight was the American pilot Wiley Post.[5] In addition to developing technology, research in the field of aviation medicine pointed to the need for medical standards in the selection of aircrew, which influenced early space exploration selection standards. During the 1930s and 1940s, researchers explored basic questions related to space flight such as tolerance of humans to lower oxygen content, rapid accelerations, and lower barometric pressures. This work led to the realization that the human body can compensate for the environmental changes experienced during space flight, and scientists began to elucidate the adaptive mechanisms to develop better protective systems to the flight environment. Aviation medicine expanded to include means for supporting life in hostile environments and measuring the tolerance of the body to the increased gravitational forces, and to issues of psychological health and performance.[6,7]

Early studies in aviation medicine have provided a wealth of data and observations contributing to the success and safety of human space flight. In the mid-1950s, for example, the American X-15 aircraft tested many boundaries of technology and human endurance. Piloting the X-15 necessitated a number of studies in human factors and performance since the aircraft had the capacity to travel nearly seven times the speed of sound and elevate its pilots to an altitude of 50 miles. Many scientists offered pessimistic predictions about human survival and performance in the harsh environs of space; detractors of human space flight were certain that the force of gravity was fundamental to human function. They prophesied that the combination of acceleration during liftoff, the subsequent weightlessness, and deceleration during entry back into gravity was beyond human tolerance. Scientists increased their ability to monitor crewmembers during all phases of flight in order to assess the effects of these three phases of flight on human physiology.

Subjecting the human body to increasingly harsh environments necessitated the use of an in-flight medical monitoring and biotelemetry system to follow changes in crew performance and health over time. Before Yuri Gagarin's space flight, several orbital flights of spacecraft with animals (dogs and primates) provided monitoring and telemetry of physiological functions. Special medical monitoring equipment was developed for the first manned flights on the Mercury and Vostok spacecrafts. This equipment recorded electrocardiographic (ECG) activity and respiration. By the time of the Vostok-5 and Vostok-6 flights, a rather extensive number of physiological parameters were recorded, including electroencephalographic activity (tracing brainwaves), skin galvanic response, and seismocardiographic activity (balistocardiogram).[8] During the first flights of American astronauts on the Mercury spacecraft, ECG, respiration, body temperature, and blood pressure were recorded.[9] Medical monitoring systems have evolved from flight to flight as a result of advancing technology and lessons learned. Additional monitoring was added over time as new physiological changes were observed and recorded.

Early in the program, there was no delineation between medical monitoring and scientific research. Data were considered as scientific discovery as well as information on crew health. During the Voskhod missions, medical monitoring became an independent element of medical support, separate from scientific research. This 1-day flight of a three-man crew with the participation of the first physician-cosmonaut, B. Yegorov, was the prototype for subsequent medical monitoring. As human flight continued, increased research efforts emphasized the need for better monitoring and protective measures that would define normal parameters (Table 1). Systems and protocols have evolved to today's successes with a minimum of serious medical events. Future systems for medical monitoring will have a greater degree of sophistication and automation for data acquisition. The knowledge gained in Russian and American programs is coalescing in the International Space Station (ISS) (data summarized in Table 2).

During the 40 years of space exploration, two medical monitoring concepts have developed in parallel: that of Russia (formerly U.S.S.R.) and that of the United States. These concepts require different medical and technical solutions. The Russians developed medical monitoring systems for space flight lasting many months with one to three crews on the Salyut and Mir orbital stations. The NASA program tested biomedical monitoring during long-duration Skylab missions[10] and then focused on supporting the health and safety of many crews consisting of up to eight members for missions lasting up to 16 days on the Space Shuttle. With the ISS, the many years of experience of the two programs are merging to address the biomedical problems that are vitally important to the development of future human space exploration.

A. Operational Concepts

A successful mission relies on three independent yet interrelated elements—the spacecraft, the human, and the environment, each of which can impact crew health and safety. The successful function of the human-rated spacecraft relies on system design and performance characteristics (see Chapter 12, General Requirements for Flight Safety). Performance of the human in the space flight environment is dependent on a continuum that begins with stringent selection (Chapter 1), training (Chapter 2), and preflight health monitoring of the crew (Chapter 3). During flight, comprehensive monitoring of all three systems is necessary for timely intervention and application of countermeasures to maintain the integrity and safety of the mission(s). In the postflight period, crew health is monitored in light of readaptation to Earth and guides physical rehabilitation.[11]

B. Goals

The primary goals of in-flight medical monitoring are to assess and forecast the crew's health, safety, and performance; to determine when changes are pathological and not merely adaptive; and to measure environmental parameters that could affect crew health. The human body undergoes significant physiological changes in space; these changes result in new state(s) of physiological function within days to weeks on orbit (see Table 1). Tracking these changes over time and assessing potential impacts on health are critical aspects of medical monitoring. Techniques to assess these trends should:

- Identify and track changes in crew health and performance;
- Identify and track changes in environmental parameters;
- Determine the risk of developing pathological conditions either as a result of adaptive changes or exposure to disease;
- Assess individual reactions to microgravity;
- Detect detrimental changes that might affect the crew's ability to maintain homeostasis;
- Determine the risks to crew survival in the event of various emergency situations; and
- Assess the immediate and long-term consequences on the health, safety, and performance of the crew after flight.

II. Scientific Foundations for In-Flight Medical Monitoring of Crew Health in Space

A. Russian and U.S. Scientific Concepts

The monitoring and assessment of crew health and performance is important for assuring the safety of human space flight. This safety is dependent on the proper interaction among systems—the human, the environment, and the spacecraft. Health, according to the definition of the World Health Organization, is not only the absence of disease or physical defects, but also physical, mental, and social well-being. Maintaining health, safety, and performance of flight crews are the central tenets of the U.S. and R.F. space medicine programs. The differences in the U.S. and R.F. practices to medical monitoring reflect cultural traditions, structures of their national health care systems, and prior experience. The driving forces include scientific interpretation of health in various cultures, the definition of normal parameters, the importance assigned to various medical findings, and the general principles for creating and operating an in-flight medical monitoring and assessment system. Currently in Russia and in the U.S., two scientific approaches have evolved that are consistent yet different in form.

The health care system of Russia is based on the principle of ambulatory evaluation by medical specialists. It has three goals: screening for disease, establishing deviations from health, and predicting future medical risks. The traditional Russian public health care system influenced the development of in-flight medical monitoring of the space program. The approach is to integrate parameters relating to the cosmonaut's health and those relating to the environment. The predictive approach encompasses examinations that assess the current state of the health of a crewmember and evaluate risks that might appear in the future. Medical monitoring includes both clinical and physiological parameters.

The U.S. public health care system relies on the primary care physician who provides for initial medical screening and treatment of disease and refers patients to medical specialists based on identified risks or diseases. This approach has influenced the medical monitoring of the astronauts. Thus the primary care physician, in space medicine referred to as a flight surgeon, evaluates the results of the medical monitoring and is the primary medical specialist for interactions with the crewmember on orbit. The flight surgeon holds private medical conferences with the astronaut to address issues concerning health and well-being and personally monitors all the data transmitted from the spacecraft. The flight surgeon consults with other medical specialists as indicated.

The joint flights of American astronauts with Russian cosmonauts onboard the Mir space station (Shuttle-Mir and NASA-Mir programs) allowed the integration of the Russian and American approaches for in-flight medical monitoring. Thus, during the long-duration flights of American astronauts on the Mir station, the NASA flight surgeon was an integral member of the Russian multidisciplinary team. During the flight, the NASA flight surgeon participated together with specialists from the Mission Control Center (MCC) medical group in assessing the crewmembers' state of health and performance. These experiences and interfaces have strongly influenced the development and implementation of medical monitoring for the international crews of the ISS.

B. General Principles of Medical Monitoring Methods:

Guidelines for crewmember performance and supporting medical interventions have been described.[3,7,12–16] These guidelines are implemented based on traditional medical principles and knowledge gained from previous space flight investigations, including availability of new monitoring technologies. The rationale for monitoring of humans during space flight is designed to maintain the mental and physical health of the crew in order to continue the mission.[13,17–20] The experience and knowledge gained on short- and long-duration missions have demonstrated that there are physiological and psychological changes, which over time can present health risks to humans in space. In addition to the assessment of the current state of health and environmental factors, space medicine includes the evaluation of the adaptation process in microgravity and the development of pathological changes and associated illnesses.[18] All human-rated spacecraft require monitoring systems for health and environmental assessment[13,21–24]:

- Diagnosis and prediction of physiological measurements;
- Specific biomedical tests to improve diagnostic specificity and sensitivity;
- Monitoring during ascent, docking, EVA;
- Periodic, health examinations during the flight (according to the flight plan);
- Emergency medical evaluations based on specific indications; and
- Comparison of data from in-flight and preflight clinical assessment.

Russian medical monitoring relies on the collection, transmission, processing, and analysis of medical data obtained during the flight. The primary sources of medical data are:

- Information on the spacecraft, environment, and crew status;
- Private medical conferences;
- Health questionnaires;
- Telemedicine; and
- Evaluation of crew using audio and video means on the spacecraft.

Three types of medical monitoring are identified: continuous, experimental, and unscheduled medical evaluation, as shown in Table 2. Both original and processed data and data collected before and after flight are stored in databases.[25,26] Since Skylab, the U.S. has maintained a database of crew health and medical findings from data collected before flight, during flight, and after flight. Data acquired in flight can be divided into subjective and objective categories. Subjective information (data from audio and video exchanges and medical private communications) is often the sole source of information concerning changes in health status. When it is not possible to substantiate this on the basis of standard medical monitoring and evaluation or periodic detailed examinations, it might be necessary to conduct an emergency evaluation. Data processing and analysis are performed using computational programs and experts' interpretation of results. The MCC medical team performs the evaluation of this data in consultation with specialists from appropriate scientific disciplines. Telemedicine also allows consultations with experts globally. Since 1972, NASA, with many organizations, has conducted remote diagnosis and treatment of patients. This experience has been instrumental in identifying current monitoring capability needs. NASA has also used these opportunities as a testbed for remote monitoring of space crews. The first experience of NASA's Spacebridge to Armenia proved that teleconferences could be held between specialists located in various parts of the world via the Internet.[24,27] This approach, using the Internet, is used on the ISS.

C. Diagnostic Aspects of Medical Monitoring

Specialists in space medicine have developed a list of specific conditions that might occur as the result of exposure to hazardous factors, including weightlessness. Three types of risks have been described: risk of illnesses; individual physiological changes resulting from space flight and functional and morphological changes in organs that are specific to space flight; and new manifestations resulting from adaptation.

Early identification of disease states is sometimes impossible because of the state of the art of medical practice. This has led space medicine specialists to search for new approaches and protocols to identify subtle changes in homeostasis.[28] The following events have been identified during long-duration missions. The latter is extremely important for the development of the predictive health evaluation[29]:

- Changes resulting from exposure to space flight factors (e.g., orthostatic intolerance, physical deconditioning, psychological stress, etc.);
- Injury such as trauma, burns, etc.;
- Impacts of the spacecraft system malfunctions on health (e.g., failure of life support systems, partial depressurization, fire, etc.); and
- Asymptomatic or undiagnosed illnesses occurring during the mission.

Diagnosis and treatment of in-flight illness is presented in Chapter 5 of this volume.

D. Prognostic Aspects of Medical Monitoring

Predicting and anticipating the health status of crewmembers is an integral part of medical monitoring. The MCC medical teams determine if a mission can continue and, if so, the impact to schedule. In order to predict the risk for the first human space missions, animals (dogs and monkeys) were sent into space. During the early flights, acquired scientific data was used as the basis for establishing the safety of the next space flights. With missions lasting several months on the Salyut orbital stations, it was necessary to develop a special medical risk assessment program, which was further refined on the Mir station. Forecasting the state of health in space has particular significance during operations of the International Space Station and future interplanetary flights that may last years. Prognosis has a degree of uncertainty, which should be weighed in assessing the risk to a mission. Predicting risks to health has three components: deterministic, probabilistic, and random.[30,31] Deterministic events are those phenomena that are known or already determined such as the time of sunrise and sunset or the orbital paths of satellites. Probabilistic health issues or events are not predetermined, but based on history from which scientists can predict or forecast the chance of an event. Predicting the health status of a crewmember in the future, based on the current information and data, is called the probabilistic approach. Random events are chance or unanticipated occurrences that can result in injury or an acute illness.

III. History of the Development of In-Flight Medical Monitoring

A. The Early Programs

In-flight medical monitoring occurred long before the first flight of either of the current programs. The first aeromedical animal flight, in 1783, was conceived by none other than Louis XVI of France, who required that the Montgolfier brothers first perform a test flight of their balloon with a chicken, a duck, and a sheep on board. The animals rose to 1,700 feet and survived, proving it was safe for mammals to fly. The first adverse effect occurred on that same flight when the sheep kicked the cock and injured his wing. Ten years later, in 1793, Pierre Blanchard made the first instrumented physiological observation by taking his own pulse on a balloon flight, obtaining an average of 92 bpm compared to 84 bpm in baselines. This also represents the first American contribution to what was to become aerospace medicine. Historians consider the beginning of aerospace medicine to be 1874–1875 when two Frenchmen trained with physiologist Paul Bert in a rudimentary hypobaric pressure chamber. Failing to comply with Bert's advice, the two men eventually died of hypoxia during a balloon ascent. Before the first powered flight in 1903, the effects of space flight such as mental disorientation attributable to hypoxia, decompression symptoms, motion sickness symptoms, and cardiovascular changes had been identified through ballooning experiences. Paul Bert and an Austrian, Hermann von Schrotter, conducted extensive and systematic studies of altitude physiology; in Russia, Tsiolkovsky and Pautina studied and analyzed the physiological effects of acceleration.
By 1910, the medical implications of aviation were being considered in Europe. Aviation biomedical monitoring demonstrated that the human body could function effectively during the demanding acceleration phase of takeoff and deceleration during landing. After World War II, experiments on the ground suggested that humans could also sufficiently adapt to the microgravity environment and perform various tasks.[32] Beginning with the launch of Sputnik II in 1960, when two dogs (Belka and Strelka) were successfully returned to Earth, the Soviet in-flight medical monitoring program primarily looked at physiological responses to space flight. The first human space flight by Yuri Gagarin demonstrated man's capability to withstand physical and psychological stresses during launch and entry, as well as weightlessness during orbital flight. During Gagarin's flight, the "Vega-A" apparatus weighing 4 kg was used to record ECG using three leads—respiratory rate, blood pressure, and temperature in six body regions.[33] To continuously monitor the cosmonauts, a special "electrocardiophone" device generated an audio signal for each R-wave on the ECG. The signal was transmitted to Earth via a short-wave radio frequency.

In the early phases of space exploration, medical monitoring was not differentiated from scientific research because each new flight added new knowledge that was important for assessing the risk for humans in space. A description of the medical monitoring methods and hardware during the first manned space flights is not only of historical interest, but also demonstrates the advances in technology (Table 2).[8]

During flights lasting up to 5 days on the Vostok spacecraft, the medical monitoring system was expanded considerably, and during the third and fourth flights on Vostok, the first group was observed and compared. Operating jointly with the Vega-A, an electroencephalogram (EEG) and electrooculogram (EOG) were recorded, as well as skin galvanic response with the "Neuron" and "Reflex" instruments. Research on the cardiovascular system was also expanded, and a kinetocardiogram, in the second and subsequent flights, was replaced by a seismocardiogram to study the contractile function of the heart. The multichannel onboard system transmitted a significant amount of medical information to the ground in real time via the telemetry system. The autonomous magnetic recorder stored pulse and respiratory rate during the descent when information could not be transmitted from the spacecraft.

Project Mercury's astronauts wore partially modified, fully pressurized flight suits consisting of a helmet, gloves, and a torso coverall in which biosensors were anchored. Telemetry of flight suit data allowed ground controllers to analyze basic physiologic parameters, such as blood pressure, heart and respiratory rate, ECG, and environmental data consisting of O_2, CO_2, and H_2O levels.

On the Voskhod-1, for the first time, a physician was included in the crew of three. During ascent and descent, electrocardiograms, pneumograms, and seismocardiograms were recorded continuously for all crewmembers simultaneously. A pneumoelectrocardiophone continuously monitored and transmitted to the ground heart and respiratory rates. The Polinom made it possible to record EOG, EEG, electrodynamograms, and motor skills (such as writing). This was the first medical laboratory in space for the study of the coordination of motion, muscle strength, and neurophysiology. In early 1962, the crew of Voskhod-2 performed the first egress into outer space. The medical monitoring equipment was supplemented with a monitoring console inside the cabin for pulse and respiratory rate and body temperature.

The Gemini program, initiated in 1962 as a bridge between the highly successful Mercury program and the Apollo program, featured the first medical studies to be carried out during space flight. In preparation for lunar missions, astronauts were evaluated for tolerance to increasingly longer duration flights. Medical monitoring showed losses in red blood cells, exercise capacity, bone density, bone calcium, and muscle nitrogen. None of these changes were considered prohibitive to the 2-week missions necessary for lunar landing and exploration. These physiological changes were characterized as an adaptation to microgravity, and it was assumed that these adaptive changes would subsequently be reversed upon return to Earth's gravity. A decision was made to continuously monitor the environment (especially the radiation situation) and the vital signs, augmented with medical conferences and additional evaluations.

The first extravehicular activity (EVA) of the American space program was performed during the Gemini missions. Edward White's exploration of the inhospitable environment beyond the spacecraft was brief but instructive. A 25-foot tether not only linked him to the Gemini craft, but also served as a simple life support system that provided him with ventilation and communication ability. The flight surgeons on the ground received bioinstrumentation data similar to that collected during Project Mercury. While White's EVA was indeed a success, his medical data and his own descriptions of the experience revealed that venturing outside the spacecraft exacted a higher-than-expected metabolic toll. It was also clear that for future EVAs, special training and monitoring would be required.

B. Apollo-Soyuz Test Project

The Soyuz spacecraft has been the primary transport vehicle in Russian (Soviet) manned space flight for more than 30 years. In spite of major modifications to the Soyuz spacecraft in the late 1970s and throughout the 1980s, its onboard medical equipment remained virtually unchanged in its configuration and functions. The Alpha-01 and Beta-08 apparatus installed on present-day Soyuz-TM transport vehicles have their own direct predecessors on the first Soyuz spacecrafts. The onboard medical monitoring equipment telemetered back to Earth the electrocardiogram, seismocardiogram, pneumogram, and pulse rate of each cosmonaut to Russian ground stations. The apparatus, comprised of physiological sensors with attachments and lead cables, amplifier-converter unit, and a medical monitoring panel, transmitted signals to the onboard radiotelemetry system and to the onboard magnetic recorder.[14] The functional exercise test was introduced into the medical monitoring system during the Soyuz-9 flight. This test was performed once every 2 days. The test consisted of three series of stretching using an elastic bungee cord located behind the cosmonaut's back. Each series called for 10 stretches. The physiological parameters were recorded at rest before the test, during the test, and 2 minutes after the test was completed. To study autonomic regulation of the cardiovascular system in Soyuz crewmembers, cardiac rhythm variability was evaluated. Scientists determined that this method made it possible to assess the level of stress on physiological systems and the tendency toward exposure risks.[15,34] Changes in the biorhythm, together with the heavy workload and time constraints, intensified the emotional and intellectual stress and the effect of weightlessness, making the normal course of the adaptation processes more difficult.[35] For the first time during flight, psychological support measures were employed to maintain mental health. All data was either telemetered or verbally communicated to the ground control center.

During the Soyuz program, the radiation safety system was established to collect and analyze data on space radiation from on board the spacecraft, from satellites, and from ground stations. Researchers were able to observe astrophysical and geophysical phenomena that preceded solar flares.[36] The total cumulative radiation dose on board the spacecraft was assessed, and the risks from radiation exposure to the cosmonauts were forecast. Radiation safety conditions for space flight required that three groups of ionizing radiation doses be distinguished: permissible doses, justified risk doses, and critical doses. In order to satisfy radiation safety requirements, three levels of radiation exposure were established. Doses for short-duration flights lasting up to 29 days were established: permissible–15 rem; justified risk–50 rem; and critical–125 rem. According to Radiation Safety Service data, the average intensity of a dose in 24 hours during the flights of Soyuz-3 through -16 did not exceed 60—70 millirads, substantially below permissible levels.

Meanwhile, the U.S. space program focused on lunar landing and exploration missions with the Apollo program. Program objectives were specific and ambitious: conduct scientific exploration of the Moon and determine the human capability for work on the lunar terrain. The lengthy lunar missions allowed scientists to monitor crew health and to perform biomedical research. With improved measurement techniques, three distinct monitoring modalities were achieved: monitoring of the external environment, the internal environment, and the adaptive responses of the crew. The biosensor harness was developed as an integrated set of equipment for quantifying crew health parameters and transmitting them back to Earth. Bioharnesses were used only during the critical launch, docking, EVA, and lunar exploration phases. This information was supplemented with near-real time biotelemetry data sent to the Mission Control Center with only a 2-minute delay. Audio and video transmissions further expanded the clinical data available.[37]

Although the operational complexity and rigorous activity of the Apollo missions constrained the resources available for biomedical experimentation, scientists amassed a considerable amount of knowledge about human space flight. For example, the vestibular disturbances seen early in space flight were identified as a component of the adaptive syndrome and space motion sickness. Studies of the cardiovascular system, metabolic balance, and microbial load were performed. Crewmembers performed a limited number of investigations into the effects of radiation and heavy nuclei from galactic cosmic radiation on animals.

In sum, the 1960s were an era of considerable but divergent accomplishment in the Soviet and American space programs. As cosmonauts began to establish an orbiting space station, astronauts explored the lunar surface, followed by Skylab long-duration missions in low Earth orbit with researchers developing complex and increasingly sophisticated monitoring systems.

C. Collaboration on Orbit

The Apollo-Soyuz Test Project (ASTP) in-flight monitoring program was the immediate antecedent of the Space Shuttle Orbiter in-flight monitoring programs of the 1980s. This joint flight showed that Russia and the United States still had some fundamentally different approaches to human space flight and to medical monitoring. This flight was the first time that an international docking occurred. In addition to accomplishing crew transfer between two spacecraft (Fig. 2), the mission introduced new technology solutions and scientific experimentation. From the perspective of medical monitoring, ASTP provided an important lesson about the closed confines of the flight environment: the glue used in Hatch 1 produced a noxious and toxic odor that localized in the Apollo module after the Soyuz docking.[38] While this situation would be considered a benign event on Earth, the closed-loop life support system of the spacecraft made the contaminant a critical concern and a potent illustration of the need to continuously monitor the internal environment. The ASTP joint venture added to the monitoring database, resulted in the first U.S.-Russian joint documentation on medical evaluation and observations of the crew (by Drs. Nicogossian and Yegorov), and provided a solid foundation on which to base plans for future collaborative efforts such as the Phase 1 NASA-Mir Program of the ISS.

D. Long-Duration Missions

The 1970s was an era that focused both space programs' competitive spirit on a single goal. With lunar landings and exploration a matter of history, the new goal was to introduce a more permanent human presence in space by launching a space station into Earth's orbit. The Soviets developed the Salyut station, which was the first long-duration, orbiting station with a crew. This station was equipped with virtually all the medical support elements found on today's orbiting stations. The medical monitoring system used as its basis the Alpha apparatus, enabling ECG, respiratory rate, and heart activity to be recorded for each crewmember. The next generation of monitoring hardware, the Polinom 2M apparatus, provided for expanded medical research. Polinom 2M performed three types of examinations. The first included a complete 12-lead ECG as well as temperature and respiratory rate. The second recorded blood pressure by the tachoscillographic method, kinetocardiogram (KKG), and sphygmogram of the carotid, radial, and femoral arteries. The third recorded KKG, EEG, EOG, and a plethysmogram of the extremities.[33] On June 6, 1971, Soyuz-11 delivered the first three-man crew to the Salyut-1 station. Over the course of 24 days, they performed biomedical and engineering investigations. Unfortunately, the cosmonauts perished during descent as a result of the depressurization of the descent vehicle.[39]

On the Salyut-3 station, in addition to data from the Polinom 2M apparatus, additional investigations included rheoencephalography, blood analyses, vestibular testing, and psychophysiological studies. The equipment used for these studies was then successfully used on two Salyut-4 missions with durations of 29 and 62 days. Salyut-6, which began in September 1977, was the first of seven long-duration space missions (up to 211 days) and 13 short-duration missions. During Salyut-6, for the first time, scientists observed problems in the process of the interaction between crewmembers from different countries. This was also the first time that, periodically, there were up to six cosmonauts resident on the station at one time, requiring that the crew adhere to the work and rest schedule. It was necessary that the microclimate and life support system be monitored to maintain the crew's mental and physical status.[40]

E. NASA-Mir

The Mir space station was a seven-module orbiting space station that operated from 1986 to 2000. Because multinational crews continuously occupied it during its last 5 years of operation, Mir served as an important testbed for future International Space Station technology and design. Multinational crews participated in a large number of biomedical and monitoring investigations. Table 3 presents a list of research projects that were regularly conducted on the Mir and the three types of medical monitoring: continuous during ascent and docking; during extravehicular activity; and periodic medical examinations in the course of flight. The list of medical monitoring procedures performed during flight was rather extensive. Medical monitoring data, together with the data from scientific experiments, served as the basis for the routine assessment of crew health and environmental status and for the prediction of risks requiring medical intervention. This medical monitoring program was implemented jointly by the medical team at the MCC in Houston, Texas, and by the second team at the Mission Medical Control Center (TsUMOKO), which was set up at the State Scientific Center–Institute for Biomedical Problems in Russia. These medical groups interacted with each other and with the crew using a computer network.[41]

The sources of information collected during the flight for MCC and TsUMOKO medical group specialists were:
- Radio exchanges between the ground control and the crew during which the crewmembers' well-being was assessed and the cosmonauts' speech activity was analyzed;
- Telemetry of spacecraft systems function data, including the life support system function and resulting environmental parameters in the living quarters;
- Telemetry during lower body negative pressure sessions and onboard exercise periods;
- Medical and physiological data collected during medical examinations, individual medical experiments, and extravehicular activity[42];
- Television data that could be used for medical support (monitoring of medical procedures and countermeasures) to assess conditions on the orbital station, external appearance, and behavior of the crew, and for psychological support; and
- Computer "packet" communications—the transmission of previously prepared information, including biomedical information.

Additional information was returned to Earth on transport vehicles for analysis in ground-based laboratories. These were in the form of tape recordings, biomaterials, samples for biochemical analysis, environmental samples, and radiation detectors. The results from the study of returned materials were significant for retrospective scientific analysis and to develop recommendations for subsequent crews. Table 4 presents a list of information transmitted over the on-line network of the medical groups.

F. Skylab

The Skylab program provided the opportunity for the United States to study habitability and human responses to long-duration missions, the longest of which lasted 84 days. Like their Russian counterparts on Salyut, astronauts were to live and work extensively in space and perform a multitude of experiments while on orbit. Skylab programs provided a wealth of biomedical data that were derived from in-flight monitoring of neurophysiology, musculoskeletal function, hematology, body fluid chemistry, cardiovascular function, and metabolic balance (see Table 2). Skylab studies were integrated before, during, and after flight to provide the maximum amount of data. By collecting baseline data for 21 days before flight, in-flight data continuously, and postflight readaptation information for 17 days, investigators obtained a comprehensive picture of the physiological and psychological response of humans to extended missions. They reached the important conclusion that humans could safely stay in space for periods greater than 6 months. However, further research was required in order to elucidate the mechanisms of change and to describe the time course of development.[43]

In-flight medical capabilities were the derivative of the Apollo program; the in-flight medical support system (IMSS) was a rack in the Skylab module dedicated to therapeutic and diagnostic activities. The IMSS served medical and dental needs not addressed through the more standard means of medical monitoring and telemedicine.

New research included the first sleep studies using EEG, EOG, and accelerometers for head movements. There were in-flight vectorelectrocardiographic investigations. Crewmembers had regularly scheduled private medical conferences with flight surgeons at Mission Control, which complemented the daily telemetry of physiological, environmental, and research data. The combination of medical support and research into physiological adaptation that characterized the Skylab program served as a paradigm in the development of the Space Shuttle and International Space Station medical monitoring systems.

IV. Current Systems of In-Flight Monitoring

Current systems for in-flight medical monitoring are based on past experience. The current system for in-flight monitoring integrates experiences from both short-term and long-duration missions. NASA and the international partners have embarked on a new era of medical monitoring with international crews who remain in space for months. All ISS partners have agreed on the medical protocols for in-flight monitoring of the crews.[44] A central feature of monitoring is the ability to compare data collected during flight with that collected before and after flight. One-*g* baselines established before flight are used to evaluate medical changes or detect pathologies during space flight.[19] Data collected after flight provide the time course of recovery to preflight values.

A. In-Flight Monitoring Hardware on the Space Shuttle

The monitoring systems of the Space Shuttle consist of: the Shuttle Orbiter Medical System (SOMS), the Operational Bioinstrumentation System (OBS), the Antigravity Suit (AGS), an integrated system of radiation dosimetry, and the Environmental Control and Life Support System (ECLSS). The OBS equipment provides signals from three ECG leads in real time or, when telemetry resources are limited, in storage mode with subsequent transmission to Earth. In addition, hardware exists to perform hematocrit counts, lower body negative pressure (LBNP), and ultrasound examination of the internal organs. The medical equipment allows for two-way audio and video communications, video recording on board, and transmission via telemetry of environmental and physiological parameters.

In addition, the telemedicine instrumentation pack (TIP) (Fig. 3) permits crewmembers to communicate with and receive feedback from ground physicians. It allows them to perform a multimedia medical exam in real-time, near-real time, and store-and-forward modes. The TIP, the size of a single suitcase, contains an integrated set of diagnostic tools that provides flight surgeons and ground physicians with video images, sound, and biomedical data of unprecedented quality via telemetry. Data capabilities include ECG waveforms, heart rate, blood oxygenation, and blood pressure. Medical video capabilities include eye, skin, ear-nose-throat, and general macroimaging. An electronic stethoscope collects auscultation data.

Between 1989 and 1995, NASA researchers teamed with the academic community and astronauts to examine the effects of missions of 16 days as a study called the Extended Duration Orbiter Medical Project (EDOMP). Cardiovascular research was the primary focus because historically space travelers experience decreased orthostatic tolerance after flight, which poses a concern to the ability to land the shuttle and then safely egress from the orbiter. Other studies provided in-depth monitoring of regulatory physiology, physical and psychological performance, neurovestibular function, human factors, and the environment.[45,46]

B. International Space Station (ISS)

The United States and Russia have collaborated with 14 other international partners to launch and operate the ISS. The ISS has been designed to sustain crews for unprecedented lengths of time in space as they perform a range of experiments in all fields of space sciences and commercial endeavors.

The Multilateral Medical Policy Board (MMPB) was formed to coordinate crew health activity of the international partners. Its work is supported by the Multilateral Space Medicine Board (MSMB) and by the Multilateral Medical Operations Panel (MMOP). The MMOP develops requirements for the medical support of crews before, during, and after the flight. The document that serves as the basis for regulating the medical support of ISS flights, "Requirements for ISS Medical Support," was drafted with the participation of all the international partners.[47-50]

During the first phase of ISS assembly, the Station's habitable area was the Russian Zvezda service module. The same system of examinations that was used on Mir was used for medical monitoring.[50] Heavy reliance during the early construction phase of the ISS is on telemetry and telecare.[51,52]

In-flight medical monitoring on the ISS is designed to identify potential health risks. Data accumulated on the incidence of illness during prior missions served as the basis for developing ISS monitoring systems. These data are presented in detail in Chapter 5 of this volume. One should note that 15% of all U.S. missions have had one or more reports of a problem that required in-flight medical intervention. In addition to viral or bacterial infections usually acquired before flight but manifested during the flight, other risk factors include elevated serum calcium levels, altered core body temperature, risk of renal stone formation due to changes in urine calcium oxalate and citrate levels, and changes in blood chemistry. Additive risks are anticipated from high physical loads, especially during EVA.

The following represents a list of routine medical parameters monitored during each flight and agreed upon by the ISS partners[48]:

- Daily reports concerning the crewmembers' health, well-being, and performance;
- Data concerning the habitable environment;
- Select data from scientific investigations;
- Measurements taken during the performance or applications of countermeasures;
- Weekly cumulative biomedical data, workload levels, and work and rest schedules;
- Periodic examinations of crewmembers that include consultations with the flight surgeon; and
- Medical examinations performed 2 weeks before return to Earth designed to predict the crewmembers' health status during the postflight readaptation period.

Two integrated systems aboard the ISS, the Crew Health Care System and the Human Research Facility (HRF), allow for medical monitoring as well as scientific research in the cardiovascular, pulmonary, musculoskeletal, neurosensory, radiation, and regulatory physiology disciplines.[53] By monitoring the effectiveness of countermeasures,[20] the HRF will ensure continued progress in providing for the health and safety of ISS crewmembers.

1. Crew Health Care System (CHeCS)

The Crew Health Care System (CHeCS) is comprised of three distinct subsystems: the Health Maintenance System (HMS) encompasses the areas of in-flight preventative, diagnostic, and therapeutic care for the ISS crew and offers extensive monitoring capability; the Countermeasures System (CMS) provides in-flight equipment to protect against the adverse effects of space flight; and the Environmental Health System (EHS) monitors the air, water, microbial load, and radiation exposure.

2. Health Maintenance System (HMS)

Of the six devices that comprise the HMS, the ambulatory medical pack (AMP) and the defibrillator offer monitoring capabilities. Among standard medical instruments included in the AMP is an I-STAT portable clinical chemistry analyzer that allows simplified blood sample analysis. The defibrillator is an integrated monitoring, arrhythmia recognition, and pacing device with an embedded downlink component.

3. Countermeasures System (CMS)

The CMS consists of three exercise devices and a set of physiological monitors for verifying countermeasure efficacy and equipment function. The blood pressure and electrocardiograph monitor (BP/ECG) provides the capability for automated, auscultative, noninvasive systolic and diastolic blood pressure measurements. In addition, the instrument monitors and displays accurate heart rates and ECG waveforms on a continual basis during the performance of exercise countermeasures on orbit. The BP/ECG monitor is used during the periodic fitness evaluations, for contingency purposes for health status evaluations, and by the Human Research Facility to support scientific experiments on cardiovascular physiology. A heart rate monitor provides heart rate monitoring and allows control over the exercise level. The medical equipment computer (MEC), a portable laptop, supplies the data processing and storage capability needed to maintain medical records and inventory and to control biotelemetry and hardware. There is onscreen display of physiological data from exercise devices; the computer collects and stores CHeCS data, maintains medical records, and provides uplink/downlink capability through the Control and Data Handling system.

V. Outcomes of Medical and Physiological Monitoring

The primary information concerning the effect of space flight on the human body is contained in Volume III of this work; in this chapter, only significant medical data required for decision making are presented.

A. Physiological Outcomes Associated With Space Flight

Past experience has shown that there are short- and long-term physiological effects from exposure to microgravity. Some changes last for a short term and other changes have a prolonged effect. The cardiovascular system is one of those that is affected both short and long term. As a result of the redistribution of body fluids, the central volume of blood increases; during the first hours and days of space flight, the stroke volume and cardiac volume increases, and the pulse rate goes up. However, as a result of regulatory mechanisms, these cardiovascular parameters usually approach the preflight level by the end of the first week of exposure to microgravity.[54] Changes that manifest over time include a reduction in blood volume associated with declines in plasma volume, erythrocyte count, stroke volume, cardiac output, central venous pressure, and aerobic capacity. These changes do not go beyond the bounds of physiological norms.

Disturbances in cardiac rhythm in the form of supra- and ventricular extrasystoles have been observed in more than half of the crewmembers. These are primarily isolated extrasystoles that occur during emotional or physical stress (the first few hours of weightlessness, physical exercise, or extravehicular activity). The most typical ECG change was a decrease in the T-wave amplitude, which began during the first month of flight and reached its peak at 6 months. The genesis of these changes is unclear. It is most probable that the T-wave decreases are caused by neuroendocrine and/or electrolyte shifts, which affect myocardial metabolism. Systolic and diastolic blood pressure in most cases remained unchanged, although from time to time a tendency toward decrease was observed. Stroke volume decrease was observed in the majority of the crewmembers but remained within the normal range. One of the compensation mechanisms for hemodynamic shifts in weightlessness, measured by Russian and U.S. researchers using ballistocardiographic data, consists of a change in the force and velocity of systolic ejection into pulmonary and systemic circulation.[43,55,56]

The study of the autonomic regulation of blood circulation is based on analyses of data of cardiac rhythm variability.[15,34,57] As early as the first manned flights on the Vostok and Voskhod spacecraft, Russian researchers noted a new level of cardiovascular homeostasis influenced by sympathetic and parasympathetic reaction of the autonomic nervous system in the first few hours and days in weightlessness. Mechanisms regulating vascular tone determine the risk for developing orthostatic intolerance during return to Earth.[15,58] In order to assess the mechanisms regulating vascular tone in the genesis of orthostatic disorders, Russian and French scientists continuously measured blood pressure from the finger[59] and compared those findings to blood pressure monitored for 24 hours with an upper arm cuff.[59,60] In flight, 24-hour Holter monitoring revealed changes in the T-wave and cardiac arrhythmias in many crewmembers. However, these changes were usually not clinically significant. Only in some cases were these changes deemed borderline abnormal.[43,61] Changes were also noted in the circadian rhythms of ECG recordings.

One of the untoward manifestations of the body's adaptation to weightlessness is space motion sickness. It is usually brief, lasting only the first 3 days of flight, and quite often it can affect the work capacity of crewmembers. This can have an adverse impact on the productivity of the crew or the control of a transport vehicle; it can complicate an emergency evacuation and affects extravehicular activity. Other aspects of the neurovestibular system are covered in Volume III.

Microgravity results in neurosensory and neuromotor changes with resulting ataxia—the inability to respond to posture changes and to properly coordinate voluntary movements. The severity of these disturbances varies among crewmembers.[62]

The results of an in-flight psychophysiological exam by Russian researchers showed that mental acuity decreases early in the flight and is restored after 2.5 to 3 months. Various psychophysiological changes manifest, usually during the second half of a long-duration flight.[63] Researchers found that differences in psychological status during long-duration international missions were related to ethnic, cultural, and social diversity of the crews. This was a source of friction and required additional training and intervention.[63]

Both the U.S. and the Russians observed in-flight changes in the energy and metabolism processes.[64] Hormones that control fluid and electrolyte balance are affected in space. Plasma cortisol concentrations increase during flight[64,65] and influence bone metabolism, immune function, carbohydrate metabolism, and the amounts of water and electrolytes in the body. Increases in excretion of amino acids associated with muscle atrophy have been observed; the ratio of essential to nonessential amino acids increases. Serum glucose usually decreases during space flight[66]; plasma insulin decreased during Skylab flights.[65] Changes in gastrointestinal motility in weightlessness[67] may affect the absorption of nutrients and therefore metabolism. Shifts in metabolic parameters were observed in all crewmembers as ATP levels dropped and lactate concentration increased. It is assumed that all of these changes are the result of the adaptation process to space flight.[68-70]

Using the Reflotron instrument, Russian investigators observed a reduction in the amount of hemoglobin and an increase in transaminase and cholesterol in flight. These changes were not clinically significant, but a decrease in the hematocrit indicated a reduction in erythropoiesis. A reduction in the number of red blood cells was observed in all the crewmembers of missions Mir-15 and Mir-17 from the 70th day through the 160th day. An analysis of the differential blood count showed an increase in the number of lymphocytes in all the cosmonauts.[69,70]

Immunological studies conducted after flight have shown that space flight disrupts the immune system. Cellular immunity is reduced, leading to susceptibility to infection by opportunistic microorganisms. The occurrence of infections should be viewed as a risk factor.[71]

Thus, a combination of real-time information obtained during continuous medical monitoring and the results of scientific research and experiments is important for reliable monitoring of crewmembers' health during long-duration space flights. The acquisition of scientific data on the body's adaptation in weightlessness enables us not only to clarify and expand our understanding of the risk factors, but also to enhance medical monitoring capabilities.

B. Environment

Often health is defined as the balance between physiology and environment. In a spacecraft, the environment is artificially created and regulated. Therefore, the physical and chemical parameters of the environment, sanitary conditions, and microbiological loads must be the subject of daily monitoring. Equally important is the monitoring of the concentration of trace chemical contaminants in the atmosphere caused by the constant offgassing of organic components by the surfaces and artificial polymer materials of the spacecraft. The interior environment is also impacted by external conditions, cosmic radiation, and magnetic storms, which require monitoring to evaluate levels of exposure and the impact on the crew.[72]

1. Environmental Monitoring on the Mir Space Station

Monitoring on the Mir station included basic atmospheric parameters, the acoustic environment, toxicological and bacteriological contamination, radiation, and the water supply. Table 5 presents the range of fluctuations in the basic atmospheric parameters in the Mir station compartments during missions Mir-20 through Mir-26. The observed changes were determined to be within the normal range. The most substantial change was a periodic increase in temperature in the working compartment, which cosmonauts assessed as "hot" and "very hot." As a result of working in areas with elevated temperature, some crewmembers noted an increase in body temperature and pulse rate and the development of fatigue and sleep disorders.[73]

Mir station crewmembers reported a high level of noise in the living compartments. This design problem also persisted on the ISS. Usually the allowable noise level was exceeded by 10-13 dBA during the day and night. The high level of noise was attributed to the ventilation and compressor equipment, the cycle ergometer, gyrodynes, etc. Information on the effects to crew performance confirms the need to minimize the noise levels to preserve auditory and psychological health.[74] In addition to noise levels, the Mir station atmosphere contained three components that exceeded allowable concentrations: acetaldehyde, acetone, and ethanol. This was related to the increased number of crewmembers and the docking of transport vehicles. The analysis of the total contamination of the environmental air showed that as the mission duration increased, a distinct decrease in the level of contamination became manifest. This was due to the constant improvement of the purification system.

Ecological and hygienic trends of the microflora in the air and on the surfaces of the Mir station were studied by periodical sampling of the interior and equipment. More than 100 bacterial species and microscopic fungi were detected. They were either human microflora or naturally occurring microorganisms in the environment. For the most part, the microorganisms inhabited the surfaces of the exposed surfaces and behind panels. On the whole, the Mir life support system maintained the level of microbial contamination within a normal range. On occasion, the normality was exceeded by 18% for bacteria and by 63% for fungi. The microbiological conditions on the Mir station were considered as high risk for biological damage and biological corrosion of the interior structural materials and equipment and for the occurrence of failures in the individual components of the life support system.[75]

Monitoring of condensate samples and drinking water has shown that the total concentration of microbes in the water does not exceed 50 colony-forming units (CFU) per 100 mL, which is in compliance with Russian and U.S. standards (up to 10,000 CFU per 100 mL). The physical and chemical parameters of water were also within the norms.

Space radiation is one of the most adverse factors affecting the cosmonauts' safety. The radiation monitoring program for Mir constantly assessed the radiation environment both inside and outside the station. Within the station habitat, four dosimetry units obtained data: a passive dosimeter that continuously collected individual crewmember data for postflight analysis, a passive dosimeter that downlinked continuous monitoring data each mission day to define dose rate and dose within the station module, three shielded passive dosimeters that measured distribution of dose (the data from these dosimeters were transmitted during daily communication sessions), and a linear energy transfer radiation analyzer that averaged the internal radiation dose. In conjunction with data from proton and electron spectral analyzers placed outside the spacecraft, these parameters were continuously measured, averaged, and compiled for telemetry. These data were used to estimate the crew's exposure.

2. Environmental Monitoring on the Space Shuttle

The Space Shuttle's cabin atmosphere is monitored for: chemical, organic, airborne particulate, microorganism, and airborne pathogen contaminants. Monitoring for the presence of contaminants in the numerous systems is a challenging process because it requires both identification and quantification of many substances. The microclimate within the orbiter is monitored and maintained at sea level air pressure (101.3 kPa) and air content of 78% nitrogen and 22% oxygen. Oxygen and CO_2 partial pressures are maintained at 22 kPa and 1 kPa, respectively. The air revitalization system (ARS) controls relative humidity between 30 and 75% and provides an alert via the caution and warning system when the parameters are not within acceptable levels. Chemical pollutants are monitored periodically to determine whether concentrations are increasing with time.[46] During the EDOMP, medical monitors found that most pollutants reached an equilibrium concentration within the first few days of a mission, except for hydrogen, methane, and dichloromethane. The microbial contamination increased as the mission duration increased (from a few hundred CFU per cubic meter of air to more than 1,000 in the final days), while fungi decreased to nearly undetectable levels.

A series of sensors in the water supply system measures microbial content, pH, and turbidity.[76,77] A redundant pH sensor monitors water purity at the water supply line outlet. If this sensor reads a value exceeding preset parameters, crewmembers are required to manually analyze a sample of potable water to further track the problem. The chemical monitoring system is driven by the concept of spacecraft maximum allowable concentrations (SMAC), in which values are assigned to organic compounds based either on the individual chemical's toxicity or on the toxicity of a similar class of compounds.

A sound level meter allows the flight crew to take readings of on-orbit acoustical noise levels in the cabin. Most astronauts rate the noise level as bothersome, especially as flight time increases. Light levels measured during the EDOMP indicated that light levels were acceptable.[46]

While the Earth's magnetosphere provides some protection from cosmic, galactic, and solar radiation, nonetheless crewmembers are exposed to this health hazard.[78] An extensive Radiation Protection Program was designed to minimize exposure through mission planning and monitoring via various types of dosimeters (Table 6). The local passive dosimeter located in the main crew compartment tracks two types of radiation within the spacecraft. Each crewmember has a radiation exposure plan that features lifetime dose calculations, accumulated dose, and limitations for in-flight exposure. In-flight requirements stipulate that crewmembers wear passive dosimeters; data from these dosimeters are analyzed postflight unless an anomalous radiation event precludes such delayed processing. During past Space Shuttle missions, doses have ranged from 0.05 to 0.07 rem, which is well below crew exposure limits. In case of unpredictable radiation events, a set of active dosimeters is used to determine if a modification to the mission is required. Dosimeters measure activity in three different ranges: low range ("PDL"; up to 200 mrad), high range ("PDH"; up to 100 rad), and an expanded range meter (up to 600 rad) called the "HRD." These active dosimeters afford real-time data that can be monitored in flight and logged for voice downlink to Mission Control Center.

3. Environmental Monitoring on the International Space Station

In late 2000, the first crew arrived to begin permanent habitation on the International Space Station in a shirtsleeve environment. Lessons learned from the Mir, the Space Shuttle, and the EDOMP contributed to the capabilities and design of the current environmental monitoring systems of the ISS. Because of the complexity of the biological, physical, and chemical experiments planned, the environment is monitored for numerous parameters discussed in the above sections and includes acceleration and vibration. The atmosphere is Earth-normal 101.4 kPa with 22% oxygen and 78% nitrogen. Pressure is between 97.9 and 102.7 kPa, oxygen partial pressure is between 19.3 and 23.4 kPa, relative humidity is between 25% and 70%, and medical operations require that CO_2 levels maintain a 24-hour average of 0.7% or less. Part of CHeCS, the EHS monitors toxicological material, water quality, microbiology, and the radiation environment. To meet the monitoring requirements, the EHS contains a volatile organic analyzer, a compound-specific analyzer for combustion products, and an analyzer for hydrazine. A water sampler, working with a total organic carbon analyzer, assesses water quality. Microbiological assessments are made using a surface sampler kit, a water microbiology kit, and a microbial air sampler. The radiation environment is measured using an extravehicular/intravehicular charged-particle directional spectrometer, a tissue equivalent proportional counter, and a variety of dosimeters located through the station. The EHS is described below.

4. Environmental Health System

Four distinct subsystems comprise the EHS. Monitoring methods used in the radiation, water quality, toxicology, and microbiology monitoring subsystems have benefited from technological breakthroughs in this area.

Radiation monitoring on the ISS is important to map the distribution of exposure levels in different ISS compartments. The Passive Dosimetry System (PDS) is used to monitor and record radiation levels inside the habitable volume of the ISS. The PDS records the radiation levels at specific sites and includes the Crew Personal Dosimeters (CPD), which are worn by the crew at all times. The tissue equivalent proportional counter (TEPC) is used to monitor radiation doses in near-real time at the cellular level inside the habitable volume of the ISS. The TEPC provides absorbed dose rate, dose equivalent rate, and accumulated time; it is omnidirectional, operates continuously, and is periodically moved to monitor crew occupancy areas, crew quarters, and thinly shielded regions. The Intra-Vehicular Charged Particle Directional Spectrometer (IVCPDS) is designed to measure galactic cosmic rays. The Extra-Vehicular Charged Particle Direction Spectrometer (EVCPDS) complements the IVCPDS by monitoring the external radiation environment.

The second system, measuring water quality, is a two-part process. Samples are collected in flight by the water sampler and archive kit for in-flight analysis and postflight confirmation and enhancement. The total organic carbon analyzer-ion selective electron assay system provides chemical analysis of potable water samples for total organic carbon, inorganic carbon, total carbon, conductivity, and pH.

Three pieces of monitoring equipment provide monitoring of the Station's atmospheric quality and composition. Two types of compound-specific analyzers are used to monitor carbon monoxide, hydrogen cyanide, hydrogen chloride, oxygen, and hydrazine and related products. Gas concentrations are updated continuously on the display, and the internal computer can store approximately 110 hours of data. The Volatile Organic Analyzer, consisting of a coupled gas chromatograph and an ion mobility spectrometer, identifies and quantifies the range of volatile organic substances that may be present in the ISS internal atmosphere. The carbon dioxide monitoring kit assembly contains two portable CO_2 monitors and ancillary components that are capable of detecting, quantifying, and recording the concentration of CO_2 in the spacecraft cabin atmosphere. The CO_2 concentration on the display is updated every 2 seconds. A comprehensive set of sampling and monitoring equipment is employed to detect and characterize microbial populations on the ISS. Specifically, contaminants in the ISS water supply and on internal surfaces are monitored and selectively identified. Fungal spores and microorganisms are detected and quantified from 10 locations on ISS surfaces.

VI. In-Flight Monitoring During Extravehicular Activity (EVA)

The basic information concerning the EVA support is contained in Chapter 14 of Volume II of this series. This chapter will examine specific issues associated with medical monitoring during EVA.

A. EVA Medical Monitoring on Russian Spacecraft

Cosmonaut Leonov was the first person to perform an EVA; he did this during the 1965 Voskhod-2 mission. This EVA underscored the need for more extensive medical monitoring and for improvements in the design of the EVA spacesuits. Leonov's core body temperature rose 1.8 ºC causing him to sweat profusely. While the cosmonaut is suited, medical monitoring is accomplished using the Beta-08 onboard unit, which records ECG, pneumogram, and body temperature. The electrodes are installed so that risk of ECG signal distortion is reduced to a minimum during intense muscular work. Body temperature is initially recorded in the axillary region and then in the rectum, and finally under the tongue and in the parotid region. Temperature parameters within a range of 36.0±0.5 ºC are considered optimal, with a range of 34.5–37.5 ºC.[79] Additional indicators of the metabolic processes that are measured include spacesuit pressure, pressure changes in the oxygen tanks, CO_2 concentration, and temperature. Water temperature is measured at the inlet and outlet of the liquid cooling garment, making it possible to calculate the energy expenditure and heat removal.

EVA crew medical preparations occur in several steps; the first of these is the clinical examination, which consists of two parts. Several days before the proposed EVA, a functional test is performed with the hand-operated cycle ergometer to establish the physical and metabolic baseline; immediately before the EVA,[79] physiological parameters are recorded with the Beta unit (ECG and pneumogram). After these data are analyzed, the cosmonaut is permitted to don the spacesuit and continue preparation for EVA. Heart rate, respiratory rate, and body temperature are continuously displayed on the onboard display panels, enabling self-monitoring by the cosmonauts.[79]

Information on autonomic regulation and physical stress is assessed by analyzing variability of the cardiac rhythm. In recent years this capability has been further developed in the hydro-weightlessness laboratory at the Y.A. Gagarin Cosmonaut Training Center. A mathematical model was developed for assessing cardiac rhythm data collected in the underwater laboratory.[80]

Another development in EVA monitoring was the introduction of ultrasound for detecting gas bubbles that form in an individual's circulatory system during decompression.[81,82] When gas bubbles form, the amplitude of the Doppler signal increases sharply, which is audible as sharp clicks. A special Doppler pulse locator is in development, which will make it possible to precisely set the signal direction, select its range, and distinguish signals that are characteristic of gas formation.

B. EVA Medical Monitoring on American Spacecraft

Wiley Post, referred to in the introduction to this chapter, used a pressure garment in 1935. Subsequently, the military used full-pressure suits for high-altitude flights. The early NASA EVA missions were performed as open-hatch operations meaning that not only was the EVA crewmember exposed to the vacuum of space, the entire crew was exposed. That required increased medical monitoring for non-EVA crewmembers (Gemini and Apollo) as well as the EVA crewmember. The difficulty in working while in an EVA suit caused increases in body temperature and heart rate. Early monitoring was used to assess fatigue as well as various physiological parameters. The development of the extravehicular mobility unit (EMU), consisting of a spacesuit and a portable life support system (PLSS), enabled the EVA crew to be wholly independent of the spacecraft while maintaining necessary mobility.

The PLSS provided a microclimate with the ability to monitor and control environmental parameters, including an integrated system of O_2 supply, CO_2 removal, heat supply and removal, and moisture removal. To prevent nitrogen decompression sickness (also known as the bends) that can occur during the transition from the pressure inside the cabin to the reduced pressure in the spacesuit, the EVA crewmember performed a prebreathe protocol (Fig. 4). Atmospheric pressure and gas partial pressure, as well as astronaut health, were periodically monitored during the prebreathe protocol. Monitoring while the suit was donned provided the essential proof that human and mechanical systems were in working order.

Building the International Space Station, a construction project in space, brought new challenges for EVA monitoring. The EVA suit was not returned to the ground for servicing as on a shorter duration Space Shuttle mission; it had to accommodate many crewmembers of varying sizes, and the suit itself was considerably different than earlier, bulkier versions. Initial EVAs were conducted only when the Space Shuttle was present because the space walkers could use the Shuttle to access outer space. After the arrival of the Russian docking compartment "Pirs," the Russian spacesuit was used, since Pirs did not accommodate the U.S. suit. After STS-104 and the installation of the joint air lock, space walkers could use either suit. During the first 5 years of operation on the ISS, there will be more space walks than the total since 1965. The following parameters are monitored during EVAs performed by ISS crews[47]:

- ECG;
- O_2 concentration;
- Total pressure in spacesuit;
- Partial CO_2 pressure;
- Body temperature (only for Russian suits); and
- Total absorbed cosmic radiation dose.

VII. Future Systems and Studies of In-Flight Monitoring

A. International Space Station General Principles

The International Space Station heralds a new era in space flight as international crews occupy this self-sustaining habitat and workspace for international space research. As the ISS develops, new challenges lie ahead in the ability to live for extended periods of time on a space station. Interesting factors include mixed international crews and the execution of difficult and labor-intensive tasks of assembling the station and installing equipment. Of these challenges, the most important is maintaining crew health, safety, and performance. Initiatives for planetary and lunar exploration have already begun. Like the ISS, these types of missions necessitate new health monitoring and maintenance capabilities. The challenges for these missions are considerably different from those of an orbiting station where communication between the station and the ground is relatively rapid, emergency evacuation to Earth is feasible, and weight and power are constrained but not prohibitive. Due to the inherently long duration of exploration missions, several fundamental aspects of current in-flight monitoring will prove to be unsuitable. Future systems will require teleoperation either remotely (from the Earth) or locally, in addition to autonomy, portability, efficiency, and compactness. Environmental monitoring will be critical both for radiation and for contamination. Scientists will be assessing the effects of planetary unique gases on human physiology. For example, an important prerequisite for the successful execution of a Mars mission is the ability to monitor response to various levels of gravity during mission phases (from 0 g in flight to 0.38 g on Mars, to g loads during launches and landings); to the hazardous radiation environment; and to high levels of physical and psychological stress.[11,83–85]

B. Monitoring During Interplanetary Flights

One of the promising technologies of medical monitoring during interplanetary flights might be the contactless acquisition of physiological data during the night. This method was first tested in 1991 with the flight of Mir-9. A sensor-accelerometer attached to a cosmonaut's sleeping bag recorded micromovements caused by cardiac activity, breathing, and the cosmonaut's locomotor activity in his sleep.[86,87] This method was named noninvasive ballistocardiography and was developed and modified during the joint Russian-Austrian space research of 1992-1995.[88] The advantages of medical monitoring during sleep are obvious not only because of the time saved but also the capability for obtaining routine information concerning the crew health status. The data are obtained under relatively stable conditions without the effect of the daily workloads and over prolonged times of 6 to 8 hours, making it possible to study ultradian rhythms that reflect the functioning of the higher autonomic centers. A third advantage is the capability for the routine assessment of sleep quality, which is extremely important for determining the crew's psychoemotional status and identifying early signs of stress and fatigue. Recently, NASA implemented this comprehensive monitoring with the actiwatch (see Fig. 3), a wrist-worn device that monitors all of these parameters on a continuous basis.[89]

The use of modern computer equipment facilitates the development of compact individual monitoring systems with automatic data assessment. Through micro-miniaturization, it will be possible to develop electronic diagnostics built into new portable devices for gathering medical information. Present and future research efforts that hold great promise are the biologically based technologies, which mimic naturally occurring detection or monitoring methods and introduce "smart" capability into monitoring systems. Many biological systems have evolved a novel ability to self-repair, self-replicate, self-assemble, and process information. These highly evolved abilities are one focus for future technology development research. Another arena of research focus is the synergistic interface between humans and machines, known as human-centered systems.

Telemetry in the real-time data mode will not be feasible during exploration missions, since the minimum data relay time is estimated at 20 minutes for a crew communicating from Mars, for example. Thus, more fully automated monitoring capabilities will need to be developed. Fortunately, current telemedicine technology includes a number of innovative sensing, decision-making support, and medical devices that may be applied toward this challenge. As described previously, the Telemedicine Instrumentation Pack has been developed and evaluated towards this goal (see Fig. 3). Another technology that promises to enhance and improve medical monitoring involves computer-based three-dimensional modeling and imagery of living systems. The capacity to visualize or practice complicated medical procedures could be especially useful for crews traveling far from medical facilities.

VIII. Conclusions

Beginning with the first manned space flight, in-flight medical monitoring has been one of the focal points among the myriad challenges in space medicine.[12,19,20,29,90] In-flight medical monitoring includes the interaction of the physiological systems with the environment and monitoring of the spacecraft's artificial internal environment. Space medicine includes monitoring current health status and predicting the development of pathology. The combination of these applications has led to the creation of a specific structure for the medical monitoring system with remote transmission of information via radio voice communication, telemetry, and television channels.

To date, a large amount of material has been accumulated based on the medical monitoring during flights lasting from a few days to many months. Numerous crews have successfully worked in space maintaining health, safety, and performance. Individual instances of illness or the occurrence of hazardous situations associated with the environment or technical failures have played an important role in refining and developing procedures for high-risk factors during space flight. The experience gained has been used in developing and upgrading the medical monitoring system for the crews of the International Space Station. During interplanetary flights, the methodology of medical monitoring will also change substantially. New technologies for the acquisition and analysis of medical information will increase the autonomy of new systems. During long-term space missions, robotics, expert systems, artificial intelligence, and achievements in the field of computer micro-miniaturization must be used to the fullest extent.

Over the course of its almost 40-year history, in-flight medical monitoring has developed into a new scientific discipline, which is exerting significant influence on Earth-based applications (see Chapter 14). But the main point that merits attention is the substantial progress in understanding the problems of health and disease, in space and on Earth.[44] Space medicine and one of its main elements, in-flight medical monitoring, will have a great influence on the development of medicine of the future.

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Ch 4 Figure captions

Fig. 1 Crewmembers use the in-flight blood collection system during STS-40 to study erythrokinetics in space (NASA photo STS040-17-010). Mission Specialist James P. Bagian (right) draws blood from Payload Specialist F. Drew Gaffney (center) as the second Spacelab Life Sciences 1 (SLS-1) Payload Specialist Millie Hughes-Fulford looks on.

Fig. 2 Apollo Commander, astronaut Thomas P. Stafford (foreground), and Soyuz Commander, cosmonaut Alexei E. Leonov, make their historic handshake in space during the joint Russian/American docking of the mission known as the ASTP, or Apollo-Soyuz Test Project (NASA photo GPN-2000-001052).

Fig. 3 The TIP, actiwatch, and electronic nose array (clockwise) are examples of highly portable monitoring devices for crew health and spacecraft monitoring.

Fig. 4 Denitrogenation protocol for Space Shuttle EVA.

Space Biology and Medicine
Volume IV: Health, Performance, and Safety of Space Crews

Chapter 5

Incidence of Disease and Injury in Space

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The safety and success of space flights involving human crews depend not only on the reliability of hardware systems, but also on the performance capacity and general health of each crewmember. Accordingly, one of the main objectives of space medicine is to optimize crew health and performance during all stages of training. Increases in the duration and complexity of crewed orbital flights, and the growing need for labor-intensive technological operations on board and during EVAs, underscore the importance of this objective.

Experience with crewed space flights demonstrates clearly that aspects of the space flight environment can cause numerous functional disorders and organic diseases that adversely affect crewmembers' performance, and occasionally can interfere with the accomplishment of program objectives.[1–4] Space medicine, being a form of preventive medicine, seeks to minimize the risk that such functional disorders, or preclinical organic conditions, will arise before, during, or after space flight.

The importance of understanding the types and causes of disorders that could impair the health of crewmembers mandates the analysis of etiological factors that could be present during selection and training, or those that could lead to illness during or after flight. Useful data for such analyses can be obtained in several ways, including assessments of disease incidence during flights, disease incidence over the course of careers or lifespans, or disease incidence in groups exposed to aspects of the space flight environment on Earth (e.g., confinement in closed spaces, bed rest, acceleration, or others). This chapter presents a brief overview of which kinds of factors could be expected to contribute to functional disorders in flight and in other analogous situations, goes on to describe actual episodes of in-flight diseases and injuries, and finally underscores the importance of a comprehensive set of countermeasures in preventing—or at least minimizing the complications of—in-flight medical problems.

I. A Theoretical Assessment of Potential Contributors to Functional Impairment in Space Flight

A. Existing Disorders

Careful selection procedures, identification and remediation of minor health problems found in cosmonaut candidates before flight, and preventive training all serve to optimize the health of cosmonauts and astronauts before, during, and after flight[5,6] (see Chapters 1 and 2). Nonetheless, even the most sophisticated techniques cannot unfailingly detect every specific function of every organ and system, nor can such techniques predict every potential response to the complex space flight environment.

In space, latent insufficiencies of some organs that normally would go unnoticed on Earth because of compensatory mechanisms could respond to the stresses engendered by space flight by producing acute disorders. Health problems caused by exposure to infectious agents, especially during the preflight period, also are a consideration, even for otherwise healthy individuals. Moreover, the medical selection standards for some categories of crewmember (e.g., cosmonaut-researchers) are less stringent than those for pilots or flight engineers, so that individuals with particularly valuable expertise can be allowed to fly even if they have minor health problems.[6] All of these factors are associated with some risk of developing functional and somatic disorders during flight, whether arising from latent or undiagnosed health problems or from exposure to adverse space flight factors.

B. Space Flight Factors

The numerous, unusual factors to which crews are exposed in space (see Fig. 1) are equally important from the standpoint of assessing the risk of organic or functional disease. Since the mechanisms and effects of these factors are reviewed extensively in Volumes II and III of the *Space Biology and Medicine* series, we only briefly review here those features that are clinically significant and require the use of therapeutic or prophylactic measures.

1. Physical Factors

Weightlessness. The state of being weightless is probably the most important of the space flight factors, since true weightlessness cannot be achieved on Earth. In microgravity, the human skeleton is no longer exposed to the accustomed mechanical stresses, and thus functional loading on body systems is reduced.[7–9] Musculoskeletal unloading and changes in afferent stimulation, in combination with body-fluid redistribution, cause numerous secondary responses that can interfere with physiological equilibrium and functioning in flight.[10]

Half or more of all crewmembers exhibit motor, sensory-motor, and autonomic disturbances early during adaptation to space flight.[11] These disturbances, which diminish gradually over the course of the flight, include impaired orientation; illusions of falling, somersaulting, body rotation and spatial displacement of observed objects; emotional reactions; impaired motor coordination; and space motion sickness.[4,8,12,13] (Detailed discussions of these topics can be found in Chapters 7, 22, and 23 of Volume III.)

Sensations of blood flowing toward the head, nasal congestion, and facial edema, which also occur early in the adaptation process, are associated with the redistribution of fluids.[7–9] These transient signs and symptoms disappear during the first few days of flight, and do not seem to affect crew performance.[4,12] Other manifestations of fluid redistribution that do affect performance are its effects on the cardiovascular system. Decreases in circulating blood volume, changes in vascular tonus, increases in heart rate, and frequently decreases in blood pressure and cardiac stroke volume[7,8,14–16] all represent a new level of circulatory functioning that is established in space. Functional disturbances in cardiac processes have been expressed as arrhythmias and changes in cardiac conductivity; as metabolic or cardiogenic changes in the ventricular-terminal phase of the electrocardiogram (ECG); and as changes in resting heart rate and blood pressure. Of these possible disturbances, the most likely are cardiac arrhythmias and metabolic changes in the ventricular-terminal phase of the ECG complex, which may result from complex flight-induced disturbances of the neurohumoral regulation of cardiac function, prolonged psychological and emotional stress, and shifts in electrolyte balance, particularly hypokalemia.

Changes in the functional activity of the central nervous system (CNS) in response to weightlessness and other space flight factors may foster the development of neurasthenia (psychosomatic debility) and autonomic and vascular disturbances.[12,17] Debility, changes in immunological status, and metabolic disruptions during long space flights may lead to the development of various functional and organic disorders, particularly acute inflammatory and allergic conditions.[1,2,11,12,17,18]

Changes in calcium metabolism, decreases in bone mineralization, and increased calcium excretion diminish the mechanical strength of bone structures and increase the risk of serious traumatic damage to the skeleton and teeth. Calciuria may trigger the development of kidney stones.[10,19]

In summary, long exposure of humans to microgravity is associated with the risk of developing a broad spectrum of functional and organic disturbances, the most likely of which seem to be functional disorders of the cardiovascular and nervous system, inflammatory disorders of various etiologies, and pathological states associated with disruptions in calcium metabolism.

Accelerations. Linear acceleration during insertion into orbit and return to Earth can be accompanied by sensations of general heaviness; dyspnea; pain in the chest or abdomen; disruptions in respiration, cardiac activity, and visual function; and loss of consciousness.[10]

Impact accelerations can occur as descent modules land or spacecraft dock with one another.[10,20] High-impact accelerations during spacecraft launch and landing can cause serious injuries, especially to musculoskeletal system, and pose a high risk of internal injuries such as penetrating wounds of the thoracic and abdominal cavities with rupture of viscera and blood vessels.[21]

2. Environmental Factors

Aspects of the spacecraft environment that affect habitability are reviewed at length in Volume II of the *Space Biology and Medicine* series. The following paragraphs constitute brief summations of pertinent issues.

Noise. Sources of noise on spacecraft include scientific equipment, ventilation systems, motors of life-support system equipment, and the periodic activation of the station’s attitude-control engines. Emergency alarms and warning signals produce loud noises for brief periods. Prolonged exposure to uncomfortable acoustic environments can lead to fatigue of the acoustic system, and at worst can produce hearing loss.

Vibration. Vibration generated by technological equipment, ventilators, and life-support systems seldom reaches levels of physiological significance,[10] and probably is not a cause of disease in flight.

Atmospheric pressure. Changes in barometric pressure become clinically significant when rapid pressure loss produces symptoms of dysbarism,[10] including aerotitis media, barosinusitis, and altitude meteorism. The rapid drop in barometric pressure resulting from depressurization of emergency vehicles or spacesuits is extremely hazardous, especially if the decompression is explosive.[10] Organs that contain gas, especially the lungs and gastrointestinal tract, expand suddenly during explosive decompression, producing painful pressure on the organ walls as well as vasovagal syncope.[23] In the vacuum created by emergency depressurization of a spacecraft, explosive decompression is accompanied by acute hypoxia, which can be lethal.[10,22] Another hazard associated with sudden loss of barometric pressure is the powerful air currents generated by explosive decompression, which cause objects to fly around at great speed, possibly inflicting severe mechanical injuries.[22]

Rapid drops in barometric pressure during flight also can cause decompression sickness, which in space might be expected to be more severe than usual since weightlessness reduces physiological resistance to various adverse effects. Although the likelihood of sharp drops in barometric pressure, and the disorders associated with them, is relatively small, this hazard still must be considered, particularly on flights that involve extravehicular activities (EVA).

Atmospheric composition. Malfunctioning life-support subsystems certainly can affect the composition of the cabin air. Insufficient oxygen produces health disturbances that range from moderate symptoms of hypoxia (irritability, headache, insomnia, and decreased performance) to life-threatening conditions and death. Malfunctions in the air-regeneration subsystem can cause unacceptably high amounts of CO_2 to accumulate in inhabited spacecraft modules. Depending on the amount and the duration of exposure, adverse effects from CO_2 can include decrements in performance, feelings of heaviness in the head, headache, dyspnea, and tachycardia. High levels of CO_2 in the atmosphere can depress the CNS to the point of syncope or death.

Malfunctions in life-support subsystems also can increase the risk of toxic hazards in the cabin atmosphere through the accumulation of various gaseous contaminants that would be released in open systems. Another issue is the potential leakage of toxic substances from onboard engineering and technological systems.[23,24] Increased levels of toxic substances in the cabin atmosphere could lead to poisoning, with corresponding clinical symptoms. The severity of the potential damage is associated with the crewmember's initial physiological status, which probably would be weakened by exposure to weightlessness. When overall tolerance to adverse factors is eroded, even a relatively mild exposure to toxins is serious. Although poisoning episodes arising from changes in cabin atmosphere are unlikely, the effects of such hazards can be serious enough to terminate a flight unless the situation can be rectified.

Temperature and humidity. Malfunctions in spacecraft or spacesuit thermoregulation subsystems can expose crewmembers to excessively low or high temperatures. Moderate decreases in ambient temperature, especially if humidity is elevated, can cause chilling. Under space flight conditions, the discomfort and other symptoms associated with general or regional chilling are likely to be severe, with muscular activity restricted and regional circulation affected. Another aspect of this issue is local chilling of small areas of the skin by air currents created by the ventilation system, which can cause colds or inflammation of the muscles or peripheral nerves. Severe frostbite can result from partial depressurization of EVA suits during operations in outer space. On the other hand, prolonged exposure to significantly elevated ambient temperatures can lead to systemic overheating. Violations of safety regulations during repair and maintenance work or technological operations, especially those that involve fires, can cause burns of varying severity.

Mechanical injuries/impacts. Equipment and tools with sharp edges or moving parts, and the presence of fragments of broken equipment floating in the cabin, pose the risk of injuries ranging from minor cuts on the skin or mucous membranes to serious traumas to the musculoskeletal system. Particles of dust, glass, or food are hazardous to the skin, eyes, and lining of the upper respiratory tract. Although severe mechanical or thermal injuries are unlikely during flight, such injuries, if they were to occur, could jeopardize the health and even the life of crewmembers.

Ionizing radiation. The present system of ensuring radiation safety during orbital space flights effectively protects crewmembers from exposure to harmful ionizing radiation. However, failure of radioprotective measures, particularly during interplanetary space travel, could result in radiation exposures of varying severity. (These issues are discussed at length in Volume III, Chapter 17.)

Biological factors. Biological pathogens of interest include bacteria, pathogenic fungi, protozoa, and viruses that contaminate the spacecraft during preparations before flight, or are released into the cabin atmosphere during flight by crewmembers through the skin, nose, and mouth.[10] Confining humans for long periods in pressurized, relatively small environments leads to elevated levels of microorganisms in the environment, and shifts the normal composition of species such that the proportion of pathogenic microbes increases.[25] These changes, combined with overall reductions in physiological resistance and immune function and concomitant increases in sensitivity to microorganisms, may promote acute inflammatory and infectious diseases. Molds and yeasts in spacecraft can induce mycotoxicosis as well as allergic reactions.[26]

Nutritional factors also constitute biological risk factors for disease. Prolonged consumption of canned foods, along with unfavorable changes in the neurohumoral regulation of digestive functions and activation of opportunistic microorganisms, can cause various digestive disorders and inflammation of the gastrointestinal tract.[3] Disruption of normal intestinal microbiocenosis and dysbacteriosis can induce digestive pathology.[27] Activation of opportunistic microorganisms, aggravated by disruptions in bile metabolism and perhaps in bile ducts,[28] could lead to acute cholecystitis or gallstones.

Chemical hazards. Crews can be exposed to toxic hazards if cycles of technological processes are interrupted, if scientific equipment containing irritating chemicals becomes depressurized, or if propellant leaks into the living quarters. The resultant clinical picture may include both local symptoms at the point of contact (chemical burns of the skin or mucous membranes) and systemic damage such as impairment of the CNS and cardiovascular system and renal and liver failure.

3. Psychological Factors

Logically, crewmembers' psychological and emotional condition would be affected by the demanding and frequently monotonous work schedules, by living in isolated, confined environments in close contact with a small group of people, by periodic stressful situations, by awareness of danger, and other factors.[18] Thus, crewmembers can be expected to exhibit fatigue, irritability, mood shifts, sleep disorders, diminished performance and motivation to meet program objectives, and psychophysiological disorders, primarily "vascular autonomic dystonia."[29]

Because psychological stress engendered by working conditions can lead to changes in CNS, cardiovascular, or digestive-system function (among others), space flight conditions may induce pathologies such as gastric or duodenal ulcers and high blood pressure.[3] The risk of such diseases is greater in the presence of latent problems in the cardiovascular, gastrointestinal, or regulatory neurohumoral systems.

C. Disease Incidence in Comparable Populations

Results from longitudinal studies of disease incidence in the general population and in groups of individuals who share some similarities with space crewmembers (e.g., military pilots, crews in remote outposts or submarines, or subjects in space flight simulations)[1,2,30] can be useful in predicting disease incidence in space. For example, the most common illnesses among 25- to 32-year-olds in the general population are respiratory diseases, injuries, digestive and cardiovascular disorders, infectious and parasitic diseases, disorders of the nervous system and sensory organs, and urogenital diseases.[31] Military pilots, on the other hand, typically have high rates of nervous system disorders, psychophysiological diseases, hearing loss, kidney stones, and immunological deficiencies.[32,33] At least one report[34] suggests that the incidence of myocardial ischemia (the primary medical cause of pilot disqualification) in military pilots does not exceed that found in the general population. Hypertension is another common reason for disqualification, but its incidence is lower in pilots than in the general population. Apart from diseases of the cardiovascular system, disorders of the nervous and musculoskeletal systems are common in flight personnel.

The incidence of malignant tumors in pilots is analogous to that of the general population.[34] However, disease incidence in submarine crews (whose living and working conditions somewhat resemble those of space crews) suggests that malignant tumors should be added to the list of potential space flight diseases. The growth characteristics of neoplasms are such that a tumor might not be detected before flight but could well become clinical during flight; one group calculated that 12.5% of fast-growing tumors that are not detected before flight would become evident from a clinical standpoint during a 90-day flight.[35]

Longitudinal studies of polar crews working in the Arctic and Antarctic show that the most typical illnesses are respiratory diseases of viral etiology with moderate clinical symptoms.[30] Finally, numerous investigations involving simulations of various space flight factors have demonstrated that the functional changes observed in the cardiovascular, nervous, and musculoskeletal systems and in immunological and metabolic processes during flight also are present in simulations.[36–39]

D. Disorders That Could Be Expected in Space Flight

In order to predict which diseases or disorders are most likely during space flights, we assessed information on initial cosmonaut status, possible adverse effects of space flight factors, results from longitudinal studies of the general population, and results from studies of small groups working under conditions similar in some ways to those in space. The results of this assessment are listed in Table 1, and are reviewed briefly below.

The diseases and injuries most likely to occur involve the systems and organs most vulnerable to space flight factors, i.e., the central nervous, cardiovascular, and musculoskeletal systems; and the integument and mucous membranes. Inflammatory conditions are fostered by reduced immunological resistance and the increased virulence of microorganisms. U.S. and West European scientists have reached similar conclusions.[31,35]

The predicted incidence of other pathological disorders such as cancer and infectious diseases is much lower, because such disorders typically occur as a result of errors in the selection, training, or quarantine procedures before flight. The risks of severe traumas or thermal injuries are equally low.[21] However, the occurrence of these disorders could have critical, even life-threatening, implications. Dangers associated with the development of other diseases that are relatively unlikely but could have severe medical impact must be considered significant.[31,35]

The likelihood of adverse outcomes in a life-threatening situation is elevated during space flight because qualified medical personnel and the medical technology needed to resuscitate and treat the patient may not be available on space stations. In our opinion, all life-threatening situations that might occur during flight should be classified as a single group of diseases and injuries, because these kinds of conditions demand the same tactical procedures, i.e., immediate first aid (stop bleeding, immobilize injured limbs, etc.) followed by the decision to return the injured crewmember to Earth either immediately or after a 1- or 2-day delay, during which vital functions can be stabilized and the risk of death during descent reduced.

The remainder of in-flight diseases and injuries can be grouped into two categories. The first, more serious group includes diseases and injuries having marked clinical symptoms or those that can be diagnosed by objective methods, e.g., severe disruptions of cardiac rhythm and conduction, hypertension, and several inflammatory diseases that require consultation with a ground-based medical-support team to determine treatment. Occasionally, such diseases will necessitate limiting the afflicted individual’s professional activities or terminating the flight. The second category of disorders includes those diseases or injuries having mild clinical symptoms that disappear on their own or after minimal medical treatment. They do not always require medical consultation with a ground-based medical-support team, nor do they significantly affect the health and performance of cosmonauts. Minor skin injuries, such as abrasions, scratches, cuts, and superficial burns covering a small area, are included in this category.

In summary, both ours and others’ theoretical analyses of potential diseases and injuries in space suggest that medical-support programs consider not only the structure of potential functional and organic disorders, but also their likelihood of incidence and their effect on crewmember health and performance.

II. Actual Episodes of In-Flight Diseases and Injuries

Despite much progress in preventing diseases and injuries on crewed space flights, crewmembers inevitably will develop some functional or organic disorders during flight. Experience suggests that these disorders will be expressed by a wide range of symptoms.[4,12,40,41]

Episodes of arrhythmia and inflammations of the ear, nose, and throat were present during the first Soviet space flights.[1] Diseases and injuries present during early U.S. missions are shown in Table 2.[2,41] Most have been comparatively minor, limited to irritations of the upper respiratory tract, skin, and eyes. ECG changes of note during the Apollo, Skylab, and Shuttle missions were mostly arrhythmias, including multiple and grouped extrasystoles, and one brief episode of bigeminy.[42] Analogous cardiac dysrhythmias, transient changes in atrioventricular and intraventricular conduction, and changes in ECG waveforms were noted for Soviet cosmonauts during Voskhod, Soyuz, and Salyut-5 missions.[43]

Thirteen of the cosmonauts who flew between 1964 through 1985 exhibited various types of extrasystole during flight.[44] The onset of arrhythmia frequently coincided with (and could be due to) marked emotional stress during ascent of the spacecraft and EVAs. However, many instances of cardiac-rhythm disturbances were reported at rest during scheduled ECG monitoring. Extrasystole at rest neither produces subjective symptoms nor affects cosmonaut performance, and is considered a functional disorder.

The amplitude of the QRS complex and that of other ECG waves frequently have been diminished during long flights. Moderate decreases in the T-waves on ECGs, for example, were apparent after 2 or 3 months of flight. ECGs recorded from crews aboard Salyut-7 revealed singular infrequent monotopic extrasystole, some retardation of atrioventricular conductivity, and minor decreases in the QRS and T waves. One cardiogram exhibited a two-phase and two-peak repolarization wave.[15,45] Disturbances of the terminal portion of the ventricular wave seem to be the most obvious ECG changes during long space flights.[14]

In addition to these cardiovascular signs, Soviet crewmembers who remained in space for less than 2 months reported experiencing sleep disorders, headaches, minor skin injuries, and gastrointestinal disturbances. Reports during longer flights on the Salyut-6 station also cited headaches, sleep disturbances, and minor skin injuries as well as otitis, colds, and dental problems. Of the functional and organic disorders noted in the Salyut-7/Soyuz-T crews, two episodes are of particular interest—renal colic and a urological problem accompanied by neurasthenic responses. (These incidents are discussed in detail below.) Less serious disorders included thoracic myalgia, symptoms of seborrheic dermatitis, lumbar ischialgia, rhinitis, sleep disturbances, minor burns, eye irritation (from particles of ion-exchange resin), erythema due to ultraviolet radiation, and muscle pain after EVA.

The incidence of disease and injury in cosmonauts and astronauts who flew before 1983 is summarized in Table 3.[40] Disease and injury episodes for 14 members of 6 Mir crews are listed in Table 4. The most common complaints in the latter group were sleep disorders and fatigue, followed by muscle soreness after EVAs, various dysrhythmias, and minor skin injuries and irritation. Members of prime crews, who remained aboard the station for long periods, suffered more of the symptoms listed than did visitors.

Medical problems aboard Mir generally have been similar to those experienced aboard U.S. missions (compare Tables 2 and 4). Mir cosmonauts, however, have tended to experience more cardiovascular symptoms (arrhythmias and changes in the late ventricular portion of the ECG) and CNS symptoms (sleep disorders and fatigue), most of which developed after 2 or 3 months in flight. Moreover, differences in disease incidence may reflect differences in features of the various programs and in the specific tasks to be performed by the crewmembers of those programs. As an example, strenuous exertion by Soviet crewmembers during EVA may account for the high number of complaints of fatigue and muscle pain afterward.

Any interpretation of disease incidence during flight should include the realization that data do not fully reveal the nature and specifics of medical situations. Mere identification of a functional or organic disorder does not provide sufficient information about its severity or its effect on the affected crewmember’s performance. This caveat is illustrated vividly by three medical incidents that arose during Salyut-7/Soyuz-T and Mir missions.

In the first incident, a cosmonaut developed acute pain in the left abdomen during the sixth month of flight. After several unsuccessful attempts to control the pain with drugs, the cosmonaut sought advice from the medical support team during a scheduled medical conference. The team diagnosed the condition as renal colic and prescribed analgesics and spasmolytics, to be taken both parenterally and orally. This treatment alleviated the pain within a few hours, and all signs of the condition had disappeared by the fourth day thereafter. This cosmonaut was able to resume exercise on the fifth day after beginning treatment, and resumed a standard, unrestricted work schedule the day afterward.

Another incident involved symptoms that were experienced for 14 days before being reported, as well as unsuccessful attempts at self-treatment. The medical-support team diagnosed an acute urological disorder, aggravated by neurasthenic symptoms, and prescribed anti-inflammatory, sedative, and spasmolytic drugs, restricted motor activity, and release from occupational duties. Some improvement of the organic disorder was noted during the first 2 weeks of treatment, but neurasthenic symptoms persisted. When subsequent subjective reports indicated the potential for severe complications, the decision was made to examine the affected cosmonaut in a hospital. Prophylactic and therapeutic measures were implemented to prepare the ill cosmonaut for descent, and the mission was terminated. Postflight examination revealed acute inflammation of the urogenital system, aggravated by neurasthenia.

Another complex medical situation occurred during the third month of a Mir mission, when a cosmonaut displayed supraventricular extrasystole with a trigeminal-pulse episode[4] during an EVA. This dysrhythmia was not accompanied by subjective symptoms, disappeared on its own, and was regarded by the medical support specialists as a response to the emotional and physical stress associated with the EVA, which was quite strenuous. Similar atrial extrasystoles, accompanied by marked tachycardia, appeared later during an exercise test. Prescribed therapy included adjusting that cosmonaut’s exercise schedule, monitoring the work-rest schedule, and using drugs to improve myocardial metabolism. These countermeasures stabilized the cardiac rhythm and prevented the onset of arrhythmia. Nevertheless, approximately 2 months after the first cardiac disturbance, ECG changes that indicated supraventricular extrasystole appeared during scheduled exercise tests. The dynamics of the changes suggested that the cardiac arrhythmia could persist or worsen, with potentially serious consequences to the cosmonaut's health and performance. Because the planned flight duration was 11 months, this cosmonaut was replaced during the next visit to Mir by a visiting crewmember. This solution precluded the possibility of adverse changes progressing, safeguarded the crewmember’s health, and ultimately ensured successful completion of the flight program.

In summary, despite stringent standards for selecting and training cosmonauts and astronauts, various diseases and injuries can and have developed during space flight. Mild disorders with minimal effects on health and performance are most common. Less frequent are serious medical episodes that can jeopardize the health of the cosmonauts as well as completion of the mission.

III. Major Objectives of Space Flight Countermeasures

A system of countermeasures has been devised in the Russian space program to stabilize crew health, to maximize crew performance, and to avoid—or minimize complications from—diseases and injuries during flight. Use of these countermeasures in the early phases of selection and preflight training allows selection of healthy candidates who can tolerate exposure to space flight factors and are sufficiently fit to accomplish specific mission objectives.[6] During preflight medical examinations, crewmembers with minor health abnormalities undergo treatment, including surgery if necessary, to prevent complications during flight. However, experience has shown that space flight factors can lead to clinical manifestations of latent disorders that were not detected during the selection process. In this context, further development of crew-selection procedures and state-of-the-art medical examinations, along with consistent improvement of the entire preflight training complex, are crucial.

A clearer understanding of latent disorders in otherwise healthy individuals is useful both for predicting potential flight disorders and for outlining therapeutic countermeasures. A candidate with latent or subclinical cardiovascular problems, for example, could be treated with drugs specifically targeted toward that system as a way of enhancing the effects of the regular course of countermeasures for that individual.

Training crewmembers in how to render medical aid and familiarizing them with the full range of medical capabilities aboard spacecraft also are important elements of preflight training. Equally important is the need to minimize the risk of adverse or allergic reactions to administered drugs. To this end, each individual is tested for sensitivity to all of the drugs included in the medical flight kit as part of the training program.

Preventing exposure to infectious disease before flight, particularly during prelaunch training, is essential in preventing in-flight illness. Health stabilization rules must be strictly observed and contacts limited between crewmembers and outsiders. Individuals in contact with crewmembers must be examined thoroughly and monitored continuously for medical problems. This issue is critical for Russian crewmembers, since their prelaunch preparations often take place in regions in which illness is prevalent.

Clearly, in-flight diseases or injuries cannot be prevented by selection or training programs alone; thus, a comprehensive set of countermeasures, tailored to each individual, are used. Countermeasures used to prevent disease include ways of alleviating or eliminating adverse effects of the flight itself, the artificial living environment, and psychological factors. For example, one countermeasure used to overcome adverse microgravity effects is exercise. Uncomfortable conditions with regard to barometric pressure, temperature, humidity, and atmospheric composition not only aggravate the unfavorable consequences of microgravity, but also can cause other diseases and injuries. Attention to cabin sanitation and hygiene can improve both the cabin environment and the crew's nonspecific resistance to diseases and injuries. Another approach is to offset adverse psychological factors through appropriate work-rest schedules and psychological support measures. In this way, optimal performance levels can be sustained and the risks of functional and organic disturbances of the CNS and psychophysiological diseases can be reduced.

Medical countermeasures for disorders that may develop during long space flights include continuous medical monitoring, which allows early symptoms of functional and organic disorders to be identified quickly; and the prophylactic administration of drugs that favorably affect myocardial metabolism, promote cerebral blood flow, prevent hypoxic effects, and normalize intestinal microflora.

In our opinion, the concept of preventive countermeasures also encompasses appropriate treatment of diseases or injuries. Prompt, appropriate medical intervention not only corrects pathological conditions but prevents severe complications. With regard to medical treatment during flight, one should bear in mind the fact that physiological adaptation to space flight conditions may change the normal response to drugs, thus complicating therapeutic and prophylactic regimens. This caveat has been confirmed through experience in the U.S.[46] and in Russia, where changes have been noted in pharmacokinetic and pharmacodynamic characteristics of antiarrhythmic drugs.

The issue of how to prevent severe traumas, toxic effects, and other life-threatening conditions is extremely complex. The likelihood of such occurrences is largely a function of specific work operations performed by the crewmember, the reliability of technological support, and the likelihood of emergencies. Therefore, preventing damage from such problems constitutes an engineering as well as a medical problem.

In summary, the prevention of diseases, disorders, and injuries during space flight involves a comprehensive system with which to stabilize the health of crewmembers and to promote high performance during all mission phases. This comprehensive system is continually being improved and updated as experience is gained with longer and more complex missions.

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Table 1 Diseases, disorders, and injuries that could be expected during space flight

Central and peripheral nervous system
- Concussion, spinal cord injury
- Neurasthenia, autonomic vascular dystonia
- Neuralgia, neuritis, radiculitis
- Psychophysiological or emotional disorders

Cardiovascular system
- Stenocardia, myocardial infarction
- Cardiac arrhythmias and conduction dysfunctions
- Hyper- or hypotension
- Changes in myocardial bioelectric activity
- Headward fluid redistribution syndrome

Respiratory system
- Bronchitis, pneumonia

Digestive system
- Acute gastritis, enterocolitis, colitis
- Gastric and duodenal ulcers
- Acute appendicitis
- Acute cholecystitis
- Gallstones
- Meteorism, hemorrhoids, constipation, diarrhea
- Dysbacteriosis

Genitourinary system
- Urethritis, cystitis
- Pyelocystitis or prostatitis
- Kidney stones

Integument
- Dermatitis, furuncles, carbuncles, pyoderma
- Slight injuries, bruises, abrasions, cuts, scratches, minor burns

Ear, nose, throat, and upper respiratory tract
- Rhinitis, sinusitis, tonsillitis
- Pharyngitis, laryngitis, tracheitis, otitis
- Traumatic injury

Eyes
- Conjunctivitis, keratitis
- Blepharitis, sties
- Foreign objects in the eye
- Penetrating eye injury

Mouth and teeth
- Stomatitis, gingivitis
- Caries, pulpitis
- Fractures of the jaw
- Dislocation of the lower jaw

Musculoskeletal system
- Contusions, dislocations, fractures, torn ligaments
- Arthritis, bursitis, myalgia, myositis, etc.

Other
- Allergic reactions and conditions
- Anemia
- Cancers
- Infectious diseases
- Shock (trauma, burn, anaphylactic, cardiogenic, hemorrhagic)
- Coma due to concussion
- Hypoxia, asphyxia, etc.
- Poisoning

Space environmental factors
- Aerotitis media, barosinusitis, subcutaneous emphysema, decompression sickness, explosive decompression
- Conditions caused by heat, toxins, and radiation
- Damage from ultraviolet irradiation, etc.

Table 2 Incidence of disease (1961–1982) in U.S. space crewmembers [Refs. 2, 42]

Disease or disorder	Number of incidents	Period of occurrence
Diseases of the upper respiratory tract	8	before and during flight
Gastrointestinal infections caused by viruses	3	before and during flight
Eye-skin irritation (fiberglass)	3	during flight
Overexertion	3	during flight
Toxic pneumonia	3	upon entering atmosphere
Dysbarism	2	during flight
Skin infection	2	during flight
Contact dermatitis	2	during flight
Arrhythmia	2	during flight
Arrhythmia	2	after flight
Injury of soft tissue of the head	1	at landing
Urinary tract infection	1	during flight
Serous otitis	1	during flight
Eye and finger injury	1	during flight
Sty	1	during flight
Abscess	1	during flight
Muscle strain, shoulder	1	after flight
Rash	1	during flight

Does not include isolated cases of back pain, especially in the lower back, or motion sickness

Table 3 Diseases and disorders observed in cosmonauts and astronauts during missions before 1983 [Ref. 41]

Disease/Disorder	% of total no. of sick crewmembers	Incidence rate, crewmembers/year
Psychological	6.56	1.315
Neuroasthenic syndrome	6.56	1.315
Nervous system and sense organs	0.41	0.126
Barotitis media	0.41	0.126
Circulatory system	3.32	0.971
Cardiac arrhythmia	2.91	0.845
Hemorrhoids	0.41	0.126
Respiratory system	3.32	0.971
Rhinitis	2.91	0.845
Pharyngitis	0.41	0.126
Digestive organs	9.05	2.780
Pulpitis, gingivitis and others	7.81	2.402
Enteritis	0.41	0.126
Constipation	0.83	0.252
Genitourinary system	1.25	0.344
Urinary tract infection	1.25	0.344
Skin and subcutaneous tissue	14.46	4.379
Paronychia, subunguial hematoma	2.91	0.845
Abscesses	0.41	0.126
Dermatitis	10.31	3.156
Seborrhea	0.83	0.252
Musculoskeletal system & connective tissue	2.50	0.757
Myositis	2.50	0.757
Symptoms and conditions	15.22	4.622
Meteorism	1.66	0.505
Pains in the area of the:		
heart	1.25	0.344
head	8.16	2.525
ear	0.83	0.252
leg muscles	0.41	0.126
lower back	2.91	0.845
Accidents, poisoning, and injuries	43.81	13.355
Superficial injuries	12.05	3.661
Contusions and strains	10.31	3.156
Burns	0.41	0.126
Eye injuries	0.41	0.126
Eye irritation	3.75	1.136
Dehydration	0.83	0.252
Motion sickness	16.05	5.150

Table 4 Diseases and injuries noted in 14 Mir cosmonauts

Diseases and injuries	Number of observations
Cardiac arrhythmias	8
Insomnia or fatigue	7
Fatigue and muscle pain after EVA	7
Heaviness in the head, headaches	7
Minor skin injuries	7
Skin irritation at electrode-attachment sites	5
Conjunctival erythema (from UV radiation)	3
Muscle strain	2
Changes in the terminal ventricular EKG	2
Conjunctivitis	2
Minor trauma to the ocular mucous membrane	2
Superficial burns	1
Changes in gastrointestinal microflora	1
Dental caries	1
Laryngitis	1
Constipation	1
Dry skin on hands	1
Acute respiratory disease	1
Changes in atrioventricular conduction	1

Figure Caption

Fig. 1 Space flight factors that can promote functional and organic disorders.

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Chapter 6

Principles of Diagnosis and Treatment in Space Flight

Michael R. Barratt

Without fantasy, scientific work becomes a pile of facts and deductions, empty, cachectic, and often sterile.
-- Konstantin Eduardovich Tsiolkovsky

I. Introduction: Space Medicine in Context

Humans can rarely resist a frontier. Throughout history, we have explored, exploited, and even colonized the habitats at hand, from deserts and mountains to polar regions and oceans. The powered conquest of the air during this century, like other exploration efforts before it, gave birth to another new field of medicine. Aviation medicine, like aerospace medicine, first engendered a new science that was needed to establish the necessary understanding for applying medical support. The same technologies and motivations underlying aviation have led to the beginnings of crewed space exploration, compelling us to redefine again what we know of physiology and medicine. To date, only a few hundred highly selected individuals have journeyed outside Earth's atmosphere. Every crewed space mission continues to generate new information on how humans adapt and what type of medical problems they face.

Although space physiology and medicine are closely interrelated, they do constitute distinct entities. Both involve an understanding of how humans adapt to aspects of the space environment, particularly weightlessness. Space medicine is oriented toward *medical problems* encountered in space flight. Its primary outlook is *operational*, and its focus is on the problems and peculiarities of space flight from the standpoint of their *influence on missions.* Space physiology, on the other hand, focuses on *characterizing the overall response* of the human body to the space environment, especially the response to weightlessness. The primary outlook of space physiology is *investigational*, and it focuses on the problems and peculiarities of space flight from the standpoint of *scientific return*. Space physiology provides a fundamental knowledge base from which to predict further effects, build countermeasures, and, of course, to provide a basis of understanding for space medicine.

As is true for any other Earth-based medical specialty, space medicine involves both “proactive” (preventive) and “reactive” (treatment-based) care of human beings in order to optimize their physical, physiological, and psychological well-being within the constraints of an extreme and unique environment. Practitioners of operational space medicine must know both broad aspects of life sciences and standard medical methods. Because of the unique nature of space flight, the link between discoveries in basic physiology and their application to medical practice is short. The principles and philosophy of in-flight diagnosis and treatment distill what is known of space life sciences and medicine, and translate that information into caring for the patient.

II. Approaches to Medical Problems in Space flight

A. Mission-Oriented Considerations

In addition to having undesirable effects for the afflicted crewmember, illness or injury during space flight can profoundly affect mission success and timelines, and can place other crewmembers at risk as well. The primary goal of operational space medicine is to maintain crew health for the success of the program objectives; otherwise stated, supporting the individual also supports the mission. An on-site medical system therefore is analogous to an occupational medical facility that serves terrestrial industry or military deployment. The severe constraints on weight, volume, and replenishment of materials aboard spacecraft mandate that the design and development of a supporting medical infrastructure for space flight must adhere closely to overall mission objectives. Central to this requirement is the determination of accepted risk, which is discussed later in this chapter.

NASA's philosophy for on-site medical facilities centers on three general goals: to provide medical treatment to ill or injured crewmembers in flight; to prevent medical evacuations if possible; and to increase the likelihood of success if medical evacuation is necessary. Within this framework are three basic approaches to in-flight illness or injury:

(1) *Maintain a low level of medical care and accept a relatively high risk from environmental and occupational conditions.* In this type of approach, used in the early missions of the Vostok, Soyuz, Mercury, Gemini, and Apollo programs, medical capability might consist only of a basic first-aid kit because of the extreme limitations on stowage.

(2) *Maintain an intermediate level of medical care, targeted toward the most likely medical problems, with the ability for transporting ill or injured crewmember(s) to ground facilities if their medical needs exceed the abilities of the on-site facility.* Begun with the U.S. Skylab project and continuing with the Russian Salyut and Mir space station programs, this option has been judged the most reasonable for extended stays in low Earth orbit (LEO). The same philosophy, adjusted for the relative brevity of the missions, is used in the U.S. Space Shuttle program.

(3) *Maintain a maximal level of medical capability on site and a correspondingly lower risk of mission impact from medical events.* Medical capability under this approach might include intensive care facilities and surgical and imaging equipment comparable to that of a clinical emergency department. The substantial costs involved in this approach dictate that it be reserved for missions in which medical return is not feasible.

Each of these general approaches can be appropriate within a given mission profile, and each determines the extent of the medical-support infrastructure that is needed. The first step in designing an on-site medical facility is to identify the necessary medical capabilities by using estimates of which medical problems are most likely to occur. The next step is to determine which hardware and skills will be needed by the onboard Crew Medical Officers (CMO), and to make sure that the tools and the skills needed to use those tools are well matched. On the one hand, if the sophistication of the medical diagnostic and therapeutic equipment exceeds the ability of the CMO to use it, then this situation represents, at best, an unacceptable cost for launch and stowage and, at worst, could harm a crewmember. On the other hand, the skills of a highly trained physician would be wasted if that person were to be equipped only with a basic first-aid kit. The capability for continuous, convenient emergency return also influences the design and content of medical systems, since such a capability would obviate the need for those medical supplies that support long-term patient care.

B. Defining the Risk of Medical Events

Efforts to predict which medical problems might occur during flight, and how often they occur, often involve studying “analog” populations that are similar to astronaut or cosmonaut crewmembers in age range, medical screening requirements, remoteness, and limitations on available medical resources. These populations include ground military personnel,[1] surface ship crews, submarine crews,[2,3] and Antarctic field-study teams.[4,5] Data from these populations have been analyzed and applied to medical risks associated with space flight.[1,6] The incidence of background disease such as coronary disease and gastrointestinal disorders in these populations is lower than that in the general population, as might be expected from extensive medical examinations and screening. A larger proportion of medical events are related to occupational risks associated with the work environment. One estimate of medical events for an LEO station, made from data from submarine, Antarctic, and military pilot populations,[7] suggested that minor medical problems that would require the help of a medical specialist, the use of a prescription medication, or both would take place at the rate of one to three incidents per person per year. The incidence of problems that would require hospitalization or being confined to bed ranged from 3–6% per person per year. Finally, the incidence of medical evacuation from remote sites with limited medical capability was calculated as 1.6% per person per year.

Studies such as these can help provide estimates on the incidence of general medical problems, but cannot account for specific risks unique to the space flight environment. Moreover, these groups are not entirely analogous to the astronaut and cosmonaut populations, both of which are highly screened for preexisting medical disorders and typically are free of many recognized health risk factors (e.g., tobacco use and sedentary lifestyles). On the other hand, space crewmembers may be much older during their respective missions than their analog-study counterparts. Despite the obvious value of their experience with specific missions and payloads, the relatively higher incidence of medical problems in older crewmembers[8] raises concern with regard to very long missions such as those to Mars. Longitudinal studies of the U.S. Astronaut Corps are underway to clarify the incidence of illness and injury from all causes; combining these data with better knowledge of the space flight environment is expected to produce more useful predictions.

Perhaps the most useful data are those gathered from prior experience with human space flight. Several minor medical problems have arisen in both the U.S. and Russian space programs, and usually have had minimal impact on mission timelines. Many of these problems were treated successfully by using the onboard medical facilities, and perhaps were prevented from becoming more serious. More serious manifestations of illness also have arisen that have prompted early return in at least two cosmonauts, one for persistent high fevers (later diagnosed as chronic prostatitis) and another for cardiac dysrhythmias. All of these events have influenced the selection of medical hardware items for subsequent programs. By the time projects like a crewed lunar base or a Mars mission become reality, the experience accrued from continued Mir and space station operations will have allowed the requirements for medical capabilities to be defined much more specifically.

Table 1 lists some of the medical events known to have occurred in crewed space flight. (Mishaps and catastrophic events, such as the Challenger launch-phase explosion and Soyuz-11 landing-phase decompression, are discussed elsewhere in this volume [e.g., Chapters 12 and 13].) The medical maxim that "common things occur commonly" also applies to space medicine; moreover, the more common events tend to be the least severe. This observation, culled from more than 35 years of crewed space flight, supports the premise that most on-orbit medical care will be directed toward routine disorders, such as minor respiratory infections, skin disorders, and minor trauma. Nevertheless, even minor medical problems obviously can have substantial impact, considering the cost and risks associated with maintaining an orbital work force.

C. Occupational Hazards of Space Flight

Many of the less common—yet potentially more severe—medical problems associated with space flight are related more directly to environmental and mission-specific factors. Some of the areas of occupational concern for space flight, those that uniquely define the medical milieu and those with which practitioners of space medicine must be well versed, are noted below.

- *Environmental extremes during launch and landing:* Aside from the obvious risk of mishap, these phases involve extremes of transient and sustained acceleration, vibration, and noise. Atmospheric entry and landing may involve physically strenuous activity by crewmembers who have become deconditioned from exposure to weightlessness.

- *Environmental extremes during flight:* These extremes can come from both natural sources (e.g., radiation) and from artificial sources (e.g., toxic agents used with payloads).

- *Physiological adaptation to weightlessness:* The term adaptation implies global physiological alterations, which primarily involve changes in neurovestibular, cardiovascular, hematological/immunological, musculoskeletal, endocrine, and fluid/electrolyte systems. Most contemporary research in space life sciences is concentrated in this area.

- *Life support systems and habitability:* Although atmospheric control, thermoregulation, and other aspects of the living environment are largely engineering issues, the medical support group must monitor and be prepared to respond to the failure of any component of the life support system as well as the physiological implications of that failure. A working knowledge of respirable gas mixtures and toxicology is essential in this regard.

- *Requirements for hygiene, sanitation, and nutrition:* Crew health depends greatly on capable systems, available supplies, and crew compliance.

- *Chronobiology and work/rest issues:* Accustomed circadian rhythms can become desynchronized in the absence of the standard cues of a normal solar day. Work and rest schedules must be artificially regulated and followed. The link between fatigue and industrial accidents is well established; circadian desynchrony affects many physiological systems, cognitive performance, and drug pharmacokinetics.

- *Psychosocial issues:* The chief factors that contribute to psychological stress include the rigorous training and work schedules, isolation and separation from family, close confinement, and continual close scrutiny of performance. Maintaining psychological well-being begins with crew selection, and includes such factors as crew compatibility, crew-ground interaction, crew autonomy, and family support (see Chapters 9 and 11). Problems in any of these areas can affect a mission every bit as severely as a pressure leak.

- *In-flight countermeasures:* Countermeasures can be physical means, such as exercise, lower body negative pressure (LBNP), loading suits, or artificial gravity; medical means, such as periodic health assessments, or pharmacological interventions; or psychological means, such as recreational diversions and family contacts. Although considering countermeasures as potential hazards may seem counterintuitive, some (e.g., LBNP) can produce or influence medical complications and thus require close monitoring. A balance must be struck between countermeasures, acceptable levels of health and fitness, and productive work, with the goal of optimizing productive work.

• *Extravehicular activities (EVA):* In many ways, EVAs represent the most extreme possible environment, since the separation—and safety margins—between the human and free space are at their smallest. Specific hazards associated with EVAs include decompression-related disorders, musculoskeletal strain, thermal stress and injury, and others as discussed below.

• *Planetary surface activities:* Human activities on planetary surfaces encompass concerns in all of the previous areas, plus implications for still more remote settings, which affect medical capability, available resources, communications, and possibility of medical return; for gravity-induced loading injuries, which equate to a greater possibility of musculoskeletal injuries than in microgravity; for the health and systems effects of surface dust; and for biological contamination from potential simple life forms.

In summary, the most effective specialists in space medicine will have an understanding of systems well beyond what is usually required of a clinician. Those specialists also must communicate well with others who are more directly concerned with each system (especially the life support systems), and should participate actively in all aspects of flight planning and monitoring.

D. Medical Support Infrastructure

As is true for any aspect of mission support, the end-to-end delivery of in-flight medical care involves a chain of coordinated links (Fig. 1). The onboard capability (consisting of medical hardware and an appropriately trained CMO) can be directed to some extent by a lead medical specialist on the ground. The lead ground specialist, preferably a flight surgeon trained in aerospace medicine and familiar with both the crew and the payloads, communicates in turn with paramedical personnel, such as specialists in radiation, psychology, and hygiene, and with biomedical engineers when consultations regarding medical hardware are needed. Outside medical specialists also can be consulted as needed. The flight surgeon serves as a single point of contact for flight management regarding medical issues, and provides coordinated information to the flight crew. This general scheme is used by both the U.S. and Russian space flight control centers, with some variations according to flight character and duration.

Each link in the medical chain must function well in order to provide effective support. The communications link is critical in the overall process. Communication problems such as low bandwidth, low coverage due to satellite unavailability or contingency, or delays due to far distant operations will require that the onboard capability be increased accordingly in order to protect some specified level of medical capability. The time needed for one-way signal transmission between Earth and, say, a Mars mission or outpost is not negligible; such a signal takes 3 minutes to reach the minimum distance of 56,000,000 km, and 22 minutes to reach the maximum distance of 398,000,000 km. Privacy between the flight surgeon and each crewmember must be preserved if medical communications are to be candid. Finally, the ability to provide these private medical conferences should encompass the need for unscheduled as well as scheduled conferences.

III. Diagnostic and Therapeutic Peculiarities in the Space Environment

Many if not most of the techniques used in physical diagnosis in space are little different from their terrestrial counterparts. For the more common problems encountered in space flight, standard measures of diagnosis and treatment have sufficed reasonably well for the 35 years humans have been exploring near-Earth space. However, the deviations that exist are significant, and understanding them may make the difference between successful and unsuccessful medical support. Those unique peculiarities are the subject of this section.

A. The Patient

Methods of diagnosing and treating illness or injury in space crews must acknowledge the simultaneous occurrence of the physiological response to microgravity. In a sense, space medicine involves supporting and healing "extraterrestrial" organisms—humans adapted to a totally new environment. Adaptation to microgravity should be considered a normal physiological response rather than an inherently pathologic process. With few exceptions (notably radiation exposure and bone loss [and subsequent risk of nephrolithiasis from calcium mobilization]), these changes are not limiting or hazardous, but become maladaptive only upon return to Earth. Known aspects of the human response to microgravity are reviewed extensively in Volume III of the *Space Biology and Medicine* series and will not be discussed in detail here. Nonetheless, the signs, symptoms, or presentation of various disease states clearly can be affected by the fluid shifts and changes in electrolyte balances and cardiopulmonary and hematological/immunological function characteristic of exposure to microgravity, and thus these disease states could well present in atypical ways.[9,10] The CMO and the Earth-based medical-support team must interpret all signs, symptoms, and diagnostic results in light of this new, "reset" underlying physiology.

All aspects of medical diagnosis, including physical examination, laboratory analysis, and medical imaging, must be redefined for the microgravity and partial-gravity environment. Although investigational steps have been taken in these areas, the normal complete medical examination for the weightless environment remains largely uncharacterized. However, some baseline medical evaluations have been conducted on some of the infrequent flights that have included physicians as crewmembers. In one scale developed for this purpose, numerical grades are assigned to various aspects of the physical examination to determine differences from terrestrial normal values; to date, this scale has been used with 7 crewmembers[11] (Fig. 2). These preliminary observations must be strengthened by further periodic medical examinations during multiple short and long flights.

Periodic examinations should accompany standard schedules of medical monitoring, and should include estimates of exercise performance, anthropometry, and hemodynamics (see Chapter 4, In-Flight Monitoring). These examinations will serve the dual purpose of providing a reliable overall picture of the adapted state and detecting potential pathology before it becomes clinically significant. For the International Space Station (ISS), periodic health evaluations are scheduled every 30 days, and include both physical and laboratory examinations. These evaluations will build on the experience accrued during the 10 years of laboratory and hemodynamic monitoring regularly performed aboard the Russian space station Mir.

With regard to therapeutic issues, new clinical norms probably will be established for many parameters in weightlessness, and must be considered as a new baseline from which the body deviates in injury or illness. Evaluation of lung function after a mild toxic inhalation, for example, must account for an apparent weightlessness-induced decrease in vital capacity of 10%,[12] and cannot be compared directly to preflight baseline measurements. Prudence would seem to dictate that new clinical baseline values of selected physical and laboratory tests be obtained at the outset of a long flight, after the acute adaptation process is complete, so that these baselines can be used for comparison in event of illness or injury later in the mission. (Moreover, these new baseline values should account for both adaptation to microgravity and for the conduct of standard physical countermeasures.) Returning a crewmember to optimal health during space flight may well mean returning to these new values.

Another factor in the patient's response to treatment includes the shifts in pharmacological response associated with microgravity. Some medications do not seem to producer the same therapeutic response on orbit as on Earth.[13] Certain aspects of the overall physiological response to microgravity may influence pharmacokinetics. Gastrointestinal motility, which correlates significantly with absorption of some medications, can be significantly affected, especially in the presence of space motion sickness. For example, oral use of Phenergan™ (promethazine) has relatively little effect in treating symptoms of SMS; however, the same agent, given intramuscularly, is highly effective.[14,15] Most likely, bioavailability, rather than end-organ utilization, is most affected by normal adaptation to microgravity. As such, developing alternate methods of delivery for commonly used medications (e.g., intranasal, buccal, and parenteral dose-delivery systems) is an area of active research.[13]

Little information is available on the healing and recovery process in space. However, some anecdotal evidence suggests that healing of minor traumas such as cuts or scrapes on the fingers may be delayed relative to similar wounds on the ground (M. Barratt, unpublished observations). These observations possibly might be related to known changes in immunologically active cells and humoral modulators,[16–19] including diminished response to mitogenic stimulation. One could speculate that bone fractures, especially to weight-bearing bones, may not heal properly if the remodeling process involved in both normal homeostasis and healing on Earth are affected by the relative lack of gravity in space. In essence, any organ system influenced by microgravity adaptation could follow a recovery curve different from terrestrial norms in the event of illness or injury.

B. The Practitioner

Two primary-care providers are closely involved with delivering medical care during space flight: the CMO (on board) and the flight surgeon (on Earth). Qualifications and level of training for CMOs have been discussed extensively elsewhere.[20–22] One option that would greatly enhance medical safety would be to include a physician on every space flight[22]; however, competing requirements for expertise in payloads and operations have relegated the concept of having crew physicians aboard every mission to the future. At present, flight surgeons depend on the skills and abilities of nonphysician CMOs to assess their fellow crew mates (Fig. 3). Two-way voice and video capabilities greatly enhance this process, and CMOs often can be guided through fairly complex examinations or procedures. The possibility of one CMO becoming ill or injured dictates that at least two CMOs should be trained for each mission, and these individuals preferably should not be those who engage in the most hazardous activities (such as EVA).

In the U.S. Space Shuttle program, 2 members of each 5- to 7-person crew are designated CMOs, and are given about 12 hours of specialized medical training before each flight. This training is provided by the flight surgeon assigned to that mission in order to facilitate in-flight communication and coordination. This practice has served the Space Shuttle Program well, and fortunately the system has not been challenged with severe medical problems in flight. Those crewmembers on longer missions aboard Skylab or Mir received more extensive training. For example, the Skylab crewmembers received 80 hours of paramedic training, including some practical clinical and dental experience, which focused on the medical hardware to be used during flight.[23]

Factors that drive the inclusion of physicians as crewmembers include missions of longer duration, greater remoteness, and larger crew size.[6,10,20,22] Even under those conditions, e.g., en route to Mars, any crew physician certainly will have many other duties and thus must be heavily cross-trained. One argument in favor of routinely including physicians on contemporary long flights is that a normative database and techniques for applying medical care in space ought to be developed well in advance of exploratory efforts. Leaving near-Earth space represents a quantum leap in remoteness; the on-site practice of space medicine should be as mature as possible by that time.

C. Constraints on Medical Hardware

The breadth and extent of resources needed to deliver quality medical care on Earth are substantial. Additional considerations for the space flight environment include logistics, reliability, ease of use, and operability. From a logistics standpoint, stowage space, replenishment, and power (including the need for refrigeration or other temperature- or humidity-controlled environments) are in short supply aboard spacecraft. Items with very long “shelf lives” are preferred, and all medical items—like every other piece of space hardware—must be certified to reliability standards that far exceed terrestrial norms. Medical hardware also must be easy to use; as contingency items, used infrequently by people with little medical training, they must be as simple and intuitive as possible in order to be effective.

Operability in microgravity is one of the more difficult aspects for ground designers. For example, any process that requires separation of gases and fluids (e.g., specimen collection or biochemical analysis) must rely on centrifugal force or filtration rather than gravity. Procedures that could generate particulate or fluid contamination of the spacecraft (e.g., drilling teeth or handling urine or other biohazardous samples) must be done in specialized enclosures. Finally, operators, subjects, and support items all must be restrained in microgravity. For these reasons, input from experienced space crewmembers should be considered mandatory in the development of in-flight medical systems.

Many standard diagnostic and therapeutic instruments can be used in space with little or no modification. Stethoscopes, otoscopes, venipuncture kits, and other items can be used once crewmembers become accustomed to handling them in weightlessness and adjusting for other factors such as high ambient noise and low light levels. As expected, the more advanced capabilities tend to require special consideration for weightlessness, as described below.

1. Physical Restraint Systems

As experience has shown, many medical examination and intravenous techniques can be used in the microgravity environment without specialized restraint systems. However, more complicated medical procedures cannot be performed without some means of restraint that brings CMO, patient, and medical support items together in close proximity. For those unlikely contingencies that would require acute care, the most efficacious solution would be a dedicated medical-restraint table that can be deployed immediately. Prototypes of systems such as these have been tested during parabolic flight[24] and during space flight[25] (Fig. 4). Ideally, the restraint system would accommodate the neutral body posture assumed in microgravity (by both the patient and the CMO), and would support both basic procedures (e.g., simple wound repair) and critical care. Interfaces for medical equipment and for managing wastes (e.g., pads saturated with body fluids, or sterile packaging), must be incorporated as well.

For the near future, dedicated, constantly deployed medical restraints are unlikely because of constraints on spacecraft volume; other available surfaces such as cabin walls and galley tables are used instead. However, a smaller hybrid system consisting of an easily deployed surface that can be attached to dedicated structural mounts is another alternative. In an acute, life-threatening situation, the time needed to deploy a restraint system becomes critical, and could affect survival.

2. Automated Ventilation

Techniques have been developed for establishing and maintaining airways in weightless environments.[26] CMOs have had available the equipment and techniques for endotracheal intubation on Skylab, Space Shuttle, and more recently Mir station flights. Automated ventilators, a highly desirable capability, have yet to be implemented in the space flight environment.

Given the constraints on electrical power aboard spacecraft, perhaps the best option for ventilation is a compact, pressure-driven device powered by the storage pressure of the respirable gas. Ventilators such as these are used on Earth during transport and in acute-care facilities. For patients with inadequate spontaneous respiration, these devices are lifesaving, and free up an individual who otherwise would have to provide manual respirations with a bag device. However, the ground-based devices typically contain 100% oxygen, and thus the “patient ventilator” exhaust is nearly 90% oxygen (the remaining 10% being expired carbon dioxide and water vapor). In a closed cabin, ambient concentrations of oxygen thus would rise quickly and exceed flammability limits. For the short term, a diluent gas (i.e., nitrogen) could be added to the cabin to maintain safe oxygen concentrations. This option comes at a further cost in gas as well since the cabin atmosphere must be vented to maintain pressure limits.

Two potential solutions exist. The first is to provide a “dump” by which the expired ventilator gas is either vented overboard into space or into some vessel from which the gas can be reclaimed. The second solution would be to provide an oxygen-nitrogen system that includes a blending function, which would allow the CMO to use only as much oxygen as is clinically required. This second option also would mitigate the risk of pulmonary oxygen toxicity from breathing 100% oxygen for more than 18 hours, should ventilation be required for that length of time. Since some high concentration of oxygen may be required medically, however, some combination of these two potential solutions may be optimal.

Future respiratory capabilities should include a closed breathing circuit to minimize discharge of excess oxygen into the cabin atmosphere. In addition, use of advanced technology such as molecular sieve beds would allow a gas-delivery system to obtain and concentrate oxygen from the ambient cabin atmosphere, and then vent the exhaust directly back to the cabin for a net balance of near zero.

3. Intravenous Fluid Therapy

Small doses of intravenous medications can be given easily in weightlessness. However, large fluid volumes cannot be given in the same way as they are on Earth, i.e., with gravity-driven free-flow devices or pumps that automatically separate air and fluid. The simplest means of providing intravenous fluids combines soft packaging for the fluids with a surrounding pneumatic pressure device, such as a blood pressure cuff. Regulating the pressure and the size of the flow orifice roughly controls the rate of fluid administration. Injection fluids must be specially packaged with minimal air, and care must be taken in preparing the infusion system to avoid introducing air into the line. Additional separation of air and fluid can be facilitated with an in-line filter system or “bubble trap.” More precise regulation of infusion rates, like those required for giving continuous or controlled-dose medications, will require an automated pump. Prototypes of powered infusion pumps have been tested during space flight[22,27] (Fig. 5), and will be available on the next-generation LEO station.

Although prudence dictates that a small stock of prepackaged intravenous fluids be maintained on board, storing large quantities of such fluids represents a significant penalty in terms of launch mass and stowage. Moreover, the shelf life of such fluids typically is limited to one year. Resources could be used more efficiently if sterile, injection-grade fluid could be produced from potable water during flight as needed. A crewed Mars mission or similar long and remote mission would depend on this capability. Technologies with which to produce sterile injection-grade fluid for space flight have been examined extensively, and have included ion-exchange columns and premeasured electrolyte and drug aliquots.[28,29]

4. Cardiac Defibrillation

Contemporary advanced life support methods require the ability to monitor cardiac function and provide defibrillation. A space monitor/defibrillator will consist of an off-the-shelf item modified for use in microgravity, and will include the ability to monitor cardiac function, defibrillate over a range of selected energy levels, and provide external cardiac pacing. Microgravity also dictates some unique considerations; for example, the typical 11 kg weight needed to apply the charged paddles to the patient's chest is not available in weightlessness; self-adhesive defibrillator pads must be used instead. Electrical insulation and electromagnetic interference (EMI) shielding must be provided to protect crewmembers from inadvertent electrical shock and to protect sensitive avionics from EMI pulses.

As an acute-response item, the monitor/defibrillator must be maintained in a state of readiness. Batteries must be charged to energize the capacitor that delivers the direct current (d.c.) countershock, and the unit must be accessed quickly and easily. Many of the requirements for patient positioning and insulation will be met by the medical restraint system; thus deployment of the restraint may well be a rate-limiting step in delivering lifesaving defibrillation. As is true for all medical devices, the CMO must be well trained in its safe and effective use.

5. Cardiopulmonary Resuscitation

Methods of closed-chest cardiac massage on Earth depend on the weight of the upper torso driving the force of compression; this weight, and hence the force, are unavailable in microgravity. Compressive force can be provided by a restrained rescuer's muscular power alone for a short time. Such methods have been tested during parabolic flight[30] and space flight.[25] However, the force required to deliver adequate compressions can exhaust the rescuer quickly, especially in the presence of microgravity-induced musculoskeletal deconditioning. This author recommends that the rescuer deliver compressions while reacting against an opposite surface with the feet, rather than being restrained in the Earth-standard position at the patient's side. The latter position does not require dedicated restraints and uses combinations of extensor muscles throughout the body. In addition, it leaves the volume near the patient's chest and head unobstructed for airway and intravenous procedures (Fig. 6).

Alternatively, mechanical devices could be used, such as pneumatically powered "thumpers" or simpler lever devices, such as those tested during the STS-40 mission.[25] Such devices would be best integrated into an advanced medical restraint system.

IV. Systems for In-Flight Diagnosis and Treatment

Equipment for medical diagnosis and treatment on future missions generally will be integrated into an overall health care system, which in a broad sense includes medical response, medical monitoring, environmental monitoring, and physical/physiological countermeasures. Functions and use may overlap with medical investigation equipment and activity schedules. For long space flights, designated CMOs probably will cover all of these areas, serving as overall medical and health officers familiar with all hardware and procedures. This approach will make best use of available resources. Monitoring and countermeasures are covered elsewhere in this volume (Chapters 3, 4, and 8); the following sections will focus on diagnostic and therapeutic systems. An overview of existing medical assemblies precedes a discussion on advanced (future) capabilities.

A. Skylab

The U.S. Skylab program, which flew three crewed missions lasting 28, 59, and 84 days in the early 1970s, made use of a substantial onboard medical system, called the integrated medical support system (IMSS). Hardware items, and the kits they were contained in, are listed in Table 2. Items were referenced to locker location and further classified as to whether physician approval was required for use. Table 3 is an alphabetical listing of the onboard formulary. Both of these listings were contained in the IMSS Medical Checklist, which essentially formed a "field manual" that accompanied the hardware.

As noted above, all Skylab crewmembers received 80 hours of paramedic instruction and experience, including advanced airway handling. Only one crewmember, Dr. Joseph Kerwin on the first crewed mission, was a physician. Although no serious medical problems arose during the Skylab missions, the IMSS served the orbiting laboratory extremely well in routine health and environmental monitoring during its mission lifetime.

B. Space Shuttle Program

As of this writing, the Shuttle Orbiter Medical System (SOMS) has been flown on more than 80 Space Shuttle missions. The contents of the SOMS have been refined over time and reflect experience in its use and in the types of medical problems observed during flight. Space Shuttle missions typically carry a 5- to 7-member crew, and last from 2 to 18 days. The relatively brief mission durations and large crews naturally influence the formulary, and direct the medical emphasis toward routine ambulatory care. Health monitoring and advanced life support capability are given lesser priority than on long missions, since the shuttle can de-orbit and land at an emergency site within a few hours in case of a medical emergency.

The SOMS consists of 5 fabric subpacks, plus restraints and an electrode-attachment kit (Fig. 7). The medications and bandage kit contains mostly oral and topical medications, bandaging supplies, and logs to track each crewmember's use of medications. The emergency medical kit contains diagnostic equipment, a small dental kit, injectable medications, and limited intravenous capability. The medical accessories kit contains additional intravenous fluid, extra supplies, and mission and crew-specific items. The airway management kit contains a facemask for oxygen administration, oral and endotracheal airways and support items, and a tracheostomy kit. Supplemental oxygen can be administered via an emergency resuscitator, which delivers 100% oxygen through the face mask or endotracheal tube, either on demand or through a manual trigger. The contaminant clean-up kit contains chemical-resistant and latex gloves, face masks, and goggles to protect crewmembers from toxic spills in the cabin. Electrocardiographic (ECG) monitoring is afforded via a 3-lead electrode set and other hardware common to the EVA monitoring system. A supplemental pack, the medical extended-duration orbiter pack, is flown on missions that last longer than 12 days.

Hardware items and drugs included in the SOMS are shown in Tables 4 and 5, respectively. Upgrades are incorporated as new drugs and other items become available. Crewmembers also can carry limited supplies of some personal medications in addition to the SOMS. The SOMS, like the Skylab IMSS, is accompanied by a medical checklist, a simple and intuitive medical field guide that references item locations by alphabetical listing or by their use. The designated CMOs on a particular mission are trained by the flight surgeon assigned to that flight. The flight surgeon is available in the mission control room throughout the flight for medical consultation, and has a SOMS and the medical checklist at hand to aid in rapid communication with the crew.

C. Mir

The first elements of the Russian Mir station were launched in 1986. Since that time, the orbital complex has been staffed continuously and has undergone a steady evolution in size and capability. Crews for long flights (ranging from a few to 14 months) typically are two or three cosmonauts, all of whom receive roughly equivalent training in medical care. As was true for Skylab, the overall health program on Mir involves means of monitoring the environment as well as individual fitness and health. Medical items, particularly therapeutic agents, are distributed among several compact problem-oriented kits, which can be accessed easily by crewmembers and replenished during resupply flights (Fig. 8). Table 6 lists the individual kits and their contents. Other capabilities include blood-pressure measurement (manual and automated), ECG monitoring (including a standard 12-lead ECG), rheoencephalography, blood-chemistry analysis (with a commercial "Reflotron" system), and radiation dosimetry.

D. International Space Station Program

The International Space Station (ISS) will consist of a large LEO complex with hardware and crew contributed from many nations. At this writing, the major contributing space organizations are the U.S. National Aeronautics and Space Administration (NASA), Russian Space Agency (RSA), Japanese National Space Development Agency (NASDA), European Space Agency (ESA), and Canadian Space Agency (CSA). Crews of 6 or 7 individuals will conduct long missions aboard the completed station. The experience accrued thus far from all crewed space efforts will produce the most advanced medical capability yet realized for long space flight. The challenge of integrating differing methods and standards of medical care, for both crew and ground personnel, adds a new dimension to space medicine. Much progress has been made recently with international crews aboard the Russian Mir station and U.S. Space Shuttle, and the ISS is expected to be a proving ground for more ambitious and remote international efforts such as interplanetary expeditions.

The ISS onboard medical capability will have two broad origins. The first crewed element will consist of a Russian module similar to the Core Module of the current Mir station, which will include a medical system similar to the one now on board Mir (Table 6), with several hardware and pharmacological upgrades. A NASA-supplied system, known as the Crew Health Care System (CHeCS),[31] also will be aboard in the U.S. Laboratory and Habitation modules. CHeCS comprises three subsystems: the Health Maintenance System, which includes diagnostic and therapeutic hardware and medications; the Environmental Monitoring System, which contains equipment for analyzing air, water, and surface samples; and the Countermeasures System (CMS), which includes equipment for conducting routine physical exercise and for monitoring fitness level. Table 7 summarizes current plans for the CHeCS system constituents.

In addition to supporting routine medical monitoring and the treatment of minor illnesses and injuries, the Health Maintenance System enhances the crew's ability to respond to more serious events. NASA recently has defined requirements for a minimum level of medical intervention and care, which eventually will be applicable to all space missions. Aside from basic first aid and ambulatory care, these requirements specify the provision of basic and advanced life support, including cardiopulmonary resuscitation, cardiac defibrillation and monitoring, airway management and ventilatory support, intravenous fluid and medication administration, and patient restraint and immobilization.[32] To support these requirements, the Health Maintenance System includes a cardiac defibrillator/monitor with external pacing capability, an automated ventilator and advanced airway-management hardware, and a powered intravenous pump. The Advanced Life Support and Ambulatory Medical Packs provide the diagnostic and therapeutic items that support these capabilities (Fig. 9). In addition to basic medical training for all crewmembers, more advanced paramedic-type training, commensurate with the onboard equipment, will be provided for two designated CMOs for each ISS flight increment.

E. Future Systems

The medical capability aboard the ISS is expected to evolve over its operational lifetime, as it has on the Mir station, to meet the particular needs of its crewmembers and missions. Capabilities now being considered for incorporation into the ISS program include telemedicine, computer-aided diagnostics, and medical imaging systems (e.g., ultrasound), all of which are in various stages of development. Many are evolving rapidly in association with advances in microelectronics and diagnostic algorithms. A telemedicine instrumentation pack (TIP) (Fig. 10), recently evaluated in a clinic setting,[33] will be tested soon on a Space Shuttle flight. The ability to evacuate and return severely ill or injured crewmembers quickly from LEO offsets the risk of events that would require more intensive or invasive capabilities, and thus these capabilities probably will not be included in the ISS medical-support system. However, the hardware and methods for more autonomous capability should be developed on the ISS before more remote missions are undertaken.

For the foreseeable future, crewed spacecraft that are outside of LEO will be either on or en route to a planetary surface. Each departing mission must be equipped to respond to medical events that occur in prolonged weightlessness, as well as injury-causing gravitational loads, dust-related health problems, potential acute radiation exposures, and other events associated with being on planetary surfaces. Realistic support for such missions must include not only enhancements for existing systems for LEO, but also the ability to conduct surgical procedures and deliver hyperbaric oxygen (HBO). These areas are discussed in greater detail below.

1. Surgical Capability

Few areas of medicine are as complex or as demanding of resources and personnel as surgery. At present, a surgical emergency that takes place in LEO is best handled by evacuating the afflicted crewmember to Earth as quickly as possible. However, some situations, such as acute appendicitis or penetrating trauma, would render a crewmember too unstable for transport. Moreover, maintaining the same risk level in remote missions (e.g., lunar outposts or interplanetary travel) as that accepted for LEO demands on-site capability for general surgery. In such settings, the ability to conduct basic surgical procedures could preserve mission success in situations that otherwise could not be salvaged.

The challenges of providing a surgical capability are considerable, and include supplying materials, maintaining the sterility of the operative field, avoiding contamination of the cabin atmosphere, avoiding flammability or toxicity hazards from use of common inhalational anesthetics, and handling and sterilizing surgical instruments. Means of meeting many of these challenges have been or are being considered by space medicine investigators and clinicians.[34] For example, ways of inducing anesthesia that do not involve traditional inhalational agents and systems would eliminate the need for advanced monitoring and controlled artificial ventilation. Exhaust from a patient ventilator would contaminate the atmosphere with the inhalational agent and its breakdown products, which the contaminant-removal system may not be able to remove. Local anesthetic techniques could suffice for wound repair and injury management in many instances.[35] Other proposed alternatives such as intravenous agents, epidural anesthetics, and acupuncture[36] should be further investigated for space flight.

Several surgical enclosures designed for use in microgravity have been evaluated during parabolic flight.[37–40] No problems that might limit the use of these enclosures were noted with respect to restraining instruments, putting on gloves and gowns, and maintaining sterility[21,41]; however, the time needed for these tasks could be increased by at least 50%.[24] One investigator suggested that surgical instruments could be sterilized after use by exposing them to the space vacuum.[38]

Other evaluations of surgical capability have involved the use of animal models in parabolic flight. Thirty years ago, Yaroshenko and others reported performing laparotomy and celiotomy on locally anesthetized rabbits under a closed transparent surgical canopy, using a magnetic instrument holder, during parabolic flight. During periods of free fall, body fluids and bowel contents adhered to exposed surfaces rather than spilling into the atmosphere. Venous blood formed adherent puddles that clung to the viscera under surface tension; the greater pressure of arterial blood propelled it into the atmosphere of the surgical canopy. Recommendations from this study included minimizing the length of sections and incisions and applying hemostasis earlier and more often than is customary on Earth, but overall the authors concluded that surgery in microgravity is possible and can be conducted without great difficulty.[42]

A more recent test involved evaluating generally anesthetized rabbits in a surgical enclosure that incorporated a medical restraint system and transparent surgical canopy[43] (Fig. 11). A horizontal laminar airflow with an in-line particulate filter was intended to keep the surgical field clear of body fluids, cautery fumes, and other surgical debris. This system effectively minimized particulate counts and body fluids (except for some arterial blood) within the surgical canopy. No particular difficulties were noted in dissection and control of vascular structures, exposure and visualization, ligation or repair of blood vessels, or suturing during open laparotomy in free-fall. Observations regarding the behavior of viscera and body fluids corroborated those of Yaroshenko, and again the conclusion was that surgery in microgravity does not present any limiting technical or procedural challenges.[43]

These results suggest that limitations on surgical capability in space flight probably will not be related to physiological peculiarities of weightlessness. Rather, the major challenge will be to provide adequate surgical enclosures, restraint systems, and materials, as well as training for on-site personnel. Laparoscopic surgery offers some potential advantages over traditional methods, such as small incisions, containment of abdominal contents, and faster recovery times. However, laparoscopic surgery cannot be used in all instances, and carries its own complications, e.g., the need for “high-tech” equipment, large amounts of power, longer time per surgical procedure, high skill and proficiency of the operator, and the potential complications of abdominal carbon dioxide insufflation, such as pneumoperitoneum, gas embolism, hypercapnia, and acidosis.[44] The possibility of using a telemedicine link during endoscopic activities, and allowing highly proficient ground experts to participate in real-time procedures, could mitigate some of these complications.

2. Hyperbaric Oxygen Capability

The character, risk, and prevention of decompression disorders in space flight have been reviewed elsewhere (cf. Volume III, Book 2, Chapter 24). The decompression-related disorders of interest in space medicine are decompression sickness (DCS), aeroembolism, and ebullism; all involve reduction in ambient pressure and physiological disturbances caused by tissue gas bubbles. DCS, which can include classic “bends” pain as well as more serious neurological, pulmonary, and cardiovascular manifestations, is caused by the evolution of nitrogen bubbles in tissues that had been supersaturated with nitrogen. Pressure changes, such as those that can prompt dissolved nitrogen to form bubbles, occur routinely in the course of decompressing the spacecraft atmosphere from its accustomed level to the lower levels used for EVA suits. The risk of DCS can be circumvented by "prebreathing" oxygen (thereby eliminating nitrogen from the body) before beginning the decompression, and by slowing the rate of that decompression. More rapid reductions in ambient pressure can produce aeroembolism, caused by the formation of a pressure gradient across the lung's alveolar air/tissue interface. A pressure differential of as little as 80 mm Hg can rupture the lung,[45] which in turn could introduce atmospheric gas into the vascular space, leading to gas embolism and tissue ischemia. Ebullism occurs when body tissues are exposed to a hard vacuum, which results in the formation of water-vapor bubbles in blood, mucous membranes, and subcutaneous tissues. Although only catastrophic depressurizations would cause ebullism, animal studies and limited experience with human exposures indicate that ebullism can be survived if means of rapid repressurization and adequate treatment are available.[46,47]

In addition to the risk of DCS stemming from nominal EVA operations, inadvertent exposure to vacuum or intermediate pressures is always possible in space flight, and thus decompression disorders constitute a significant occupational risk. Rapid depressurization of a module due to impact with orbital debris, or traumatic rupture of a suit during EVA, could give rise to any one or more decompression disorders. The ability to provide hyperbaric oxygen (HBO) plays a significant role in treating any decompression disorder. HBO is the definitive therapy for most cases of DCS; delays between the decompression event and HBO correlate positively with poor outcomes.[48] On-site hyperbaric capability has been recommended for LEO platforms,[45,49] lunar outposts,[50] and other more remote settings. Since human habitation modules in space already consist of pressurized structures, a logical approach to providing this capability would be to modify the structural integrity and hatch configurations of one of these modules so as to allow common HBO treatment pressures (typically around 3 ATA). The now-defunct Space Station Freedom project had included a hyperbaric airlock that could accommodate a patient and a medical attendant during hyperbaric treatments.

Aside from structural considerations, other challenges associated with providing HBO capability in space include how to provide treatment gases and to avoid the fire hazard of a high-oxygen atmosphere. Ideally, the HBO system would reclaim as much of the treatment gas as possible, and recycle that gas to the overall habitat atmosphere. To mitigate the risk of fire, 100% oxygen should be delivered to the patient via a mask system that also removes the exhaled gas from the chamber; the oxygen concentration of the chamber atmosphere itself should remain at 20% or less. The chamber also should accommodate a subset of available medical equipment (which naturally must function in the hyperbaric environment) for treatment as indicated. A small equipment lock also should be incorporated to allow small hardware items, fluids, and medications to be passed between the chamber and the rest of the spacecraft without interrupting the treatment profile.

Treatment protocols for microgravity also are needed. HBO treatment schedules for DCS are primarily empiric, based on data from diving and aviation. However, the physiological response to decompression may well differ in microgravity or in hypokinetic states relative to the terrestrial response. This supposition is based on two sets of results, one being the relative reduction in observed vs. expected symptomatic DCS events during the course of EVA[51] and the other the known reduction of circulating gas emboli in bed-rested subjects (relative to ambulatory subjects) undergoing decompression stress.[52] Logically, then, the treatment requirements for pressure levels and time to be spent at each pressure level also could be different in microgravity from on Earth. Until much more is known about behavior of decompression disorders in microgravity, terrestrial standards probably represent the best starting point for a cabin atmosphere held at sea-level pressure; reduced-pressure modules and habitats will require more conservative estimates for treatment.

3. Other Capabilities

Future exploratory missions will certainly last longer, involve larger crews, and carry more formidable occupational risks than past and current space flight efforts. A permanently crewed lunar outpost and long stays on the Martian surface are not difficult to envision within the next few decades. Smaller, more rugged, and reliable equipment will continue to evolve, with some terrestrial enhancements expected from space flight experiences. Currently emerging technologies and methods, and those yet to be developed or applied to space flight, include the following:

- Techniques for analyzing blood chemistry using dried samples, which would greatly simplify current blood-sample collection procedures and the need for refrigerated storage;
- Noninvasive means of monitoring blood chemistry, perhaps through transcutaneous spectral analysis;
- Noninvasive, accurate means of monitoring central hemodynamics, including cardiac and pulmonary pressures

and cardiac output;
- Means of “banking” autologous hematological stem cells in radiation-hardened enclosures, to support bone marrow transplant in the event of an acute radiation exposure (such as from a solar flare);
- Use of humoral agents (e.g., granulocyte-macrophage colony-stimulating factor) to stimulate the bone marrow in the event of acute radiation syndromes;
- Means of strict biological isolation for immunocompromised crewmembers, in the event of radiation events, virulent infectious illness, or contamination with newly encountered organisms;
- Means of “banking” autologous red blood cells for transfusion in the event of a major hemorrhage;
- Use of blood substitutes (e.g., perfluorocarbon emulsions or hemoglobin-filled lipid enclosures) in the event of hemorrhage;
- Oxygen-concentrator devices (e.g., molecular sieve beds) that can deliver enhanced concentrations of oxygen to medical patients without enriching the cabin atmosphere;
- Advanced imaging systems for diagnosing injury and other tissue insults and for monitoring bone density; may involve roentgenography, compact computerized axial tomography, or ultrasound technology; and
- Thrombolytic agents with long shelf lives, since the risk of cardiovascular events becomes more significant as missions become very long and perhaps include older crewmembers.

These and other methods show great promise in terms of enhancing medical preparedness for future missions, and will be developed in tandem with advanced countermeasures and preventive methods to protect and optimize crew health.

V. Response to Specific Medical Events

As noted earlier, many—if not most—of the more routine, minor medical problems encountered during space flight are managed as they would be on the ground. This section highlights those problems that engender special considerations for microgravity and remote, closed environments, and focuses on occupationally related disorders and injuries. The following paragraphs are not intended to be an exhaustive treatise on any of these problems, but rather concentrate on the unique diagnostic and treatment considerations related to the space flight environment and the medical capabilities available there.

A. Space Motion Sickness

Among the first conditions humans encountered on venturing into microgravity was space motion sickness (SMS), or more appropriately space adaptation syndrome. SMS arises as the body shifts from its Earth-normal paradigm for positional awareness, which is based on gravitational, proprioceptive, and visual references, to an environment where these cues are absent or greatly altered. Symptoms generally arise within the first several hours of arrival in microgravity, and sometimes as quickly as 15 minutes.[53] The symptom complex includes general malaise, headache, lethargy, stomach awareness, diminished appetite, and episodic emesis that often appears without warning. Afflicted crewmembers report increased sensitivity to head movements and odors[53–56]; a relative absence of clinically detectable bowel sounds also has been reported.[11,57] The incidence of SMS has varied somewhat with the type of space vehicle. In the U.S. program, a 35% incidence was seen during Apollo flights, 60% during Skylab missions, and 67% for first-time Shuttle flyers. Incidences on Russian craft have ranged from 40–60%.[55,58] The lesser incidence in earlier flights could well be related to the smaller habitable volumes on those craft, particularly those in which rotation and pitch motions of the head were restricted (N. Thagard, personal communication).

Fortunately, SMS is short-lived, with symptoms in untreated subjects resolving within the first 3 to 4 days in flight. Nevertheless, SMS can greatly affect crew health and performance during that period. Many therapeutic measures have been used with highly variable results; efforts to identify and select those individuals who are not susceptible to SMS have not proven successful in the Russian or U.S. programs.[59] Since gastrointestinal motility and absorption often are diminished in microgravity, parenteral means of administering antiemetic drugs have been explored. Intramuscular (IM) doses of promethazine (Phenergan™), first used by a physician-astronaut in the Space Shuttle program, have generated promising results.[14] In one study, doses of 25 to 50 mg eliminated symptoms of SMS in 28 of 29 crewmembers.[15] Another evaluation that included use of a scale for the four most commonly reported symptoms—nausea, emesis, stomach awareness, and loss of appetite—revealed that 90% of treated individuals reported immediate relief of symptoms, and those who were treated on the first day of flight were half as likely to have symptoms on the next day.[60] Sedation, a potential side effect of promethazine, has not posed problems.

Administering IM injections of promethazine has become one of the more common duties of Shuttle CMOs, and a separate kit dedicated to SMS treatment has been incorporated into the SOMS. Although similarly quantifiable data are not available for promethazine suppositories, early experience suggests that this route is effective as well. Some crewmembers take prophylactic oral doses of antiemetics a few hours before launch; however, this practice is a matter of choice and mostly based on prior flight experience. Preflight parenteral treatments are not given because of the potential for sedative effects during the critical ascent phase.

Aside from drug treatment, those individuals afflicted with SMS also are instructed to avoid rapid head movements, to attempt to maintain a sense of vertical reference for the first few days, and to maintain adequate oral hydration. Because of the possibility of in-suit emesis and aspiration, EVAs cannot be scheduled until after the third flight day of Shuttle missions.

B. Airborne Foreign Materials

Particles of all sizes do not settle on surfaces in microgravity, and their movement is influenced primarily by local airflow. Efforts taken to minimize the formation and dispersal of particulates aboard spacecraft include careful selection of spacecraft and payload materials, and special containment for activities that carry the risk of releasing particulate contaminants. Nevertheless, the possibility of encountering foreign objects always remains, and the main medical implications of such contact are corneal abrasion and respiratory aspiration. Any crew activities associated with airborne particulates should require that protective masks and eye goggles be worn.

Foreign objects in the eye are highly irritating, and typically produce pain, photophobia, decreased visual acuity, and occasionally a sense of a “foreign body” being in the affected eye. Anesthetic eyedrops may be required to relieve the pain enough to facilitate examination, which usually shows an injected, heavily tearing eye with blepharospasm. Means of conducting simple corneal examinations must be provided on any spacecraft, and should include the use of fluroscein dye, which under a cobalt or Wood’s lamp will reveal a corneal abrasion as a surface defect. The presence of an abrasion requires that the entire corneal surface be visualized and the tarsal plate everted. Most ocular foreign bodies are found under the superior tarsal plate,[61] and usually can be removed with a moistened cotton swab. An object embedded in the corneal surface can be removed through directed syringe irrigation or by using a small, carefully controlled needle under anesthesia. After the object is removed, the eye should be treated with ophthalmic antibiotic drops (to prevent bacterial superinfection) and a cycloplegic agent (to prevent ciliary spasm and iritis).

Chemical injuries to the eye, which can occur if chemical reagents escape into the cabin atmosphere, require immediate irrigation. Alkaline substances are more injurious than acidic ones, and can cause progressive damage long after the exposure. The first step in treating ocular chemical exposures is to irrigate the affected eye; several liters of water may be required. (An emergency eyewash system is carried aboard the U.S. Space Shuttle for this purpose.) After irrigation, conjunctival pH should be verified as being normal before the cornea is examined.[62] Minor injuries to the corneal surface can be treated with antibiotic drops or cycloplegic drugs and a patch applied if necessary; more severe injuries require prompt consultation with ophthalmology specialists. Corneal abrasion and chemical injury require that the CMO conduct daily follow-up examinations, and provide reports and possibly camera views to Earth-based specialists.

Most oropharyngeal aspirations of foreign bodies on Earth involve food particles during meals. The likelihood of such events is not expected to be any greater in microgravity. However, smaller airborne particles could be aspirated and lodge in the oropharynx or bronchial tree. In addition to activities associated with high atmospheric-particulate counts, exercise, which increases respiratory minute volumes, may increase the risk of aspiration. Symptoms can include localized pain, dysphagia, odynophagia, and cough. Small particles deep in the bronchial tree can producing coughing, some degree of bronchospasm, and audible wheezes. High-risk circumstances and sudden onset of symptoms are typical of foreign-body aspiration. Examination of the oropharnyx with a light and a curved dental mirror may localize the object, which can be removed using appropriate forceps and topical anesthetic if needed. If symptoms persist and no object is seen, ground specialists must be consulted to determine the disposition of the afflicted crewmember and the impact to the mission. Onboard fiber-optic endoscopy, such as that incorporated in the telemedicine instrumentation pack, would be highly desirable in this circumstance.

C. Nephrolithiasis

Nephrolithiasis is relatively common in the general public; as many as 10% of men and 3% of women will develop a stone during their adult lifetimes.[63] Renal stones result from crystalline and organic constituents forming an insoluble matrix in the urinary tract. The main types of stones are calcium oxalate, calcium phosphate (brushite), magnesium-ammonium phosphate (bacterial-induced struvite), uric acid, and cystine. Calcium-containing stones constitute 75 to 80% of all renal stones.[63,64] Nephrolithiasis is associated with hypokinesia, and the risk correlates positively with bed rest.[65] Several physiological and environmental aspects of space flight, especially microgravity, can contribute to an increased risk of nephrolithiasis. Reviewed extensively elsewhere, these risk factors include diminished urine volume and increased urinary excretion of calcium, phosphate, sodium, and potassium. In addition, concentrations of urinary citrate, which normally serves to inhibit stone formation through forming complexes with urinary oxalate, is lower immediately after flight than before, as is urinary pH, both of which further increase the potential risk of stones forming.[66,67] Studies are underway to measure amounts of the constituents during flight in order to better characterize the specific risk of stone formation associated with microgravity.

The symptom complex of acute nephrolithiasis is familiar to most clinicians, consisting of moderate to severe pain in the flank, costovertebral angle, or lateral abdomen. Pain is typically colicky (spasmodic) but can be steady, and may radiate to the ipsilateral genital area. Nausea and vomiting are common, and bowel sounds may be diminished. Autonomic stimulation due to pain can cause mild hypertension and tachycardia. Frank or occult hematuria is almost always present. White blood cell count may be slightly elevated, but values greater than 15,000 per µL are suggestive of concomitant infection, especially in combination with a temperature above 38°C. Although several disorders can mimic urolithiasis on Earth (e.g., renal infarct, tumors, papillary necrosis, and others), the odds are overwhelming that suggestive symptoms represent true stone disease in such a heavily screened population in a high-risk environment. In addition to the acute clinical presentation, nephrolithiasis also can be diagnosed presumptively on the basis of routine periodic in-flight urinalyses, such as those conducted with chemical strips every 30 days aboard Mir, that show new or progressive hematuria.

The "gold standard" diagnostic method for nephrolithiasis is radiological evaluation with plain abdominal films and with an intravenous pyelogram. These methods are not expected to be available in flight for the foreseeable future, and thus the diagnosis will be based on clinical presentation, physical examination, and limited laboratory results, such as urine dipstick and white blood cell count. Adjunctive measures that might be available on long-duration platforms would include urine pH and microbial analysis. Ultrasonography, if available, would allow larger stones and obstructive hydronephrosis to be visualized.

The approach to the patient in space should begin as it does on Earth, with aggressive pain control (which usually requires parenteral narcotics) and hydration; significant vomiting requires intravenous hydration with crystalloids and perhaps parenteral antiemetic drugs. This treatment should be considered as the minimum capability that should always be available for long space flights. Anticholinergic and spasmolytic agents can be used but are of questionable value. Urine should be cultured if feasible, and should be strained to try to retrieve any stone(s) for later analysis on Earth. Stones tend to be passed spontaneously in approximately 90% of acute episodes of nephrolithiasis; thus, control of pain, hydration status, and vomiting usually are all that is required. Failure to pass a stone within 48 hours would be grounds for return from LEO, because of the risks of ureteral obstruction and obstructive nephropathy. Definitive treatment would include ureteral intervention or extracorporeal shock-wave lithotripsy. Stones smaller than 5 mm in diameter usually pass spontaneously, but those greater than 8 mm rarely do[68]; however, without diagnostic imaging, the prognosis must be based on clinical trends. Fever, high white blood cell counts, and significant pyuria are suggestive of infection and potential urosepsis, and as such constitute cause for promptly returning the afflicted crewmember to Earth.

The disposition of a crewmember who spontaneously passes a stone depends on many factors. On Earth, after an initial presentation of nephrolithiasis, the probability that another stone will form eventually ranges from 50 to 70%.[69,70] Moreover, additional stone(s) may be present but not yet mobilized. Contributing factors can be reduced by increasing oral hydration and decreasing dietary oxalate. Treating individuals with hypocitraturia with potassium citrate can protect against recurrence of stones,[71–73] and could be useful during flight if hypocitraturia is verified. In the future, using biphosphonates to reduce the hypocalciuria associated with microgravity-induced bone loss may be effective for both primary prevention and preventing recurrence. For a relatively uncomplicated event, with spontaneous stone passage and no more than a few weeks remaining in the mission, maintaining a crewmember on-orbit with a combination of the above methods is reasonable. On the other hand, acute nephrolithiasis, complicated by prolonged course for passage and even mild urinary tract infection, especially near the beginning of a long mission, is cause for "non-urgent" Earth return at the next available opportunity. A crewmember with isolated, asymptomatic, progressive hematuria should be assumed to have passed a stone until definitive imaging can be conducted.

The effect of acute nephrolithiasis on a mission can be profound. Because microgravity seems to increase the risk of forming stones, the prospect of extended travel outside of LEO underscores the need for better physiological characterization of this risk and development of effective countermeasures. Methods of imaging and intervention also should be developed and tested for on-site use so as to provide "end-to-end" management.

D. Infectious Disorders

Current flight operations include several measures to prevent infectious diseases among space crews. In the Shuttle and Mir programs, general access to crewmembers is limited during the final few weeks before launch to individuals who must be demonstrably free of disease. During the week before launch (a period that covers the incubation period of the most common viral illnesses), crewmembers are quarantined and access to them is restricted. Once a crew reaches orbit, the possibility of new pathogens being introduced comes only from visiting crews or cargo vehicles. Changes in the autogenous microflora of crewmembers, and changes in the microbial composition of atmospheric and surface samples, noted during long flights have led to the conduct of periodic sampling, microbial analysis, and disinfectant wipe-downs. No increased risk of infectious diseases has yet been seen in flight,[74] but some evidence exists to suggest that the risk of infectious disease can be influenced by the space flight environment.

Decrements have been noted in several aspects of immune function after space flight (Volume III, Book 2, Chapter 6). Although these decrements thus far have been subclinical, Konstantinova has described a syndrome of transient immune deficiency characterized at the cellular level by disturbances in lymphocyte locomotion, diminishments in the ability of natural killer cells to recognize targets, and reductions in lymphocytic responses to mitogens.[17] Others have reported dysfunctions in human T lymphocyte and monocyte activity.[18,19] Cell-mediated immunity, as assessed by cutaneous tine test, seems to be blunted after even brief Space Shuttle missions[75] as well as after longer flights[16] relative to terrestrial controls. Attributing all of these observations to microgravity is difficult, however, since physical and psychological stress are independently associated with down-regulation of lymphocyte activity.[76]

Aside from the observed immune system anomalies, the possibility of shifts in the infectious organisms themselves must be considered. In one experiment, a strain of *Escherichia coli* grew better aboard a brief Space Shuttle mission than on the ground in the presence of the antibiotic dihydrostreptomycin.[77] This finding suggests that even short flights may be associated with antibiotic resistance. Longer flights may well allow the emergence of more aggressive and resistant strains of some human pathogens, either through primary mutation or through selectivity resulting from inadequate treatment with antibiotics. Colonization of an air or water system in a space habitat with a pathogenic organism such as *Legionella* or *Staphylococcus* could be disastrous if sufficient means for identification and remediation are not in place.

The medical response to most of the clinically significant infectious disorders during space flight, such as upper respiratory, urinary tract, and skin infections, will follow terrestrial practices, with a few caveats. The onboard formulary will be limited, so care must be taken in deciding to administer antimicrobial agents and selecting the proper agent. For long missions, the ability to culture organisms for microbial identification and antibiotic-sensitivity testing on board should be considered mandatory. In this way, positive identification of organisms and use of the best available antibiotic can help prevent the emergence of resistant strains. Most common infectious disorders may be treated with oral and topical medications. However, as noted earlier in this chapter, the pharmacodynamics of many drugs may be different in space vs. on Earth. A clinical presentation suggestive of even early sepsis should prompt the immediate use of parenteral antibiotics. The availability of a limited store of broad-spectrum parenteral antibiotics, which will probably require refrigeration, would be considered highly desirable in LEO and mandatory for long-term excursions out of LEO.

E. Trauma

Patterns of trauma will undoubtedly reflect the character of the particular space flight environment, i.e., whether it is an LEO platform or a planetary surface. As is the case for most occupational health settings, most of the expected traumas will be musculoskeletal, and most of those will be soft-tissue injuries. The most common traumas on Earth, major bone fractures, tendon and ligament injuries, and head trauma, arise largely from forces associated with falls and motor-vehicle collisions, which of course will not be present in microgravity. However, sprains and strains could be induced during EVA, especially during activities that involve manipulating large objects from fixed positions. For example, recovering satellites or assembling equipment while restrained at the feet can produce forces that are concentrated at the ankle, with the body acting as a moment arm. Soreness and fatigue in the wrists and hands have been reported,[78,79] and frequent entry and exit from foot restraints can generate considerable soreness in the lateral knee joints.[79] Other patterns of muscle-strain injuries can result from resistive exercise. Small bone fractures could result from being crushed between a structural member and large moving mass. Avulsion fractures associated with tendon strains also are possible.

Activities on planetary surfaces will produce injuries that more closely resemble terrestrial patterns. Even the 1/6 and 1/3 *g* of the lunar and Martian surfaces, respectively, could be offset by the heavy suits and life support packs worn during EVA. Specific activities such as excavating and extracting surface samples can generate straining forces, as noted during the Apollo lunar missions (Fig. 12). Musculoskeletal deconditioning from prolonged exposure to microgravity before surface EVAs will only increase the risk of injury. Although the extent of bone loss probably would not be sufficient to increase the fracture potential, even after several months of flight, the microdamage associated with repetitive bone trauma can cause fractures even if the actual mechanical stress is well below the ultimate strength of the bone.[80,81] Thus, stress or fatigue fractures, particularly of the feet, may pose concern for a vigorous EVA schedule on the Martian surface, after several months of space travel. Changes in body mechanics and positional awareness in microgravity also can contribute to the risk of injury.

The initial response to musculoskeletal injuries in space flight must involve careful consideration of the force that generated the injury. Questioning the crewmember with regard to circumstances, pain experienced, and whether popping or breaking sounds were noted will help characterize the injury. Inspection of the injured area for associated surface trauma, deformity, ecchymosis or purpura, and swelling, and physical examination for joint stability, point tenderness, and distal neurovascular integrity will be central in diagnosis and treatment, as they are on Earth. Radiography and advanced imaging systems may be available on future platforms; however, the physical findings alone may have to suffice. Treatment would consist of resting or unloading the injured limb or area, and applying compression bandages and cold packs to minimize swelling. Pain medications and anti-inflammatory agents can be used for comfort. Splints should be available for application as indicated. In remote planetary settings, more extreme fractures and dislocations may require surgical intervention.

The disposition of injured crewmembers will depend on both the setting (i.e., spacecraft vs. outpost) and the expected recovery time. An injury to a lower extremity, e.g., an ankle sprain from an EVA-related foot-restraint injury, can be treated conservatively and the crewmember returned to normal intravehicular duties fairly quickly. Some countermeasures and assessment activities must be avoided, such as treadmill running and lower body negative pressure. A complicated injury that would preclude participation in exercise countermeasures for many weeks could be cause to consider non-urgent Earth return at the next available opportunity. In more remote settings, treatment and gradual rehabilitation would be required on site, with the injured crewmember’s duties being shifted to minimize the effect on the mission.

Various other somewhat less likely incidents can produce a wider spectrum of trauma. In microgravity, minor contusions, abrasions, and lacerations may result from crewmembers bumping into hard surfaces or sharp edges. Deep lacerations and penetrating trauma can result from rupture of a pressure vessel that contains compressed gas or propellant. Burns from heated surfaces or equipment or from fires also are possible. Working on planetary surfaces further widens the spectrum to include the possibility of falls. The ability to perform simple wound repair and management (e.g., cleansing, suturing, and bandaging) is necessary in all space flight settings. Appropriate antimicrobial agents for treating bites from laboratory animals should be provided on missions that include animals. In LEO, major trauma events are best handled by stabilizing the affected crewmember’s condition and returning him or her to Earth as quickly as possible. Maintaining the risk to the crew at levels similar to those in the LEO environment will require that medical facilities outside LEO include the capability for basic surgery as discussed earlier (Section IV.E.1).

F. Toxic Inhalation

In spacecraft atmospheres, crewmembers are exposed to trace levels of many airborne constituents, primarily those off-gassed from onboard materials, for much longer periods that those typical of most terrestrial work settings.

Concentrations of these constituents usually are well below toxic thresholds.[82] However, leaks in storage vessels or conduits, fires, or mishaps can inadvertently release toxic amounts of chemicals or particulates into the cabin atmosphere. Toxic agents can include propellants and oxidizers (e.g., hydrazine, monomethylhydrazine, nitrogen tetroxide, and hydrogen peroxide); coolants (e.g., ammonia and synthetic fluorocarbons); combustion products (e.g., carbon monoxide, hydrogen cyanide, and hydrogen chloride); and experimental agents such as tissue fixatives (e.g., formaldehyde and glutaraldehyde), metallic oxides from industrial furnace experiments, and chemical solvents. Minor spills and combustion incidents have occurred in the U.S. space program; one of the more serious incidents involved an Apollo crew being exposed to toxic amounts of nitrogen tetroxide during return to Earth, which led to chemical pneumonitis and hospitalization.[83]

Onboard detection equipment and knowledge of the circumstances regarding the incident should help with identifying the agent and the specific treatment measures. Contaminants with a characteristic odor, such as ammonia or smoke, can be identified quickly by the crew; generic responses would include donning a safe-breathing source, leaving the exposure area, and shutting off or modifying the operation of the affected system. Afflicted crewmembers should be given 100% oxygen immediately, and their level of consciousness, vital signs, and level of respiratory distress determined. Although each toxic agent produces its own spectrum of clinical insult, several common management points should be emphasized.[84] If upper airway obstruction from laryngeal edema or laryngospasm is present, advanced airway management will be needed. Also possible are acute tracheitis, bronchitis, and bronchiolitis, which can be complicated by bronchospasm or pulmonary edema. Systemic effects from absorption of toxins also should be considered.

Factors useful in predicting the development of injury patterns from inhalation of a toxic agent include its concentration and the duration of exposure to it, its chemical reactivity, and its solubility in water. Highly water-soluble agents, such as ammonia and hydrazine, react immediately with mucous membranes of the oropharynx and upper airways as well as with eye surfaces. The clinical syndrome associated with exposure to these kinds of agents appears quickly and can be assessed quickly as well, and the decision can be made readily as to whether the exposed crewmember can be maintained on a LEO platform or should be evacuated to Earth. Conversely, agents that are much less water-soluble, such as the commonly used oxidizer nitrogen tetroxide, react minimally with the upper-airway mucosa and can create a more diffuse pattern of alveolar injury with delayed onset.[84,85] Careful observation over several days may be required to determine the disposition of an exposed crewmember under these circumstances.

With regard to patient assessment, sequential chest examinations may reveal early reactive wheezes or progressive rhonchi. Transcutaneous pulse oximetry and pulmonary spirometry, both simple and effective techniques that already have been used in space flight, can be very helpful in following the clinical trend and determining a course of action. Arterial blood gases also would be helpful, and will probably be available in on-site medical systems within the next few years. Chest radiography may be useful in the event of non-cardiogenic pulmonary edema or adult respiratory distress syndrome (ARDS), but this capability is not available in space flight. Because few inhalational toxins have true antidotes, on-site therapy will be largely supportive. Oxygen, titrated to pulse oximetry and clinical factors, should be used until improvement is noted. Bronchodilators may be helpful in bronchospastic conditions, but corticosteroids are of questionable value for inhalation injury. Treating ARDS generally requires ventilatory support with positive end-expiratory pressure; thus, the operational use of toxic agents in a remote setting from which Earth return is not available mandates that advanced airway management and ventilatory-support capabilities be included in the on-site medical facility.

G. Decompression Disorders

As noted earlier in this chapter, the major risk of decompression disorders in space flight is associated with EVAs. DCS can be viewed as an expected—albeit infrequent—consequence of even routine pressure reductions, as is true for high-performance aviation and diving environments. Aeroembolism and ebullism result from inadvertent, rapid pressure reductions in contingency situations, such as a suit being ruptured against a sharp edge or by a misplaced digging implement on a planetary surface. Rupture and pressure loss in a habitable module, a much less likely—but catastrophic—event, would affect several crewmembers and produce any combination of decompression disorders. Just as appropriate diagnostic and treatment plans must be provided for aviation and diving operations, so must these capabilities (or viable plans for transport to treatment) be available for space missions.

DCS arising during EVA should not be difficult to diagnose, given the circumstances of pressure reduction and symptom development. Most DCS cases involve only pain, which typically is located in or near joints that are used actively during the period of reduced pressure. Symptoms can range from mild “awareness” to incapacitating pain. For EVAs in LEO, joints of the shoulders, arms, wrists, and hands are the most active, and may be the most vulnerable because of the need to work against the suit pressure, especially while handling large masses. Musculoskeletal pain must be differentiated from true DCS. Signs and symptoms suggestive of DCS include unilateral rather than bilateral joint involvement, a deep ache, resolution upon return to normal cabin pressure, relief from local application of pressure (e.g., with a blood pressure cuff), and response to hyperbaric treatment. Peripheral nerves may be involved to yield mild paresthesias, and a pruritic rash may arise; both are considered mild manifestations and usually resolve upon return to sea-level pressures.

Fortunately, the more serious manifestations of DCS are rare. Pulmonary DCS or “chokes” arising from multiple pulmonary emboli present as substernal chest pain, dyspnea, and nonproductive cough. Central nervous system involvement generally is characterized as either brain or spinal cord DCS. Brain DCS is more often associated with altitude exposures, and can present as multiple deficits in sensory, psychological, and motor functions, often accompanied by headache and visual disturbances. Spinal cord DCS, typically associated with diving, results from congestive infarcts as blood-bubble interactions occlude drainage of venous plexi; signs and symptoms reflect the location of spinal cord injury. Significant neurocirculatory alterations can produce characteristic skin mottling (“cutaneous marbling”). Untreated pulmonary or central nervous system DCS can lead to general circulatory collapse, with significant loss of intravascular volume through heavily damaged vascular endothelium. For the EVA crewmember, pressure excursions would more closely reflect those typical of aviation; however, microgravity may affect fluid distribution and circulatory drainage in ways that resemble water immersion.

As of this writing, the most severe manifestation of DCS during space flight has been pain-only. Terrestrial data on the incidence of DCS cannot be applied directly to space flight because of the effects of microgravity and the global physiological response to it. Nevertheless, altitude DCS probably best approximates the distribution of symptoms. In one study of 447 instances of DCS resulting from altitude-chamber exposure, 83.2% involved musculoskeletal manifestations, 2.7% involved pulmonary DCS or chokes, 2.2% had skin manifestations, 10.8% had paresthesias, and 0.5% presented with frank neurological DCS.[86]

The medical response to DCS during space flight will depend on the availability of HBO. Once DCS is suspected during an EVA, the operation should be terminated as soon as possible and the crewmember returned to cabin pressure and given 100% oxygen by mask. In a review of 175 cases of pain-only DCS resulting from altitude-chamber exposure, 135 resolved with sea-level oxygen (2 hours of breathing by mask), but 40 did not respond and required HBO. Of the 135 who responded, 8 experienced recurrence of symptoms and required HBO; thus, 127 of 175 cases (71%) resolved completely without HBO.[87] For a crewmember with pain-only DCS who does not respond to 100% oxygen, additional pressure can be provided by sealing and pressurizing an EVA suit as well as the cabin pressure. The Space Shuttle EVA suit can be pressurized beyond its normal 0.29 atm to 0.55 atm; increasing the cabin atmosphere to a maximum of 1.09 atm thus would provide a total treatment pressure of 1.64 atm.

If on-site HBO capability is not available, a crewmember in LEO with pain-only DCS that does not resolve with the above measures, or with DCS that involves the circulatory, pulmonary, or central nervous systems, should be considered for Earth return as soon as possible for definitive HBO treatment. Delays in providing treatment correlate with poorer outcomes.[48] An on-site chamber could preclude such an evacuation, and should be considered mandatory in circumstances in which ready evacuation is not feasible.

Aeroembolism, with sudden, often severe neurological impairment, should be considered in the presence of rapid decompression. A crewmember whose suit ruptures and loses pressure will be unconscious, and must be transferred to an airlock and repressurized as soon as possible. If repressurization takes place within a very few minutes but the crewmember does not regain consciousness, then cerebral aeroembolism should be assumed until proven otherwise; such an individual should be considered critically ill, and immediate HBO treatment is indicated. Vigorous intravenous hydration with balanced or isotonic saline solutions is recommended to overcome hemoconcentration; pharmacological doses of steroids also may be helpful.[88] In a gravitational field, the afflicted crewmember should be placed in the left lateral head-down position to limit cerebral migration of circulating bubbles; in microgravity, of course, such positions are useless. Any on-site hyperbaric chamber must be able to accommodate a CMO and supportive medical hardware, including airway management and ventilatory support. If HBO capability is not available and Earth return from LEO is possible within a few hours, the patient should be stabilized for transport as quickly as possible, i.e., intubated and provided with ventilatory support, a cardiac monitor, and intravenous hydration. In a more remote setting without HBO facilities or rapid return capability, the prognosis for cerebral aeroembolism is decidedly poor.

Ebullism beyond localized tissue exposure, e.g., from a loss of suit pressure during EVA, will produce immediate anoxia and unconsciousness, with the only hope for reversal being rapid repressurization. The skin will be distended from expansion of subcutaneous gas; distension of the abdomen could be accompanied by vomiting, urination, and defecation caused by the rapid expansion of gastrointestinal gas.[89] Vomiting produces the hazard of aspiration and chemical pneumonitis. The condition may be complicated further by cerebral aeroembolism, manifested by persistent unconsciousness in spite of rapid repressurization. Ebullism is probably best treated with HBO,[46,47] although no standardized approach is available.

How soon a crewmember can return to duty after a decompression-related disorder should reflect the severity of the incident. For a simple, pain-only bends event that either resolves completely upon return to a pressure environment or responds rapidly to HBO, return to intravehicular duties within 24 hours, with no pressure excursions allowed for at least 72 hours, is reasonable. (This latter recommendation agrees with those of the U.S. military aviation and space administrations.) Recurrence of decompression symptoms when operating within normal decompression guidelines should require ground consultation and possibly limitation of further reduced-pressure activity for the rest of the mission. Anything beyond simple pain-only bends should be treated more conservatively, with at least 30 days between the resolution of symptoms and any further exposure to reduced pressure. Return to duty after aeroembolism or ebullism events must be considered on a case-by-case basis, and depends on the medical outcome of the primary incident.

Other disorders related to pressure excursions include barotitis media and alternobaric (pressure) vertigo. Barotitis, also known as “ear block,” occurs during increases in atmospheric pressure, e.g., during repressurization in an airlock after EVA. If equal pressure is not maintained between the middle ear and ambient atmosphere via the eustachian tube, the resulting pressure differential can cause local inflammation and transudation. Severe differentials can cause hemotympanum or rupture the tympanic membrane, with resultant tinnitus and conductive hearing loss. A pressure differential that exceeds 80 or 90 mm Hg may exceed the capacity of the small palatal muscles at the pharyngeal end of the eustachian tube[90]; without intervention (such as forced Valsalva or Politzer maneuvers), trauma to the middle ear is likely. Pressure differentials in the middle ear can also lead to episodes of alternobaric vertigo, which usually are transient.

After an EVA, crewmembers must maintain equalization throughout repressurization, which may require frequent swallowing, occasional Valsalva maneuvers, and perhaps slowing the rate of repressurization. Any condition that might hinder equalization, such as upper respiratory infections or rhinitis of any etiology, may be cause to defer an EVA. The headward fluid shift that accompanies adaptation to microgravity may increase the risk of ear block, and special attention should be given to the ability to perform adequate Valsalva maneuvers. Topical nasal sprays containing sympathomimetics may be helpful in treatment and prevention, and should be available for all flights that might include EVAs. CMOs on all space flights should be trained and equipped to examine the tympanum and to take appropriate actions or relay their findings to ground specialists.

H. Cardiac Dysrhythmias

Several types of dysrhythmia have occurred during microgravity exposure, with some episodes apparently related to specific events such as EVA, exercise, and LBNP. Observed dysrhythmias have ranged from premature ventricular contractions (PVC) to sustained ventricular bigeminy and atrial quadrageminy.[91] Potential contributing factors include changes in fluid and electrolyte status, workload, and psychological stress. None of these rhythm disturbances have been considered malignant, nor have any been proven to occur more frequently during flight than on Earth. However, one Russian cosmonaut was returned from the Salyut-7 space station earlier than planned after an intermittent cardiac dysrhythmia appeared during an EVA.[92,93] This rhythm disturbance resolved completely upon return from microgravity, and it is unclear whether the dysrhythmia reflected a change in cardiac conduction related to the flight environment.

Electrocardiographic monitoring during physically stressful events, with simultaneous transmission to Earth, could alert onboard and ground crews in the event of a threatening dysrhythmia, and allow prompt termination of the activity. The ability to conduct a standard 12-lead electrocardiogram during symptoms suggestive of dysrhythmia (e.g., resting tachycardia or palpitations) should be considered essential and will help determine the underlying cause of such dysrhythmias. Because the electrocardiogram is sensitive to a variety of metabolic and other physiological conditions, the ability to evaluate these conditions should be considered in the treatment algorithm. For example, a general flattening of waveforms might suggest hypokalemia; the ability to confirm this possibility with laboratory blood analysis would allow potassium repletion, which presumably would resolve the underlying problem. The ability to treat certain malignant dysrhythmias (e.g., ventricular tachycardia or fibrillation) definitively with d.c. countershock also should be considered essential for remote settings. Cardiac monitors/defibrillators are now being tested for potential inclusion in on-site medical facilities.

I. Acute Exposures to Ionizing Radiation

Radiation is omnipresent in space, and radiation exposure remains the single most important factor that could limit human exploration of space beyond LEO. Providing adequate protection for crews requires shielding of enormous mass in order to limit exposures to anywhere near terrestrial-normal values. The character and biological effects of space radiation are described in detail elsewhere in the *Space Biology and Medicine* series (Volume III, Book 2, Chapters 17 and 18). Briefly, the primary sources of space radiation include background galactic cosmic radiation (high-energy protons, alpha particles, and a small fraction of heavy nuclei), geomagnetically trapped radiation (primarily protons and electrons), and solar particle events (SPE) associated with solar flares (primarily protons, with a small percentage of alpha particles). Spacecraft in LEO are protected from SPE by the same magnetic fields that trap and hold the radiation belts. The dipolar orientation of the geomagnetic fields means that radiation dose increases in parallel with increasing altitude and increasing latitude. In fact, LEO could be defined in practical terms as the range of altitudes bordered by unacceptable atmospheric drag (below) and unacceptable radiation (above).

Clinical manifestations of radiation exposure can be expressed as delayed effects or acute syndromes. Delayed effects result from chronic, low-level cumulative exposure or from an acute but survivable event, and can include tissue damage, fertility impairment, lens opacification, and cancer induction. The cancers observed include leukemias (primarily acute lymphoblastic, and myeloblastic and chronic granulocytic), which appear 7 to 15 years after exposure, and solid tumors of the breast, lung, gastrointestinal tract, lymphoid system, and various sarcomas, which appear several decades after exposure.[94] Both the U.S. and the Russian space programs try to limit the incidence of delayed effects by setting and following strict career limits for radiation exposure. Delayed effects are not expected to appear during any crewed mission in the foreseeable future; thus, this section focuses on acute radiation exposures and their medical management during a mission.

Although the most common acute radiation incident in industrial settings involves local skin exposure,[95] acute events in the space flight environment will most likely involve whole-body exposures from SPE. Aboard an LEO platform in a low-inclination orbit, significant SPE could be barely detectable. However, a geosynchronous platform or a transplanetary spacecraft outside the geomagnetic field is highly exposed, and the dose delivered to the crew will depend entirely on shielding. A major flare, like that of October 1989, could impart a dose of a few to several tens of rem to blood-forming elements over a 2-day period in areas shielded with the equivalent of 5–10 g/cm^2 of aluminum; no shielding would result in doses of a few hundred rem.[96] The worst case with regard to radiation exposure would be the dose delivered to a crewmember outside the spacecraft during such an event, since the shielding in spacesuits is minimal. Planetary shielding cuts the dose on the lunar surface to half of that in free space, but the lack of a protective atmosphere and the presence of a negligible magnetic field still make the lunar surface a hostile radiation environment. The thin Martian atmosphere, which consists mostly of carbon dioxide at a pressure of about 7 mm Hg, affords protection equivalent to that of 16 g/cm^2 aluminum; an SPE might impart a dose equivalent of 10 rem to blood-forming elements.[97] In all settings, preventing exposure is paramount, and ground and flight-based radiation detectors will be used to monitor solar emissions and prompt crewmembers to seek shelter in the best-shielded areas when those emissions rise. For in-flight and orbital stations, the best-shielded areas will be the heaviest available structural barrier; for lunar and planetary surfaces, the best-shielded areas will be subsurface structures shielded by available regolith.

The clinical presentation of acute whole-body exposures correlates roughly with the dose received, although individual reactions vary.[98] Table 8 lists some of the clinical findings associated with various doses of ionizing radiation, and can be used as a guide for management and prognosis. However, given the global physiological changes induced by the weightless environment, especially anemia and immune suppression, these symptomatic thresholds and dose-response relationships may not be the same for long-duration space travelers. A tremendous amount of investigative work is needed in this area.

Differential diagnosis of acute, whole-body radiation exposure should not be difficult if means of radiation detection were in use. Personal dosimeters and tissue-equivalent dosimeters that estimate the biologic effects of radiation should provide vital information as to what dose was absorbed and what clinical spectrum should be prepared for. In general, acute radiation exposures can cause three broad dose-related syndromes: hematological, from a 100- to 600-rad dose; gastrointestinal, from 600–2000 rad; and central nervous system, from more than 2000 rad.

A constellation of prodromal signs and symptoms known as acute radiation syndrome (ARS) also can be present, with severity related to total dose. ARS includes nausea, vomiting, occasional diarrhea, fatigue, and weakness.[98,99] Other potential findings include dizziness, malaise, abnormal sensations of taste and smell, irritability, and insomnia.[96] Some manifestations of ARS can resolve in one or two days, to be followed by a latent period of a few days to several weeks. Bone-marrow suppression, with destruction of stem cells and granulocytes, typically is expressed by clinical signs of infection and hemorrhage, and is associated with an expected nadir at 4 to 6 weeks after exposure. The LD_{50}, the dose at which 50% mortality can be expected, is 450 rad with optimal treatment; 90% mortality (LD_{90}) is expected at 700 rad.[98] Humans exposed to doses that lead to the gastrointestinal and central nervous system syndromes rarely survive long enough to develop the hematological syndrome.

Because lymphocyte counts fall in the first 1–2 days after exposure, the lymphocyte count after 48 hours may be useful as a prognostic index. Lymphocyte counts above 1200 per µL indicate good prognosis; those below 300 are associated with poor prognosis and high mortality.[98] The gastrointestinal syndrome can be associated with significant intravascular volume loss, with hemoconcentration and electrolyte imbalance. Evaluating circulating white blood cells for chromosomal abnormalities (biodosimetry) gives another indication of the severity of exposure. As the nadir in marrow-cell population approaches, the numbers of red cells, white cells, and platelets drop as well, and clinical microbial cultures show infections that can range from mild to overwhelming sepsis.

In the space flight environment, single events that involve doses of 1000 rad or more would be very unusual; moreover, treatment after such a dose would be palliative given the grim prognosis, whatever the level of care available. The more likely events that might give rise to hematological syndromes should be given the most attention in planning missions out of LEO, with plans for either on-site treatment or return to Earth. Planning should consider multiple casualties, i.e., an entire spacecraft crew or a smaller surface-EVA crew.

Because the hematological syndrome can be self-limiting, treatment is oriented toward overall physiological support until the marrow can regenerate. This may require several months after the nadir of stem-cell production, and may be incomplete.[94] Managing marrow pancytopenia and immune suppression may require microbiological isolation, transfusions of blood fractions, provision of intravenous fluids and electrolytes, and broad-spectrum antibiotics. Advanced treatment modalities include bone-marrow transplant and infusions of granulocytes and granulocyte-macrophage colony-stimulating factor.[94,96,99]

Victims of significant whole-body radiation exposure would require treatment modalities that are highly demanding of resources, supplies (many of which have limited storage lives), and expertise. Clinical management of any exposure beyond 100–200 rad probably would quickly overwhelm the resources available on a crewed space platform, and thus the patient would be best managed in terrestrial facilities. The latent period between exposure and illness represents a clinical and operational period during which the patient(s) should be monitored with sequential blood counts and returned to Earth; this should be the approach to treating individuals exposed in near-Earth space or on the lunar surface. (Parenthetically, people who are exposed to radiation are irradiated, not contaminated; thus, they pose no hazard to people who treat them, whether on site or after return to Earth.)

Events occurring in more remote settings (such as en route to Mars) from which timely return to Earth is not an option pose a major challenge for medical management. Again, the main emphasis must be aimed at detection and shielding in order to avoid and minimize exposures. However, plans for responding to exposures of a few hundred rem should be in place. Complete documentation of the event should be undertaken, including time of exposure, shielding, and all available radiation dosimetry. The initial evaluation of the patient(s) should include the most complete possible physical and laboratory examination. Notably, most radiation exposures in this range will not result in any abnormal physical findings, aside from possibly some signs of ARS. Laboratory examination should include blood counts and samples for leukocyte cytogenetic analysis. New methods and equipment would be needed to support this capability at an onboard facility. Results then could be relayed to ground specialists, who can best predict the ensuing clinical syndrome.

Because several if not all members of a crew may be affected to varying degrees, resources for supporting crew panmyelosuppression should be provided accordingly. These resources would include sterile fluids for injection (stored or locally produced), broad-spectrum antibiotics for opportunistic infections, and lyophilized preparations of blood-modulating agents such as colony-stimulating factors and interleukins. Autologous donations of stem cells and other blood fractions might be maintained for each crewmember in a radiation-hardened freezer, to be used for autologous marrow transfusions should the need arise. Methods of extending storage life and decreasing transit time en route may make such blood components a viable treatment option. Methods such as these represent a realistic medical response using currently available concepts, and such equipment and resources as might be required for a single SPE constitute a reasonable inclusion in the on-site capability. Failure of these methods can create a situation that must be regarded as an unlikely but acceptable risk; even a single case of overwhelming sepsis with circulatory shock will be beyond the scope of a space medical facility for many years to come.

VI. Conclusions

In addition to describing progress made thus far in medical support for crewed space flight, this chapter was intended to highlight the tremendous amount of work still needed to carry standard methods of medical practice into the future of space exploration. In particular, leaving LEO for permanently staffed lunar or Mars settlements (Fig. 13) will require considerable expansion of the on-site medical capability. As space becomes more of a workplace and less of an expeditionary setting, the eventual outcome will be a near-terrestrial standard of care.

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Table 4 Contents of the Shuttle Orbiter Medical System, excluding drugs[a]

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*Medications and Bandages Kit**

- Ace bandage
- Adaptic bandages
- Alcohol wipes
- BandAids™
- Benzoin swabs
- Cotton swabs
- Data logs
- Gauze pads, 4x4 inch
- Eye pads
- Eye patch, metallic
- Kerlix roll dressing, 4.5 inch
- Kling roll dressing, 3 inch
- Injector (Tubex™)
- Magnifying glass
- Pope otowicks
- Silver nitrate sticks
- Splint, finger
- Steri-Strip™ skin closures
- Tape, Elastoplast
- Tegaderm™ skin dressing
- Telfa™ pads

Emergency Medical Kit

- Ace bandage
- Air-temperature monitors
- Airway Management Kit
- Alcohol wipes
- BandAids™
- Blood-pressure cuff
- Butterfly infusion sets
- Catheters, intravenous, 18 & 20 Ga

Emergency Medical Kit, cont'd

- Chemstrip 7™
- Cotton balls
- Dental kit
    - Carver/file
    - Mirror
    - Needles, 27 Ga
    - Orangewood sticks
    - Syringe
    - Temporary filling
    - Toothache kit
        - Eugenol anesthetic
        - Tweezers
        - Cotton pellets
    - Bupivacaine (Marcaine™)
    - Drape, sterile
- Flourescein strips
- Forceps, blunt
- Gauze pads, 4x4 inch
- Gloves, nonsterile surgical
- Gloves, sterile surgical
- Hemostat
- Injector (Tubex™)
- Intravenous infusion set
- Nasal packing, merocel pope
- Needles, 22 & 18 Ga
- Operational bioinstrumentation system
- Ophthalmoscope
- Otoscope
- Scissors, curved
- Scalpels, no. 10 & 11
- Skin-temperature monitors

Emergency Medical Kit, cont'd

- Stethoscope
- Surgical instrument assembly
    - Forceps, small point
    - Needle holder
    - Hemostat, small
    - Scissors, curved
    - Tweezers, fine point
- Sutures, with needles:
    - 4-0 Dexon; 5-0, 4-0, and 3-0 Ethilon; 2-0 Vicryl
- Swabs, Betadine™ (povidone-iodine)
- Syringes, 10 cc
- Thermometers, air, oral, and skin
- Tongue depressors
- Tourniquet (penrose tubing)
- Urine test strips

Contaminant Clean-Up Kit

- Bags, chemical-resistant
- Biohazard identification labels
- Gloves, chemical-resistant
- Gloves, sterile surgical
- Masks, surgical
- Shuttle emergency eyewash system

MAK, Medical Accessories Kit

- Ambulatory urine bag
- Catheter, Foley (urinary)
- Laryngoscope
- Lubricant, water-soluble

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[a] Medications are listed in Table 5.

Table 1 Medical events in crewed space flight

Common	One or a few reported cases
Space motion sickness	Urinary tract infection
Nasal or sinus congestion	Prostatitis
Constipation	Nephrolithiasis
Headache	Cardiac dysrhythmias
Back pain	• extrasystoles, bigeminy, quadrageminy, supraventricular tachycardia, ventricular tachycardia (sustained, asymptomatic)
Skin irritation or dryness	
Abscess	
Minor abrasions or contusions	Chemical pneumonitis
Musculoskeletal sprain or strain	Aspiration of foreign body
Corneal irritation or abrasion	Gastroenteritis
Upper respiratory infection	Decompression sickness (limb bends)
Insomnia	Eye trauma
	Contact dermatitis
	Spatial disorientation
	Serous otitis

Table 2 Contents of the Skylab Integrated Medical Support System, excluding drugs[a]

Item(s)	Kit	Use code
Accumulator assembly	Microbiology	A
Adhesive tape, Dermicel™	Bandage	A
Adhesive tape, Micropore™	Bandage	A
Air sampler	Bandage	--
Airways, pharyngeal	Therapeutic	A
Aneroid sphygmomanometer	Diagnostic	A
Applicator, dental	Bandage	A
Applicators, silver nitrate (12)	Bandage	A
Antibiotic lubricant	Catheterization	A
BandAids™ (100)	Bandage	A
Bandage kit	--	--
Barrier, sterile-field (2)	Minor Surgery	B
Batteries (8 ea. AAA, AA, C)	Diagnostic	A
Betadine™ squares (4)	Minor Surgery	A
Bili-Labstix Reagent Sticks™	Hematology/Urinalysis	A
Binocular loupe	Diagnostic	A
Blood lancets (75)	Hematology/Urinalysis	A
Calcium alginate balls (50)	Hematology/Urinalysis	A
Can opener	--	--
Cannula	Therapeutic	B
Capillary pipettes (50)	Hematology/Urinalysis	A
Catheter, urinary	Catheterization	B
Catheterization kit	--	--
Coagulase plasma	CSM Resupply	A
CO$_2$ accumulator assembly	Microbiology	A
CO$_2$ generators (24)	Microbiology	A
Collection bag (3)	Catheterization	A
Container, injectables	Therapeutic	B
Dental kit	--	A
Demerol™ injectors (5)	Therapeutic	A
Dermicel surgical tape	Hematology/Urinalysis	A
Diagnostic kit	—	A
Digital hand counter	Hematology/Urinalysis	A
Disinfectant pads (60)	—	A
Disposable bags (20)	Microbiology	A
Dressing boot (Unna's)	Bandage	A
Dressing, abdominal (6)	Bandage	A
Drug modules (2) / in-use drugs	Drug Supply Module	--
Drug supply kit	--	--
Elastic wraps (3)	Bandage	A
Elevator, dental	Dental	A
Endotracheal tube	Therapeutic	B
Eye patch, cotton (8)	Bandage	A
Eye patch, plastic (2)	Bandage	A
File	Dental	A
Filter strips (10)	Microbiology	A
Fluorescein strips (12)	Bandage	A
Forceps, 6-inch (3)	Microbiology	A
Forceps, mandibular, ant.	Dental	A
Forceps, mandibular, post.	Dental	A
Forceps, maxillary, ant.	Dental	A
Forceps, maxillary, post.	Dental	A
Forceps, mosquito	Minor Surgery	B
Forceps, splinter	Bandage	A
Forceps, tissue	Minor Surgery	B
Gauze, dental	Dental	A
Gauze, roller (6)	Bandage	A
Needles, hypodermic, continued		
18 gauge (2)	Therapeutic	A
20 gauge 4 inch (1)	CM Medical Kit	B
20 gauge (2)	Therapeutic	A
25 gauge (4)	Therapeutic	A
27 gauge - 13/16 - (3)	Dental	A
Neurological exam instruments	Diagnostic	B
Nozzle	Catheterization	B
Ophthalmoscope	Diagnostic	A
Otoscope	Diagnostic	A
Otoscope specula (33)	Diagnostic	A
Oxidase strips (25)	CSM Resupply	A
Petri dish, large (20)	CSM Resupply	A
Petri dish, small (20)	CSM Resupply	A
Pressure infuser assembly	—	B
Probe	Minor Surgery	B
Resupply container (2)	CSM Resupply	A
Retractors, skin and muscle	Minor Surgery	B
Scalers, curette	Dental	A
Scalpel, #10 (2)	Minor Surgery	B
Scalpel, #11 (2)	Minor Surgery	B
Scissors	Bandage	A
Scissors, sharp	Minor Surgery	B
Sedative restorative material (8)	Dental	A
Sensitivity disks	CSM Resupply	—
Ampicillin (50)	CSM Resupply	A
Cephalothin (50)	CSM Resupply	A
Erythromycin (50)	CSM Resupply	A
Gantrisin™[b] (50)	CSM Resupply	A
Penicillin G (50)	CSM Resupply	A
Tetracycline (50)	CSM Resupply	A
Sensitivity disk dispenser (3)	Microbiology	A
Silver-nitrate applicators (12)	Bandage	A
Slide dispenser (75 slides)	Microscope	A
Slide stainer	—	A
Slide streaker (2)	Drug Supply Module	A
Slide stainer expendables	—	A
Specific gravity refractometer	Hematology/Urinalysis	A
Specula, disposable	Diagnostic	A
Sphygmomanometer	Diagnostic	A
Splint assembly (4)	—	A
Sterile water (2)	CSM Resupply	A
Steri-strips™ (20)	Bandage	A
Stethoscope	Diagnostic	A
Stewart's transport media (58)	CSM Resupply	A
Streaking loops	Microbiology	A
Suture material, chromic catgut; 000 W / FS - 2 Needle	Minor Surgery	B
Suture material, dermal #5-0; W / FS - 2 Needle	Minor Surgery	B
Suture material, silk - 00	Minor Surgery	B
Swabs, cotton (24)	Bandage	A
Swabs, dry (20)	Therapeutic	A
Swabs, dry, for nasal and throat samples (18)	Microbiology	A
Swabs, dry, for illness (12)	Microbiology	A
Swabs, dry, for culture transport (48)	Microbiology	A

Table 2 Contents of the Skylab Integrated Medical Support System, excluding drugs,[a] continued

Item(s)	Kit	Use code
Gauze squares:		
4x4 (24), 2x2 (12)	Bandage	A
2x2 (20)	Minor Surgery	A
Gauze squares, w/Betadine™	Bandage	A
	Minor Surgery	B
Gauze, with Vaseline™ (6)	Bandage	A
Glass marking pencil (2)	Microbiology	A
Gloves, examination (2 pr)	Hematology/Urinalysis	A
Gloves, surgical (2 pr)	Catheterization	A
Glucose (2)	Therapeutic	B
Heat sink	CSM Resupply Module	A
Hematology/urinalysis kit	—	—
HemaCheck Slides™	Hematology/Urinalysis	A
Hemoglobin meter	Hematology/Urinalysis	A
Hemolysis applicators (50)	Hematology/Urinalysis	A
Hemostat	Catheterization	A
Hemostat, crile, curved	Minor Surgery	B
Hemostat, crile, straight	Minor Surgery	B
Hemostat, Kocher	Minor Surgery	B
Hemostat	Therapeutic	A
Hydrogen peroxide	CSM Resupply	A
Immersion oil bottles (3)	Microscope	A
Incubator	—	—
Injectables container	Therapeutic	A
Intravenous kit	—	—
Lancets (75)	Hematology/Urinalysis	A
Laryngoscope	Therapeutic	B
Lens (100x)	Drug Supply Module	A
Lens tissue	Microscope	A
Light bulbs (14)	Diagnostic	A
Loop holders (2)	Microbiology	A
Light source, head-mounted	Diagnostic	A
Microbiology kit	—	—
Microscope	Microscope	A
Microscope stage	Drug Supply Module	A
Minor surgery kit (2)	—	—
Mirror/light	Dental	A
Myringotomy knife	Diagnostic	B
Nasogastric tube	Catheterization	A
Needle holder	Minor Surgery	B
Needles, hypodermic 16 gauge (2)	Therapeutic	A
Swabs, wet, antibiotic-sensitive (48)	Microbiology	A
Swabs, wet, for body samples (18)	Microbiology	A
Swabs, wet, for environmental surface samples (90)	Microbiology	A
Syringe, dental	Dental	A
Syringe, epinephrine	Therapeutic	A
Syringe, plastic, 2 1/2 cc (2)	Therapeutic	A
Syringe, plastic, 50 cc w/needle (2)	Therapeutic	A
Syringe, 1 cc tubex holder	Therapeutic	A
Syringe, plastic w /needle, 50 cc (3)	Therapeutic	B
Syringe, 2 cc tubex holder	Therapeutic	A
Syringe, 5 cc	Therapeutic	A
Syringe, with needle, 1 cc (6)	Microbiology	A
Syringe	Catheterization	A
Taxos A disks (50)	CSM Resupply	A
Taxos P disks (50)	CSM Resupply	A
Therapeutic kit	—	—
Thermometer, oral (2)	Diagnostic	A
Three-way valve	CM Med. Accessory Kit	B
Tissue forceps	Minor Surgery	B
Tongue depressor	Diagnostic	A
Tourniquet	Hematology/Urinalysis	A
Towel	Catheterization	A
Tracheostomy equipment	Therapeutic	A
(Unna's) boot dressing	Bandage	A
Urinary catheter	Catheterization	B
Urine sample bag (6)	Microbiology	A
Valve, three-way	CM Med. Accessory Kit	B
Vaseline™ gauze (6)	Bandage	A
Velcro, sticky-back (6)	Hematology/Urinalysis	A
Vials (58)	CSM Resupply	A
Water, sterile (2)	CSM Resupply	A
Work table	—	—
Zephiran™ wipes (81)	Minor Surgery	A
	Hematology/Urinalysis	A
	Catheterization	A

[a] Medications are listed in Table 3. [b] Sulfisoxazole. A, no restrictions on use; B, requires physician approval for use

Table 3 Drugs in the Skylab Integrated Medical Support System

For use as needed (no approval required)

Analgesic (aspirin)
Antitussive syrup (Robitussin-DM™)
Laxative/stool softener (Peri-Colace®)
Lip balm
Lubricant gel (K-Y™)
Nasal decongestant (Afrin™)
Nasal moisturizer
Skin cream, anti-infective
Skin lotion, emollient (Alpha Keri™)
Skin ointment, anti-infective (Neosporin™)

Use requires physician approval

Acetazolamide (Diamox™)
Actifed™ (pseudoephedrine HCl & triprolidine HCl) (decongestant)
Aerosporin™ solution (polymyxin B sulfate) (anti-infective)
Ampicillin (antibiotic)
Ascodeen (aspirin/codeine)
Benadryl™ (antihistamine)
Cephalexin (Keflex™) (cephalosporin antibiotic)
Chloral hydrate (sedative/hypnotic)
Chloramphenicol ophthalmic drops (antibiotic)
Chlorpromazine (Thorazine™) suppositories (phenothiazine)
Cyclizine (Marezine™) injection (antiemetic)
Dexamethasone phosphate (Decadron Phosphate™) injection (glucocorticoid)
Dextroamphetamine (amphetamine)
Diazepam (Valium™) (benzodiazepine)
Diazepam (Valium™) injection
Digoxin (Lanoxin™) (cardiac glycoside)
Donnatal™ (gastrointestinal anticholinergic combination)
Epinephrine intracardiac injection, 1:10,000
Epinephrine injection, 1:1,000
Erythromycin (antibiotic)
Fluocinolone acetonide (Synalar™) (topical corticosteroid)
Flurazepam HCl (Dalmane™) (sedative/hypnotic)
Heparin-sodium injection (anticoagulant)
Idoxuridine ophthalmic solution (antiviral)
Lidocaine HCl dental injection (Xylocaine™) (local anesthetic)
Lidocaine HCl injection 1% w/epinephrine
Lidocaine HCl injection 2%
Lomotil™ (diphenoxylate and atropine sulfate) (antidiarrheal)
Mafenide (Sulfamylon™) sulfonamide cream
Mephentermine sulfate (Wyamine Sulfate™) injection (vasopressor)
Meperidine HCl (Demerol HCl™) injection (narcotic agonist analgesic)
Methylcellulose drops (optic lubricant)
Mycolog™ (triamcinolone) (corticosteroid/antifungal cream)
Mylanta™ (gastrointestinal antacid)
Penicillin G (Procaine™) injection (antibiotic)
Penicillin V-K
Pentobarbital-sodium injection (sedative/hypnotic)
Phenazopyridine HCl (Pyridium™) (urinary tract analgesic)
Phisohex™ disinfectant soap
Pilocarpine HCl (mitotic eyedrops)
Prednisolone sodium-phosphate (ophthalmic corticosteroid)
Proparacaine HCl (Ophthaine™) (ophthalmic anesthetic)
Propoxyphene (Darvon Compound-65™) (narcotic agonist analgesic)
Pseudoephedrine HCl (Sudafed™) (nasal decongestant)
Scopolamine/dexedrine tablets (antimotion sickness)
Scopolamine drops (cycloplegic mydriatic)
Secobarbital (Seconal™) capsules (sedative/hypnotic)
Sulfisoxazole (Gantrisin™) (sulfonamide)
Tetracycline (antibiotic)
Tolnaftate (Tinactin™) solution (antifungal)

Table 5 Drugs in the Shuttle Orbiter Medical System

Acetaminophen (Tylenol™) 325 mg
Acetaminophen w/codeine (Tylenol #3™) (acetominophen 300 mg; codiene 30 mg)
Acetazolamide (Daimox™) 500 mg
Afrin™ nasal decongestant spray
Amikacin (Amikin™) 250 mg/cc injection
Amoxicillin (Amoxil™) 500 mg
Anusol-HC™ suppositories
Aspirin (Ascriptin™) 325 mg aspirin w/Maalox™
Atropine 1 mg/cc injection
Bisacodyl (Dulcolax™) 5 mg tablets
Bisacodyl (Dulcolax™) 10 mg suppositories
Blistex™ Lip Balm
Bupivacaine HCl (Marcaine™) 0.5% w/epinephrine (dental block)
Cefadroxil (Duricef™) 500 mg
Ciprofloxacin (Ciloxan™) ophthalmic solution 0.3%
Clotrimazole (Lotrimin™) cream
Cough lozenges (Dextromethorphan 5 mg)
Cyclopentolate (Cyclogyl™) 1%
Dexamethasone (Hexadrol™) 10 mg/cc injection
Dextroamphetamine (Dexedrine™) 5 mg
Diazepam (Valium™) 5 mg cc injection
Diazepam (Valium™) 5 mg tablets
Diphenhydramine (Benadryl™) 50 mg/cc injection
Diphenhydramine (Benadryl™) 25 mg tablets
Epinephrine (Adrenalin), 1:1000, 1 cc injection
Erythromycin 250 mg
Eye drops (artifical tears)
Flurazepam (Dalmane™) 15 mg
Haloperidol 5 mg cc injection
Heparin 100 units/cc injection
Ibuprofen 400 mg
Lidocaine (Xylocaine™) 2% w/epinephrine, 1:100,000 injection
Lidocaine (Xylocaine) 2% Plain, 1:100,000 injection
Lidocaine (Xylocaine™) Cardiac 20 mg/cc injection
Loperamide (Immodium™) 2 mg
Meperidine (Demerol™) 50 mg/cc injection
Metaproteronol (Alupent™) 20 mg
Metronidazole (Flagyl™) 250 mg
Morphine sulfate 10 mg/cc injection
Mylanta Maximum Strength™ (simethicone) 125 mg
Naloxone (Narcan™) 0.4 mg/cc injection
Nitroglycerin patch 15 mg
Nitroglycerin tabs (Nitrostat™) 0.4 mg (1/150)
Norgestrel/ethinyl estradiol (Ovral 21™)
Pepto-Bismol™
Phenazopyridine (Pyridium™) 200 mg
Phenylpropanolamine/Guaifenesin (Entex LA™)
Polymyxin/Bacitracin ointment (Polysporin™)
Polymyxin B/Neomycin w/lidocaine (Neosporin Plus™)
Promethazine (Phenergan™) 50 mg/cc injection
Promethazine (Phenergan™) 25 mg tablets
Promethazine (Phenergan™) 25 mg suppositories
Proparacaine eyedrops
Pseudoephedrine (Sudafed™) 30 mg
Saline 0.9% infusion, 100 ml, 250 ml, 500 ml
Salt (sodium chloride) tablets 1 g
Silver sulfadiazine (Silvadine™) cream
Temazepam (Restoril™) 15 mg
Terfenadine (Seldane™) 60 mg
Triamcinolone (Kenalog™) cream
Trimethoprim/sulfamethoxazole (Bactrim DS™)
Verapamil (Isoptin™) 2.5mg/cc injection
Vidarabine (Vira-A™) ophthalmic ointment
VoSol HC™ otic solution
Zolpidem (Ambien™) 10 mg

Table 6 Contents of the Mir Medical Therapeutic Kits

Onboard medications and supplies
Adhesive bandages, bacteriocidal
Ammonia spirits (inhalant)
Aspirin
Atropine sulfate
Bandage
Bellalgin (Analgin, belladonna, ethyl aminobenzoate, sodium hydrocarbinate)
Caffeine
Chloramphenicol (Levomycetin)
Clemastine (Tavegil)
Dressing pack
Furosemide (Lasix™)
Metapyrin (Analgin)
Methyl valerate (Validol)
Methyluracil ointment
Nitrazepam (Radedorm)
Nitroglycerin (Nitrostat)
Oleandomycin/tetracycline (Oletrin)
Ophthalmic spatula
Papaverine (Papazol)
Perphenazine (Aethaperazine)
Phenibut
Potassium/magnesium apariginate (Panangin, Asparcam)
Scissors
Senadexin (Senekot)
Sulfadimethoxonum (Madribon)
Tetracycline ointment
Trimeperidine (Promedol)
Tusuprex (Libexin)
Verapamil (Isoptin)

Splint Kit
Splints 12 pieces
Bandage 4 pieces
Tourniquet

Cardiovascular Medicine Kit
Ammonia spirits (inhalant)
Atropine sulfate injection
Methyl valerate (Validol)
Moricizine HCl (Ethmozine)
Nitroglycerin (Sustac Forte)
Nitroglycerin (Trinitrolong)
Papaverine (Papazol)
Potassium/magnesium aspariginate (Panangin)
Propranolol (Anaprilin)
Trimeperidine (Promedol)

Gastrointestinal and Urologic Kit
Atropine sulfate 1% injection
Baralgin (Analgin plus antispasmodics)
Charcoal, activated (Carbolen)
Nifuroxazide (Ercefuryl)
Nitroxoline
Senadexin (Senekot)
Sodium carbonate
Triamterene (Triampur)
Trimeperidine (Promedol)
Trimethoprim/sulfamethoxazole (Bactrim™)
Vitamin K (Vicasol)

Prophylactic Medicine #1
Potassium/magnesium aspariginate (Asparcam)
Potassium orotate (Orotas)
Riboxine (Inosie-F)

Prophylactic Medicine #2
Lactobacillus acidophilus/colibacillus (Bifidobacterium)
Levamisole (Decaris)

Prophylactic Medicine #3
Piracetum (Nootropil)

Ointment Kit
Bandage
Clostridil peptidase/chloramphenicol (Iruxol)
Nonivamide/nicoboxyl (Finalgon)
Solcoseryl ointment
Spatula, plastic
Troxevazin gel

"Aspro" Kit
Aspirin
Aspirin, dissolvable tablets
Aspirin/caffeine (Aspro S Forte)
Scissors

Emergency Kit #1
Atropine sulfate injection
Ethyl alcohol
Gauze pads
Lincomycin ointment (Linocin)
Scissors
Trimeperidine HCl (Promedol)

Emergency Kit #2
Adrenaline 0.1% (epinephrine)
Ampule saw
Atropine sulfate
Baralgin (Dipyrone) (Analgin plus antispasmodics)
Bendazolium HCl (Dibasol)
Caffeine
Dexamethasone (Dexacon)
Diazepam 0.5% (Renaium, Valium™)
Drofaverine 2% (Nospa)
Enclosure bag for manipulations
Ethyl alcohol
Fentanyl 0.005% (Duragesic)
Furosamide (Lasix™)
Gauze pads
Lidocaine 2% (Xylocaine™)
Lidocaine 10% (Xylocaine™)
Metapyrin (Analgin)
Needles for injection
Nikethamide (Cordiamine)
Scissors
Sectioned pack
Sulfocamphocaine (Sulfocamphoric acid Novocaine)
Syringes
Syringes with needles
Triplenamine (Suprastatin)
Vitamin K (Vicasol)
Waste product pack

Table 6 Contents of the Mir Medical Therapeutic Kits, continued

Psychotropic medications
Glutaminic acid
Nitrazepam (Radedorm)
Phenibut
Phanzepam
Pyriditol (Encefabol)
Sydnocarb
Tofizopam (Grandaxin)
Valerian extract
Vitamin / mineral preparation (Pantogem)

Aseptic Medicine Kit
Brilliant green tincture
Ethyl alcohol
Iodine tincture

Medicine for burns and injuries
Brilliant green tincture
Flucinar ointment
Ethyl alcohol
Iodine tincture
Lincomycin ointment
Lorindin C ointment (Flumethasone, Iodochlorhyroxyquinolone)
Olasol spray (Chloramphenicol, boric acid, ethyl aminobenzoate, sea buckthorn oil)
Ophthalmic spatula
Sulfacetamide solution (Sulamyd)

Dressing Kit
Bandage 5x5 cm
Bandage 5x7 cm
Bandage, adhesive
Bandage, adhesive, bacteriocidal
Bandage, elastic
Dressing pack
Gauze 14x16
Gauze 45x29
Scissors
Tampons, cotton
Waxed paper

Antiphlogistic Medicine Kit #1
Aspirin
Clemastine (Tavegil)
Diclofenac (Voltaren)
Dipyrone (Analgin)
Erythromycin
Pyrabutol (phenylbutazone, amidopyrine, dimethylaminoantipyrine)
Sulfadimethoxonum (Madribon)
Tetracycline/oleandomucin (Oletetrine)
Tusuprex (Libexin)

Antiphlogistic Medicine Kit #2
Ascorbic acid
Camphomen aerosol
Capsicum plaster
Cefecon suppositories (salicylamide, caffeine, amidopyrine, phenacetin)

Antiphlogistic Medicine Kit #2, continued
Ethyl alcohol
Nozzle
Sulfacetamide solution (Sulamyd)
Xylometazoline (Xilomesolin)

Antiphlogistic Medicine Kit #3
Ascorbic acid
Ampicillin/oxacillin (Ampiox)
Bromehexin expectorant
Doxycycline (Vibramycin™)
Nystatin
Remantidine

Antiphlogistic Medicine Kit #4
Ethyl alcohol
Faringosept
Fluoroquinolone (Taravid)
Gauze pads
Sofradex drops (Framecytin, Gramicidin, Dexamethasone)
Syringes
Syringe needles
Tampons, cotton

Otorhinological/Ophthalmological Kit
Adapter
Atropine sulfate
Aural extraction instrument
Aural probe with thread
Aural speculum, large
Brilliant green tincture
Catheter
Camphomen aerosol
Ethyl alcohol
Faringosept
Forceps, bayonette
Forceps, nasopharyngeal extraction
Forceps, ophthalmic
Gauze pads
Gentamicin sulfate (Garamycin™)
Illuminator/protective cover, spare bulb
Laryngeal mirror
Light guide, nasal
Lorindin C ointment (Fulmethasone Iodochlorhydroxyquinolone)
Metapyrin (Analgin)
Opthalmic extraction instrument
Opthalmic loop
Opthalmic spatula
Scissors, blunt
Slit lamp
Sulfacetamide solution (Sulamyd)
Sulfadimethoxonum (Madribon)
Tampons, cotton
Tetracycline ophthalmic ointment
Turunda, anterior nasal tamponage
Turunda, posterior nasal tamponage
Turunda, ear
Vitamin K (Vicasol)
Xylometazoline (Xilomesolin)

Table 6 Contents of the Mir Medical Therapeutic Kits, continued

Stomatological (Dental) Kit
Aspirin
Cement spatula
Cutters
Dental drill
Dentine paste
Drills, hand-operated
Ethyl alcohol
Excavator, double-ended
Extractor, Type 33
Extractor, Type 51A
Flask, sterilized instruments
Forceps, curved dental
Fuse
Gauze pads
Indomethacin (Indocin™)
Metapyrin (Analgin)
Nozzle, angled
Plugger
Pulp extractors
Promecon (EmeteCon)
Pyrcophen (dimethylaminoantipyrine, caffeine, Analgin)
Scraper, double-ended
Speculum, dental
Scalpel, dental
Tampons, cotton
Tampons, small ball
Tooth probe, angled
Triplenamine (Suprastatin)

Common names (or trade names where available) shown in parentheses

Table 7 Crew Health Care System (CHeCS) for the International Space Station

Health Maintenance System (HMS)
Advanced life support pack
Ambulatory medical pack
Cardiac defibrillator/monitor
Central supplies kit
Crew contamination protection kit
Crew medical restraint system
Respiratory support pack

Countermeasures System (CMS)
Blood pressure/ECG monitor
(shared with HMS)
Body mass measurement device
Cycle ergometer
Metabolic gas monitor
Resistive exercise device
Rower
Treadmill/vibration isolation device

Environmental Health System (EHS)
Charged-particle directional spectrometer (intravehicular)
Charged-particle directional spectrometer (extravehicular)
Compound-specific analyzer, combustion products
Compound-specific analyzer, hydrazine
Dosimetry package (radiation)
Fungal spore sampler
Incubator
Ion-selective electrode assembly (water analysis)
Medical equipment computer
Microbial air sampler
Microbial safety cabinet
Microscope/camera
Slide staining apparatus
Spectrophotometer (water)
Surface sampler kit
Tissue equivalent proportional counter
Total organic carbon analyzer, water analysis
Volatile organic analyzer
Water microbiology kit
Water sampler and archiver

Table 8 Acute effects from whole-body radiation doses

Dose (rem)[a]	Clinical / Physiological presentation
50–100	5–10% experience ARS for one day only; transient reduction in lymphocytes and neutrophils
100–200	25–50% experience ARS for one day only; lymphocytes and neutrophils reduced by up to 50%, with nadir at 4–6 weeks
200–350	ARS prevalent on the first day, may persist intermittently over 4-6 weeks; all circulating blood elements reduced by up to 75%; fever, infection appears within 4 to 5 weeks; 5 to 50% mortality
350–500	All have moderate to severe ARS on the first day, with fluid and electrolyte balance affected; other symptoms include fever, hemorrhage, diarrhea, emaciation; 50 to 90% mortality within 6 weeks from complications of pancytopenia, sepsis, and bleeding.
500–750	All experience severe ARS within 4 hours, with dizziness and disorientation; destruction of most bone marrow stem cells and granulocytes; gastrointestinal syndrome at >600 rem; nearly 100% mortality, overwhelming gram-negative sepsis, bleeding by 2–3 weeks; moderate to severe hemorrhage, headaches, hypotension, dehydration, electrolyte imbalance, syncope are common
750–1000	Rapid-onset severe ARS, which may continue into third day; hypotension in 80%; moderate to severe headache during first day; 30–45% experience moderate fever; early electrolyte imbalance, from 6th hour on; survival time reduced to less than 2.5 weeks for untreated individuals.
1000–2000	Severe ARS within 30 minutes; death in the second week; central nervous system syndrome predominates for doses over 2000 rem

[a] 100 rem = 1 Sv. ARS, acute radiation syndrome (nausea, vomiting, diarrhea, fatigue, weakness).

Figure Captions

Fig. 1 Schematic of in-flight medical support system.

Fig. 2 Astronaut-physician Bernard Harris conducts an in-flight physical examination as part of the Microgravity Examination Techniques experiment. (NASA photo STS055-225-014)

Fig. 3 Russian and U.S. crewmembers learn physical diagnosis techniques in preparation for the Mir-18 mission. (NASA photo S94-035095)

Fig. 4 A prototype medical restraint system, which was flight-tested on the STS-40 mission. A surgical instrument pack, surgical tray, artificial arm, and restraining shoes and wedges are shown. (NASA photo S90-28918)

Fig. 5 Astronaut Tami Jernigan evaluates an in-flight intravenous therapy system aboard the STS-40 mission. (NASA photo S40-30-34)

Fig. 6 A method of cardiopulmonary resuscitation (closed cardiac massage) for microgravity being evaluated with a mannequin during parabolic flight. By reacting against an opposite surface, the person doing the chest compressions impinges minimally into the work area. (NASA photo S92-32716)

Fig. 7 The Shuttle Orbiter Medical System (SOMS), showing major subpacks, cardiopulmonary resuscitation restraints, and emergency oxygen resuscitator. (NASA photo S95-15005)

Fig. 8 A representative kit from the Mir onboard medical system.

Fig. 9 The International Space Station ambulatory medical pack, showing internal drug and equipment pallets. (NASA photo S95-20815)

Fig. 10 The telemedicine instrumentation pack, a prototype telemedicine unit for space flight. (NASA photo S95-12335)

Fig. 11 A surgical overhead canopy in preparation for microgravity evaluation in parabolic flight. (NASA photo S91-39777)

Fig. 12 Lunar surface extravehicular activity during the Apollo-17 mission. Surface EVA increases the risk of some types of musculoskeletal injuries. (NASA photo AS17-134-20425)

Fig. 13 Erecting solar panels on the Martian surface. (NASA photo S88-44971)

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Chapter 7

Postflight Rehabilitation of Space Crews

Valeriy Vasilyevich Bogomolov and Tatyana Dmitriyevna Vasilyeva

As described throughout this volume, a central goal of space medicine is to optimize the health, productivity, and occupational longevity of space crewmembers. The entire medical support system for space travelers, including crew selection, biomedical training for space flight, flight support, and postflight rehabilitation, is directed toward this goal.

Medical rehabilitation has been defined as the combined and coordinated use of medical, social, educational, and vocational measures for training or retraining an individual to reach his or her highest possible level of functional ability.[1,2] In clinical medicine, rehabilitative measures are taken after pathology caused by disease or injury has caused loss of or decline in work capacity. After space flight, medical rehabilitation is used to restore those physiological changes associated with the crewmember having adapted to the space flight environment. In general, these changes are considered adaptive rather than pathological, since they constitute a natural response to the effects of space flight. Theoretically, the reverse process—readaptation to Earth conditions—could be allowed to follow its natural course[3] without the use of special rehabilitative measures. However, we contend that the duration as well as the results of the natural, uncontrolled readaptation process can be less than optimal, particularly given the exposure to unaccustomed G-loads (accelerations) during return to Earth.

As the duration of space flight has increased, the challenges associated with restoring the health and work capacity of space crews after flight have become more urgent. Moreover, crewmembers often participate in more than one flight, thus complicating the effects of space flight itself with those of repeated exposure and aging. Some non-career astronauts or cosmonauts (i.e., payload specialists or cosmonaut-researchers) tend to be older, less physically fit, and have more health problems than their pilot or mission-specialist/flight-engineer colleagues (see Chapter 1, this volume). All of these factors combine to underscore the importance of identifying ways of facilitating rapid and complete recovery from space flight.

I. Readaptation Symptoms After Space Flights

Symptoms of readaptation after space flight are of two general types. The first type of symptoms seem to reflect short-term, compensatory reactions to the process of returning to Earth (e.g., acceleration on descent, inertial impact at landing, reexposure to gravity). These reactions are considered to constitute the first phase of readapting to Earth conditions; they demand activation of all the physiological capacities of the crewmember, including mobilizing functional reserves, but by no means ensure the requisite readaptation. Symptoms of the second type, in contrast, result from long-term exposure to the unaccustomed conditions of space flight, which induces restructuring in many functional systems.

Symptoms characteristic of the first type of readaptation are observed during the first 3 to 7 days after flight. Their severity is not so much a function of flight duration but rather of individual adaptive capacity. Symptoms include vestibular disorders, features of a stress response, and to some extent coordination problems and orthostatic intolerance. On the other hand, symptoms that reflect changes in musculoskeletal structure or function, fluid redistribution, cardiovascular conditioning, hematological indices, fluid-electrolyte and calcium metabolism, and immunological function are more likely to result from long exposure to weightlessness. However, it should be noted that this classification scheme is somewhat arbitrary, since the body, being an integrated system, develops integrated responses to the space flight and Earth environments.

Below we describe readaption symptoms experienced after space flights that lasted from 2 days to 1 year. These descriptions, which include both short-lived and longer-lasting symptoms, were culled from medical observations of 73 cosmonauts after landing.

A. Symptoms Experienced After Short (2- to 14-day) Flights

During the first minutes and hours after relatively brief space flights, all crewmembers experienced a common set of readaptation symptoms, although marked differences among individuals were evident. The most notable of these symptoms have been nonspecific stress responses, and vestibuloautonomic, orthostatic, and coordination disorders. These phenomena typically are relatively short-lived, do not limit crewmembers' ability to function on their own, and do not present serious medical problems. Return from short space flights also has been accompanied by relative destabilization of adaptive physiological processes and imbalances in cardiovascular-system regulation. We believe that these reactions are caused by incomplete adaptation to weightless conditions, emotional stress stemming from the amount of work required by the flight program, and the critical nature of atmospheric entry.

In general, the status of all cosmonauts returning from space flights of up to 14 days was rated good or satisfactory. All were active and able to evacuate from the descent module. Typical symptoms during this period were slight vertigo, sensations of increased body weight, mild pallor, increased perspiration, tachycardia (with labile pulse amplitude and frequency), and superficial arrhythmic respiration (12–32 breaths per minute).

By 15–20 minutes after landing, heart rate had declined to about 100 beats per minute, skin color had returned to normal, and respirations had slowed (to no more than 16–20 breaths per minute) and become even. Upon removing their pressure suits, cosmonauts were frequently sweat-soaked, with skin warm and damp and body temperature not exceeding 36.9°C. No visceral abnormalities have been found during the initial medical exam. Some degree of thirst is universal, and many cosmonauts report being fatigued from lack of sleep during the late portions of the flights.

During the first 20 to 30 minutes after landing, cosmonauts typically displayed unstable standing and gait, and gave the impression of constraining or “controlling” their posture and voluntary movements. Inconsistent, variable neurological signs of broadly fluctuating severity and duration also were noted.

Stand tests conducted 30 to 40 minutes after landing have tended to show more pronounced fluctuations in blood pressure (BP) and heart rate (HR) than were present in baseline tests, although orthostatic tolerance generally has been rated good or satisfactory. Postural disequilibrium of various severity has been present but varies among individuals.

No marked deviations in resting HR or BP have been noted after 2- to 14-day flights (Table 1), although individual differences do affect the severity of readaptive reactions. During the first 10 to 20 minutes after evacuating the descent module, some cosmonauts experienced severe tachycardia (up to 160 beats per minute), which subsided after a short rest. Resting BP and HR had returned to near-baseline levels by 40–60 minutes after landing.

Poor coordination and vestibuloautonomic symptoms during the first 20 to 30 minutes after landing also have varied among individuals. For example, three cosmonauts returning from a 7-day flight experienced dizziness and near-collapse while standing or sitting during the first 15 minutes after leaving the descent module; these symptoms were alleviated within 2 or 3 minutes of lying down.

On the whole, cosmonauts’ reserve capacities after short space flights seem to be adequate, and their readaptation symptoms are moderate and relatively short-lived. In our opinion, most of the readaptation symptoms described (labile BP and HR, shortness of breath, tendency to perspire) are due to general fatigue, psychoemotional stress, acceleration, and impact during the final stage of flight. Cosmonauts who had completed additional flights of similar duration had less severe readaptation symptoms. Occasional neurological deviations observed during the first few minutes after landing are worthy of particular attention, since concussion or dynamic disruption of brain circulation during the landing process are possible but difficult to rule out. As described later in this chapter, medical support offered during the postflight period includes limiting motor activity and time spent in upright positions during the first few hours after landing; ample rest; an untaxing schedule during the early stages of readaptation; and exercises to restore strength and coordination during the first 5 to 10 days after landing. The functional status of most cosmonauts typically returns to baseline within a few days after short flights.[4]

B. Symptoms Experienced After Long (1- to 12-Month) Flights

1. Short-Lived Symptoms

Symptoms present during the early period of readaptation generally are more severe and persistent after long space flights (from 1 month to 1 year) than after shorter flights. However, the relationship between severity of readaptation symptoms and flight duration does not seem to be strictly linear. Physiological changes, especially early during readaptation, are subject to marked individual differences that reflect not only individual adaptive capacities but also the use of in-flight countermeasures. The fact that readaptation symptoms after early several-month flights were often worse than those after later flights that were just as long probably reflects improvements in both the in-flight countermeasure system and compliance on the part of the cosmonauts in its use.

As was true after shorter flights, cosmonauts experienced sensations of increased body weight and vertigo immediately upon landing. Also present was marked pallor, which increased upon assuming an upright position; cyanosis of the lips and hands; damp skin; tachycardia; and soft pulse. During the first few minutes after evacuating the descent module, cosmonauts tend to move slowly and carefully, avoiding sharp movements and turns of the head, and, while still wearing the pressure suits, are helped onto stretchers or chaise lounges, where they rest in a "physiologically neutral" semirecumbent position.

In this position, preliminary medical exams have revealed smoothing of muscle contours and hypotonia in the back and legs, but no significant visceral abnormalities. Tachycardia decreased significantly during this period, with HR declining to no more than 100 beats per minute, and BP returning to normal limits (Table 2).

During this period, cosmonauts at rest, in the absence of orthostatic or vestibular stimulation, have always rated their own general state as being good or satisfactory; their HR and BP have not differed significantly from those observed after short space flights. However, a wide range of uncomfortable vestibuloautonomic symptoms and orthostatic intolerance have been induced by orthostatic stimulation (sitting, standing, or walking), vestibular stimulation (turning the head or changing position), or provocative tests (5-minute tilt test, vestibular studies, evaluation of postural equilibrium). The largest individual differences are present in the vestibuloautonomic reactions to postural and vestibular stimulation, which range from vertigo to nausea to vomiting. During this period, vestibuloautonomic disturbances are the most likely to limit unassisted locomotion and impair tolerance of provocative tests. Medical examinations have consistently revealed autonomic deviations (of various severity) and disruptions in coordination, i.e., fluctuations of the center of gravity while standing and an unstable gait that makes walking or standing with the eyes closed nearly impossible.

Electrocardiograms of cosmonauts during this period have revealed moderate sinus arrhythmias, decreased voltage and flattening of the T peak, and transient alternation of QRS peaks. HR is labile, with marked tachycardia in response to standing and walking and unstable cardiac rhythm during periods of vestibular discomfort. Typically, about 2 hours after landing, cosmonauts begin to feel better, vestibular discomfort decreases somewhat, and HR and BP parameters stabilize.

Overall status during the first few hours after long flights generally has been judged satisfactory. However, several neurological disorders have been noted within minutes or hours after long flights. Some cosmonauts have experienced episodes of near or actual collapse (alleviated by assuming a horizontal position) in the first 15 to 20 minutes after landing. Others have displayed spontaneous nystagmus, transient short-term dysarthria, and difficulty swallowing (choking). Collapse at this stage often is preceded by fixed gaze, confusion, and slow and unclear speech. These problems have led to the policy of restricting motor activity, limiting the time cosmonauts can spend in an upright position, and conducting strict medical monitoring during this period. The accelerations experienced during the landing process may well affect the initial readaptation reactions of the blood and the cerebrospinal fluid in the brain.

The severity of readaptation symptoms after long flights does not seem to be related directly to flight duration. On the whole, readaptation reactions were more severe in the prime crews on Salyut-6 and -7 than in crews aboard Mir, even though some of the Mir flights have been considerably longer. Generally, no drug treatments have been needed immediately after long space flights; the exceptions have been isolated incidents in which drugs were used to alleviate vestibuloautonomic discomfort. In most cases, restricting motor activity and limiting the time spent upright have been sufficient to alleviate or prevent these symptoms.

In summary, even though cosmonaut health and performance capacity generally has been good or excellent during long flights, even during the stressful final stages, deviations from preflight function have been observed soon after landing.

2. Longer-Lasting Symptoms

General fatigue and debility (asthenia).[4–10] Fatigue is especially pronounced during the first 3 days after landing, and has been attributed to the heavy workloads characteristic of the last few days of flight and anxiety and the lack of sleep during this period. Debility (asthenia), which we contend results from prolonged exposure to adverse flight factors, manifests itself during the postflight period in the rapid development of fatigue in response to a variety of physical, psychological, and emotional stressors; mood shifts; occasional sleep disturbances; and decreases in performance capacity. The severity of symptoms does not always correspond to flight duration but instead depends on factors such as the living conditions on board the spacecraft (including hygienic factors), the countermeasures program and how well it was followed, difficult or stressful tasks within the flight program, the psychological atmosphere, and individual differences, among others. Symptoms of debility tend to fade during the first 2–3 weeks of rehabilitation (i.e., Phase I), but disappear completely only during the sanatorium phase.

Vestibuloautonomic disturbances[11–13] take the form of vertigo, discomfort, nausea, and a tendency to perspire in response to head movements and changes in body position. The severity and persistence of these disturbances vary by individual. During the first few hours and days after 6- to 12-month flights, about half of returning cosmonauts experienced vestibuloautonomic disturbances that limited their ability to move around unassisted. Discomfort was not present when they lay down, but they experienced vertigo and nausea, which sometimes led to vomiting, when they moved their heads (especially sharp movements), stood, or walked. These symptoms were accompanied by pallor and labile HR and BP. On the other hand, symptoms in other cosmonauts during the same period were no worse than slight vertigo.

Vestibular dysfunctions during the early readaptation period seem to be most common in individuals who were ill during the first few days of flight. Typically, symptoms are the most severe on landing day and decrease over the ensuing 3 or 4 days. However, one cosmonaut had no vestibular symptoms at landing site after a 1-year flight, but had severe symptoms the next day when he was active, i.e., walked short distances unassisted and moved his head rapidly. Apparently this level of activity was what had provoked the vestibular discomfort, albeit one day later than was typical.

Orthostatic intolerance.[14–16] The severity of orthostatic intolerance in this sample depended greatly on flight duration, the efficacy of in-flight countermeasures, and individual differences in tolerance of orthostatic stimulation. After a 75-day flight, reactions to a 10-minute stand test performed 1 hour after landing were satisfactory. After a 150-day flight, tolerance of a stand test conducted 2 days after return was poor. After 211- and 237-day flights, orthostatic intolerance was particularly marked on both landing day and the day after, when vertigo and visual disturbances developed, BP dropped to 10 mm Hg, and subjects nearly collapsed upon sitting up from a supine position. No further worsening of orthostatic intolerance was observed when space flight duration increased to one year; in fact, tolerance of stand and tilt tests was much better than after shorter flights. We interpret this observation to mean that the longer flights allowed the vascular system to adapt fully to the effects of weightlessness, and establish a new homeostatic level; thus, further exposure to weightlessness after this level has been established does not produce further deviations in cardiovascular status. We also recommend that ways of improving vascular tone and elasticity should be sought to improve orthostatic tolerance after long flights, particularly for the vessels of the lower legs.

Cardiovascular deconditioning during exercise.[17–18] The extent of cardiovascular deconditioning in response to exercise seems to depend more on the use of in-flight countermeasures than on flight duration. As countermeasure programs have improved from one flight to the next, the response of the cardiovascular system to exercise during the postflight readaptation period have become less severe. Also worthy of mention is the difference between the heart-rate response to exercise done in the vertical vs. the supine position: The former is associated with significant increases in heart rate, and is associated with orthostatic intolerance; cycle-ergometry in the supine position, in contrast, evoked an “appropriate” cardiovascular response. We conclude from these results that change in the vascular system is the predominant factor in decreased exercise capacity. We also note that the ability to exercise at moderate rates for long periods is diminished after all long space flights, and takes 6 to 8 weeks for full recovery.

Neuromuscular disturbances.[19–20] Symptoms of neuromuscular disturbances include decreases in muscle mass, tone, and strength in the spine, buttocks, and legs; and disruption of coordination. These disturbances are associated with changes in physical loading on the muscles and ligaments during weightlessness, and the corresponding change in efferent and afferent information and blood supply to the muscles, all of which result from the decline in effort needed to work against gravitational force. The severity of neuromuscular symptoms depends on flight duration and on the use of in-flight countermeasures. After 11- to 12-month flights, changes in the muscle system were no greater—and sometimes were less—than changes noted after shorter flights. Loss of muscle mass after 6- to 12-month flights was significantly less severe than after previous 6- to 8-month flights, and motor coordination, muscle strength and speed properties, aspects of vertical equilibrium, reflex status, and central mechanisms controlling movement were not as severely affected. These results underscore the importance of appropriate in-flight countermeasure programs, especially with regard to exercise.

Fluid redistribution.[21–23] Evidence of body-fluid redistribution was apparent in all cosmonauts to some degree, manifested by slight facial puffiness during the first few days after landing, accentuation of the second sound above the pulmonary artery (observed in certain cosmonauts after 75-, 96-, 151-, 185-, 211- and 241-day flights), signs of venous stasis (engorgement) in the fundus oculi, nasal stuffiness, and increases in liver and kidney size. These phenomena persisted for 1 to 3 weeks, and were not directly related to flight duration (at least for flights lasting longer than 1 month).

Hematological changes.[16–17, 24–25] During the first hours and days after long flights, cosmonauts regularly display anisocytosis and fewer reticulocytes (reductions of 30–70%) and erythrocytes (reduction of 8–12%) than preflight measures. During the first week of readaptation, during which fluid intake increases and symptoms of dehydration disappear, hemaglobin, hematocrit, and erythrocyte numbers continue to decline, and reticulocyte numbers increase, over R+0 and R+1 values. Recovery typically is complete by 4 to 6 weeks after landing.

Sympathoadrenal reactions[26–27] were manifested by increases in blood epinephrine and norepinephrine, and increases in urinary concentrations of these substances, on the day after landing, results that are indicative of a stress response. Catecholamine concentrations recovered over the course of the next week.

Immunological function. On flights longer than 2 or 3 months, numbers of T-cells declined and stabilized at a lower level, and antiviral resistance was depressed. Interestingly, antiviral resistance was unchanged after a 1-year flight, and other immunological shifts were less pronounced than after shorter flights.[28]

3. Summary

The types of physiological change observed after space flight, and the time needed to recover from those changes, are summarized in Table 3. In this table, short flights lasted up to 8 days, and long flights from 1 month to 1 year.

The nature and severity of readaptation symptoms after flights lasting several months has varied within rather wide limits. The most severe changes were noted after 211- and 237-day flights, which some investigators interpreted as meaning that readaptation symptoms could be expected to be more severe as flight durations were increased. After these flights, “space anemia” and immune-system disorders were added to the list of reactions that might limit the safe duration of living in weightlessness. Postflight observations of cosmonauts who completed 326-day and 1-year flights[29] have not confirmed these fears, no doubt because of improvements in the countermeasure program and in the compliance of the crews. Functional deviations in these cosmonauts during the initial phase of readaptation to Earth conditions were of the same type as those noted earlier after months-long flight, and were occasionally less severe. Functional status recovered fairly quickly during the postflight period for all cosmonauts who completed 11- and 12-month flights. In fact, changes noted all were of a functional nature regardless of flight duration, and were completely reversible.

In general, the initial readaptation period should include means of normalizing changes in physiological status that took place during flight, as well as means of preventing changes from developing after flight. In particular, the focus of the rehabilitative program should be to restore the status of the circulation and neurohormonal regulatory systems and to determine physiological reactivity and adaptive capabilities. Since substantial variation in postflight status is present among individuals, rehabilitative and remedial measures should be designed to meet the needs of each cosmonaut, e.g., their specific symptoms, the severity of those symptoms, and their characteristic level of physiological reactivity.

II. General Principles for the Use of Rehabilitative Measures

Restoring cosmonauts to their preflight level of conditioning efficiently and productively requires that rehabilitative measures be selected on the basis of physiological principles.[30] An effective rehabilitation system also requires consideration of the individual cosmonaut’s general condition and the stage of the rehabilitation period. In order to be effective, rehabilitation programs must be tailored to each individual, which requires identifying the nature of changes that occur in that individual as a result of flight, as well as the condition of that person’s functional-adaptive and compensatory physiological capacities. The individual's temperament, inclinations, and personality also should be taken into account in prescribing particular procedures or schedules.

Successful recovery after space flight requires that the amount, nature, and intensity of rehabilitation all correspond to the functional capacities of the cosmonaut. Also, rehabilitative measures must be used regularly over sufficient periods. Therapeutic results cannot be expected after two or three sessions; only prolonged, regular, and systematic use of rehabilitative measures can guarantee total recovery of physiological status.

The efficacy of rehabilitative measures increases significantly when they are used in combination. The specific measures included in a program can vary for many reasons, including the capacity of rehabilitation facilities, the time of year, the location, and so on. However, all measures must be directed toward attaining maximum rehabilitation.

Finally, rehabilitative and remedial measures—and the entire process itself—should follow the principle of gradual increase, especially with regard to exercise loads. For example, a specific therapeutic exercise should be introduced in stages (e.g., preliminary, main, and final), and specific exercises should be systematically and gradually increased in duration and intensity. Similarly, the total rehabilitation program should incorporate gradual increases in the number and duration of procedures, and in the number of repetitions and required speeds. The program also should allow new measures to be introduced as physiological recovery progresses.

III. Testing Rehabilitation Programs After Head-Down Bed Rest

Before developing a rehabilitation program for returning cosmonauts, the Soviet Union explored various means and combinations of rehabilitation techniques for use with healthy subjects after long-term hypokinesia. The first test of rehabilitative therapy took place after a 49-day head-down bed-rest period during which no countermeasures were used.[31] After the bed-rest period, several combinations of physical therapy, drugs, diet therapy, and balneotherapy were explored, and the recovery of the test group was compared with that of a control group. (The control group had no restrictions on motor activity nor any systematic use of rehabilitative measures.) The greatest effect(s) in the test group were noted from the use of specific exercises and training that included morning calisthenics; gymnastics in a swimming pool, in a gymnasium, and on an athletic field; manual massage of the legs and back; and graded walking and running.[32] The exercises and physical training included in this program were selected on the basis of experience in clinical medicine and the known physiological benefits of exercise on the nervous, cardiovascular, and muscle systems. Improvements in the functional status of these systems were expected to have positive effects on other physiological systems.

Readaptation symptoms develop quickly after long-term bed rest because of the abrupt transition to normal gravity and the corresponding orthostatic stimulation, which is incompatible with the functional state developed in hypokinesia. Therefore, we attempted to smooth the readaptation of vascular and neuromuscular tone by using a combination of therapeutic baths and gymnastics in swimming pools. Therapeutic baths create a state of relative weightlessness, decrease axial loading, and diminish the severity of orthostatic reactions. Physical training in swimming pools, especially when exercise loads are increased gradually, facilitate readaptation to vertical postures and walking without evoking marked cardiovascular reactions. Systematic therapeutic gymnastics in the water had positive effects on cardiorespiratory function, regulation of vascular tone, and the neuromuscular apparatus, as demonstrated by increased cardiac ejection parameters and an increased rate of blood flow.

In the course of these studies, we learned that inappropriate or excessive exercise loads soon after long periods of head-down bed rest disrupt compensatory adaptive mechanisms. This disruption was evidenced by sharp activation of kinin and the sympathoadrenal system, negative shifts in central and peripheral hemodynamics, decreased myocardial contractility, and disruptions in neuromuscular functions.[33,34] For that reason, strict regulation of motor activity was needed to restore disrupted functioning and to prevent acute readaptative symptoms. In order to restore major physiological functions, prolonged moderate physical loads at tolerable levels are preferable over short-term physical loading at maximal and submaximal levels. Also, carbonate baths were found to be useful in restoring vascular tone and in alleviating circulatory and thermoregulatory disruptions relative to recovery of an untreated control group.[35]

The importance of restricting motor activity soon after bed rest was demonstrated by complaints of fatigue, exhaustion, nausea, and muscle and ligament pain from the control group as early as the first recovery day. Muscle pain was particularly intense on the second and third days after hypokinesia, but decreased significantly or disappeared completely after exercise in the therapeutic pool. In contrast, the test group showed positive results from therapeutic exercise in the pool, therapeutic massage, and graded walking during the rehabilitation period.

Results from objective tests also verified the ability of the therapeutic exercise program to restore normal functioning of several physiological systems. Neurological status and cardiovascular and neuromuscular functioning had returned to normal by the end of the recovery period in the test (rehabilitated) group. In contrast, hemodynamic responses to exercise in the control group on the 20th day of readaptation still were significantly different from before-bed-rest baselines (Fig. 1). Myocardial hypodynamia was still present, and most neuromuscular-function indicators had yet to reach their baseline values.

In summary, the greatest positive effects (in terms of recovery of disrupted functions) seemed to result from strict regulation of motor activity and the use of gymnastics in a pool during the early readaptation period. The schedule, methods, and equipment used in this early rehabilitation program were modified in subsequent head-down bed-rest experiments that lasted 182 and 370 days, and served as the basis for the rehabilitation program developed for use after space flight.

IV. Medical Monitoring During Rehabilitation

The effectiveness of rehabilitation programs, and assessments of the appropriateness of the techniques used, are enhanced by monitoring physiological functions during the rehabilitation process. To this end, cosmonauts returning from space flight underwent extensive medical evaluations that served as baselines for the functioning of physiological systems and the body as a whole during the recovery period. Clinical examinations covered the status of the cardiovascular, nervous, respiratory, digestive, and musculoskeletal systems; metabolic processes; immunological resistance; and psychological status. These observations were supplemented by results from electrocardiography, echocardiography, regional impedance plethysmography, muscle tonometry and isokinetic dynamometry, blood and urinalyses, and other tests (e.g., cycle-ergometry, stand, and tilt tests). All of these data were used to design a comprehensive program of rehabilitation that could be tailored to each individual.

Cosmonauts also were monitored during the application of the rehabilitative measures, with the goal of assessing tolerance of therapeutic exercises, the appropriateness of those exercises, and optimum loads during exercise sessions. Recovering cosmonauts were monitored during daily exercise sessions, balneotherapy (therapeutic baths), and physical therapy with electrocardiography; BP, respiration rate, and general appearance were recorded as well. These data were used to identify those training loads that would safely stimulate the cardiovascular system while beneficially activating other physiological systems. Appropriate “training zones” were identified through cycle-ergometry tests, and ways of achieving these zones identified, e.g., cycling, sets of gymnastic exercises or athletic games, or some combinations thereof.

At the end of the recovery period, the effectiveness of the entire program was evaluated in terms of the status of the central nervous system, heart, vasculature, and musculoskeletal system; tolerance of provocative tests; and the cosmonauts’ readiness to resume their profession. Especially useful were impedance plethysmography and ultrasound dopplerography, which can reveal a great deal about changes in regional circulation and vascular tone and reactivity. We believe that medical monitoring during rehabilitative therapy constitutes an empirically justifiable and creative approach to identifying and applying effective rehabilitative techniques during the postflight period.

V. Rehabilitative Methods

In Russia, the rehabilitation program used after long space flights is implemented in two phases. Phase I activities last up to 3 weeks and take place either at a rehabilitation base near the landing site or at the Yu. A. Gagarin Cosmonaut Training Center. Phase II activities take place at a sanatorium/health spa after Phase I, and last 30 to 40 days (i.e., until about R+6 weeks). Table 4 lists the phases, goals, and techniques used in rehabilitation, and Fig. 2 shows the relative proportions of their use during the rehabilitation process.

As noted earlier, the most severe readaptation symptoms tend to be expressed within the first few minutes and hours after cosmonauts return to Earth, because normal- and microgravity make different demands on physiological systems. Readaptation not only places a strain on these systems, but also mobilizes reserves. For this reason, rehabilitative-remedial measures used soon after return must be limited in terms of stressful vestibular, physical, orthostatic, and emotional demands.

Limitations on exercise during the early rehabilitation period also are appropriate in light of the fact that exercise activates the sympathoadrenal system, which already tends to be activated in returning cosmonauts.[26,27] Exercise causes release of catecholamines from the adrenal gland and norepinephrine from the sympathetic terminals in tissues.[36,37] If exercise is not intense or prolonged, then tissue catecholamine levels remain fairly constant. However, more intense or prolonged exercise has been associated with sustained elevations in blood catecholamine concentrations[37] but drops in tissue levels,[38] perhaps because of a lag in the rate of catecholamine synthesis vs. secretion and use. When exercise is excessive, the synthesis mechanism becomes exhausted, and both tissue and blood catecholamine levels drop.[39] This situation can substantially complicate and extend the readaptation process, because excessive activation of the adrenergic and hormonal regulation systems can lead to negative and harmful effects if exercise is not appropriate for the deconditioned individual. If, in contrast, physical exercise is increased gradually, then the reaction of the adrenergic system decreases and the capacity to synthesize catecholamines increases.

Changes in immune-system function, especially decreased resistance to viruses, observed after space flight have made it necessary to limit cosmonaut contacts with others, especially during the early readaptation period. This measure both protects them from pathogenic viruses and microorganisms, and allows steps to be taken to bolster nonspecific immune resistance.

In general, Phase I activities focus on identifying indications for rehabilitation, determine each cosmonaut's functional capacities, and develop individualized rehabilitation/remediation programs. Specific activities associated with Phase I are described below.

A. Phase I Measures

Major rehabilitative measures used during Phase I include light therapeutic exercises for the first 3 or 4 days, followed by a restricted training schedule, therapeutic massage, and water and thermal procedures. Attention is focused on regulating the work-rest schedule and psychological and emotional factors. Other rehabilitative measures include diet, herbal "adaptogens" (substances considered to foster adaptation), and other measures as indicated.

Most important during this early readaptation period are massage and therapeutic gymnastics in water. Indications for the use of massage include diminished functional capacity of the muscles, muscle pain, or disruptions of peripheral circulation (e.g., engorgement or edema). By triggering reflex reactions, massage can affect the entire body, especially the circulation, muscles, ligaments, and joints. Massage should be used not only for its independent therapeutic effects, but also because it creates optimal conditions for strengthening muscles through exercise. Massage methods and techniques are selected on the basis of postflight symptoms.

Therapeutic massage[40–43] begins on the first day of the readaptation period, and is given first twice daily and then once daily. Tonic massages are given during the first half of the day before maximal exercise, and relaxing massages are given in the evening before sleep. During the first days after landing, the area around the portal vein and the portion of the head covered with hair are massaged to decrease symptoms of intracranial hyperemia. "Segmental" massage, another form of manual massage, involves stimulating the zones associated with reflex arcs between spinal nerves and the organs innervated by those nerves. Point massage (based on the theory of meridians from traditional Chinese medicine), variants of Shiatsu, and reflex massage of the feet (Marquart's method) also are used along with vibratory and vacuum massage. Vibration therapy[44] seems to normalize cortical-subcortical interactions and autonomic- and endocrine-system status, improve the functional lability of the nerve centers, and has analgesic, anti-inflammatory, and desensitizing effects. Hydromassage also may be recommended during the early rehabilitation period, although manual massage is preferred. Hydromassage is given with a stream of water while the subject is underwater. Indications for the use of this type of massage include decreases in functional capacity of the muscles, prolonged hypokinesia, or intervertebral disk problems with symptoms of secondary radiculitis.

Therapeutic exercises in water are recommended from the first day after flight. Some of the beneficial effects of immersion and exercise in water were noted earlier in this chapter. The decrease in static load underwater considerably reduces body weight, which creates favorable conditions for training the musculoskeletal system.

Being underwater induces muscle relaxation and facilitates slow, smooth movements. This factor becomes especially important for rehabilitation after long flights, when stressful static loads on the spine and lower limbs are not desirable, but the muscles of the back, abdomen, and legs need strengthening. Water exercises can be critical in this situation.

Hydrostatic pressure, the pressure exerted by the weight of water on the body, also contributes to the effectiveness of exercise in water. Hydrostatic pressure strengthens circulation, and increases cardiac output by compressing blood vessels at the surface of the skin and increasing blood flow to the heart. Compression of peripheral veins also facilitates and accelerates venous outflow to the heart. In addition, the muscle conditioning produced by movements made in water is different since the muscles must overcome water resistance; the faster the movements, the greater the resistance.

The temperature and chemical composition of the water also are significant. Immersion in warm (31–32°C) water relaxes muscles, facilitates joint movements, and decreases muscle pain during exercise. Exercises performed in warm water tend to increase the amplitude and coordination of motor movements that can be performed freely. Later in training, when loads are increased and cardiac activity is increased, the temperature of the water is reduced to 27–30°C. Exercising in water at this temperature stimulates the nervous system, conditions the cardiovascular system, and increases muscle tone and endurance.

Water-exercise sessions are held in therapeutic pools equipped with devices such as horizontal railings, steps for entering the water, flotation tubes, and plastic foam floats to reduce body weight. Initial training sessions last from 5 to 20 minutes, and combine breathing exercises with exercising fine, intermediate, and large muscle groups. Sessions begin with exercises for the distal portions of the limbs and alternate with exercises for the arms and legs. Subsequent exercises target intermediate muscle groups. Subjects rest between each exercise. In the middle of the session, large muscle groups in the back and abdomen are exercised. Subsequent loads are decreased gradually and sessions end with exercises for fine muscle groups and coordination. Exercise workloads are greatest in the middle of the session.

Vital signs are always monitored during the water exercises. During the first few days after flight, HR is not allowed to increase by more than 20 beats per minute and BP by no more than 20 mm Hg during the exercise session. Our experience has shown that therapeutic exercises in water help alleviate vestibular disturbances and facilitate recovery of movement coordination and locomotion after space flights lasting up to 1 year.

Gymnasium exercise and graded walking also are used during the early readaptation period. Systematic physical exercise mobilizes and increases the functional reserves of the systems being exercised directly, as well as those of the entire body. This process ultimately facilitates functional readaptation after space flight.

Gymnastic exercises are the most widely used, especially during the initial stages of readaptation when cosmonauts are on restricted and restricted-training regimens. Gymnastic exercises allow physical workloads to be increased and decreased with relative accuracy, and can be used to work specific muscle groups and joints selectively. Finally, gymnastic exercises can be developed and used, in various complexities, for specific postflight changes.

During the first few days after landing, gymnastic exercises ideally are separated into brief (10- to 30-minute) sessions held two or three times daily, depending on the condition of the cosmonaut. The exercises generally begin with the cosmonaut in a supine position in order to strengthen the muscles of the back and abdomen, to prevent postural changes, to strengthen leg muscles in preparation for walking, and to prevent flat feet. As physiological function improves, the exercises are made more complex with the use of weights, dumbbells, rubber bands, bungee cords, and expanders; the number of repetitions is increased; and rest pauses are made shorter. Competitive elements are introduced, and exercises are performed with objects that make demands on coordination (e.g., Indian clubs, balls, and sticks). The beginning position of the exerciser is shifted from supine to seated to standing. Exercises specific to space medicine include postural exercises that alternate upright and head-down positions to condition the vascular system and increase its tolerance to changes in body position, especially the upright position.

Walking is another form of exercise used during rehabilitation. Walking has general therapeutic effects on the body, moderately stimulating metabolism, circulation, respiration, and the musculature of the entire body. The rhythmic contraction and relaxation of lower-limb muscles improves blood and lymph circulation and prevents engorgement (stasis). Walking also is indicated for rehabilitating vertical locomotion and for improving motor coordination. Walking also has positive emotional effects and increases neuromuscular tone.

During the first few days of readaptation, cosmonuts wear postflight antigravity suits while they walk, and are observed closely for walking speed and signs of orthostatic intolerance. The use of the antigravity suit, which impedes fluid redistribution to the legs during walking, is especially important after long flights because of the likelihood of orthostatic reactions upon assuming upright postures. Three paces are distinguished, i.e., slow (60 to 80 steps per minute), moderate (80 to 100 steps per minute), and rapid (100 to 120 steps per minute). Returning cosmonauts begin at the slow pace, which is increased to moderate as recovery progresses. Seated rest periods are prescribed during walking. The distance walked depends on the status of the individual cosmonaut, which depends in turn on the duration and difficulty of the flight. Workload during walking subsequently is increased by increasing the distance and rate walked while decreasing the number and duration of rest periods.

During the various phases of readaptation, several forms of walking are used, i.e., graded strolls and outings, graded walking on level ground, graded walking on a specially selected uneven hilly route (the “Terrainkur”), and excursions to points of interest short distances away. Because the Terrainkur makes greater demands on the physiological systems than does graded walking on a horizontal course, the Terrainkur is used during the second (sanatorium) phase of rehabilitation (described in section B below).

Rehabilitation is especially critical during the early postflight period because secondary changes may develop in the status of individual organs and systems that can prolong recovery and require lengthy treatment if rehabilitation is inappropriate or absent. For example, placing increased demands on spinal muscles that have not been adequately strengthened may lead to pain in the sacrolumbar region, which requires additional therapeutic measures and limits the use of standard means of rehabilitation. As another example, excessive exercise in the presence of cardiorespiratory-system deconditioning may lead to changes that require drug therapy.

If postflight gravitational loading on the spine is sufficient to cause back pain, a step-by-step program of therapeutic exercise is conducted that progresses from one step to the next according to the degree of improvement shown. First, isometric and other exercises are prescribed for the trunk to facilitate muscle relaxation and to increase back mobility; manual manipulations often are performed. In addition, exercises that have general strengthening effects are performed in the pool, and exercises that take place in a standing position are added gradually to the routine. Next, mobility and strength exercises in the water and swimming are added to isometric exercise. Parenthetically, swimming also is recommended for other disorders of the musculoskeletal, peripheral nervous, and cardiorespiratory systems; however, those benefits must be balanced against the risk that inadequate loads on the cardiovascular and muscle systems (relative hypodynamia) may worsen existing postflight changes, which can prolong the process of recovery still further. For this reason, during every period of readaptation, the rehabilitative/remedial regimen must be appropriate to the functional capacities of the cosmonaut’s body at that time.

As the recovering cosmonaut reaches the next stage, the “restricted-training regimen,” his or her motor activity is gradually increased. In the restricted-training regimen, the rehabilitative measures used in the previous (restricted) phase (i.e., massage therapy, therapeutic exercises in the water and gymnasium, and graded walking) continue to be used, but more intensely. Therapeutic exercises in the gymnasium are made more difficult; numbers of repetitions are increased, and exercises with objects and elements of athletic competition are introduced. Exercises in the gymnasium are accompanied by music, which has a positive influence on mood. The initial position for therapeutic exercises in the gymnasium progresses from supine to sitting to standing. As in the earlier stage, exercises focus on strengthening the muscles of the back, abdomen, and legs. Stretching, coordination, and postural exercises are used. Finally, exercises to train the vestibular system are included, e.g., exercise that involves head and trunk inclination or rotation or an unstable support surface.

Swimming is introduced gradually into the exercise sessions in the pool, and exercises in the water are alternated with various types of swimming. Starting on recovery days 6–8, exercises in the water are performed at the beginning and end of the session, and the middle portion is devoted to graded swimming. Distance and speed are increased gradually, and the number of rest periods are decreased. Swimming, one of the most difficult forms of exercise in water, is an excellent way of improving endurance. Our experience with the use of rehabilitative/remedial measures after long space flights has confirmed the cardiovascular effectiveness of therapeutic exercises in the water and graded swimming (Fig. 3).

Graded walking during the restricted-training stage gradually becomes rapid race walking. Slow jogging is introduced gradually; walking is increased to jogging, then jogging is alternated with walking and speed is increased. During this period, HR during exercise is allowed to increase to 160 beats per minute. Recovery dynamics during the rehabilitation process are illustrated in Fig. 4.

Balneotherapy also is desirable to include in the rehabilitative/remedial process.[45–47] Beginning on the fourth or fifth day after most long flights, carbonate (Narzan) baths are given every other day for 10–15 sessions. These baths have positive effects on the nervous and cardiovascular systems; contraindications include infections, skin diseases, and acute cardiac ailments.

Therapeutic exercises in the water and gymnasium, graded walking, and baths are scheduled throughout the day in order to avoid excessive fatigue, both in general and for specific systems, especially the cardiovascular and neuromuscular systems. Morning calisthenics precede the day's exercise and prepare the body for them. Exercises and swimming in the pool are scheduled 2 hours after morning calisthenics and no sooner than 1–1.5 hours after breakfast. During the early stages of readaptation, the interval between therapeutic exercise and bath must be at least 2 hours.

Physiological-system functions generally recover by the end of the second week of rehabilitation. However, isolated symptoms of asthenia may remain, with hematological and biochemical shifts reflective of the functioning of the musculoskeletal system. Coordination often has not recovered fully, and muscle strength and reaction time often are still diminished, as are endurance and performance capacity. All cosmonauts therefore follow the three weeks of Phase I rehabilitative activities with those of Phase II, as described below.

B. Phase II Measures

This phase, which begins three weeks after landing and continues for another 30 to 40 days, typically is conducted in the city of Kislovodsk, which is on the south shore of the Crimea in the Northern Caucasus region. The health resorts of the Northern Caucasus offer a unique combination of natural therapeutic factors. The location of the health-spa complex, between two seas bordering subtropical and steppe climatic zones, ensures sunny weather throughout the year, and the proximity of the subtropics and Black Sea are conducive to warm weather. Mean annual temperatures in the Crimea are comfortable, relative humidity is moderate (mean of 65%), and the sun shines for 2100– 2400 hours per year. Precipitation is low (400 to 600 mm annually) and occurs primarily in the winter.[48] The propitious combination of environmental factors—mild climate, warm sea, proximity of picturesque mountains covered with forests, rich park-like vegetation, and therapeutic mineral water and mud—endows the Crimea with exceptionally favorable conditions for postflight rehabilitation.

The Kislovodsk health spa leads other nearby health resorts in terms of the amount of sunshine (300 sunny days a year), moderate altitude (1000 m above sea level), pure, dry air, absence of fog, and unique terrain. Kislovodsk also is the source of the Narzan mineral waters, long known to the local population as possessing curative and invigorative properties.[49] The curative properties of Narzan—a mineral water of the carbonate-hydrocarbonate sulfate-calcium type—stem from its high concentration of carbon dioxide and the presence of ions of iron, manganese, zinc, copper, aluminum, and other trace elements. The water can be ingested (sulfate Narzan) or used for bathing (dolomite Narzan).

In addition to its climate, Kislovodsk's altitude also beneficially affects the recovery process. Adaptation to the relative hypoxia at high altitudes (where oxygen partial pressure is less than at sea level) increases the oxygen capacity of the blood and numbers of blood cells, expands the numbers of capillaries in the brain and heart, and increases nonspecific immunological resistance.[49] Several authors[50,51] consider these adaptations to hypoxia to be the opposite of the reactions to hypodynamia and analogous to reactions to physical training.

During the sanatorium-health spa phase of rehabilitation, rehabilitative and remedial measures initially follow a restricted-training regimen, which later is replaced by the training regimen. Considerable importance also is attached to psychosocial rehabilitation. Rehabilitative measures make optimal use of the climate and the health-spa facilities, and include physical factors of rehabilitation and mineral baths.

Climatotherapy, which includes aerotherapy, heliotherapy, and swimming in the sea or in a pool containing sea water, plays an important role in the sanatorium-health spa phase. Climatotherapy is prescribed only when weather conditions are favorable, and is strictly regulated in accordance with the cosmonauts' tolerance of cold. Aerotherapy facilitates conditioning of cosmonauts' thermal-adaptation mechanisms, stimulates oxidative processes in the body, and increases enzymatic activity. Types of aerotherapy used include graded exposure to fresh air, sleeping on the seashore, and air baths. (Air baths are prescribed only after acclimatization.) The major form of heliotherapy is sunbathing, which is prescribed only after cosmonauts have acclimated during the warm portion of the year. Swimming in the sea is regulated with respect to exposure to cold: only dips are permitted at first, followed by short periods of sea-bathing, the length of which are increased every 2 to 4 days.

Therapeutic exercises during this phase are performed in the open air. All types of exercise can be used, but athletic games dominate. Morning calisthenics involve 20–25 exercises that focus on enhancing strength, endurance, speed, and coordination. These execises are combined with sports and rapid running to total 25-minute sessions.

Preference is given to exercises that increase endurance for several reasons. First, exercises that build strength, in contrast to endurance, increase muscle-fiber mass through thickening existing muscle fibers (hypertrophy). (Some evidence suggests that prolonged, intensive training may also produce hyperplasia, i.e., numerical hypertrophy.[52]) Endurance training produces not hypertrophy, but rather increases the power of the system that supplies energy to the muscles, as evidenced by proliferation of mitochondria.[53–58] Second, physical exercise enhances the blood supply to skeletal muscles by opening potential collaterals and by increasing the number of capillaries in the muscles.[59] Increases in capillary density are not associated with muscle-fiber hypertrophy; indeed, strength training (which does induce hypertrophy) has been shown to *decrease* capillary density.[60] Third, different forms of physical exercise induce different respiratory reactions. During static loading (strength training), increases in pulmonary ventilation, oxygen consumption, and carbon dioxide emission are not great, and tend to peak after the exercise session terminates. This reaction, known as the Lindgart phenomenon, reflects the fact that static loading disrupts and delays the rhythm of respiration. As a result, coordination between ventilation and blood supply to the lungs is disrupted, and hypercapnia and hypoxia develop, leading to hyperventilation after exercise.[61] Vital (respiratory) capacity typically does not change in strength training; however, vital capacity can be increased greatly by endurance training. For example, the vital capacity of swimmers and cyclists ranges from 5.6 to 6.3 liters; those of track and field athletes, 5.4–5.7 liters; wrestlers and gymnasts, up to 4.5 liters; and weight lifters, 3.9 liters.[62,63] Increases in vital capacity are thought to reflect increased contractile ability of the inspiratory muscles.[64] Fourth, endurance training increases the maximal level and stability of cardiac contractility.[65,66] Prolonged dynamic loading (i.e., endurance training) increases the maximal rate of relaxation of the myocardium, which ensures the necessary diastolic pause, expands the heart, and increases coronary blood flow.[66,67] Endurance training leads to increases in the numbers of capillaries in cardiac muscle (as well as in skeletal muscle) and enlarges their diameters.[68] For these reasons, cyclic endurance exercises like graded walking on various terrains and swimming are included in the postflight rehabilitation program.

Walking sessions during Phase II are done either along a flat course or along the Terrainkur. Four Terrainkur routes are available, each having different angles of ascent and distance. For Route 1, the angle of ascent ranges from 0° to 5°, and distance is up to 500 m. Route 2 angles of ascent are between 5° to 10°, and distance is 1000 m; Route 3 angles are 10° to 15°, and distance is 2000 m; Route 4 angles are 15° to 20°, and distances are 3000–5000 m. During the recovery process, the Terrainkur routes prescribed for the cosmonauts gradually are made more difficult with respect to steepness, distance, speed, and duration of rest periods.

Use of the Terrainkur fosters tolerance of increased physical loading, since walking up an incline of 2 to 20° at a moderate speed is a typical endurance exercise. The Terrainkur is used after all long space flights. At the beginning and end of Phase II, electrocardiograms are collected via biotelemetry while cosmonauts traverse a 4000-m Terrainkur that rises by 250 m, from 913 to 1163 m above sea level. Typical improvements in energy expenditure and speed are shown in Table 5. By the end of Phase II, recommended routes can be as long as 20 km.

Other measures used during Phase II include games such as volleyball, tennis, badminton, football, or water polo. Water or snow skiing are used extensively, depending on the time of year and location of the health spa. Recommended balneotherapies involve contrast baths in various media, which have a tonic effect on the autonomic nervous system, improve circulation, and increase general tone and endurance.[45] Russian steam baths and saunas also are used.[40,43,69] The high temperatures in these baths expand the vasculature of the skin; stimulate metabolism, respiration, and circulation; and condition the thermoregulation system. Metabolic products are eliminated from the body though copious sweating. The frequency of sauna baths must not exceed twice a week, and the maximum temperature is 100°C for 10–15% humidity. Typically, the first sauna lasts only 5 minutes, with exposure time increase gradually to a maximum of 20 minutes. After the sauna, the cosmonauts rest in a supine or seated position for 30 to 45 minutes. Massage therapy in the sauna increases the efficacy of the massage and has positive effects on the emotional state.

Finally, psychosocial measures also play important roles during this phase of rehabilitation. The social components are defined broadly, and include cosmonauts' recognition of their new social status and relationship with others. The latter part of Phase II allows more time for meetings between cosmonauts and representatives of various organizations; presentations by cosmonauts at these meetings are thought to facilitate their social rehabilitation. In addition, time is devoted to leisure and cultural recreation, such as excursions to museums, exhibits, concerts, and theaters.

VI. Conclusions

Our experience suggests that postflight rehabilitation has done much to enhance the professional longevity of cosmonauts and protect their ability to perform repeated space flights. However, several problems still remain to be resolved; for example, measures are still needed for rehabilitating older cosmonauts who develop health problems during flight. Moreover, plans for very long-term flights, such as those involved in interplanetary exploration, compel us to pay close attention to rehabilitation during flight, on the target planets, and after return to Earth.

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Figure Captions

Fig. 1 Hemodynamic reactions to exercise on recovery day 20 after 49 days of head-down bed rest. Six subjects were given no rehabilitative measures (Group 1, top), and 6 others (Group 2, bottom) were given a comprehensive rehabilitation program. White bars, before exercise; black bars, after exercise; dotted lines, “at-rest” baselines for that group before bed rest.

Fig. 2 Relative proportions of various rehabilitative measures during the two phases of postflight rehabilitation. The Phase I circle (left) reflects a typical “restricted” regimen (see text), in which passive measures constitute 75% of the program and active measures 25%. Progression through the “restricted-training” stage involves a 50%–50% mix of passive and active measures. By the end of Phase II (right), passive measures constitute only 25% of the rehabilitation program.

Fig. 3 Improvements in the heart-rate response to swimming on the 5th, 7th, 9, 12th, and 13th days of recovery after a 75-day space flight. The numbers at right indicate the distance swum and the number of days after landing.

Fig. 4 Improvements in number of steps walked per day after long space flights.

Table 1 Resting blood pressure and heart rate in cosmonauts after 2- to 14-day space flights

		Duration of flight			
Measurement time	Measurement	2 days (n=9)	7–8 days (n=30)	14 days (n=3)	Total (n=42)
After leaving descent module	HR, beats/min	108.6±4.04	124.5±3.18	101.3±15.73	118.9±3.04
15–20 min later	HR, beats/min	97.5±4.28	105.7±3.48	93.3±11.2	102.8±2.69
30–40 min after removing pressure suit	HR, beats/min	79.8±2.62	91.0±3.08	82.0±8.42	87.6±2.54
	BP_{syst},mm Hg	115.4±4.76	120.9±2.26	126.7±8.42	120.1±1.73
	BP_{dias}, mm Hg	77.2±3.57	79.0±1.86	81.7±5.62	78.8±1.42
60–90 min after leaving descent module	HR, beats/min	78.7±2.85	81.7±1.36	82.0±8.42	81.05±1.06
	BP_{syst},mm Hg	117.8±2.38	119.8±1.13	123.3±5.62	119.6±1.33
	BP_{dias}, mm Hg	77.8±1.197	79.3±2.01	78.3±2.81	78.8±1.42

Table 2 Resting blood pressure and heart rate in cosmonauts after 30- to 366-day space flights

		Duration of flight			
Measurement time	Measurements	30–96 days (n=10)	140–240 days (n=18)	326–366 days (n=3)	Total (n=31)
After leaving descent module	HR, beats/min	119.0±5.84	116.2±5.07	116.0±3.36	117.9±3.31
15–20 min later	HR, beats/min	111.0±6.51	96.6±4.39	106.6±3.36	102.1±2.69
30–40 min after removing pressure suit	HR, beats/min	78.3±5.19	86.3±3.19	80.0±3.36	89.55±2.09
	BP_{syst},mm Hg	121.0±4.25	119.4±1.19	150.0±8.40	122.9±1.74
	BP_{dias}, mm Hg	76.5±3.25	80.56±1.66	80.0±8.40	79.2±1.52
60–90 min after leaving descent module	HR, beats/min	86.5±3.03	77.6±2.13	74.0±2.52	79.8±1.38
	BP_{syst},mm Hg	123.0±3.78	121.6±1.99	140.0±12.60	123.8±1.52
	BP_{dias}, mm Hg	76.5±2.70	78.6±1.66	83.3±4.20	78.4±1.30

Table 3 Physiological changes observed during readaptation after short and long space flights

Physiological parameters	After short flights	After long flights
Cardiovascular function		
Resting heart rate	Somewhat elevated; recovery within 3–5 days	Elevated; recovery within 2–3 weeks
Orthostatic tolerance	Somewhat diminished; returns to baseline within 3–7 days	Diminished, especially during first 3 days; returns to baseline within 3–4 weeks
Exercise tolerance (cycle ergometer test)	Unchanged or somewhat diminished; returns to baseline in 3–5 days	Diminished; recovery within 3–4 weeks
Endurance	Nearly unchanged	Diminished; recovery in 4–6 weeks
Vascular compliance in legs	Unchanged	Elevated; recovery in 2–4 weeks
Vascular tonus in calves	Somewhat diminished during first 3 days	Tonus of arterioles and veins diminished; recovery in 2–4 weeks
Asthenia (debilitation)	Not observed	Observed for up to 3–4 weeks
Vestibular disorders	Noted in 40–50% of cosmonauts during first 3 days after landing	Noted in nearly all cosmonauts; passes in 7–10 days
Muscle system		
Muscle tonus	Normal or somewhat diminished during first 3 days after landing	Diminished in back, leg, and abdominal muscles; recovery within 3–4 weeks
Calf circumference	Nearly unchanged	Decreased; recovery within 3 weeks
Speed-strength properties	Somewhat diminished in first days after landing	Diminished; recovery within 3 weeks
Coordination	Somewhat affected during first hours after landing	Disrupted; recovery within 3–5 weeks
Hematology		
Erythrocytes (number)	Somewhat diminished; recovery within 2 weeks	Somewhat diminished; recovery within 2–8 weeks
Hemoglobin	Normal or slightly changed	Depressed for 1–2 months
Reticulocytes	Normal or slightly changed	Elevated, beginning on day 2–4 after landing; gradually return to normal within 3–4 weeks
Immunological resistance	Somewhat diminished for first 3–5 days	Diminished, especially antiviral resistance; recovery within 2–3 weeks

Table 4 Rehabilitation techniques and goals after long space flights

Rehabilitation phases	Goals	Techniques
Phase I (R+0–R+21 days) restricted regimen (3–5 days)	• arrest symptoms of postflight asthenia • decrease severity of orthostatic intolerance • curtail vestibular disorders • adapt to moderate exercise • improve major locomotor functions • prevent postflight complications	• regulation of motor activity • manual massage • restricted vestibular and orthostatic stimulation • physical therapy • therapeutic exercises in water • therapeutic exercises in ward • brief walks
restricted-training regimen (up to 21 days)	• arrest symptoms of asthenization • improve functioning of major systems • recover orthostatic tolerance • increase physical performance • improve immune resistance	• regulation of motor activity • manual massage • hydromassage • balneotherapy • physiotherapy • manual therapy • acupuncture and acupressure • morning calisthenics • therapeutic exercise in gym (using balls, Indian clubs, sticks, expanders, and exercise machines) • therapeutic exercise in the water and swimming • graded walking • sports • thermal procedures (sauna)
Phase II (R+22~R+60 days) restricted-training regimen (7–10 days) training regimen (21 days)	• restore functioning of major systems • recover muscle strength and speed, and coordination • increase conditioning and endurance	• use of climate factors (exposure to moderately high altitudes, sun and air baths) • manual massage • endurance training • balneotherapy • physical training • morning calisthenics • swimming • “Terrainkur” • running alternating with walking • sports (table tennis, tennis, volleyball) • water or snow skiing (toward end of phase) • sauna, massage, and hydrotherapy • social rehabilitation measures

Table 5 Progress on the “Terrainkur” before and after a 30-day rehabilitation period at a sanatorium-health spa after a 5-month space flight

	Beginning	End
Time of ascent, min	43	38
Mean speed, km/h	5.58	6.3
Calories consumed/h	9.55	8.63
Calories consumed, total	382.24	345.45

Space Biology and Medicine
Volume IV: Health, Performance, and Safety of Space Crews

Chapter 8

Countermeasures to Short-Term and Long-Term Space Flight

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The human body is exquisitely sensitive to changes in its surroundings and reacts to such changes with a high degree of precision. Modest changes to the gravitational force, for example, result as a sitting person stands or a sleeping person rises; these force differentials experienced by the cardiovascular system induce a host of regulatory mechanisms, which ensure that blood consistently reaches all extremities. More significant changes to the gravitational environment—such as the microgravity of space flight—challenge the body's homeostasis to a much greater extent and initiate a host of complex adaptive mechanisms.

In trying to predict how the human body might react to the novel space flight environment, flight physicians and researchers of the 1950s speculated that microgravity and space flight itself would present significant challenges to the human body. They hypothesized that the combination of acceleration during launch, weightlessness, and heavy deceleration during entry would be intolerable for a human being, causing serious disorders in organs and systems that relied on gravicentric cues. Given this grim forecast, every attempt was made to simulate the most challenging aspects of human space flight and assemble a database of aviation experience. By the middle of the 20th century, researchers had employed high-speed aircraft, human centrifuges, water immersion, bed rest, and an assortment of other physiologic challenges. While these simulations proved that human space flight was indeed possible, they emphasized the importance of protecting and conditioning crews for the harsh new environment to which they would be subjected for the first time.

Thus, the initial focus of human space flight was to demonstrate that humans could survive space flight and the subsequent return to Earth gravity. The central challenge for the Russian and American space programs was to ensure the safety and performance of crewmembers given the protection of life support and medical technology. An intrinsic focus of human space flight was identifying the specific physiologic changes—both transient and long-term—that would need to be countered for a successful mission. Basic parameters, such as time course and severity, were measured to ascertain whether they constituted a normal reaction, an abnormal physiological state, or a serious impairment to function upon return to the 1-g environment. Volume III of this series describes these changes in detail. This chapter covers both American and Russian program experience with countermeasures to negative effects during short- and long-duration flights.

I. Origins of Space Medicine and Countermeasures

The high-speed, high-altitude flights of the 1950s can be viewed as a natural precursor to human space flight. These flights, which reached upwards of 39.6 km (130,000 feet) with rocket-powered aircraft, were the closest available approximation of space flight. Research into full-pressure flying suits, centrifuge conditioning to high acceleration forces, and telemetry of medical data available for study and development became directly applicable to the challenges and concerns faced by the first space medicine researchers.

While aviators had considerable experience flying at attitudes similar to those of space flight, astronauts and cosmonauts would be required to live and work for extended periods of time in this environment. Thus, space medicine developed as a branch of preventive medicine that focused on identifying and minimizing the hazards of space flight. Although its foundations were clearly rooted in aviation medicine, space medicine focused on a number of questions that the aviation medicine community had no need to address.

Early missions demonstrated that multiple physiologic systems were affected both during and after flight, as had been predicted by extensive simulations and research. Consequently, the area of countermeasure development occupied a pivotal role in the early days of space medicine. The changes that astronauts and cosmonauts encountered upon return to Earth became the focus of specialists—physiologists, doctors, and engineers—since these alterations posed a significant threat to crewmembers and were more obvious than those observed during flight. However, as missions became increasingly complex and required more crew activity, researchers developed countermeasures to attenuate the most detrimental symptoms of the microgravity adaptation syndrome and maintain high crew performance at all stages of the mission.

Despite individual and operational differences, all crewmembers returning from both short- and long-duration orbital flights report two periods of adaptation. Both occur as the mission transitions from one gravitational environment to another: the first is experienced upon exposure to microgravity and the second upon return to Earth.

The human body reacts to microgravity by exhibiting adaptations to a new stimulus. The symptoms of space motion sickness—cephalic fluid shift, atony, later atrophy of “antigravity” muscles, bone demineralization, and impaired metabolism of minerals—develop and become evident. Because space flight requires that crewmembers perform in and interact with a novel environment, the adaptations they experience are appropriate (albeit unpleasant); countermeasures to in-flight adaptations are designed to minimize crew discomfort and maximize crew safety.

The return to Earth’s gravity requires a second period of readaptation, which again presents a significant challenge to crew activity and safety. Cosmonauts from long-duration Russian missions of eight months have required more than four weeks of rehabilitation to function normally. The most prominent in-flight and postflight adaptations include orthostatic intolerance, neurosensory dysfunction, and musculoskeletal decay. Orthostatic intolerance relates to the long-term functioning of the cardiovascular system during cephalic fluid shift that occurs in microgravity, which limits, upon return to Earth, the ability of many crewmembers to maintain long-term activity in a vertical position due to presyncopal or syncopal episodes. Neuromuscular and neurovestibular adaptations produce postflight disequilibrium (including marked vertigo in some cases) and gait disorders, which are conditions that clearly limit coordinated maneuvers and interfere not only with nominal egress but also with contingency egress. Significant and sustained loss of bone stiffness, documented at 10–20% during extended-duration missions, may cause injury, including bone fractures, especially during landing and postflight activity.

II. Definitions and Parameters

Countermeasures are operational tools, essential components of mission activities that permit crews to accomplish their duties with competence and ease. Although myriad complex and interrelated adaptations occur in response to microgravity exposure and the challenges of space flight, countermeasures target those physiological changes that threaten mission success or functioning upon return to the 1-g environment.

Terms such as preventive measure, reconditioning, or rehabilitation denote different types of countermeasures. Preventive measures or prophylactics generally refer to a countermeasure that is employed when an adaptation is anticipated but can be minimized. Reconditioning and rehabilitation are applicable when a function or activity has been altered and adaptive responses have ensued. The distinction between these terms serves mainly to illustrate the scope and challenges of developing countermeasures.

The American program does differentiate between levels of preventive measures. In order to prevent or minimize adverse health and medical risks, primary, secondary, or tertiary levels of prevention can be enacted. Primary measures, according to U.S. regulations, seek to mitigate or eliminate risks before they occur and in this sense can be defined as truly preventive. Secondary measures limit a potentially dangerous event by mitigating the risk or protecting astronauts from the risk, and may be defined as countermeasures. Finally, tertiary measures target the disease, injury, or condition that has already occurred and may be considered as rehabilitation. These levels are used mainly as parameters to guide countermeasure development.

The efficacy of any countermeasure is gauged by its ability to neutralize the most detrimental effects of microgravity. During a relatively short mission, priority is placed on preventing functional shifts—like dehydration, orthostatic intolerance, physical deconditioning, decreased muscular and vascular tonicity, and decreased skeletal mass; rehabilitative or antidotal measures more often serve as countermeasures. As mission duration lengthens into months or even years, the program of countermeasures focuses on minimizing the effects of weightlessness and other negative effects, reducing medical risk for the mission, and facilitating the process of readaptation to the gravity of Earth.[1]

The space station development program was an important step in the development of the system of Russian countermeasures. More than 70% of the missions on Salyut and Mir lasted six months and longer (Fig. 1). Based on this experience, Russian cosmonauts perform a complex multi-component countermeasures program, of which the primary objectives are:

- compensating for the effects of sensory deficiency in muscle, skeletal, and other systems;
- ameliorating the symptoms and effects of cephalic fluid shift, including orthostatic intolerance;
- maintaining crew performance at the level necessary for successful mission implementation and timely postflight readaptation; and
- facilitating the readaptation process upon return to the 1-g environment.

The American program of countermeasures does not focus on protecting specific physiological functions, but instead directs countermeasures at improving or reversing a critical decrement in performance; these are in turn defined by operational parameters such as mission duration and activities, and by additional physiological factors. Understanding these mechanisms and subsequent adaptations is critical to the development of any countermeasure.

III. Time Course of Adaptations and Countermeasures

Countermeasure objectives are partially determined by the length of a mission, since this factor defines which countermeasure will be most effective for each aspect of the continuing adaptation process. The earliest orbital flights were conducted in small capsules and lasted only a few minutes or hours. The limited capability for movement and short exposure to microgravity meant that crewmembers mainly reported rapid onset adaptations. Countermeasures for this type of mission aim at preserving the normal physiological status of the 1-g environment and limiting the adaptive process.

As mission duration was increased, crews were faced with further adaptive events that caused new problems. Adaptation to microgravity in this case was neither instantaneous nor consistent but instead dependent upon mission duration, individuals, and operational activities. Preserving the 1-g physiological status was no longer feasible, and countermeasures instead focused on reconditioning crewmembers for the return to Earth gravity. Some symptoms, manifested early in the mission, abate as the adaptation is resolved; the sensory conflict produced by the visual and vestibular systems is one example that is limited to the first 3–5 days of a mission and completely disappears after two weeks. Other more obscure changes are observed only during specific functional tasks or after return to Earth. Bone and muscle changes, for example, begin as early as one week into a mission and are demonstrated upon return to Earth via locomotion problems, increased risk of bone fractures, and kidney stones.

Presently, the American program considers a mission of 14 days or more to be a long-duration mission. Russian experience with space stations defines missions lasting several months as long duration. As mission duration continues beyond a year or more, the variety and complexity of adaptive effects remains a dominant factor. The standard for American Shuttle flights was seven days or less until the initiation of the Extended-Duration Orbiter Medical Program (EDOMP) in 1988.[2] The EDOMP was designed to accumulate medical support experience during missions lasting up to 16 days. This program served as a precursor to the Shuttle-Mir program and defined the concerns that would dominate the countermeasure objectives for extended-duration missions. The Russian program initiated its focus on a long-term human presence in space much earlier. Flights of long duration revealed a whole set of negative effects of microgravity on human physiology, varying in manifestation and time course. These data, which are explored in detail in Volume III of this publication, served to reorient the Russian countermeasures program from the challenge of preserving the 1-g physiological status, to that of minimizing the adaptations that will occur.

IV. Prerequisites for the Development of a Countermeasures Program

The goal of a countermeasure for both programs is to improve performance levels that have been affected by exposure to microgravity and to facilitate body functioning in the 1-g environment upon mission completion. Although a complete return of physiological systems to preflight function is desirable, countermeasures are often designed to restore operationally necessary capabilities. In the most general sense, astronauts and cosmonauts face two crucial operational events during the course of a mission. The first occurs during extravehicular activities or other tasks that require extensive mobility, strength, or endurance. The second is the return to Earth, when crewmembers again find it difficult to complete simple functional tasks, many of which are required during the final postflight stages of the mission. These tasks—crucial in the event of an emergency egress or other contingency—are typically the focus of countermeasures. Therefore, a number of factors are used to assess the efficiency of a countermeasure, the most important of which is maintaining adequate performance. A compromise between other factors must be reached to produce the ideal countermeasure: space and volume requirements, ease of performance, user compliance, minimal environmental disruption, and operational time constraints.

The present approach to countermeasure development consists of several stages: investigation and research, development, testing via simulation studies, testing via in-flight studies, and finally, inclusion in the countermeasure program.

V. Confounding Factors

Ideally, a particular countermeasure interferes with the adaptive mechanism underlying a structural or functional change.[3–5] However, in reality, countermeasures have not always been developed based on research into the underlying mechanism, but instead have been developed as a remedy to some observed change: facial edema, illusory position and motion, nausea, and locomotion difficulties. Many of the earlier measures practiced in the first stages by American and Russian programs were "antidotes," whose success was mainly measured by the absence of the adaptation. Even today, as dedicated research and investigations occupy a significant part of each mission, complete validation of the utility of a single countermeasure is a difficult objective and is seldom attained.

Multiple factors have confounded the systematic testing and analysis of countermeasures. Factors such as preflight physical fitness of crewmembers, differences in body composition, hydration status, or gender complicate the process of defining a baseline. Evaluation of these multiple variables requires large sample sizes, which are often difficult to obtain given the limits of spacecraft capacity and the ability to duplicate conditions from mission to mission. Superimposed upon these considerations is the problem of validating a single countermeasure within the context of multiple, possibly antagonistic methods.

VI. Countermeasures: Primary Objectives and Development

A. Current Understanding of Physiological Adaptations

In the space of a few decades, human space flight has evolved considerably from the first flights proving that humans could survive in microgravity. Since those flights, the Russian program has maintained a crewed space station in orbit and American astronauts have shepherded the orbital shuttle through over 100 missions. An intrinsic, even critical component of this evolution has been to define and expand human endurance during space flight. Refinement of technology and expedition planning has freed crewmembers from operational tasks and allowed them to devote more mission time to physiological investigations. Although the complexity of the adaptive response to microgravity requires ongoing research, numerous studies have accomplished significant inroads in understanding the adaptive process. The definition and characterization of these adaptations is an important prerequisite for developing effective countermeasures.

At the most basic level, microgravity may be considered an environmental stimulus that induces a cascade of regulatory mechanisms. The results of these mechanisms are adaptations, changes in function and structure that yield altered performance. In the following scheme (Fig. 2), a general representation of systemic regulation following microgravity is presented.[6] The accompanying phases of launch acceleration and entry deceleration are included in this the scope of microgravity, since these disturbances cannot be fully distinguished from other phases of space flight. Points at which countermeasures may be applied are indicated by shaded figures.

B. Main Areas of Concern

Because the primary concern of countermeasure development is restoring functional performance level, two general adaptations are considered the most important by American researchers. These two adaptations are orthostatic intolerance and diminished work capacity. Although these high-level changes result from complex, multisystem mechanisms, they are the focus of most countermeasure development. The primary cause of orthostatic intolerance is believed to result from physiological adaptations to microgravity during the course of a mission. Circulating blood volume is decreased, and corresponding changes occur in the autonomic control of blood pressure. Delayed onset functional adaptations, including changes to cardiovascular parameters, confirm this point of view. As in the case of orthostatic intolerance, impaired performance is observed as a logical adaptive response to the hypogravity environment of space flight.

While in-flight activities are minimally affected, postflight functioning—including the critical stages of landing and egress—is significantly impacted by altered aerobic fitness and orthostatic tolerance.

C. Cardiovascular System

The human cardiovascular system has evolved in the presence of gravity as an intricate network of vasculature fed by the powerful cardiac muscle. This vasculature is composed of both muscular arterial vessels that supply oxygenated blood to tissue and nonmuscular venous vessels that return blood to the heart. Baroreceptors and stretch-sensitive receptors monitor the critical parameter of blood pressure in vessels throughout the body; integrated cardiovascular, renal, and autonomic nervous mechanisms regulate anomalies. On Earth, simple motions such as sitting, standing, or reclining result in significant and rapid alterations of the gravitational force imposed upon the body. These constant but short-lived challenges to cardiovascular function are regulated by the simple feedback loop illustrated in Fig. 2.

Unlike the limited and short-lived changes in gravity encountered on Earth, microgravity presents a challenge to the cardiovascular system throughout the flight, constantly stimulating appropriate adaptation mechanisms. Fluid pooling no longer occurs in the lower extremities, but is instead localized to the upper body. This shift manifests in facial swelling, sinus congestion, and decreased calf and thigh volume ("bird legs"). This shift is perceived as excess fluid, which in turn effects a series of immediate but long-lasting adaptive changes.

The changes to cardiovascular function that compromise physical performance and orthostatic tolerance have been defined and characterized in a number of studies.[7] An immediate decrease in plasma volume and a more gradual loss of red blood cell mass (approximately 10%) leads to a reduction in circulating blood volume. In addition, a multitude of cardiac parameters are altered: reduced stroke volume and cardiac output, reduced central venous pressure, reduced cardiac mass, and the risk of cardiac arrhythmia may increase. Studies conducted during short-term flights reveal decreased heart rate and diastolic pressure, together with reduction in atrial and ventricular contraction strength. Diurnal variations in heart rate occur, and systolic and diastolic blood pressures are decreased in flight as well. Although there is large inter-individual variability in seated and standing heart rates, crewmembers show a substantial increase in heart rate upon standing after touchdown. Standing heart rates were increased 70% relative to preflight values.

Concurrent with changes to the heart, changes in vascular function and structure occur as well. These include reduced blood flow to muscles and limited vasoconstrictive response when presented with hypotensive stimuli. Finally, afferent and efferent autonomic nervous system functions are altered.

Cardiovascular symptoms associated with microgravity exposure have ranged from postflight orthostatic intolerance and decreased exercise capacity to serious dysrhythmias noted during the early orbital flight programs. As early as the American Gemini program, cardiovascular deconditioning was documented in all crewmembers without exception. Systematic investigations have proven difficult because of individual differences in diet, sleep patterns, exercise, medications, fluid intake associated with various space missions, and, finally, differences in use of countermeasures.

Studies on the effects of microgravity on the functional parameters of the cardiovascular system have targeted the following objectives:

- establishing a normative database of cardiovascular changes that result from space flight;
- studying the mechanisms that underlie these cardiovascular changes; and
- evaluating potential countermeasures which have been developed as a result of the database and mechanistic research already compiled.

A most crucial result of the microgravity environment is the lack of hydrostatic pressure. Without this pressure, venous walls in the lower extremities are no longer distended by the blood and do not pool as much blood as in Earth's gravity environment. Instead, venous pressure decreases in the lower torso and increases in the veins of the neck and head. Similarly, microgravity produces increased transmural pressure and decreased transmural absorption on the capillaries, which is a mechanism that initiates the exodus of fluid volume from intravascular space to interstitial space.[8,9] In early stages of flight, initial absolute hypervolemia is observed, and during later stages of flight it evolves into relative hypervolemia.

The cascade of changes that accompany fluid redistribution are understood to result from the perception by baroreceptors in the neck that functional blood volume has increased, and hence must be regulated through complex compensatory mechanisms. Russian investigations have identified numerous symptoms that result from this complex process of fluid redistribution: an exponential decrease in leg volume (also documented by U.S. researchers), decreased thickness of soft tissue in the tibia, decreased elasticity and blood flow in several cutaneous veins in the calf and thigh, an increase in these same indicators for cutaneous veins in the head, an overall decrement in venous pressure of the calf area,[10] and increased thickness in the soft tissues of the forehead.[11]

D. Musculoskeletal System

An integrated response from the skeletal, muscular, and connective tissue, controlled by the nervous system, permits movement in the 1-g environment. This response is predicated on the fact that certain directional forces will have to be overcome in order to complete such tasks as lifting an object or walking down stairs. In the microgravity environment, however, these directional forces are altered; the result is a cascade of functional and structural changes to the locomotor mechanisms. These changes yield reductions in muscle contraction strength and power and in muscle endurance that ultimately influence crewmembers' ability to perform routine motor activities.

Changes to skeletal bone occur in microgravity via a complex series of metabolic and structural mechanisms.[12] Although in-flight studies have established a general relationship between decreased bone mass and decreased body mass, site-specific bone changes take place even when body mass is maintained or changes are minimal. Although not all the specific mechanisms of microgravity bone mass loss have been fully studied, it is generally accepted that weightlessness disturbs the balance of osteogenesis and osteoresorption in favor of the latter. This bone loss is evidenced by high urinary and slightly elevated serum calcium levels. Elevated calcium levels in turn initiate increased calcium absorption in the gastrointestinal tract and kidneys. Not only does this put crew at increased risk for forming kidney stones, but it may also make them susceptible to hypercalcemia in flight and a host of other more dangerous conditions postflight. Although bone demineralization and the accompanying alterations are not readily apparent during the mission, changes can be demonstrated with postflight bone X-rays or other scans. Scans document losses in the lower spine and hip, posterior elements of the vertebrae, femoral neck, and tibia. Bone demineralization may begin as early as one week into a mission and continue for the duration of the mission. Recovery of bone mass may take up to two years despite the rapid normalization of calcium levels after landing.

In response to the reduced gravitational force, skeletal muscle undergoes a readily apparent atrophy that particularly affects the so-called "antigravity" musculature of the lower extremities and trunk. Both slow-twitch and fast-twitch muscle fibers are affected, although postural fibers are impacted to a greater extent. In addition, skeletal muscles exhibit numerous alterations in functional and structural properties of antigravity muscles, including force- and power-generating capacities, shortening and relaxing rates, differing neural activation patterns from those exhibited on Earth, protein isoform expression, and metabolic utilization profiles.[13] Connective tissues undergo similar atrophy and functional alteration. If the appropriate countermeasures are absent, we may see a decreased ability to perform simple static and dynamic work on orbit, greater evidence of functional alterations in the musculoskeletal system,[14] and a significant decrease in the muscle factor in blood circulation. It is evident that these changes mean that crewmembers are at risk for increased falls, bone fractures, and limited mobility—a condition that, at the very least, could make emergency egress a challenge.

E. Neurosensory Systems

The central nervous system (CNS) controls both our perception of and interaction with the environment. Sensory systems respond to environmental stimuli and supply a constant flow of input to the CNS; the CNS processes and then employs this input to direct the motor systems. Each step in this intricate process is contingent upon the influx of information about the external and internal environment. In the microgravity of space flight, however, the CNS must adapt to a loss of input from the vestibular system, altered firing patterns in motoneurons, and functional and structural changes in muscle tissue. Adaptation to unexpected, unusual, or even absent sensory information is neither an instantaneous nor constant process; thus identifying the mechanisms responsible and the appropriate countermeasures is somewhat of a challenge. Neurosensory adaptations have traditionally been difficult to measure, but are fortunately evidenced through motor performance changes. Because astronauts must be capable of piloting the Shuttle in order to land safely, or egress it in case of emergency, motor performance and coordination are of special concern to American researchers. For this reason, American studies and countermeasure development have been focused on specific motor performance capabilities that are measurably impaired during and after space flight.

These changes include: occurrence of sensory illusions; dysfunction in spatial orientation; experience of space motion sickness during the first few days of flight; altered eye-hand coordination, including the horizontal, linear, and vertical vestibulo-ocular reflexes, and smooth pursuit target tracking; altered proprioceptive function; impaired "state transition"—that is, very inconsistent and sudden loss of motor control when transitioning between one gravitational state and another; increased visual dependency; and decrements in postural equilibrium control and locomotion.

By virtue of their strong dependence upon gravicentric cues, the proprioceptive and vestibular systems are the sensory systems most significantly affected by microgravity. Additionally, these two systems are influenced by changes in other physiological systems that all contribute to an adaptive neurosensory process that Russian researchers term functional deafferentation. Based upon studies of the functional deafferentation process—that is, microgravity-induced decreases in these specific neuronal populations—Russian researchers have been able to construct a comprehensive picture of the sensory systems as they function in the novel microgravity environment.[15] According to this concept, space motion sickness is but one symptom that results from deafferentation. Other physiological changes include intense shifts in motor performance activity and even hypothalamic and pituitary dysfunction.[8, 9,15,16]

F. Behavior and Psychology

The space flight environment consists of many elements that, even if experienced separately, are challenging. A confined living space, high public interest and visibility, isolation from family and friends, often unappealing or crowded space craft conditions, and a requirement for strong group dynamics are but a few of the obstacles that cosmonauts and astronauts face. As the potential for increasingly longer missions becomes feasible, psychological and behavioral support has become an element of both the American and Russian countermeasures program. Efforts of both programs to provide psychological support are considered extensively in a separate chapter (Chapter 9 of this volume).

G. Basic Approaches

Three general approaches are used in developing a countermeasure. Of these, exercise has proven the most practical, widely used, and easily implemented—despite documentation that exercises should be used along with other countermeasures to provide the most comprehensive protection. Nonetheless, pharmaceuticals and reconditioning measures hold promise of benefit against some of the more prevalent adaptive changes. One caveat must accompany this discussion: a comprehensive understanding of the mechanisms that underlie physiological adaptations is often incomplete or lacking and confounds the development of efficient countermeasures. The challenge of developing fully effective exercise countermeasures lies in optimizing the presently available methods, conclusively documenting their success, and ensuring crew compliance.

H. Pharmacology

Although, as stated above, the issue of pharmacological countermeasures to symptoms of physiological adaptations that occur in response to microgravity is as yet unresolved, some symptoms seem especially well-suited to pharmacological or nutritional countermeasures. These changes include space motion sickness, fluid shift, cardiovascular deconditioning, bone mineral loss, and metabolic disorders. Space pharmacology remains an obscure area due to the fact that comprehensive studies of the benefits conferred by such measures are difficult to conduct and interpret. Medical kits carried aboard a spacecraft typically include routine medications, such as aspirin, antihistamines, stimulants, and sedatives, and a number of emergency medications, which are not considered countermeasures. Although pharmaceuticals have proven particularly useful in preventing motion sickness and dehydration, their regular use as a countermeasure tends to be limited. Russian and American scientists are conducting research in this area.

I. Exercise Countermeasures

A wide variety of exercises are appropriate for the resource-constrained environment of a spacecraft. These different exercises can be combined into a comprehensive system, which preserves cardiovascular condition, performance and coordination skills, and psychological health. Resistive exercises, for example, may be employed to target a specific group of muscles, while activities such as walking, jogging, or running, under a simulated gravitational load, maintain overall fitness by slowing muscle atrophy and improving coordination. This is very important since crewmembers often experience diminished coordination skills as a result of the microgravity environment. Exercise increases sensory inputs, which in turn contributes to mental well-being.

It is clear that the effectiveness of exercises during a mission depends greatly on the design of exercise devices. Given the size, mass, and power constraints of space flight, simple devices are preferred. Unfortunately, many of the simplest, so-called "expanders" or capstan-type stretchers are not highly effective in preventing orthostatic intolerance or decreased performance. Treadmills used in space flight, outfitted with subject load devices that tether the crewmember to the device and compensate weight load deficit, turned out to be very effective. However, when used they cause vibrations, a significant disturbance to the microgravity research environment.

Both the American and Russian countermeasure programs have implemented exercise regimens with varying degrees of success. Although cosmonauts and astronauts do have access to the same basic equipment (ergometers and treadmills), protocols for the use of these devices are quite different. The Russian countermeasures system is described in more detail in the corresponding section of this chapter.

J. Reconditioning Devices

A number of devices have been designed to counteract the blood and fluid shift that occurs during and after space flight. The antigravity suit, a direct descendant of the inflatable abdominal belt designed for military aviators, limits the pooling of blood in the lower torso that results in orthostatic intolerance as crewmembers return to the gravity of Earth. Currently, both cosmonauts and astronauts wear modified antigravity suits: astronauts use the conventional five-bladder antigravity suit, a component of their launch and entry suits, while cosmonauts wear elasticized garments to apply pressure to the lower torso. The lower body negative pressure (LBNP) device is also used during flight to encourage fluid redistribution to the lower torso and is utilized both to diagnose and prevent cardiovascular deconditioning (see the section of this chapter addressing the Russian countermeasures program). The LBNP procedure is integrated into exercise or physical training countermeasure programs, as its independent use provides only limited protection.

VII. Countermeasures for Short-Term Space Flight: the U.S. Countermeasures Program

Until the onset of International Space Station (ISS) missions, the U.S. human space flight program was primarily focused on short-duration flights. The earliest Mercury and Gemini flights were completed in capsules of such limited size that crewmembers did not fully appreciate the immediate effects of microgravity. As mission duration and spacecraft size necessarily increased during the Apollo program, a number of immediate onset, unpleasant symptoms were documented by crews. These were defined as space motion sickness (SMS), a syndrome of neurosensory and neuromotor dysfunction that manifested itself immediately and abated within the first days of the mission. Other adaptations, such as orthostatic intolerance and muscular atrophy, were more apparent postflight when crews returned to the 1-g environment of Earth. Because most American missions were of short duration, only symptoms that might have been detected were the central target of U.S. countermeasures program developers.

In 1988, the EDOMP was established to gain operational experience with missions of up to 16 days, and thereby enhance understanding about the time course and duration of adaptive effects. At the outset of EDOMP, the sole element of the countermeasures program was mandatory fluid loading. This program was particularly important to countermeasure development, as it extended operational experience to include longer duration missions while maintaining a focus on adaptive events and countermeasures.[2,17,18] With the initiation of the Shuttle-Mir docking missions in 1995 during the NASA-Mir program, American long-duration operational experience expanded considerably. A number of critical studies conducted during these two phases of the American program have led to new or improved countermeasures; this research is briefly summarized in the context of the effectiveness of the countermeasures incorporated into the U.S. countermeasures program.

A. Fluid Loading

The first countermeasure to be implemented in the American program was fluid loading— approximately two hours before landing, crewmembers ingested eight 1-g salt tablets with a liter of water. This approach was designed to combat decreased plasma and blood volume. Unfortunately, this measure was both unpleasant and inefficient: compliance declined sharply after some crewmembers vomited upon attempting it. Emesis not only obviated the intended benefit of fluid loading, but also made it impossible to convince crewmembers that this procedure was useful. Moreover, some crewmembers with SMS early during flight often did not achieve adequate hydration throughout the flight and clearly were at risk for orthostatic events during entry and landing. Throughout the latter part of the Shuttle program, then, the importance of maintaining adequate hydration during the entire mission (instead of concentrating solely on the period before entry) was emphasized. Taking the above into account, other fluid-loading preparations have been tested in ground-based studies. In these studies, six normally hydrated subjects were seated comfortably for the 4.5-hour test periods. Changes in plasma volume were estimated by tracking hematocrit values.[19] Control subjects lost approximately 8% of their plasma volumes during that period. Testing included the following fluids: isotonic salt water, isotonic sodium citrate in water (Astro-Ade™), isotonic bouillon (0.9% NaCl), and a commercially available sugar-sweetened drink (Exceed™). As shown, isotonic fluids that do not contain sugar, a diuretic, are the best alternatives to isotonic salt loading for space crews. The isotonic sodium citrate solution may be less irritating to and better absorbed by the stomach lining than salt tablets.

A synthetic aldosterone (fludrocortisone, Florinef) has also been investigated as a countermeasure against orthostatic intolerance. This objective of this measure is two-fold: expand plasma volume to preflight levels and potentially improve total peripheral resistance by affecting α-2 receptors in the arterioles. Unfortunately, pharmacological countermeasures are complex because of different absorption kinetics in the microgravity environment. Dosage regimens that proved effective in subjects after head-down tilt bed rest were not beneficial in flight trials. When an effective dose was tested during flight (0.1 mg, BID for the last five flight days), the side affects made it unacceptable.

In summary, these studies resulted in refinement of the fluid load protocols currently in use (Table 1). Therefore, the standard fluid load is now an isotonic fluid, 15 ml/kg preflight body weight, taken two hours before landing. Astronauts more frequently comply with this measure than in the past. Future studies will focus on factors that improve total vascular resistance.

B. Lower Body Negative Pressure (LBNP)

The purpose of applying lower body decompression is to reintroduce fluids that have shifted, due to altered gravitational forces, back into the lower extremities. Initially this decompression approach served as a diagnostic tool to assess cardiovascular deconditioning, and thus predict the degree of orthostatic intolerance that might arise during entry and landing. A step gradient of increased decompression, known as the Ramp test, was developed to evaluate the time course and extent of deconditioning.

Beginning in the late 1970s, however, the application of LBNP was evaluated as a countermeasure to orthostatic deconditioning and was found to be insufficient as a countermeasure. It was not until the late 1980s that this approach was used in comprehensive analysis of two separate reconditioning protocols. The first involved “soak” procedures, which required that the subject be exposed to a four-hour LBNP decompression at 30 mm Hg after consumption of standard oral fluid load. A “soak” was performed once during the middle portion of each flight followed by Ramp tests (five-minute stages of decreasing pressure in 10 mm Hg steps up to -50 mm Hg) on the two subsequent days to determine how long any protective benefit lasted. The criterion in this case was heart rate response.

Based on results from the first study, the second investigation required that the “soak” be performed 24 hours before landing, to represent the actual operational implementation of the countermeasure. Heart rate responses to LBNP Ramp tests were similar to preflight for approximately 24 hours following an in-flight “soak.” Orthostatic tolerance was quantified by use of the Holter monitor in combination with an ambulatory blood pressure monitor. This instrumentation was used to monitor subjects during entry, landing, and egress. A postflight laboratory stand test was also performed on each subject, and no statistically significant differences were shown for LBNP “soak” treated versus nontreated subjects. Although sample sizes were small, trends in the five treated subjects showed slightly lower heart rate responses, both seated and standing, relative to nontreated subjects. Diastolic pressure also decreased less upon standing in treated subjects relative to nontreated subjects. When these studies revealed that LBNP itself was not an appropriate countermeasure to cardiovascular deconditioning, it was reserved for diagnostic use. Instead, the concept of applying positive pressure to certain areas of the body proved useful in the development of an improved launch and entry suit.

C. Liquid Cooling Garment (LCG)

The liquid cooling garment, which is part of the bulky suit for launch and entry, is a fluid circulating loop that covers most of the body and is located under the antigravity suit. The LCG is a network of plastic tubing that provides conductive cooling to minimize peripheral vasodilation and increase comfort for crewmembers. It was designed in direct response to the thermal stress induced by the launch and entry suits. Because thermoelectric cooling is used to cool the fluid in the LCG, the delta temperature relative to cabin ambient is directly proportional to efficiency of the cooler. Power limitations exist in the Shuttle; these in turn restrict the delta temperature for the cooling water and necessitate that the LCG cover most of the total body surface. The resulting full-coverage garment increases the bulkiness of the protective ensemble and is compressed beneath the launch and entry suits. The bulk could be alleviated by using a redesigned upper torso LCG that includes greater cooling tube density to provide adequate total cooling capacity.

D. Modified Re-entry Antigravity Suit (REAGS)

A primary element of the launch and landing equipment is the antigravity suit with adjustable pressure that was used by Shuttle crews. During vehicle launch and landing all astronauts don a gravity suit (a set of inflatable bladders) that applies pressure to the abdomen, hips, and calves during acceleration and braking. In case of an orthostatic emergency, the suit can be further inflated.

To determine the effectiveness of the re-entry suits, a final investigation was designed to measure integrated cardiovascular and cerebrovascular responses to standing before and after space flight. A set of parallel measurements—including heart rate, systolic blood pressure (SBP), diastolic blood pressure (DBP), stroke volume, and cardiac output by echocardiographic technique and transcranial Doppler flow—were measured together with plasma catecholamines. It was determined that the operational fluid load did not fully restore plasma volume, but loss of plasma volume per se was not a reliable predictor of orthostatic intolerance. Presyncopal and nonpresyncopal astronauts appeared to respond differently to standing both preflight and on landing day. Those who became presyncopal preflight had lower norepinephrine release, SBP, DBP, and calculated total peripheral resistances on landing day. Further, those who become presyncopal on landing day displayed differences before flight, including lower SBP, DBP, and total peripheral resistance (Table 2).

On the whole, investigations of the cardiovascular system helped to perfect the nominal fluid loading, optimize use of the antigravity suit, and develop the LCG as part of the protective complement. Further study will focus on factors that will help improve the total vascular resistance. Table 3 includes data on countermeasures dedicated to combating orthostatic intolerance.

E. Exercise

Specially developed cycle ergometer, rower, and treadmill exercise devices are used for exercising and physiological studies. Individual crew preferences drive equipment type and specific protocols selected for each mission. The cycle ergometer has been flown most frequently, followed by the rower and the treadmill.

Results from these investigations showed no correlation between performance and orthostatic tolerance. Postflight changes typically included increased heart rate in response to exercise; thus the cardiovascular stress for performing an equivalent amount of work was observed to be greater postflight relative to preflight. On average, crewmembers performed less intense and shorter exercise sessions in flight relative to preflight. Those who performed moderate intensity (> 70% age-predicted maximal heart rate) exercise for more than 20 minutes, three times per week, demonstrated minimal decrements postflight. Flight duration did not correlate with magnitude of performance decrements for these relatively short missions.

Muscle performance was assessed by dynamometry tests pre- and postflight. Statistically significant decrements were noted for both concentric and eccentric back and abdominal, eccentric shoulder, and concentric quadriceps musculature. Most groups recovered preflight strength by 7–10 days postflight. A single bout of maximum effort cycle ergometer exercise, performed 18–24 hours prior to landing, was evaluated as a preventative measure. Although head-down tilt bed rest studies of this protocol had shown protection of both performance and orthostatic tolerance, this protection was not demonstrated in the flight trials.

Heart rate response to exercise was virtually identical for given workloads in flight relative to preflight, especially at workloads greater than 150 watts. Further effort is needed to refine protocols and develop resistive exercise equipment suitable for flight. Consideration is being given to both preflight exercise fitness requirements and the postflight rehabilitation physical training program.

F. Biochemistry and Nutrition

Biochemical investigations were conducted during the EDOMP to determine energy utilization patterns. The doubly labeled water technique of Lane and Schoeller[2] was used to determine mean metabolic rates mid-mission for 12 subjects. Fluid intake and body weight were statistically significantly lower in flight versus preflight. Typically, mean body weight decreased 1.5 kg postflight with respect to preflight and caloric intake was lower as well. Energy expenditure was similar during both periods. Energy requirements in flight are very similar to preflight. One cause of decreased caloric intake may be the fact that astronauts often experience malaise and nausea as they adapt to microgravity, and consequently eat less. Decreased caloric intake is not a significant problem on missions of approximately two weeks' duration, but clearly could not be tolerated on longer duration ISS missions. In view of the above, body weight should be monitored as a gross indicator of changes in body composition, as is done in the Russian program.

Dehydration is typically observed in returning crewmembers, and this was anticipated to increase risk for renal stone formation. This concern was evaluated in one study by collecting 24-hour urine samples pre- and postflight and subsequently analyzing these samples with standard laboratory techniques,[21] and later in another study that included in-flight urine sampling.[22] In both studies, clinically significant increased risk of calcium oxalate and uric acid stone formation was noted for subjects on flights up to 16 days in duration. Risk of calcium oxalate and uric acid stone formation seems to increase slightly on longer missions.

Countermeasures range from simply requiring at least 2.5 liters of fluid intake daily to administration of potassium citrate. Logistical issues associated with urine collection and in-flight storage limited participation in comprehensive studies, but previously collected flight data imply that potassium citrate therapy may be beneficial especially during early phases of a mission. These data also support the interpretation of a prior observation that this did not merely reflect dehydration on landing day.

Status of studies in these areas can be defined as sufficient by noting that hydration levels are carefully monitored in flight, as well as other factors that might increase risk profiles for renal stone formation. Future studies may evaluate specific drug therapies if they are deemed necessary to ensure crew health.

G. Nervous System

During the Shuttle program and longer term missions, neurosensory investigations focused on several clearly defined goals that would culminate in an effective countermeasure program for extended-duration missions. For example, a critical uncertainty about flights of extended duration was whether the manual and visual control skills required for piloting and landing the orbiter would degrade as a function of mission length. In order to study this problem, it was necessary to develop a statistical database that would help to gauge the effectiveness of countermeasures and crew performance during long-duration flights. Pre- and postflight studies were aimed at determining the effectiveness of countermeasures at protecting such postflight functions as postural control, gait stability, and equilibrium. In addition, the database was to identify what, if any, operationally significant relationships exist between muscular and cardiovascular countermeasures and neurosensory modification. Finally, as a result of assessment and database development, these investigations were designed to produce the necessary preflight adaptive training (PAT) and in-flight countermeasures required for an extended-duration mission. Table 4 shows data on neurosensory adaptation countermeasures that have been flight-tested, are currently in use, and are under development. Four neurosensory investigations were performed during and after flight to address the above goals:

- coordinated head and eye movements, to include target acquisition and pursuit tracking;
- postural equilibrium;
- head and gaze stability during locomotion; and
- perceptual verbal reporting.

The first investigation sought to identify strategies of visual target acquisition and quantify their accuracy during combined head and eye movements. This study revealed that several crucial parameters of target acquisition, such as acquisition time, head velocity, and visual tracking time, change dramatically during flight. The time to acquire known targets is increased postflight, indicating a potentially serious decrement in performance. Head velocity during active head movement trials was reduced in flight and immediately postflight, indicating that a new neural strategy develops to trade off reduced head velocity for increased vestibulo-ocular reflex (VOR) gain.[17] Visual pursuit tracking and VOR suppression functions (consistent with an increase in VOR gain) were greatly impaired after flight; this causes increase in the error in keeping the object tracked in the retinal clear vision area. Perhaps most importantly, mission duration was identified as a crucial factor in target acquisition abilities. As a result, recovery of preflight function was slow and directly dependent on postflight activity levels.

The second investigation evaluated recovery of postural equilibrium control following space flight. This study focused more specifically on characterizing the parameters that influence postflight postural equilibrium and establishing criteria for related countermeasures. Sensorimotor control of balance was assessed in astronauts before and after space flight by quantifying their sagittal plane postural sway during periods of upright stance with normal and/or altered (sway-referenced) sensory feedback cues. These tests were administered automatically by a modified clinical posturography system.

Results from the second investigation demonstrated that all 40 subjects exhibited postflight balance disturbances as a consequence of adaptive responses to microgravity. The most severe postural disturbances occurred when vestibular sensory input was used as the primary feedback loop for postural control. Crewmembers depended heavily on somatosensory and visual cues immediately after space flight, even when these cues were inaccurate or conflicting.

Recovery of normal postural control occurred in two phases: a rapid initial recovery with a time constant in hours and a slower, late recovery on the order of days. As a group, first-time fliers demonstrated more postural instability than crewmembers with previous flight experience. Initial results suggest that the magnitude of postural instability may increase as a function of mission length for novices, but not for veteran fliers. Preflight postural performance correlated positively with postflight postural performance for all crewmembers, and implies that preflight postural control performance may predict postflight postural instability.

The third neurosensory investigation examined head and gaze stability during normal locomotive tasks (walking, running, and jumping) before and after flight. During pre- and postflight testing, subjects performed three major tests. The first two called for subjects to walk and run, respectively, on a motorized treadmill while maintaining their gaze on an Earth-fixed target. The third task called for subjects to voluntarily jump from a 30 cm platform with and without the aid of vision.

Results from this investigation demonstrated key modifications to several aspects of normal locomotive tasks. During free locomotion after flight, crewmembers moved at significantly lower speeds in order to achieve preflight performance levels. A breakdown in the compensatory relationship between pitch head movements and vertical trunk translation during locomotion after space flight was documented.[2,17,18] This breakdown resulted in oscillopsia (blurred vision, inability to focus) and disruption in the descending control of locomotor function. Lower limb kinematics and muscle activation patterns required for effective locomotion were also modified after space flight; in particular, the heel strike phase of the gait cycle was affected such that increased energy was transmitted to the head, and concomitant visual-vestibular dysfunction was exacerbated. Jumping ability (decreased hip flexion at impact) was altered postflight, indicating that maladaptive landing strategies increase the probability of falling.

The fourth investigation involved perceptual reporting and measurements by voice recording accompanying head and body movements in pitch, roll, and yaw on orbit, during entry, and immediately upon landing. These recordings were intended to fully characterize motion perception disturbances by obtaining quantitative descriptions and determining incidence rates. Results from the fourth investigation demonstrated that over 80% of crewmembers experienced perceptual disturbances during and after flight.[17] Illusory self and surround motion occurred more frequently during the entry/postflight period as compared to in-flight values. Although more long-duration data are required, these disturbances occurred slightly more frequently on medium- than short-duration missions. Secondly, this study revealed that in microgravity, the astronauts' rest frame might be based on visual scene polarity cues provided by the vehicle interior and other crewmembers, or by the internal head and body z-axis (ideotropic vectors). A device for sensory stimulation known as the device for orientation and motion environments (DOME) successfully simulated the same pattern of motion sickness symptoms as SMS. Crewmembers who participated in preflight adaptation training demonstrated a 33% reduction in SMS symptoms compared to nonparticipants. Not only did the DOME generate useful study data, but also it may be a useful operational countermeasure for neurosensory, sensorimotor, and SMS disturbances.

In conclusion, these studies demonstrated significant operational limits and factors that will require further investigation. Adaptive changes in sensorimotor control present significant risks to crew safety during entry, landing, and egress. Overall, first-time astronauts were more severely affected than experienced crewmembers. Visual and motor control tasks, postural control and locomotion, and spatial perception were among the neurovestibular functions altered. Visual and manual control tasks required for piloting and landing the orbiter are degraded in microgravity, although the role of mission duration on this degradation needs further study. The data obtained suggest that egress immediately upon landing will be impaired, especially for the more severely affected crewmembers whose postural instability was well below the normative fifth percentile (clinically abnormal) at wheel stop. This population may also be at increased risk on subsequent flights. In addition, severe postural and gait instabilities were present immediately postflight, such that methods and speed of egress must be modified for successful locomotion upon landing. Likewise spatial orientation and motion perceptions are altered, which compounds the performance decrements of operators.

The focus of future studies should include more individualized preflight training directed toward risk reduction, with initial focus upon enhancing performance, and shuttle egress training. Implementation of PAT countermeasures should be instituted to assure astronaut crew health and safety during entry, landing, and egress. In order to accomplish these goals, more data from long-duration (months to years) flights are needed. Postflight data must be acquired immediately upon landing with rigorous adherence to scientific protocols. Priority studies include hand-eye coordination and identification of vestibulo-spinal adaptation characteristics in flight. Studies and theory suggest that the ability to introduce linear accelerations under controlled conditions in flight using centrifugation will be required for the development of effective countermeasures.

H. Summary

Investigations with crewmembers as subjects have now encompassed over 50 Shuttle missions. These investigations added considerable experience to the knowledge base about human space flight. Among the several important products that arose from these investigations were flight rules that formalized recommendations for fluid loading, exercise, and use of antigravity suits.[23] Extensive countermeasure hardware was developed, evaluated, and validated during the EDOMP program. Special vibration attenuation systems were developed and validated to minimize interference between countermeasure sessions and sensitive microgravity science being performed concurrently on Shuttle flights.

VIII. Countermeasures for Long-Term Space Flight: the Russian Countermeasures Program

A. Historical Overview of the Russian Countermeasures Program

The idea that countermeasures are a necessity in space flight was conceived long before the beginning of the era of manned cosmonautics. In brief-duration flights lasting up to 18 days, conducted by the U.S.S.R. on the Vostok, Voskhod, and Soyuz series vehicles, countermeasures were essentially not utilized. However, biomedical research performed during these flights demonstrated the fundamental possibility of a human safely staying and working in flight conditions for two to three weeks. Along with this, the research also revealed the tendency for negative reactions to develop in the human body in weightlessness, such as: space motion sickness, changes in several cardiac activity parameters, signs of muscular deconditioning, and others.[24–30] An analysis of postflight examination results revealed changes of increased intensity proportionate to flight duration.[31] It became obvious that for flights with increased duration it would be necessary to develop a system of appropriate countermeasures, and such a system was developed in Russia for Salyut orbital station flights.

Even during its early stages of development, the countermeasures system focused on physical training. The results of numerous ground-based simulations successfully demonstrated the high effectiveness of physical exercises as countermeasures to the development of negative shifts in the body's basic physiological systems. Various modes and methods of physical training were tested while developing the system of countermeasures.[32–34] The system included resistive loads imposed during cycle ergometer work, which under conditions of extended hypokinesis helped to maintain basic muscle properties but did not eliminate orthostatic disturbances.[35–37] Additionally, countermeasures, which include strength exercises (isometric and dynamic) and intensive locomotor loads (walking, running, and jumping),[34] were fairly effective in counteracting the development of orthostatic intolerance. The main result of this research was the creation of the physical training complex (УКТФ), based on the treadmill and the countermeasure exercise protocol.

The means and methods for antigravity protection were developed at the same time. During the first stages of space flights, including flights on orbital stations, standard aviation antigravity suits were used for this purpose. Later, special Karkas and Centaur suits were developed. An important landmark in the formation of the Russian system of countermeasures was the experimental validation of the effectiveness of using lower body negative pressure[3,38,39] during the final flight stage as a countermeasure to reduced orthostatic tolerance. The first vacuum chamber for LBNP (the Veter type) was used on space flights on the Salyut-1 through Salyut-3 orbital stations.[40,41] During this stage, the suit was used as a functional orthostatic tolerance test. Later, the Chibis vacuum suit and LBNP training protocols aimed at orthostatic intolerance prevention were developed and experimentally approved.[42,43]

Disruptions to the work and rest schedule in space flights were occasionally accompanied by sleep disturbances, drowsiness during work hours, the development of fatigue, and asthenia, which significantly decreased performance of crewmembers. As a countermeasure for sleep disturbances and the development of desynchronization and exhaustion during space flights, requirements for a rational arrangement of work and rest were formulated. These requirements helped maintain work capacity and support effective cosmonaut activity throughout the entire long-duration space flight. In connection with the increased length of space flights, the necessity also became very apparent to develop special psychological countermeasures directed at prevention of the negative effects of weightlessness and other factors accompanying extended space flights. During the first flight on the Salyut-6 orbital station, crew psychological support was used for the first time.[44] It was aimed at maintaining cosmonauts' emotional condition and motivation for work. Detailed material pertaining to the work and rest schedule and psychological support is presented in Chapter 9 of this volume.

As was shown in ground-based experiment simulations, one of the most important factors in developing orthostatic intolerance in weightlessness is the decrease in the level of the body's hydration and the volume of circulating blood.[45,46] Based on these data, it was suggested that water-salt additives be taken to replenish the fluid and electrolyte balance (see Table 5).

On the first Salyut station, launched 19 April 1971, the system of countermeasures included: an integrated trainer for physical exercises (treadmill), a training suit, "Sekofen" medication, and an antigravity suit.[47] For Salyut-4 station flights, countermeasures were supplemented by an ergometer, a vacuum chamber to create lower body negative pressure, and water-salt additives.[48] Similar countermeasures were used on Salyut-5 station.[49] Later, as experience was gained in long-duration space flight on orbital space stations, the system of countermeasures continued to improve.

In the materials presented in this section of the chapter, we will review the prerequisites for developing the system of countermeasures in space flights, the arrangement of countermeasures in space flights of varying lengths and, briefly, the results of using countermeasures in long-duration space flights.

B. Effects of Microgravity on the Human Body

The results of research performed in space flights and in ground-based experiment simulations have shown that weightlessness is the most significant influence on the human body during flights on modern manned stations and other spacecraft that have pressurized living compartments with a fairly large volume of atmosphere that approximate the Earth's atmosphere.[31,50,51] Functional shifts that appear in the human body under the effects of microgravity are a combination of specific changes brought about by the physical nature of microgravity, and also secondary nonspecific occurrences associated with the development of adaptive reactions.[8,9,31,50–53]

Based on the physical nature of microgravity, the main factor (primary component) in the mechanisms of its effect on the body's physiological systems is the removal of body weight and, as a result, the gravity-dependent deformations and mechanical tension of body structure.[50,54,55] This also includes the main gravity receptors, i.e., the otoliths, proprioceptors, etc.[56,57] Changes in the activity of the aforementioned structures are accompanied secondarily by the development of reflex atony of antigravity muscles and disruption of other mechanisms and systems, as a result of which orthostatic tolerance is decreased and body fluids are redistributed.[9,16,31] The results of research into the activity of the proprioceptive and vestibular afferent systems in space flight provided the basis for concepts regarding the development of functional deafferentation processes in weightlessness, which are associated with changes in the otolithic input activity, a reduced load on the skeletal/joint and muscular apparatus, deactivation of proprioceptive input, and a decrease in muscle receptor activity.[15,58,59] These are caused, in turn, by changes in the condition of otolith receptors in weightlessness, the elimination of weight-bearing load, and a resultant sharp decrease in muscle tonicity. According to this concept, lowering the overall afferentation flow and changing the intersensor interaction in weightlessness cause the development of SMS symptoms as well as intense shifts in the motor control system activity, dysfunction of hypothalamic and pituitary systems, and other changes in the activity of physiological systems.[8,9,15,16,53]

A specific characteristic of weightlessness is the lack of hydrostatic pressure, which causes the development of changes of opposite signs in areas located above and below the hydrostatic indifferent point. In areas above the hydrostatic indifferent point, conditions are created that increase transmural pressure and decrease transmural absorption in the capillaries, which in turn, facilitates the transfer of fluid from the intravascular space into the interstitial space. In areas located below the hydrostatic indifferent point, the changes occur in the opposite direction. On Earth, the venous walls in the lower extremities are distended by the blood that accumulates in them and have a higher pressure than the venous walls in the neck and head. Typical for Earth conditions, this gradient of the elastic force of the venous walls located above and below the hydrostatic indifferent point facilitates the expulsion and shift of blood from the veins of the lower extremities to the cranial regions in microgravity conditions. When this occurs, a new Starling equilibrium level is established. The probable development of initial absolute hypervolemia, and in later stages of space flight, relative hypervolemia (an increase in the fluid transfer to the interstitial space in the vascular regions, located above the hydrostatic indifferent point and changes in the opposite sign in areas below the hydrostatic indifferent point) may cause the appearance of changes in the distribution of impulse flows from interoceptors of vessels and adjoining tissue in areas above and below the hydrostatic indifferent point.[8,30,53] The redistribution of the fluid in weightlessness is manifested by a number of symptoms. They include: an exponential decrease in leg volume; a shift of the body's center of mass towards the cranium and a decrease in the content of the interstitial fluid in the thighs to 1.5–2 liters[60]; an increase in the thickness of soft tissues in the forehead area and a decrease of this indicator in the tibial area[11]; a decrease in distention and blood flow of several cutaneous veins in the calf and thigh and an increase of these parameters in cutaneous veins in the head[60]; the formation of a zone of free distensibility of calf veins[61]; and a decrease in venous pressure in calf area and stabilization of the pressure at the shoulder level.[10] The shift of the body fluids to the head and the change in the Starling equilibrium develop due to the elimination of hydrostatic pressure when a person is exposed to microgravity and are interpreted by the system receptors as an increase in the functional blood volume. They are accompanied by the activation of a number of neurohumoral mechanisms that lead to the development of compensatory reactions.

The summary results of numerous studies performed in flights of varying lengths which have been summarized in a series of recent publications[9,50,51,53,62-67] verify that the depressory reflex reactions develop in the initial period of exposure to microgravity. These reflex reactions are manifested by: a change in the ratio between the perfusion and pulmonary ventilation; a decrease in the activity of the renin-angiotensin-aldosterone system; suppression of the antidiuretic pituitary hormone secretion; short-term activation of secretions of the right atrial natriuretic factor and, possibly, E_2 prostaglandins; as well as hypohydration and increased elimination of a number of ions. In the latter stages of a stay in weightlessness, a) a decrease in the volume of plasma, the circulating blood, and extracellular fluid; b) the hypovolemia in areas located below the hydrostatic indifferent point; and c) hypervolemia in vessels in upper areas together stimulate the development of secondary reflex reactions, which activate the renin-angiotensin-aldosterone and other regulatory systems. This, in turn, inhibits the formation of red blood cells and stabilizes the circulatory and fluid and ionic homeostasis at a new level.

The body's reactions associated with removing the weight-bearing load and with the decreased muscular force when performing dynamic work in microgravity are manifested by: a decrease in activity and tonicity of extensor muscles, which perform postural function in the 1-g environment; antigravity musculature deconditioning; a decrease in the role of muscular factors in blood circulation; as well as a decline in the intensity of muscle metabolism. Major changes are noted at this time in bone homeostasis.[14] Natural shifts noted in various body systems in long-duration space flights are summarized in Table 6.

A more detailed description of the changes caused by weightlessness in the various body systems is provided in special chapters of this publication. Research into the nature of these occurrences is the primary source of information for development of concepts relating to the mechanisms of the effects of microgravity on the human body as well as for determination of the primary trends for developing and further improving countermeasures.[15,52,53] The efficacy of a countermeasures system is determined by its ability to neutralize the leading adverse effects of microgravity. As follows from the data presented above, the countermeasures must aid the reestablishment of conditions specific for Earth gravity, such as deformation and mechanical tension of the body structure; they must compensate for the afferentation deficit from weight-bearing and muscular receptors, and smooth out the effects of a redistribution of the blood. All of these requirements are met by the Russian countermeasures system,[62] which is used currently on long-duration space flights. This system includes the following basic elements: physical training[62,68]; a rational work and rest schedule[69] and psychological support[44]; routine pharmacological countermeasures; and wearing the Penguin suit[43] and thigh occlusion cuffs to mitigate the effects of microgravity. During the final stages of flight, LBNP training,[41,70] water-salt additives, and antigravity suits are used[71] (Table 7).

The results of numerous studies performed during the early stages of training for long-duration space flights demonstrated the ability of physical training to prevent or significantly reduce the appearance of a wide spectrum of changes caused by microgravity in various body systems. Having confirmed the concept of the role of reduced muscular activity leading to the development of negative effects of weightlessness,[32–34,72] these data led researchers to search for and develop highly effective methods for physical training. The work begun in the late 1960s and early 1970s[35–37] in ground-based simulations of space flight conditions (see Introduction) and continued during the course of long-duration manned flights, resulting in the formation of a system of physical countermeasures for long-duration space flight. Characteristics of the system, the principles on which the system is based on, and the use of methods and means are reviewed in this section of the manual.

C. The Current Russian Countermeasures System

1. Physical Training

Physical training plays a primary role in the system of countermeasures in the long-duration space flights. The primary objectives of physical training in flight are to: a) maintain good health and a high level of performance in crewmembers during all stages of flight and after flight completion; b) prevent dysfunction of the cardiovascular system and orthostatic intolerance after flight completion; c) preserve muscle structure and function and thereby muscle strength, body strength, and general endurance close to initial level; d) maintain coordination abilities at a level sufficient to maintain a vertical posture and perform locomotions, walking, running, and the precise voluntary movements; and e) prevent impairment of metabolism (in particular, fluid/electrolyte and mineral). These goals are achieved by effectively organizing training based on several general principles,[34,62,68,73,74] of which the most important is that training is continuous throughout the entire length of the flight, is diversified, and is dedicated to maintaining various muscular properties and body functions.

The necessity of systematic training in multi-month orbital flights is dictated chiefly by the constant tendency in weightlessness to rapidly lose conditioning and its possible progression with increased flight length. According to the reports of cosmonauts, a break in training of 7–10 days was accompanied in long-duration space flights with the feelings of “a sharp reverse” which was very difficult to recover from. The high load level necessary to reestablish the conditioning might prove to be excessive for some body systems, especially the cardiovascular system. Meanwhile, the high requirements for volume and intensity of work that currently exist on space stations might not be fulfilled if deconditioning develops.

The emphasis of training on maintaining aerobic and anaerobic capacity, orthostatic tolerance, bone and muscle tissue structure, and other functions is determined by the multifaceted effect of weightlessness on various structures, organs, and tissues. The multifunctionality of the physical training provided by Russian countermeasures system is assured by a highly effective training protocol and a four-day microcycle, which includes three days of training and one day of active rest. As shown in Table 8, the exercises are aimed at maintaining velocity, force-velocity, and overall endurance at various days of the cycle. The total load from day 1 to day 3 of the microcycle gradually increases; the microcycle concludes with a rest day.[34,41,68] The results of simulations have shown that cycles with four, five, and six days of work are less effective and are characterized by rapid accumulation of fatigue.

Finally, it is known that training is effective only when it is performed against the growing fatigue. Willfully overcoming fatigue associated with objective internal changes serves to stimulate responses, which compensate for these changes and reestablish homeostasis. The principles of physical training on Russian space stations also include loading to the point of fatigue and willfully overcoming it. The possibility of implementing this principle is supported by the internal structure of the training which allows frequent variation of the type of exercise (locomotor-resistive), the modes used (high-speed running on a motorized treadmill, walking in passive or in “breaking force” mode), and the muscle groups being trained.

2. Onboard Physical Training Equipment

Comparative testing of various countermeasures has shown that locomotor training on a treadmill is the most effective in counteracting the negative effects of weightlessness on the human body.[34,41,62] Therefore, an onboard integrated trainer was developed and manufactured for orbital stations to comprise, in addition to the “treadmill,” a loading system which includes a subject load device, an individual load suit with shoes, a moveable crosspiece, and a selection of bungee cords of different sizes—long, medium, or short—to perform movements which include various muscle groups. The subject load device supports the performance of exercises with a constant static load (up to 70% of the body mass) along the longitudinal axis of the body and enables the reproduction of weight-bearing reactions while performing exercises in microgravity. The treadmill enables walking, running in active and passive modes, and also jumping, squatting, and lifting “weights” in weightlessness. In active mode, the treadmill moves at a speed of 5.8 and 12.6 km/hour. In passive mode the treadmill can move with speeds up to 14.0 km/hour or greater.

The onboard ergometer allows for supplementing and diversifying the exercise protocol, providing the capability of a standard loading on the cardiovascular system in flight.[74] With an assortment of modes available—passive, active, and free—the ergometer provides the capability of performing discrete loading with a power from 50 to 225 W given a pedaling frequency of 40–80 rpm.

The training loading suit (THK-1) and the Penguin suit are also part of the onboard system of countermeasures. They are used to compensate for the load deficit on the musculoskeletal apparatus when performing exercises (THK-1) and in the interim between training sessions during normal working hours (Penguin) (Fig. 3). The tension of the elastic elements, which make up these suits, creates “compression” relative to the body’s longitudinal axis (from the shoulders to the foot), loading the skeleton and the postural musculature over an extended period of time.[74] The amount of the load in the Penguin suit, which is worn for 8–12 hours during the day, can be as much as 30% of the cosmonaut’s weight in ground conditions, and in the training-loading suit as much as 70% of his ground weight. The suits reestablish to a certain level the body structure deformation, which disappears in microgravity; they create a load on the muscles of the back, legs, trunk, and skeletal bones, which should prevent a decrease in the energy and structural metabolism. They activate the proprioceptor and mechanoreceptor afferent systems, which, in turn, aid in the activation of postural and locomotor mechanisms.

The set of bungee cords with various characteristics are intended for 10–15 minute exercise sessions aimed at maintaining the strength of the antigravity muscles that are the most underloaded in weightlessness: the trunk, hip, calf extensors, and the hip abductors and adductors.[34,74]

Controlled multichannel electrostimulation of muscles in conditions of long-term bed rest helped maintain strength and static and dynamic endurance at their initial levels. Based on these data, a six-channel stimulator was included in the set of onboard equipment; it provides intense stimulation of the muscles of the leg, back, and abdomen and may be used in addition to the recommended physical training methods or in place of an active training program when one cannot be performed.[41] In ground-based simulation experiments, myoelectrostimulation in combination with LBNP increased the effectiveness and safety of performing decompression of the lower body and improved endurance during electrical shocks of maximum intensity.

3. Physical Training Methods in Long-Duration Space Flight

In accordance with the specific types of body reactions and flight objectives, three stages are identified. These stages are presented as: the initial period of adaptation to flight conditions (acute adaptation phase), which lasts from 12–14 days; the period of relative stabilization of health status and conditioning (stabilization phase), which replaces the previous phase; and the final stage, which comprises the final 4–6 weeks of the long-duration flight before landing.

In the initial period, due to the high level of activity during station activation and the possible development of motion sickness, accompanied by dizziness, occasional nausea, and illusions, physical training is not scheduled. To alleviate the symptoms of motion sickness it may be useful to perform short, 2–3 minute static contractions of the neck, back, leg, and arm muscles during this period. The performance of these exercises should be alternated with attempts to maintain the head and gaze stability and with electrostimulation of the neck and shoulder muscles. It is recommended that the muscle contraction and myoelectrostimulation sessions be repeated when the precursors of motion sickness appear.

Training (Table 8) is usually scheduled beginning with the fifth day of flight. In the beginning, training is performed on the ergometer with a load of approximately 50% of the recommended load, which is attained by working in the passive mode (500–600 kgm/min) or at the level of 700–900 kgm/min. Later, the load is gradually increased to include exercise on the treadmill, and at the end of the third to fourth week of flight the training is at full volume and intensity. Besides the mandatory exercises twice a day for one hour on each trainer, several crewmembers perform additional strength training with elastic bands in their free time.

During the stabilization phase, which covers the main portion of the flight time, full-scale physical training is performed regularly with the structure of the four-day cycle maintained. The microcycle first day training is mainly directed at maintaining force-velocity endurance and includes walking and running at a rate of 120–140 steps per minute along with a session of high-speed running at a rate of 200–300 steps per minute (12–14 km/hour). This aids the maintenance of force-velocity properties of skeletal muscles and the anaerobic mechanisms of the cardiovascular system. The pulse rate when performing physical training on the first day is 140–160 bpm, achieving a rate of 180 bpm and greater after intensive exercises. Since long sessions of this type of running are impossible, the exercises are structured based on the interval training principle.

The primary objective of the second day of the cycle is strength endurance training. Consequently, the load volume on this day is moderate and the intensity is moderate or above moderate. The total energy expenditure for two exercises is 450–550 kcal (as opposed to 380–420 kcal for the first day of the cycle).

The basis for the third day of training is a relatively slow- or moderate-speed monotonous running over a relatively long period of time, i.e., up to 4–6 minutes and longer, and pedaling on the ergometer in a similar mode. This facilitates stabilization of the tissue oxygen consumption indices and increases tissue blood supply (aerobic mode).

In total, the recommended loads on long-duration space flights for various days of the cycle are from 3100–4400 m walking and running on the treadmill with an average speed of 117–135 m/min and 19500–24000 kgm pedaling on the ergometer with an average work intensity of 800 kgm/min.

During the final stage of the flight (3–6 weeks prior to landing) training is performed primarily on the integrated trainer and includes a series of speed runs with intervals between them for walking and exercises with expanders; the volume and intensity of the loads during this stage are close to the maximum capabilities. It is recommended that during one training session cosmonauts perform 4–5 series, with a run intensity during specific periods within the series (30–60 seconds) of 200–240 steps per minute and greater,[74] and a peak heart rate of 180 bpm and greater.

Prior to egress into open space in a spacesuit, training includes additional strength exercises for arm muscles that will experience heavy loads during extravehicular activities (EVA). These exercises are performed with short and long bungee cords, and specifically the ergometer, where 14–15 days prior to EVA (in addition to daily protocol), cosmonauts perform pedaling with the arms at a load of 150 W.

4. Monitoring Cosmonauts' Physical Condition

The effectiveness of training is largely determined by the amount of exercise, and, in particular, by its intensity. To monitor the amount and intensity of loads during the performance of physical training on the treadmill and ergometer, as well as the quality of features and compliance of the training structure with recommended procedures, there are periodic, monthly sessions for recording crew performance parameters on the trainers (with simultaneous recording of heart activity indicators). The data are subsequently downlinked to Earth via the telemetry system. The data, which are actually recorded during the three-day training microcycle, allow specialists not only to determine the number of training sessions, their volume, intensity, and level of skill on the trainers, but also the cosmonaut's conditioning level. The intensity of loads selected by the cosmonaut, the volumes of work performed, the length of work periods at high intensity, and the duration of breaks after their completion quite accurately reflect the cosmonaut's work capabilities. Thus, during the flight of the second long-duration crew on the Mir station (Table 9) the crew commander's locomotion volume during the first half of the flight fluctuated in the range of 85% (the first two months) to 95% (subsequently) with a load intensity close to the recommended level. During the second half of the flight the locomotor exercise volume increased significantly, and in the last month of the flight, the 11th month, it reached 120% of the recommended level. At the same time the training structure changed. The running exercise volume abruptly increased and during this period was almost 80% of the total volume, instead of 60% for the length of the flight.

The dynamics of the training indicators for the flight engineer of this same mission in the first months of the flight were even a bit more appropriate; the volume and intensity of locomotor exercises were initially small and towards the end of the adaptation period (the first month) had reached the planned amount. They fluctuated in a range close to 100%, thereby verifying the stabilized level of training. However, recorded data beginning with the third month of flight showed a decrease in the cosmonaut's work capabilities; the volumes and intensity of locomotions were significantly reduced, the running exercise volumes were normally 70–75% and approached the walking volume, and the speed of both abruptly declined. Recorded data analysis, which confirms the abrupt decline in the cosmonaut's conditioning level, was a sign of the urgent medical problem for the medical support services and was confirmed during subsequent medical tests and exams.

The level of conditioning and, consequently, the effectiveness of the training performed by crewmembers are also determined in long-duration flight according to the parameters of the treadmill test with gradually increasing locomotor loads on the treadmill. The length of the test is 11 minutes, and the energy expended during the experiment is approximately 100 kcal. A distinctive feature of the test is the standardization of the sequence and length of each of the five load levels (Fig. 4) with voluntary selection of work intensity within each level. The mean speed limits of slow, moderate, and fast running, which constitute the basis of the test, are shown in the crew procedures. However, during flight training the crew receives instructions to use these speeds as general guidelines only, and is instructed to select exact running speeds within each level based on how they feel. Conditioning indices are the intensity of work performed, the running speed within each level, and the heart rate.

During a 360-day flight the intensity of work and, consequently, the volume of work increased, but the heart rate recorded while performing "maximum" running somewhat decreased, stabilizing at 170 bpm. A similar dynamic of test parameters was also noted for the commander of an 11-month space flight. Along with this, test indices of the flight engineer of the same mission from the third month of flight later showed a different decrease in tolerance to locomotor loads: the running speed within the levels was unusually low and in a number of cases the cosmonaut did not follow the structure of the test, abruptly stopping the run or changing to a cool-down walk, passing the maximum run phase. ECG showed that during this time, the increase in the heart rate was inappropriate to the load and occasional paroxysmal tachycardia and arrhythmia (supraventricular extrasystole) were observed.

The principles outlined above were the basis for generating exercise countermeasures for long-duration space flights aboard Russian space stations.[62,74] Analysis of flight results and data from postflight examinations of crewmembers allows us to conclude that the requirements of the onboard training system for time, volume, and intensity meet the two primary objectives. Specifically, they a) successfully maintain the physiological systems at a level necessary and sufficient to support health and high performance during all stages of flight, including readaptation to Earth gravity and b) do not require special professional qualifications. After appropriate ground training, these protocols are accessible to crewmembers of various ages and body types.

5. Occlusion Cuffs And LBNP Training

Comparatively short orbital flights of Russian cosmonauts and American astronauts have shown that upon returning to Earth, a worsening of the cardiovascular system response to the orthostatic test was observed. A decrease in orthostatic tolerance may result from many factors peculiar to space flight. However, the main etiological factor that has a negative influence on the homeostatic mechanism of the circulatory system is the length of time in microgravity. Data obtained in ground experiments with simulations of hypokinesis contributed significantly to the study of this area.

The results of numerous short-term and long-duration model studies of the unique physiological effects of microgravity, in which various countermeasures for orthostatic intolerance were developed, showed that the application of negative pressure to the lower body (LBNP) to a certain degree counteracts the decrease in the orthostatic tolerance.[3,4] The system of countermeasures which was developed for use on long-duration flights on orbital stations, one component of which was LBNP training, successfully passed testing in numerous simulations (in particular, in conditions of 182-day head-down tilt bed rest[75]) and was recommended for use on long-duration space flights.

Initially, during the space flight of the first long-duration crew to the Salyut-6 orbital station, LBNP training was performed during the last five days. The first day training consisted of two microcycles with a total length of 60 minutes. Days 2–5 consisted of three microcycles with a total length of 90 minutes.[74] Later, beginning with the flight of the second long-duration crew to the Salyut-6 orbital station, in compliance with experimental data, the general program of LBNP exposure was modified and expanded. Instead of five days, a two-stage training program was used beginning 18 days prior to the end of the flight and consisted of "preliminary" and "basic" training (Fig. 5 and 6). This method of LBNP training provided: a gradual adaptation of the body to a redistribution of blood and fluids analogous to that on Earth; the possibility of flexible scheduling and an individual LBNP training program, taking into account the physiological reactions of the crew to the preliminary LBNP tests; and additional data to predict orthostatic tolerance during flight and changes to it during LBNP training.

Based on the results received from LBNP testing, particularly the test that approximated the time of LBNP training, the quantity of preliminary and basic LBNP trainings was determined. If there was poor or satisfactory tolerance to the test, the quantity of preliminary LBNP training could be increased up to six cycles and the negative pressure was changed in accordance with the individual tolerance to the test.

In order to prevent or mitigate the negative effects of microgravity associated with the redistribution of blood, it was recommended that along with the LBNP training, mechanical (Bracelet-type) or pneumatic (Pnevmatik) occlusion cuffs be used in short-duration space flights, or in the beginning of the adaptation period in long-duration flights. According to data,[76] the use of occlusion cuffs in the acute period of adaptation to weightlessness was accompanied by alleviation of symptoms of vestibular dysfunction. The issue concerning the usefulness of the Bracelet occlusion cuffs throughout long-duration space flights still remains open.

a. Some Physiological Effects of the Occlusion Cuffs and LBNP

Occlusion cuffs. The prophylactic effect of occlusion cuffs in space flights is based on the pooling of a certain volume of blood in vessels of the lower extremities. This pooling is caused by an occlusion of the superficial veins of the calf and consequently leads to a decrease in blood volume that is shifted towards the head. When using pneumatic occlusion cuffs in experiments with simulated microgravity conditions (head-down tilt bed rest), the subjects developed the illusion of shifting from an actual antiorthostatic position to an orthostatic position with the head raised in relation to the horizontal. Meanwhile, the unpleasant feelings of heaviness in the head and edema of the soft tissues of the face and neck decreased; the cardiac output and the cranial and pulmonary blood flow indices decreased; and the sensitivity of the vestibular apparatus to linear accelerations changed.[41]

Direct research methods (probing the femoral artery and vein) have shown that during short-duration use of mechanical occlusion cuffs, the pressure in the vein on the upper surface of the foot markedly increased, the pressure in the femoral vein showed a tendency to decrease, and the arterial pressure in the vessels of the lower extremities did not change.[77] During a seven-day head-down tilt bed rest (-15°) the use of occlusion cuffs, with pressure in them ranging from 30 to 50 mm Hg, was accompanied by artificial pooling of blood in the lower extremities (about 250 ml) and the normalization of central hemodynamic indicators. The most pronounced effect was observed with a pressure in the cuffs of 50 mm Hg.[78] Similar data have also been obtained in longer experiments with 30-day head-down tilt bed rest (-8°) in which Bracelet-type mechanical cuffs were used daily for 12–15 hours per day. The research results also revealed the training effect of a systematic pooling of blood in the lower extremities on the body's antigravitational functions.[79]

Extended wearing of the occlusion cuffs may mitigate the development of such complications as fainting and increased distensibility of the veins of lower extremities, although with the degree of occlusion recommended for flights, these occurrences, as a rule, are not observed. With extended wearing of the cuffs, it is possible to exclude the possibility that the distensibility of the veins in the lower extremities may increase which, in turn, may have a negative effect on the tolerance to orthostatic loads during landing.[41] Authors[80] believe that the results of research involving 70 days of bed rest in which the application of physical and occlusion training did not result in a pronounced positive effect on the orthostatic tolerance of the subjects can be attributed to the increased distensibility of veins. In the experiments conducted by the same authors with 18 hours of water immersion, the training that included wearing occlusion cuffs on the upper third of the hip for eight hours with a pressure in them of 60–70 mm Hg (with a cycle of 1 minute of pressure, 1 minute of rest) aided the maintenance of orthostatic tolerance.

Use of the cuffs during short-term flights was accompanied by insufficient pulse engorgement in the chest and head and in several cosmonauts—a disappearance of feelings of heaviness in the head and unpleasant sensory and autonomic symptoms.

The occlusion cuffs during long-term flight were subjectively assessed as useful by the crews of Mir expeditions 4, 5, and 6. However, objective studies of their impact on the cardiovascular system, conducted with three crewmembers during months 1, 2, 4, and 6 of the Mir-9 and Mir-10 expeditions, were inconclusive.

<u>Lower body negative pressure (LBNP).</u> In space medicine the LBNP method was introduced as an analogue to orthostatic test.[81,82] The physiological shifts that occur in the human body due to LBNP are determined by an entire set of factors: the negative pressure level and rate in the vacuum chamber; the portion of the body undergoing decompression; the design of the pneumovacuum article; and the intensity of the weight-bearing stimulations that accompany decompression.

It is believed that the primary effect of LBNP is the redistribution of blood and the pooling of the blood in the lower extremities which lead, subsequently, to a decrease in the volume of actively circulating blood.[83] Under the effects of LBNP at a pressure of 40 mm Hg, in just one minute about 215 ml of blood may be pooled in the legs and 510–600 ml of blood in 5–20 minutes,[84] which approximately corresponds to the effect of standing upright on Earth.

As a rule, under the effects of LBNP, the cardiovascular system responses are very similar to those during an orthostatic test. The following are observed during the test: a decrease in the volume of circulating blood, an increased heart rate, a decrease in the stroke volume and cardiac output, a decrease in the systolic and pulse pressure, an increase in the diastolic pressure, and activation of the neuroendocrine regulation of fluid-electrolyte metabolism with subsequent retention of fluid and electrolytes.[42,85–93] Subjectively, a reaction to LBNP is accompanied by sensations of vertical posture with weight borne on the soles of the feet and a fairly noticeable physical load. If the test tolerance is good the feelings are pleasant; if the tolerance is bad, the feelings are accompanied by a tingling sensation and heaviness in the legs due to the overfilling with blood. This is accompanied by sweating, dizziness, and, in some cases, severe visual and auditory disturbances, general weakness, and nausea.

The results of numerous studies, conducted in real and simulated microgravity, confirm the hypothesis that exposure to LBNP to a certain degree simulates the blood distribution characteristic of a vertical position. The capacity of the venous bed is able to increase under the effect of the blood hydrostatic pressure or during a simulation of the pressure. As a result, in the decompression zone blood is pooled in a volume proportional to the distensibility of vessel walls. The venous return and blood filling the atria, the ventricles, and the heart-lung area are decreased, and this, in turn, leads to a change in the hemodynamic situation not only due to a redistribution of blood, but as a consequence of the reflex reactions from the atria, central veins, and heart-lung area receptors.[90–92] A decrease in venous return and blood filling the ventricles causes a decrease in the stroke volume, a compensatory increase in the heart rate, peripheral resistance and the rate of pulse wave distribution along the aorta, and an increase of vascular tonicity. A decrease in the load on the heart is accompanied by a decrease in myocardial tension and, in compliance with Starling's law, a decrease in the strength of heart muscle contractions. This is also observed during orthostatic activity. [90–92] The decrease in venous return and central blood volume that occurs during the orthostatic test also causes a subsequent pressure decrease in the heart ventricles, which may lead to greater distention in the left ventricle walls, and, thus, slower myocardium relaxation.

The results of studies also indicate that the LBNP functional test accurately reflects the cardiovascular system's level of adaptation to microgravity conditions. Based on these observations the cosmonaut himself and the physicians who are monitoring his condition in flight, focusing on simple physiological parameters such as heart rate and blood pressure, can assess the regulatory capabilities of the circulatory system and, most importantly, predict the tolerance to g-loads during the space vehicle descent phase and the probable orthostatic tolerance of the cosmonaut in the early readaptation period.[37,94–96] Along with this, when using LBNP as a model of the longitudinal positive gravitational loads on the circulatory system, it should be remembered that this method has its own serious shortcomings associated with an absence of hydrostatic pressure gradient in various circulation areas. This apparently causes certain qualitative and quantitative differences in the physiological reactions on decompression and orthostasis.[4,94–96]

b. LBNP Training Methods in Space Flight

As shown above, in-flight training is performed mainly in two modifications: as a functional test to assess the function of the cardiovascular system[73,97–100] and, in the second, as a training for orthostatic intolerance prevention. [4,40,73,101–103]

The LBNP methods performed during simulations and space flights are primarily based on the following principles[41,70,74]:

- LBNP training is conducted only during the final stage of flight;
- training consists of two stages: the preliminary training stage, directed at testing the cosmonauts' orthostatic tolerance and preparing them for intensive LBNP exposure; and, the basic training stage, directed at activating the mechanisms which regulate vessel tension, neuroendocrine regulation of the cardiovascular system, and fluid and electrolyte homeostasis;
- training protocols involve: a gradual adaptation of the cosmonaut to a redistribution of the blood characteristic to the vertical position of a body on Earth by using gradually increasing level and duration of negative pressure exposure in both the training session as well as in repeat training;
- the training uses submaximal and maximal exposures which alternate with negative pressure release to the ambient pressure level, which is necessary for increasing the tolerance of the cardiovascular system to pressure fluctuations; and
- based on safety regulations, LBNP training includes constant monitoring of the level and duration of negative pressure and the cosmonaut's condition.

c. Profile of LBNP Training in Space Flight

As stated above, training sessions are held in two stages.[41,70,74,102,103] The first (preliminary) stage schedule includes four preliminary training sessions, held 18, 14, 10, and 6 days prior to end of flight. The sessions involve the following pressure levels: session 1: -20, -25, -30, and -35 mm Hg; session 2: -25, -30, -35, and -40 mm Hg; session 3: -25, -35, -40, and -45 mm Hg; and session 4: -25, -35, -40, and -45 mm Hg. The duration is five minutes at each level of negative pressure on each training day.

The second (final) stage is held during the last two days prior to the end of flight and consists of two training cycles:

- cycle 1 of first day: -25, -35, -40, and -45 mm Hg for five minutes at each level, then a smooth descent to "0" over the course of one minute;
- cycle 2: -25, -35, and -45 mm Hg for 10 minutes at each level of negative pressure, then -30 mm Hg for five minutes and a descent to "0" over the course of one minute;
- cycle 1 of second day: -25, -35, -40, and -45 mm Hg for five minutes at each level, then a smooth descent to "0" over the course of one minute; and
- cycle 2: -25, -35, and -45 mm Hg for 10 minutes at each level of negative pressure, then -30 mm Hg for five minutes and a descent to "0" over the course of one minute.

Prior to beginning LBNP training it is recommended that the cosmonaut drink 300 ml of liquids. During negative pressure application, the cosmonaut is required to simulate walking with a rhythm of 10–12 steps per minute, shifting from foot to foot.

For safety assurance LBNP tests and training in flight take place under strict medical monitoring. LBNP is scheduled so that the maximum exposure is always used during the telemetry session when there is direct recording of the cardiovascular responses. Flight hardware is used (the Gamma-01 hardware on the Mir orbital station) to continuously record the electrocardiogram in "DS" leads, a rheoencephalogram in bimastoidal leads, and once every 2–3 minutes (more often if necessary) the blood pressure using a tacho-oscillography method. If for one reason or another, it is impossible to receive telemetry data, the evaluation of the cardiovascular system status and the tolerance to the LBNP is made based on heart rate and blood pressure data received by the cosmonauts using self, or mutual, monitoring methods. It is then transmitted to the medical monitoring specialists immediately during the communication session or as soon as possible after the session is completed.

For safety assurance, the safety push-to-talk button on the Chibis suit, the pneumovacuum suit discussed below, is used when negative pressure is -35 mm Hg and higher. The final decision about the LBNP training schedule at any stage is made by the medical monitoring specialists.

6. Hardware

a. The "Bracelet"

The "Bracelet" preventive device, used in the early stages of flight, is an integrated device consisting of two occlusion cuffs (right and left) and a belt, made from a special elastic fabric, and tension straps that are connected during use. The device's geometric shape lends the cuffs a certain configuration that allows the user to place them obliquely across the upper third of the thighs, in close contact with the body. The Bracelet device is worn over flight clothing or underwear. Compression in the proximal part of lower extremities is caused by tightening the cuffs using a special buckle.[104] Each cosmonaut can determine the degree of cuff tightness based on subjective feelings and can adjust the cuffs as needed throughout flight.

The use of Bracelet is recommended when cosmonauts complain of headaches and head fullness, impaired hearing or vision, vestibulo-autonomic disorders, facial puffiness, and hoarseness, frequently observed in the early days of flight. Contraindications for Bracelet use include varicose vein enlargement in the legs, thrombophlebitis, wounds and abrasions on the legs, and other contraindications determined by medical personnel.

If the device is used improperly, the following may be observed: swelling of extremities below the cuffs, irritated skin under the cuffs, and petechial hemorrhaging in the skin of the extremities. These symptoms are not hazardous to the health and will resolve on their own after the device is removed.

b. Pneumovacuum Suit

During the early Russian space flights on space stations Salyut-1 and Salyut-3, the Veter vacuum chamber was used for LBNP,[4,41] but later, beginning with flights of Salyut-4, the "Chibis" preventive vacuum suit[43] was used.

The Veter vacuum chamber was a sectional frame with longitudinal and lateral stiffness in a cylindrical shape, covered with airtight fabric. During LBNP exposure, one could perform certain exercises in the chamber (for example, walking in place). In that case, the chamber would be firmly fixed to the floor.

The Chibis, a pneumovacuum suit, consists of a) boots and b) a chamber for the pelvis with two corrugated pant legs made from rubberized fabric that connect to the pelvis (Fig. 7). The suit is secured and sealed at the iliac crest. It also has shoulder straps to transfer some of the static load that emerges during negative pressure exposure, from the waist to the shoulders and spine. The chamber is equipped with a control handle (lever switch) for emergency cut-off of negative pressure in the chamber, if necessary, and a negative pressure relief valve (for rest at approximately 60–70 mm Hg). Depending on the goals and objectives of its use, the suit allows for various negative pressure settings and exposure lengths.

By creating negative pressure around the lower body, the Chibis preventive suit, as a more effective countermeasure device, allows cosmonauts to do certain physical exercises (shifting from one foot to the other, squatting) at the same time, which is one of the main elements of the training cycle. The combination of decompression in the lower body and walking provides ideal conditions for conditioning the blood vessels in the legs, preventing blood pooling in the legs, and facilitating blood flow to the heart. As a result, stroke volume, cardiac output, BP value, and cerebral vessels engorgement and tonicity are maintained at the appropriate level.

7. Water-Salt Additives (Fluid Loading)

It is well known that a long-duration stay in weightlessness results in a hydration status different from that on Earth and in specific, unique new conditions of vital activity and fluid and electrolyte homeostasis. One of the natural manifestations of the adaptive changes is the lowering of the body's hydration level and the volume of circulating plasma.[46,105] The latter, in its turn, can cause the development of orthostatic intolerance and other hemodynamic disturbances during the early stages of postflight readaptation. In connection with this, the system of countermeasures for the final stage of space flight includes water-salt additives.

Fluids and minerals, chiefly sodium, which aid in replenishing the intravascular fluid volume, that is the circulating plasma volume, and thus increasing the body's hydration level[41,106] are used according to the program that was developed in simulation experiments on Earth. The results of studies with long-duration head-down tilt bed rest have shown that LBNP exposure, followed by intake of additives, and regular physical training increase the capacity of the vascular bed and aid in pronounced and lengthy retention of fluids, sodium, and chloride in the body.[74,107] In ground-based experiments it was also shown that a gradual (several times during the day) administration of fluids and sodium chloride[107] is optimal, allowing their quick absorption through the gastrointestinal tract and even distribution throughout the body's fluids to raise the capacity of the vascular bed and its volume as well as the vascular tonicity. In other words, the water-salt additive adapts the circulatory homeostasis of the body to the gravity exposure.[41,107]

The composition of the water-salt additive, that is, the dose of sodium chloride and fluids, as well as the timetable for ingesting them, changes in accordance with specific flight conditions, the landing schedule, and individual parameters of the crewmember's health status, which is assessed using LBNP test results.[74] However, the standard schedule for ingesting sodium chloride and fluids, developed for typical flight conditions and for a cosmonaut who does not have any deviations in his health status, follows this ingestion sequence. Prior to donning the spacesuit, the cosmonaut takes three tablets (0.9 g each) of sodium chloride and drinks 300 ml of fluids during a meal. Water-salt additives are preceded by LBNP exposure, which is performed during the last days prior to the end of the flight and with the regular physical exercises. This ingestion timetable, in large measure, also helps to increase orthostatic tolerance during the early postflight period. Unpleasant side effects when taking water-salt additives are generally not observed by cosmonauts.[74]

To support ingestion of water-salt additives, the standard first-aid kit includes a package containing sodium chloride tables, 0.9 g each, for oral intake. For the liquid portion of the water-salt additive, drinking water may be used as well as any juice or drink contained in the on-board menus.

We may note that the cosmonauts who take water-salt additives as part of countermeasures experienced better g-load tolerance during the final flight stage and, during the rehabilitation period, had a more stable hemodynamic condition and a less pronounced decrease in excretions of fluids, sodium, and osmotically active substances.

8. Antigravity Protective Equipment Used on Soyuz-TM Space Flights

A crucial and particular factor of space flight are g-loads which occur during a space vehicle's orbital insertion and descent to Earth. During the final stage of flights performed under the Russian space program, the g-loads for crewmembers are in the "chest-back" direction ($+g_x$) and under nominal conditions they are relatively small (about 4 g). However, in off-nominal situations the g-loads may approach the limits of physiological tolerance.[108–110]

The results of ground-based studies have shown that simulating microgravity conditions causes changes in the body's physiological systems and their deconditioning, and may be accompanied by a decrease in endurance to g-loads and crewmembers' performance during the descent of manned vehicles from orbit to Earth.[108,111–114] These data were confirmed by studies conducted in space flights which show that the stress on the body's physiological systems under the effects of $+g_x$ loads during the active phases of flights significantly increased. In comparison with preflight studies on the centrifuge using similar schedules, pronounced tachycardia and tachypnea were noted. During the descent from orbit, crewmembers in some instances experienced visual disturbances in the form of gray-outs.[108,112] A most noticeable stress of physiological systems, in comparison with additional studies on the centrifuge, was noted during the space vehicle's descent from orbit after a long-duration stay in microgravity. According to the data,[115] $+g_x$ loads of 4–5 g after microgravity lasting 2–8 months were accompanied by a marked deterioration of the cosmonauts' health and the cosmonauts' objective status as compared to short flights.

The results obtained indicate the necessity for using antigravity protection devices for cosmonauts in actual conditions of space flights during the $+g_x$ loads after a long-duration stay. The Russian countermeasures system includes the following:

- the optimal posture for the cosmonaut in the spacecraft seat which creates conditions for the most favorable g-load vector ($+g_x$);
- the cosmonaut's torso is pressed tightly to the seat liner which provides counterpressure to g-load effects; and
- compression of the lower body which counteracts the shifting of large volumes of blood into this area when there are longitudinal g-loads in the "head-pelvis" ($+g_z$) direction and enables a sufficient level of cerebral blood circulation to be maintained.

a. Means and Methods for Cosmonauts' Antigravity Protection

Optimal body position in the spacecraft seat. The results of experimental studies show that the optimum angle of inclination for the seat back in these situations is 80º in relation to the g-load vector. This position was selected during space flight training of the first group of Soviet cosmonauts.[116–118] Data from publications around the world showed that the transverse direction of g-loads on the "chest-back" ($+g_x$) were more easily tolerated by the body than g-loads in other directions, and especially, g-loads in the "head-pelvis" direction ($+g_z$). During g-loads, the $+g_x$ direction vector effects do not coincide with the direction of the great vessels of the body and therefore, during this effect, there is no pronounced redistribution of blood from the head to the lower extremities and critical disruptions in the blood circulation are not observed in the carotid artery with subsequent syncope as there is with g-loads in the $+g_z$ direction.[119] When selecting the optimal position in the spacecraft seat the results of previously conducted studies[120] were also considered. These studies showed that given a strictly perpendicular direction for the g-load vector in relation to the great vessels of the body (angle of 90º in a "seated" position), the endurance of g-loads is limited due to chest pain and pronounced breathing difficulties.

According to data,[108] the cosmonaut's seat-back position should be at an 80º angle to the vector of the g-load effect in order to eliminate the pain sensations, decrease the g-load along the "head-pelvis" axis more than two times (from 42% to 18–20%), and increase the g-load tolerance by an average of three units (from 10.1+ 1.26 to 13.0 + 1.4 g). This position was used in the Russian Voskhod space vehicles and is used at the present time in Soyuz-type spacecraft.

Shaped seat liners. Shaped seat liners are also used as protective devices in space flights. They provide even distribution of the g-load pressure created over the large surface of the body and prevent or substantially reduce vascular compression and the development of pain sensations.[121] Complete contact of the torso with the seat liner is assured in Soyuz-type vehicles through the use of shoulder and waist belts which the cosmonauts tighten when seating themselves in the seats and periodically readjust during the orbital descent g-loads.

Antigravity Suit (ППК). The antigravity suit is the basic equipment for individual protection of the body from the effects of g-load. It is used in Russian space flights on Soyuz-type vehicles during the return to Earth since during this particular flight phase, in a number of cases, signs of disruption to physiological compensatory mechanisms have been noted in the form of visual disturbances and other symptoms. The ППК operating principle consists of creating counterpressure to the lower body. By exerting external pressure on the soft tissues of the calf, thigh, and abdominal organs the ППК limits the mechanical shifting of blood during g-loads and decreases the blood volume pooled in the vessels of the lower extremities and abdomen.[122,123]

The postflight preventive suit (ППК-С), which had several changes from the aviation inflation-type suit,[124] was used by the space flight medical support system up until 1985 during the implementation of the Russian space program. Pressure in the chambers of this suit was created using a manual sphygmomanometer. The ППК-С suit was not used during descent. Although cosmonauts donned the suit prior to the start of descent, pressure was only created in the suit chambers after landing and until egress from the descent vehicle. Therefore, the basic goal of using this suit was to prevent orthostatic collapse during the initial period of readaptation to Earth gravity.[124,125]

Beginning with the Mir-4 mission of the Salyut-7–Soyuz orbital complex during 1985–1994, the chamberless Karkas-2 and Karkas-3 antigravity suits[126] were used as antigravity protective equipment for members of long-duration missions during the descent from orbit to Earth. The ergonomic properties of these suits needed to be improved and in connection with this in later missions, beginning in 1992 on the Mir–Soyuz-TM orbital complexes, the new Centaur antigravity suit, developed by A.S. Yarov,[71] was used. The Centaur suit was manufactured from an elastic fabric which has great elasticity and consists of a pair of long shorts and a pair of gaiters (Fig. 8). The side portion of the shorts and gaiters are outfitted with laces used to adjust the suit to the body and to compress the lower portion of the body. The shorts are secured at the waist with a belt. The length of belt is regulated using two straps. Nylon material was used to decrease the weight of the article. The Centaur article also includes short underpants.

The effective antigravity pressure of the Centaur suit on the human body is 30 mm Hg. In order to create this pressure, each cosmonaut is individually sized for the suit and the lacing gap along the thighs and calves prior to the start of the space flight. Two to three days prior to descent to Earth, the cosmonauts perform an adjustment of the Centaur suit to account for the body size changes caused by microgravity. The correctness of the adjustment is finally checked when donning the suit prior to descent from orbit to Earth.

IX. Russian Countermeasures Effectiveness During Long-Term Flights

As was noted in the introduction to this part of the chapter, microgravity ranks first among space flight factors that have a negative effect on the human body. The primary mechanism of negative effect, according to Russian experts, is elimination of g-dependent deformation and mechanical tension on the body structures which causes a redistribution of the body fluids as well as development of changes in the afferent systems activity level, a decrease in the functional load on the body's weight-bearing structures and, connected with this, a decrease in the postural antigravity muscle activity. The primary objective of countermeasures in long-duration space flights is to maintain health, a high level of performance, and the state of the body's physiological systems at the level sufficient for a safe return to Earth.

Taking these principles into consideration, a system of countermeasures was developed in Russia. Primary components of the system include: physical methods aimed at maintaining the distribution of fluids at levels close to those experienced on Earth (occlusion cuffs, and the Chibis and ППК-С antigravity suits); physical training and loading suits (Penguin, training-loading suit) which assure the creation of loads on the musculoskeletal apparatus and the cardiovascular system, the activation of proprioceptive and weight-bearing sensory systems, and preservation of postural and locomotor functions; measures that prevent the loss of fluids—water-salt additives that prevent fluid losses and thereby maintain orthostatic and g-load tolerance during the return to Earth; and a well-balanced diet and medications directed at correcting possible negative reactions of the body to weightlessness—vestibular, metabolic, endocrinal, etc.

This system of countermeasures successfully passed testing in flights with more than 80 participants of primary missions who worked on Russian space stations from 16 to 438 days, demonstrating the capability to maintain cosmonauts' health and performance during flight at approximate preflight levels and to prevent or significantly reduce the negative consequences following long-duration stays in weightlessness. All participants of the missions successfully completed the flight work program, the complexity of which in recent years increased significantly, and upon return to Earth had completely regained their work capacity within 45–60 days and returned to work. Twenty-five of these cosmonauts completed a second long-duration flight. Three worked on the station three times, and one, A.Ya. Soloviev, four times with breaks between flights of 2–3 years.

It is important to note, however, that while the recommended system of countermeasures was used as a basic framework, the majority of cosmonauts used it with significant deviations, changing the protocol of the training on the trainers and adding new elements. Analyzing the physical exercises that were recorded, data presented in verbal reports, and conversations of crewmembers with countermeasure specialists, as well as the results of load testing performed, the specialists evaluated the level of cosmonaut performance of countermeasures and revealed their individual characteristics.

During all of the apparent various changes made by the cosmonauts to the flight countermeasures system, they were in fact sufficiently uniform due to the unique characteristics of work regimens on the space stations, the cosmonauts' health condition and fitness level, as well as their personal athletic experience. One of the most frequently encountered deviations in performing physical training was switching to a once per day regimen. It is clear that given high work motivation and the heavy workload, training in full measure twice a day is a fairly difficult task. The majority of crewmembers used the once per day regimen during various flight phases when some changed the training to alternate with the twice per day mode, others stayed with the once-per-day regimen continuously throughout the flight except for during the final phase. As a rule, once having selected the once per day regimen as their primary regimen, cosmonauts performed training only on the treadmill. In certain cases during one training session both trainers were used if possible, and only in one instance was the ergometer selected as the primary trainer.

A number of cosmonauts considered it necessary to increase the force load of training and regularly supplemented the recommended protocol with strength-training using bungee cords and rubber bands. A set of bungee cords with very high strength properties was manufactured for one of the crew commanders who had weightlifting experience on Earth.

As a rule, the cosmonauts used the standard LBNP training regimen in flight and water-salt additives and antigravity protective equipment during the final flight stage. At the same time, use of the Penguin loading suit varied widely for individual crewmembers of long-duration missions: from complete refusal to wear the suit (a number of members of 15–25 missions on the Mir station) to daily wearing of the suit with maximum loads for 12–16 hours (the majority of crewmembers on the Salyut-6 and -7 stations).

Evaluating the status of the cosmonauts' physiological functions and work capacity level after completion of the flight, the specialists had the opportunity to evaluate the effectiveness of the system when it was fully utilized, in reduced modes, and when it was used in one or another modification proposed by crewmembers. The results of these analyses showed that the countermeasures system that is recommended for use in long-duration flights—which includes special physical training regimens, axial loading (using the Penguin suit), the use of an antigravity suit during the final flight stage, and occlusion cuffs during the critical period of adaptation to weightlessness, as well as well-balanced diet and an appropriate work and rest schedule—significantly levels out the development of negative effects of weightlessness in various physiological systems of the body independent of flight duration.

Therefore, given a comparison of changes in the force-velocity properties and endurance in five cosmonauts after flights lasting from 160–366 days (Fig. 9), the largest change was noted in the cosmonaut who had been in weightless conditions for 160 days and the smallest change, even with a small increase in the postflight level, was in the crewmembers of the 366-day mission.[127] Cosmonauts who were in flight for 330 and 173 days were the intermediate group. Similar data were obtained during an analysis of changes in the characteristics of vertical stability, spinal reflex mechanisms, and other motor function parameters which are, first and foremost, the ones that suffer in weightless conditions.

The key role in the countermeasures system belongs to physical training. This statement was confirmed by the results of a comparative analysis of the intensity of dysfunction of the musculoskeletal apparatus after flights with lengths of 60 to 439 days using a point method to rate the degree of change for each function studied and subsequent integral ranking of the status from the best preserved to most compromised. Complete performance of the physical training was also evaluated using a 24-point scale (Fig. 10). As Fig. 10 shows, the level of maintenance of locomotor function in the cosmonauts after long-duration flights highly correlated with the intensity and volume of the physical training used during the flight and did not correspond with the duration of the flights.

More indicative were the results of a comparative analysis of the intensity of locomotor dysfunction in two flights, the first and second, of 17 cosmonauts who each completed two long-duration space flights (Table 10). The length of flight in the group of the first and second flights was identical, ranging from 2–3 to 8 and more months with an average length in the group of the first flights of 5.7 months, and in the group of the second flight of 5.9 months. The intervals between the two flights were, as rule, within the 1–3 year range. Five of the 17 cosmonauts had a first flight longer than the second, and for seven others the length of the second flight was greater. Five cosmonauts had first and second flight lengths that were identical and were 5–6 months.

As in all flight groups in general, in the group of "two-time fliers," the intensity of changes caused by a stay in weightlessness did not depend on the duration of the flight in the first flight nor in the second (Fig. 11). When comparing the extent of the changes caused by the first and second flights, only five cosmonauts had integral evaluations for two flights that coincided. In all others there were significant differences, appearing in a number of cases of negative dependence. So the four cosmonauts for whom the intensity of disturbances was the greatest (ranked as 17th, 15th, 16th, and 14th) in the first flight, which was associated apparently with a decreased volume of physical training during flight (from 50% to 60% of the recommended level), were among the top (ranked as 1st or

2nd) or approached the top (ranked as 6th) during the second flight. Given that, flight duration for two of the cosmonauts was three or more times that of their first flight, and the level of preventive physical training was two times greater. Similar results were also obtained for four cosmonauts who were ranked at the bottom of the scale (14th, 15th, 16th, and 17th place) during the second flight (Fig. 11). The results of studies have shown, in this way, that individual tolerance while performing countermeasures also is not a factor in determining the extent of locomotor dysfunctions in long-duration space flights. A pseudo-negative correlation between data of the first and second flights (Fig. 12) observed during studies had, apparently, a psychological nature. The correlation was associated with a voluntary change during the second flight in the level of countermeasures to a higher level associated with the training insufficiency during the first flight and the dissatisfaction of the cosmonaut with the condition of the locomotor (and, as a rule, other) functions after the flight, or to a lower level in the opposite case. Only a small number of cosmonauts used a relatively similar protocol and volume of exercise countermeasures in both flights, showing relatively similar locomotor changes. It is important to note that the extent of locomotor dysfunctions after long-duration flights, as a rule, correlates with the disruptions of other functions, such as, orthostatic intolerance, the amount of bone loss, and changes in the immunological status.

Having presented the material of this chapter, we may conclude that in Russia a system of countermeasures was developed and tested. This countermeasures system assures the maintenance of vital functions of the body and a high level of work capacity for crews of flights lasting more than one year. Studies, performed during flights and within the framework of physiological clinical examinations, have shown that the level of disruptions which develop in weightlessness in various body systems correlates in large measure not with the length of the flight but with the frequency of use of countermeasures during flight. Further flight stage disruptions that appear in connection with insufficient use of countermeasures may be countered by high-intensity loads. This allows us in turn to conclude that with the use of the current countermeasures system it is possible to complete space flights of significantly greater lengths than one year. Nonetheless, we must note that while the present system of countermeasures is sufficiently effective, it is not perfect and should be further developed.

X. Primary Trends of Countermeasures Development

Historical differences in mission objectives have meant that the American and Russian countermeasures programs developed along two different paths. The Russian program has focused its efforts on accomplishing long-duration stays aboard orbiting space stations. These types of missions necessitated the thoroughly regulated use of countermeasures—constant physical training supplemented by reconditioning devices and pharmacological measures. In contrast, the American program achieved numerous short-duration flights, which required a less comprehensive program of countermeasures, and only limited space station experience with Skylab and Shuttle-Mir missions. Nonetheless, both programs recognize certain potential “critical moments”—that is, symptoms or adaptations that must be limited in order to make future missions possible—and the approaches that must be implemented in order to counter these negative trends.

The combined experience of the American and Russian countermeasures program has revealed several areas that need further research and development (Table 11). Russian researchers have studied the experience of using countermeasures aboard space stations and have identified elements of the system that should be deleted for significant improvement of the countermeasures system. The twice per day training on the treadmill and the ergometer, which composes the basis of the system, takes up a comparatively large amount of time, is relatively monotonous, and is not individualized in accordance with the special physical characteristics and preferences of the operator and with the peculiarities of the flight programs, their length, and work objectives. The training is not sufficiently comfortable and is not outfitted with equipment for effective real-time monitoring of the cosmonauts’ health and conditioning level, which interferes with the capability of real-time corrections during training.

The current countermeasures system does not sufficiently account for the differences in the change mechanisms of the body’s physiological responses in various flight phases. Studies performed in space flights and ground-based experiments have shown that weightlessness causes the development of a number of complex sensory, locomotor, and autonomic disruptions, whose development rate in the very first hours of activity indicates their reflex nature. It is obvious that during this stage, compensatory and corrective measures addressed to sensory and reflex mechanisms have the best results. During the latter stages of flight a significant role in the development of locomotor and other disruptions belongs to atrophic changes in the muscles and bones, generating and strengthening the adaptive shifts in the locomotor and autonomous regulatory systems. During this phase the system of countermeasures must be oriented to control these disorders.

At the present time a large number of loading devices have been developed whose use allows us to outfit the space vehicle with a number of different trainers in addition to the treadmill and ergometer. Given the current level of automation there is no fundamental difficulty in creating training systems that perform loads which will be psychologically simplified due to the introduction of motivational stimuli into the training (game trainers and trainers which allow training in "competition" modes", etc.). There is the capability to increase the length and intensity of physical training during specific flight stages and if necessary (due to illness or intensive work schedule) not to perform them for a specified period. A comparative analysis of data from postflight physiological clinical examinations and simulated hypokinetic experiments has shown that the operational locomotor activity of cosmonauts in vehicles of relatively large volume has a preventive effect. This effect can be enhanced significantly by strength and resistance loading of the operators' controls using simple (springs, magnetic clamps) and modified (hydraulic) devices. With these the volume and length of loads during training sessions can be significantly reduced.

Another way of meeting this objective is the development of so-called "passive" training equipment whose effectiveness has been tested under simulated conditions. These include equipment which simulate in weightlessness specific loads: various types of load suits, electro- and vibrostimulators of varying characteristics, training with biofeedback, and a short-radii centrifuge which allows us to intensively load the muscles and bones in a relatively short period of time and to simultaneously increase the activity of the vestibular proprioceptor and weight-bearing afferent system.

The necessity of increasing the effectiveness of monitoring the process, results, and endurance of countermeasures requires the creation of a highly informative, automated system for monitoring and controlling the training process to provide a current evaluation of the health status of the operator undergoing training and to use the data obtained as biofeedback to regulate the volume and intensity of the loads utilized by the operator himself or in automatic mode. This system is currently under development and is incorporating the rich experience gained in the Russian countermeasures system.

The beginning of International Space Station operation reveals extensive possibilities to use advanced technologies. As technological capabilities grow, new types of missions—for example, research missions to the Moon and Mars—will become priorities for international space efforts.

XI. Conclusion

From the earliest attempts to transition from aviation into human space flight, countermeasures have been essential to mission success. The development of an appropriate and comprehensive countermeasure program is a difficult test complicated by a number of reasons: adequate interpretation of the physiological mechanisms mentioned above; the difficulty presented with the indirect influence of weightlessness and the adaptive processes associated with it; and the even greater difficulty of preventing, minimizing, and limiting these effects. This conundrum is compounded by the difficulty of testing and validating a single countermeasure against the background of numerous other necessary measures, individual differences, and operational constraints. With the advent of multinational ventures into space, the experience and knowledge of the American and Russian space programs continue to converge and to strengthen each other, and that is the key to success.

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Space Biology and Medicine
Volume IV: Health, Performance, and Safety of Space Crews

Chapter 9

Psychological Support for Crewmembers

Olga Pavlovna Kozerenko and Albert W. Holland

The concept of “psychological support” entered the realm of space medicine as piloted space flights became longer and increasingly complex. Long flights, which became possible largely as a result of scientific and technological advances during the 1970s, demanded guarantees, based on scientific principles, that the health, work capacity, and “fail-safe” performance of human crews would be maintained during long exposure to flight-related environmental, psychological, and occupational factors. In their most general form, these factors can be described as changes in the habitable environment (including weightlessness); curtailment of living space (i.e., being confined in small areas); isolation and remoteness from Earth; and limitations on the freedom to choose ways of satisfying various needs.

Observations of various groups on Earth operating under analogous conditions (e.g., crews on polar expeditions, submarines, or long sea voyages) have demonstrated that long exposures to such factors are accompanied by changes in human behavior and performance. Such changes primarily take the form of psychological or emotional disturbances such as narrowing of interests, diminishments in motivation and activity level (both general and work-related), emotional lability (mood swings), depression, apathy, and ennui.[1–3] Characteristics of the psychosocial-adaptation process under these conditions also include disturbances of sleep, memory, and concentration, psychosomatic symptoms, intragroup conflicts, and aggressive behavior.[4,5] Such negative reactions during space flights constitute risk factors that threaten to reduce the psychological and behavioral reliability of crewmembers[6,7] and compromise the success of their missions. Thus, the need for appropriate protective measures in space is both clear and imperative.

Long space flights, as conceived in the sociological systems theory developed by U.S. and Russian scientists,[8,9] represent a complex, integrated system. The major subsystems of such a system include the spacecraft, the crew, the environment in which the flight takes place, the ground personnel and organizations supporting the flight, the nature of the relationships among the crew and the support personnel, and societal attitudes, among others. The efficiency—and efficacy—of a complex system of this type depends on the extent of coordination among its interacting components (subsystems), which in turn supports its internal stability and constancy. Aside from the constraints associated with the space environment and technology, the destabilizing factors during the long functioning of such a system primarily involve interpersonal and intergroup interactions. For this reason, the most important psychological problems of a flight to Mars are thought to be those associated with human isolation and the dynamics of small groups that must operate autonomously for long periods.[5]

The composition of groups, the selection of leaders, the structure of work, and the creation of optimal living conditions all are important for fostering favorable adaptation and for minimizing psychosocial discomfort during long periods of isolation. Also important in these “minicultures” are aspects of the environmental design that allow each crewmember some privacy, and allow minor modifications to the spacecraft interior (e.g., by moving partitions).[2,4,5] Opinions differ with regard to contacts with the outside world, especially in how to regulate personal information given to members of isolated small groups. Some researchers in the Antarctic report that personal contacts with families and friends serve as reminders of how far away they are, thereby intensifying the stress of isolation, having negative effects on psychological adjustment, and giving rise to doubts and emotional breakdowns—in short, negatively affecting performance.[5] For space crews, personal communications with Earth generally are considered a positive psychological factor, except when the information received is upsetting. Although the desired frequencies and types of communication with families vary widely among crewmembers, the existence of such a link brings an element of “normal life” to the living conditions of an isolated group.

The challenges associated with supporting the psychological well-being of crews on long space flights touch on many behavioral issues, including crewmembers’ psychological needs, mental states, emotional responses, communications, roles, planning activities, criteria for success, and external stimuli. All of these issues are directly related to the structure of life in small groups that are confined in an artificial living space within an extreme environment, isolated from familiar social conditions. The complexity of psychological support for such groups tends to increase with flight duration.

Although many aspects of the lives of space crews are dictated by technology, psychologists and other medical personnel have sought to improve living conditions as much as possible in order to alleviate the psychogenic consequences of living in an artificial environment. Understanding the psychological problems of long space flights thus provides a basis for selecting means of psychological “protection” for adverse effects as well as psychological support for crews on such missions.

I. Psychological Support Systems

A. Principles and Objectives

In analyzing how to support the psychological well-being of space crews during long missions, Russian and U.S. specialists generally agree on the goals of that support, which are to ensure the efficient performance of cosmonauts and astronauts in flight by not allowing their collective performance capacity to drop. Nevertheless, some differences exist in the diagnostic and corrective methods between the two programs. The philosophies of the Russian and U.S. support programs are summarized briefly below.

1. Russia

Russian specialists define *psychological support* as a set of supportive and therapeutic methods, means, and measures used by ground services for cosmonauts to ease the process of their psychological and occupational adaptation to their living conditions, and to prevent psychosocial discomfort during flight.[10] The current set of Russian psychological-support measures were first approved during a 96-day flight on Salyut-6 (1977–78), and subsequently became part of the standard medical-support system for long space flights.

A central goal in the Russian system is to provide the crew with information to help them regulate their adaptation to space flight.[11] The sharp curtailment of social contacts, social support, and communications with people remaining on Earth all dictate the amount and type of informational support needed. Typical information would include news of conditions on Earth as well as news of personal and social significance. However, given existing constraints on time, weight, and economics in space, the amount and type of informational support provided must be selected carefully to be the most effective, both emotionally and intellectually. Moreover, the nature of the processes that lead to the need for specific types of information may change over the course of a flight. Various mental states, friction between individuals and groups, fatigue, and other factors can change a crewmember’s perception, attention, and memory, so that the initial guidelines for what information is provided may need to be adjusted during the crew’s stay on the station. Finally, the human need for novelty—to learn something new and unfamiliar—also must be addressed. According to one source,[12] this need results from both internal chemical mechanisms (increased levels of endorphins in the brain) and adaptive psychological mechanisms. In an isolated environment, the need for novelty is likely to increase, which places increasing demands on informational support services during long flights.

The Russian psychological-support system seeks to provide the crews with significant information in a way that considers the particular stage of the flight, the individual characteristics of each crewmember’s personality, and that crewmember’s current mental state. In this way, Russian psychologists attempt to influence crewmembers’ emotional states so as to support psychologically comfortable contacts between the individual and the external world. Results from psychological observations and examinations of crewmembers during the selection and training phases are important in this endeavor, since they facilitate understanding of the personal idiosyncrasies, relationships and reference groups, role requirements, habits, and sociocultural preferences of each crewmember.

In summary, the Russian concept of informational support, within the psychological support system, involves the following: structuring crewmembers’ leisure time on board; psychologically “reconstructing” living conditions to prevent monotony (see Section III); compensating for deficits in social contacts; attempting to influence emotional states; optimizing group relations; and maintaining motivation. All of these steps are related to the habitability or “livability” of the spacecraft environment. Traditional definitions of habitability concern the overall acceptability of environmental conditions from the point of view of the human operator[13]; “livability,” on the other hand, refers to the comfort and aesthetic qualities of the conditions in which human operators live and work.[14] Informational support seeks to improve livability. This support is provided in close coordination with psychoneurological monitoring, adjustments of the work-rest schedule, and resolution of individual, interpersonal, and intergroup problems (see Chapter 11, this volume).

2. U.S.

In planning for orbital space stations, NASA specialists proposed that an extensive, onboard health maintenance system should be developed, and that that system should include some capability for psychiatric diagnosis.[15] In considering crews of 3 to 12 individuals, each consisting of male and female career astronauts and scientists, on missions lasting 30–90 days, these planners correctly presumed that even the most painstaking selection process could not completely preclude the risk of psychological disturbances arising in stressful situations, especially those disturbances that have a genetic component. Early predictions of the most likely types of psychological and behavioral deviations to occur in flight are still valid, and include anxiety reactions (e.g., phobias), dysphoria or depression (and possibly suicide attempts), behavioral disorders (including interpersonal conflicts), disturbances in memory and cognition, and psychoses caused by toxins that could be present in the environment. Ideally, an onboard facility would include ways of diagnosing and treating disturbances such as these through the use of computer-based psychological assessments, biofeedback techniques, and others.

In addition to psychological disturbances such as those noted above, other states that could require psychological support or intervention can arise from family or marital problems, bereavement, interpersonal conflicts within the crew or with members of ground crews, and reactions to extended separation from family members and traditional social support systems. NASA specialists believe that the decision as to whether to provide a crewmember with disturbing personal information (e.g., about the death of a family member or the threat of divorce) during flight must be made on an individual basis.

With the advent of the U.S. and Russian cooperative flights in the Shuttle-Mir Program, NASA began a program of psychological support that de-emphasized diagnosis and shifted the focus to preventing the occurrence of psychological difficulties. The U.S. support program was designed and implemented on the basis of the extensive Russian experience with long space flights. The Russian flight system has an extensive infrastructure in place to deal with crew psychological needs and diagnosis before, during, and after long flights. As they exist now, the U.S. support activities for the Shuttle-Mir Program are tailored to conform with existing Russian procedures for crewmembers living aboard Mir, so that the support systems for astronauts and cosmonauts living together there are as compatible as possible.

As of this writing, this new NASA support system has only been applied to U.S. crewmembers who are training abroad and living aboard a foreign (i.e., Russian) space station. This application has been a challenging and instructional beginning for a support system still in its infancy, and the theoretical underpinnings of a U.S. system have yet to evolve. However, the working tenets of the current program are to maintain meaningful informational and relational linkages with Earth, while infusing degrees of the familiar and the diverse into an otherwise abnormal and repetitive situation. During a difficult and extended absence from familiar physical and social surroundings, as well as from the accustomed amount of sensory and social stimulation, maintaining personal motivation and self-regulation over time is easier when the crewmember can draw upon those familiar referents that are an integral part of his or her coping strategies.

In the U.S. program, emphasis is placed on providing arrays of diverse support methods and resources that crewmembers can access as desired, rather than attempting to shape the mood of the crewmembers during the course of the flight. Individual crewmembers clearly differ in their styles and preferences for communications with home, use of leisure time, behavioral expectations of other crewmembers and ground personnel, personalities, and so on. However, U.S. crewmembers are not flying on their "home system" and cannot receive support over and above that provided to their hosts. Consequently, the U.S. program encourages reliance on individual coping mechanisms during flight, in combination with improved preflight selection and preparation procedures.

For both the U.S. and Russian programs, the lessons learned from the current "distant support" approach are expected to be valuable in preparing for extremely long missions, such as those to Mars. Self-reliance on such missions will carry a still greater premium, since those crews will operate even more autonomously from Earth.

B. Psychological Support Measures

The Russian and U.S. systems of psychological support are based on principles of preventive medicine. In addition to psychodiagnosis, they place significant emphasis on a set of measures intended to prevent or compensate for psychoemotional disorders, and to solve any social or psychological problems that arise.[10,16]

Some of the current means and measures provided on board and from Earth to influence crewmembers' emotions and intellect on long flights are shown in Table 1. The selection of literature and programs for listening and viewing takes into account the individual tastes, needs, opinions, and social and cultural preferences of the crewmembers, all of which are determined before flight through questionnaire and interviews. On Mir flights, support measures also include computer programs, the opportunity for ham-radio contacts, and other types of informal communication sessions.[17]

On long flights, onboard means of support are supplemented with new materials according to the needs and desires of the crewmembers and medical indications at various stages of the flight. These materials are delivered to the station by the cargo vehicles and by visiting crews. Visiting crews also provide a powerful source of psychological support for the prime crews.

Ground-based means of psychological support include daily information delivered via radio and television communications, informal communications (typically supplied on days off, holidays, or days of family celebration), transmission of “personal” information, and use of socially significant feedback. In general, the information made available during the course of a flight is developed and selected by an operational-psychology support group in accordance with the nature of work tasks, the stage of the flight, the status of onboard devices, the needs and desires of the crewmembers, and current societal events. The goal of the selection, whether planned or extemporized, is to satisfy the human need for information and provide feedback to support creative potential and active work on orbit.

II. The Dynamics of Psychological Adaptation

The efficacy of the psychological support system ultimately is determined by the flexibility with which various information structures are used, by which aspects of the information are emphasized, and by how the various sources of information are used. The dynamics of adaptive processes, especially those of psychological adaptation, must be considered if any psychological support system is to be effective.

Russian authors contend that several stages can be distinguished within the dynamics of psychological adaptation over the course of a space flight.[18] The remainder of Section II is devoted to descriptions of these stages, and how they differ with regard to psychological status, emotional experiences, needs, and use of self-regulation mechanisms. According to this concept, the characteristics of the stage of adaptation determine the appropriateness of some psychological-support technique if that technique is to have the intended emotional and intellectual effect.

A. Before Launch

Strictly speaking, social and psychological adaptation to flight starts during preflight training, when the crewmember begins the process of psychological preparation by studying the flight program, gaining necessary job-related skills and knowledge, and acquiring skills of self-regulation and group interaction. At that point, the crewmember begins to construct an internal representation of the space flight.[19]

B. Adjusting to the New Living Environment

This stage covers the first 4 to 6 weeks of flight, during which an individual acclimates to the new living environment and experiences the direct effects of novel sensations, impressions, movements, and modes of interaction. During this stage, the crewmember’s initial (preflight) orientation, which was focused almost exclusively on performing the job while mastering life in weightlessness, changes as a result of actual experiences in the flight environment. These experiences compel the crewmember to adjust his or her internal representation of space flight. Among other factors, these adjustments reflect the facts that the crewmembers must learn to:

- perform personal and housekeeping tasks for themselves;
- do without some things that are available routinely on Earth;
- spend considerable time supporting mission tasks and scientific experiments; and
- interact with the Flight Control Center, including conversing with numerous specialists, and maintain radio contact with Earth every 90 minutes.

These tasks tend to lead to a sense of time pressure, with the corresponding fear of not being able to accomplish tasks on time. This condition can form the foundation for feelings of stress and fatigue.

C. Stabilization

This period encompasses the remainder of the flight, after the crewmembers have adjusted to their new environment and schedule. During the stabilization period, the novelty of the space flight environment loses its significance, and the dominant emotional influences become the monotony of the spacecraft, activities, and contacts with the same people. This period is marked by the appearance of "deprivational" effects, i.e., a state in which unsatisfied needs are experienced acutely. These deprivational effects, especially in combination with diminished psychological "tonus," can be manifested as asthenia or changes in the sleep-wake cycle, among others. Deprivational effects tend to be the most intense during periods of forced reduction in work load. Individual crewmembers can experience brief episodes of behavioral changes as a result of the need for change in social status, e.g., after an important task is completed successfully. Conflicts and tensions between groups[20] also tend to develop during this period; one example would be disagreements between the crew and the ground control center regarding corrections to the flight program.

Finally, a substage within the stabilization period often is present during the last 2–4 weeks of flight, when crewmembers begin to reorient themselves emotionally to the final periods of flight (i.e., descent from orbit and landing).

III. Providing Psychological Support on Long Space Flights

The opportunity to support orbital flights lasting a year or more has presented extensive opportunities for testing various types and schedules of psychological support. Activities used to support the first 22 Mir missions are listed in Table 2, and some are summarized briefly below.

Space crews' living environments are "psychologically reconstructed" through the daily provision of emotionally and socially significant information. Crews also receive audio and video reports from radio and television broadcasts concerning current events from around the world; audio "letters" and reports about the lives of families, friends, and co-workers; musical fragments and videotapes of episodes from popular TV programs and new movies; and press reviews.

Much attention is devoted to onboard facilities and programs for leisure time. The Mir station is equipped with audio-video playback and recording equipment, computer technology, libraries of audio- and video tapes, as well as reading material, computer games, a guitar, art (painting) materials, etc. The audio, visual, and print libraries in particular must satisfy the crewmembers' needs for variety, novelty, and interest, and allow each crewmember to select and develop an individualized program of listening, viewing, and reading.

Compensation for the lack of social contacts is provided though informal communication sessions between the crew and members of their families, leading representatives of science, culture, art, sports, and others of significance to individual crewmembers. Crews aboard Mir flights also can contact ham-radio operators, conduct radio and video-bridges with various other crews, and contact political figures, including participants in current events around the world.

Attempts to influence a crewmember's emotional state generally are undertaken when their behavior and activity change in association with sensory deprivation; when they lose interest in specific types of operations and work; when a crewmember becomes ill or is replaced; when a flight program changes; when negative personal news is received from Earth; when interpersonal relations change within the crew; or when contingency (emergency) situations develop on board the station. Psychological support under conditions such as these must be corrective in focus and include components of individual and group psychotherapy.

In anticipation of interventions that might be needed for the events noted above, the following are provided:

- library items specially designed for various functional purposes (e.g., musical programs to exercise with);
- a private communication line to transmit confidential recommendations for therapeutic or psychologically corrective procedures;
- opportunities for the crew physician to discuss matters with a psychotherapist;
- complete information about reasons for changes and future prospects of the flight program;
- personally significant information (e.g., letters, packages, "surprises"); and
- training for individuals in contact with the crew (including Ground Control Center staff) as to the psychologically appropriate form and content of conversations, both with individual crewmembers and the crew as a whole.

Other forms of psychological support are designed to maintain crew motivation through supporting professional creativity and providing positive psychosocial feedback on their work. For example, the scientific-pedagogic and social activity of crews can be supported through organizing contacts between crewmembers and ground-based specialists to discuss experimental results and explore new problems. Particular care should be taken to inform crews about how their recommendations are adopted in the work of the ground services and agencies, including actions taken from their reports of observed natural disasters, weather conditions, or biological situations on Earth. In addition to official forms of feedback (e.g., answers from organizations, reports from services, radio conversations, etc.), other less formal communication channels can be used for this purpose, e.g., published letters from individuals with questions for the crewmembers, requests from various work groups, "meetings" with groups of children, and crew participation in various charitable events (e.g., radio or TV marathons). In general, sets of psychological-support measures are implemented over the course of flights by groups of specialists in medicine, psychology, and engineering, and is conducted in close contact with specialists in various divisions of the Ground Control Center.

Details of the the psychological support system instituted for prime crews aboard Mir from 1986 to early 1997 are presented in Table 2. These missions are remarkable for both the extremely long duration of some of the missions and the inclusion of international crews in the four most recent missions. Of the 34 crewmembers who participated in these 22 missions, 13 had completed two or three previous space missions. In 1987, Yuri Romanenko completed a 326-day flight (Mir-II); in 1988, Vladimir Titov and Musa Manarov extended that record to 366 days on Mir-III. Over the course of Mir-XV to -XVII, cosmonaut-physician Valeriy Polyakov set the current record for the longest stay in space (437 days 15 hours). The previous record for the longest flight by a female crewmember (169 days, by Yelena Kondakov on Mir-XVII) was broken in October 1996 by Shannon Lucid, an American who completed a 188-day stay on Mir-XXI. The unusual circumstances of these and other flights, especially the very long periods of uninterrupted work by some crewmembers, led to the creation of special medical and psychological support activities. For example, particular note was taken of chronologic milestones during Polyakov's flight. Also, experiment developers "met" with a crew (via audio and video links) to discuss ongoing results from their studies. Special support activities such as these helped maintain the psychological state of crewmembers and to reinforce positive interactions among groups.

The 12 members of the Mir-XVIII, -XX, XI, and -XX missions included participants from NASA and the European Space Agency. The diversity of these crews encompassed age, sex, social and ethnic origin, professional and space flight experience, programs of activity, and range of duties; only 4 of these 12 people had had previous experience with long space flights. Establishing a psychological support system for these missions has involved the integration of principles, approaches, and requirements of both sides. Particular attention has been devoted to expanding the range of material available on board, e.g., including books, newspapers, and magazines in English, as well as music recordings, videocassettes, compact disks, photo albums, and so on. Other support measures provided include the transmission of informational segments in Russian and in English; communications with families and friends; and the delivery of packages on both the *Progress* vehicles and the U.S. Space Shuttle.

IV. Comparing the Efficacy of Various Means of Psychological Support

The efficacy of specific support activities during the course of space flights are evaluated on the basis of two sources of information, one being reports from the crewmembers themselves and the other results from psychoneurological monitoring. Nearly all crewmembers have noted that work is the best 'psychological medicine' during flight. This statement echoes results from a 1967 survey[21] of isolated groups living in bunkers, on rocket bases, and in the Antarctic. In that survey, the most popular uses of leisure, aside from work, were conversation, reading literary works, and watching movies or television broadcasts; the opportunity to design one's own recreational activities also was considered important.[21] A popular recreational pastime in space is viewing Earth from a window. Similar conclusions regarding the relative dominance of work and popular leisure activities formed the basis for one set of "habitability" requirements for a crewed expedition to Mars.[22] These guidelines were developed on the assumption that the work day of such crews will not be as full as those for orbital-flight crews.

Russian experience with Salyut and Mir missions has confirmed that clear-cut, full programs provide crews with a sense of systematic occupation. The feeling of satisfaction with work performed, with feedback provided regarding the importance of the results, is thought to lead to a state of subjective comfort and stimulates creative activity in crewmembers. Problems occur in the presence of program changes, especially those in which timely information about future prospects of a flight is not available, or when societal upheavals are perceived as leading to a loss of prestige for the space endeavors. (The latter problem was experienced on a Mir flight.) In cases such as these, news concerning the course of solutions to the problems is transmitted to crews regularly, in order to foster feelings of participation and decrease emotional stress. Some examples of problem situations and the ways in which they are resolved are provided in Table 3.

In general, all crews on long-duration missions thus far have acknowledged that the standard psychological-support system is important for maintaining their normal mental health and performance. According to the crews, the most important factors in that system tend to be private communications with family and informal communications with family, friends, and various public figures. Organized communications such as these can take place via two-way audio contact or one-way or two-way video. Two-way video is greatly preferable to the crews, and has also been effective in resolving issues that arise during extended ground-based chamber tests. If one-way video must be used, the better direction is that in which the crew can see people on Earth rather than vice versa. As new communications technology evolves, two-way electronic mail is becoming a valuable way for space crews to keep in touch with family and friends at home. The greatest advantage of two-way e-mail is that it can be sent—and read—at any time, thus eliminating the need to establish specific communication times or calculate differences in time zones or sleep-wake schedules. Another new resource is a compact disk/software program that can hold hundreds of high-quality pictures, video clips, and audio clips from family members and friends. These packages serve as a “family album” that crewmembers can peruse as desired.

Several crewmembers also have given positive evaluations of the ham radio and “packet” forms of communication. Television reports (telebridges) beamed to the spacecraft from sites where notable events are taking place also have greatly positive effects. The worldwide amateur radio network also serves as an effective alternative for family communications when technical or scheduling difficulties preclude crewmembers from accessing the usual communication channels.

The positive effects from the use of these modern technologies do have their down side. Crewmembers can grow to depend on certain forms of communications, and technology failures can have emotional consequences that reduce the efficacy of a specific means of psychological support. For this reason, both the Russian and U.S. programs emphasize the importance of crews having a wide variety of choices in the form and content of onboard materials and broadcasts, as well as in selecting those individuals on Earth with whom to participate in audio or video “meetings.”

Other aspects of the psychological-support program rated positively by the crews include “special deliveries” by cargo spacecraft or visiting crews, and self-regulation training. Mail delivered via the *Progress* cargo ship, or in some cases by the U.S. Space Shuttle, has included audio “letters,” family videos, and special editions of newspapers. Books of artwork or photographs, scenic videos, and music are especially valued for their aesthetic contribution to life on board, thus providing another source of psychoemotional support. Problems occasionally arise in connection with the need to give crewmembers negative personal information (e.g., illness or death of a family member or friend). Decisions in these situations are made on an individual basis, with consideration given to onboard circumstances. Finally, skills in self-regulation (“autotraining”) acquired during preflight training also an important psychological countermeasure. Skills of this type help not only with overcoming difficulties in adapting to life on board, but, as some crewmembers have noted, can also be useful in dealing with interpersonal tensions among the crew.

In summary, our experience with supporting orbital space flights lasting 1 year or more, and lately involving international crews, confirms that the current psychological-support system, used in combination with a well-planned program of work, a rational work-rest schedule, and periodic monitoring, can effectively protect the psychological status of human crews during these missions. The advent of the “Mir-Shuttle” program marked a new era in the development of psychological support for crewed space exploration. Specialists from Russia and the U.S. worked together to ensure that requirements of all parties were addressed to the greatest extent possible. The diversity of experience of these international crews led to the establishment of a psychological-support system that can be used as a model for future initiatives. The experience of long flights, and the skills needed to conduct them most effectively, are qualitatively different from those of short flights. Skills required to live and work effectively during long flights include patience, the ability to allocate inndividual resources over the course of a flight, and the ability to improve interpersonal relationships in the process of going about daily life together. In contrast, short missions emphasize the need for rapid mobilization of individual psychological resources, the ability to tune out distractions, and the ability to act quickly and efficiently to carry out assigned activities. The Mir-Shuttle missions also demonstrated the importance of accounting for cultural nuances in the organization of psychological care. The language barrier, differences in lifestyles and work habits, traditions, and social and psychological mindsets all can set the stage for additional psychological pressure on crewmembers, if due attention is not paid to those factors. Nevertheless, early experience with this program[23] allows optimism about the prospects for developing a successful psychological-support system for the International Space Station.

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Table 1 Constituents of the psychological support system for long space flights

Provided from Earth

Information via TV, radio links
- News reports
- News of home and work
- Media coverage of mission
- Feedback regarding crew recommendations
- Voices and sounds from Earth
- TV broadcasts and video recordings
- On-site TV reports of notable events

Informal communication sessions
- Video and audio conversations with families
- Video and audio “meetings” with friends, cultural or sports figures
- Ham-radio communication sessions
- E-mail

Deliveries to spacecraft
- Mail
- Newspapers, magazines
- Books
- Special packages
- Audio and video programs
- Surprises

Provided onboard

- Print, audio, and video libraries
- Computer programs
- Musical instruments
- Ham radio

Table 2 Psychological support measures used with Mir prime crews

			Information provided		*Communication types*			*Delivered to Mir*			
Mir crew no.	Flight duration, days	No. crew-members	Audio news broad-casts	Specially compiled audio & video programs	Audio/ Video convers-ations with families & friends	Audio convers-ations	"Meetings" with GCC Staff, cultural & sports personalities	No. of vehicles	Audio-cassettes	Video-cassettes	Books
I	125	2	daily	12	14	–	22	2	6	–	10
II	326	2	daily	14	44	–	37	5	15	49	9
III	366	2+1	daily	46	44	–	48	5	18	19	25
IV	152	3	daily	22	35	–	23	3	5	16	11
V	167	2	daily	17	24	–	36	2	6	4	13
VI	179	2	daily	22	11	3	18	2	6	5	8
VII	131	2	daily	27	9	17	9	1	3	2	4
VIII	176	2	daily	21	9	22	14	2	6	5	5
IX	145	2	daily	17	13	19	15	3	11	4	6
X	175	2	daily	11	15	18	21	2	6	9	3
XI	146	2	daily	17	17	14	23	2	6	4	3
XII	189	2	daily	20	28	15	13	2	6	5	2
XIII	179	2	daily	12	7	53	11	3	9	6	8
XIV	198	2	daily	13	11	49	14	2	6	4	4
XV	182	3	daily	17	7	51	11	3	12	9	9
XVI	126	3	daily	15	6	29	5	1	4	4	1
XVII	159	3	daily	14	5	73	13	2	6	5	3
XVIII[a]	115	3	daily	11	8	14	3	1	3	2	4
XIX	75	2	daily	6	5	14	1	1	2	1	2
XX[a]	180	3	daily	7	13	59	18	2	6	5	3
XXI[a]	193	3	daily	6	11	63	15	2+1 Shuttle	10	6	20
XX[a]	196	3	daily	5	17	62	13	1+2 Shuttles	13	11	8
Totals		53[b]		352	353	575	383	49/3	165	175	161

[a] Involved participation of crew members from NASA or the European Space Agency

[b] Crewmember-flights (34 crew members on 22 flights)

Specially compiled programs were broadcast, and conversations with families and friends held, via the Ground Control Center (GCC); "meetings" with others were broadcast from the GCC, television studios, or elsewhere.

Table 3 Examples of problem situations arising on long-term space flights and possible ways of solving them

Situations	Solutions
General problems	
Fatigue, sleep disruption, emotional stress, etc.	Rest, drug treatment (as indicated); monitoring everyday routine; rational psychotherapy
Deprivational phenomena	Satisfying crew requests for information; expanding the scope of informal and family communications in native language
Work-related problems	
Heavy workload (time-sensitive repairs or similar work; jobs undertaken on own initiative; receiving visiting crews; EVAs)	Monitoring the work-rest schedule; providing additional rest and emotional releases
Insufficient workload (failure of technological systems that must be fixed from Earth)	Supportive monitoring; providing information about the course of repair operations; conversations with past crews; back-up work tasks
Errors (committed in joint work with Ground Control Center to control the station, support EVA, etc.)	Joint analysis of the operations performed; maintaining professional communication style; rational psychotherapy
Working under uncertain conditions (restoring the viability of an unmanned station; probability of changes in flight program)	Supportive monitoring; discussions with supervisors and specialists; monitoring the work-rest schedule; providing stage-by-stage information to the crew regarding decisions being made
Changes in crew composition (crewmember illness, adding a physician to the crew)	Providing preliminary information to the crew; joint decision-making; psychological preparation of an “understudy”; rational psychotherapy. Determine tactics for group interactions, providing psychological support by the flight physician
Unplanned prolongation of flight for a crewmember (need for trained specialist to continue work on a mission task)	Providing preliminary information to the crew and joint analysis of the situation; decision-making by the crew/crewmember; holding discussions on personal communications line
Interpersonal-interaction problems	
Within the crew (elements of incompatibility, domination by one crewmember during communications or in requests for support; relations between members of the prime and visiting crews)	Planning work-rest schedules (with the crew); holding discussions with ground personnel in contact with the crew; familiarizing crew with the visiting crews’ work program; rational psychotherapy (release of tension)
Between the crew and ground service staff (didactic style in discussion; preferentially addressing one of the crewmembers; inappropriate remarks, etc.)	Holding discussions with operators and observing communication rules; training ground-control staff in how to communicate with crews; organizing after-work conversations
Personal or family problems	
Difficulty adapting; illness or loss of family members; other family problems	Taking individualized approach to communications; forming tactics for passing negative or disturbing information to the station; providing leave (if needed); holding conversations on personal lines. Providing additional communications with family; providing supportive monitoring (at the family’s or crewmember’s request)

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Chapter 10

Ergonomic Support of Crewmember Performance

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Experience with human space flight provides convincing evidence that the crewmember “operator” plays an important role in ensuring the efficiency and safety of the “crew-spacecraft” system. The history of crewed flights contains many instances in which only human intervention allowed critical situation to be resolved, or catastrophes to be prevented. Examples include the switch-over to manual control during the descent of Voskhod-2; the in-flight decision to change the landing site for the first lunar mission followed by the successful landing; maintaining viable life-support conditions on the Apollo-13, Skylab-2, and Salyut-7 missions; creating conditions under which Kvant module could be docked to Mir, and others. The presence of crews on board spacecraft has made it possible to conduct unique scientific research, to discover many physical phenomena, and to perform operations previously considered impossible, such as satellite repair.

Human flights will continue to be an important component of future programs for the further exploration of near-Earth space, the moon, and Mars. The well-established tendency for the human role to increase on space flights is due primarily to the unique advantages of humans over even the most sophisticated computer systems, advantages such as the capacities for heuristic, creative, logical, and associative thought, for rational risk-taking, and for sophisticated learning from the ever-increasingly complex research conducted on board spacecraft. Nevertheless, in most cases, realizing the full potential of crewmembers can take place effectively only through interactions with technology. The final result of these interactions, which can be evaluated with integral criteria such as mission success and safety, naturally depends on the characteristics of both the human and the technological system components. These characteristics must be optimally coordinated, so that the advantages of one component of an integrated human-machine system are not negated by the shortcomings of the other.

Solving this systems problem with regard to crewed spacecraft is based on general principles and methods of ergonomic design, standardization, and expert evaluation, and on the use of expertise developed in areas such as:

- crew life-support systems (discussed in Volume II of this series);
- functional adaptation of humans to space flight factors (discussed in Volume III); and
- supporting human reliability in space flight (discussed in Volume IV).

Because the efficacy and reliability of crewmembers’ performance depends on interactions within the “crew-spacecraft-ground control” system, the present chapter examines issues relating to the allocation of functions among the crew and onboard and ground control facilities; ergonomic requirements for work stations, displays, and controls on board the spacecraft; and the chief methods used in ergonomic design of crewed spacecraft.

I. General Issues Concerning Ergonomic Design of Work Stations and Crew-Performance Technology

Solutions for the entire set of problems (considered both separately and as they interact) involving human factors form the content of ergonomic support of human-machine systems at the stages of design and use. In essence, ergonomic support represents a cyclic process that includes phases of determining ergonomic requirements, evaluating their implementation (ergonomic certification), and taking the necessary corrective steps suggested by the previous phase. The incorporation of ergonomic concepts (called “human factors” or “human engineering” in the U.S. lexicon) in building crewed spacecraft represents a reasonable compromise between obtaining the maximum benefit from the human presence in space vs. the limitations of resources there, and also ensures the ease, safety, and productiveness of work performed by the crews.

The multipurpose sociotechnological “crew-spacecraft” system has several specific features that must be considered in designing such a system. The most important of these features, which are distinct from those that are characteristic of “Earth-bound” human-machine systems, are:

- the complexity of the interactions among system components;
- the multiple levels and large numbers of tasks for which relatively few crewmembers are responsible;
- the uninterrupted, prolonged exposure to the extreme external environment and the artificial internal environment;
- the duration of the autonomous existence of the system;
- the high cost of its creation and use, and the limited possibilities for correcting problems during flight; and
- the relatively small number of norms and standardized variables for crewmember performance provided by data from past flights.

A. Allocation of Functions Among the Crew, the Onboard Facilities, and the Ground Control Facilities

Of all the numerous tasks confronting developers during the creation of human-machine systems, the allocation of functions between human operators and technology is the most important. Indeed, only after allocations have been made can rationales be generated for specifying the number and qualifications of operators, algorithms, the tools and conditions under which operators act, and ways of ensuring their work capacity, professional training, and so on.

References 1–4 constitute a good analytic review of the principles and methods for allocating functions in human-machine systems. In terms of method, the two primary approaches, machinocentric and anthropocentric, deserve mention, since all other approaches represent compromises between those two extremes. In the machinocentric approach, automated machines are assigned the main role in supporting system efficacy and reliability, and the human operator is considered an auxiliary element or communication channel in the control loop. This approach was formulated in the 1940s and 1950s in the development of control systems for relatively simple objects that could easily be described in formal terms, thus allowing their functioning processes to be automated. This condition simplified the problem of coordinating the human-technology interactions by reducing those interactions to definition of operator characteristics such as transmission function, channel capacity, reaction time, etc.

Technological advances, especially the manufacture of high-speed and high-capacity computers, opened up new possibilities for creating more hierarchically and functionally complex systems. However, the heterogeneity of structural elements, their interconnections and states, and the large numbers of variables that had to be controlled led to significant problems when system developers attempted to generate formal descriptions of control processes. This led in the 1960s and 1970s to the development of a new anthropocentric approach, which is still in use in the 1990s. The anthropocentric approach essentially involves considering the human operator to be the central component of the system, with all the remaining components considered means of supporting that person's performance. In other words, the human operator is assigned the main role in attaining control and ensuring reliability.

The main achievements of the anthropocentric approach are associated with solving problems associated with adapting technology to humans, developing principles and methods for formulating information-processing models, designing operator performance paradigms, and so on. Thus, in accordance with the active-operator principle,[5] a system must be automated to the degree needed to ensure completely adequate monitoring of the control process on the one hand, and prompt human intervention in the process when that process deviates from its nominal course on the other, i.e., preference is given to semi-automated modes.

Two other promising approaches to allocation of function deserve note. The first, called "dynamic allocation,"[2] allows allocation of functions to be adapted in response to a particular situation while the system is functioning. This approach means that allocation of functions is no longer "set in concrete," but can be determined on-line, on the basis of an evaluation of current conditions and the behavior of the operator and system as a whole. Such an approach can be implemented with special computer programs that make introducing changes into the system relative easy. Presumably, in the near future dynamic allocation of functions will take place automatically on the basis of information about the operator's physiological functioning.

The concept underlying the second, "equivalent" approach[3] is considered by its author to be an extension of the anthropocentric approach. In the equivalent approach, the inadequacy of the formal models of processes characteristic of complex, open, ill-structured systems can be compensated for by the human operator through the use of qualitative, substantive criteria of reliability and efficiency, thus allowing holistic analyses of the situation and allowing acceptable variants of semi-automatic or manual control to be found and implemented. In extreme conditions, however, control must be shifted automatically to the automated mode in order to prevent possible errors by the operator. Thus, in this approach the relationship of human with technology is considered a complementary interaction involving equivalent components. This approach has been used to justify mutual back-up by both the human and automated (machine) components.[4] In other words, the human operator backs up the technology (if unforeseen circumstances occur that cannot be dealt with automatically) by independently decreasing the degree of automation, while the automated technology backs up the operator (if complex problems arise in the operator's performance) by triggering increased automation of the controlled processes.

Allocation of functions remains one of the most complex and crucial tasks in designing human-machine systems. Despite the acknowledged advantages of the anthropocentric approach, the potential of this approach has yet to be fully realized in practice, in part because progress in developing increasingly complex technology has been faster than in solving problems associated with human factors. Another reason is that some project directors and design engineers still hold the opinion that operations performed by humans and machines are independent. This point of view impedes optimal coordination of human psychophysiological capacities and the tools that humans must work with.

Crewmembers perform an extensive variety of tasks during flight. Aside from the routine tasks associated with daily living on board spacecraft, these tasks can include maintaining and repairing onboard systems and equipment; conducting scientific and technological experiments; carrying out extravehicular activities; analyzing contingency situations and making decisions about how to deal with them; performing dynamic operations; exchanging information with ground services; using countermeasures to maintain work capacity; filling out documentation, and others. Allocation of functions among the crew and onboard and ground control facilities on flights of Russian and U.S. spacecraft are similar in many respects. The spacecraft and its systems can be controlled by the crew, by the onboard computer, or by commands from a ground control center. The major advantages of such multilevel, combined control are to:

- increase the flight reliability and safety from mutual back-up by system components;
- decrease the workload of the crew by removing the need for them to perform certain functions; and
- offer the possibility of spacecraft test flights in “unmanned” mode.

In addition to flight-trajectory data from tracking stations, the ground control center obtains a great deal of telemetric information about the status of the onboard systems of the spacecraft; the crew, however, usually receives only fragments of this information. Thus, the ground control center holds the primary responsibility for identifying deviations in those parameters or variables that could lead to problems or breakdowns. The resposibility for monitoring the performance of systems that are important for flight safety is distributed among the crew, the onboard computer, and the ground control center. While crewmembers are sleeping or performing other work tasks such as EVA, operation of the spacecraft systems is monitored by both onboard and ground facilities.

Spacecraft systems and equipment can be controlled through semiautomated, automated, or manual modes. In the semiautomated modes, functions are allocated in various forms depending on the type of task among the crew, the onboard systems, and the ground systems. In the automated mode, the crew must receive information about the course of the control process, so that if the onboard automated control system fails, they can step in promptly and either interrupt it or switch to a manual back-up mode. In the latter case, several conditions must be met:

- switching from automated to manual mode must be simple (i.e., limited to one or at most two commands);
- the crew must be notified that the control mode has been switched;
- the information provided to the crew must be identical and continuous (in form and content) in the main and back-up modes; and
- switching between modes should be allowed in both directions if at all possible.

B. Information-Processing Support

Aside from direct visual observations of the exterior and interior of the spacecraft cabin, crewmembers receive much information from various displays and signals that deal not with actual objects, but rather with *information models.* An information model is a set of information that is organized in accordance with principles regarding the functioning of a controlled object and the state of the environment.[6] With this information, the operator develops a mental representation of actual conditions, analyzes and evaluates the current situation, makes decisions, and implements control actions. According to this definition, then, information processing has the leading role in the interactions among modern human-machine systems.

Information models must be congruent with mission and task objectives and human capabilities to assimilate and analyze information, and should reflect in graphic form only those features, relationships, and connections of the objects and processes being controlled that support an unambiguous understanding of the situation and its perception as a whole. An information model of a spacecraft fulfills two major functions: it provides the crew with the preconditions necessary for monitoring and control, and warns them about the occurrence of unforeseen situations.

The information received by the crew can be classified on the basis of level of detail as generalized (designation and type of mode, the time it began and ended), specialized (the general state of individual systems and subsystems, the fact that certain control operations have been performed), and detailed (the specific parameters of a system, module, or instrument). In designing information interactions, it is essential that the information provided to crewmembers be logical, concise, and hierarchically structured. That information also should provide some idea of the previous, current, and predicted state of the parameters monitored, and should not require additional recoding for identification and processing. The most significant information should be presented in several different forms (alphanumeric, graphic, auditory, etc.) to avoid overloading crewmember input modalities.

Improvements in the reliability of crew decisions during contingency situations are more likely when emergency warning signals accompany unanticipated shifts in parameter values. Of course, the information provided in that warning must be sufficient to allow rapid recognition of the nature of the deviation or failure. If contingencies are to be prevented, then warning information should be provided when the monitored parameters approach their limits of acceptability and should include details of their behavior thereafter.

The onboard caution and warning system, in combination with the flight control center, in a sense functions like an additional crewmember who monitors the status of the craft.[7] The main purpose of this system is to inform the crew of what has happened and what must be done. The system must be designed so as to alert busy or fatigued crewmembers (especially important for rare, unexpected events), but without startling or frightening the operator. If the signal can be deactivated manually after being heard, then the system must automatically return to a state of readiness for providing the next warning message. In designing warning systems, every effort should be made to prevent false alarms, which tend to reduce vigilance and increase emotional stress for the crewmembers. Requirements for visual and auditory warning signals can be found in international ergonomics standards[8,9] and elsewhere.[10–12]

1. Displays and Signals

Implementing information models involves the use of various devices for depicting information, e.g., instruments, signals, displays, and others. The ergonomic requirements for specific ways of depicting information, and requirements for controls, are presented in international and local standards and instructions. Although standards are the highest level of regulatory documents, the developers of human-machine systems do not always have access to national or sector-wide standards of other countries. For this reason, we focus in this chapter on the standards or guidelines that were available to us.[6,10–15]

Ways of depicting information can be classified on the basis of purpose, level of dynamism, the generality of the information presented, design features, and so on. The choice of which means are selected for use is based on which tasks are to be performed with the information and on human sensory capacities.

Vision, hearing, and proprioception are used most frequently in discharging work tasks, and smell and taste only rarely. Reference information about the human capacity for perceiving distinctions, and recommendations for the use of the various senses to perceive information, are given in Reference 7.

Vision is the main channel through which crewmembers receive information in flight. Visual displays are typically used to:

- present quantitative data;
- present qualitative data (e.g., definition of approximate values, tendencies, or the rate or direction of parameter changes that do not require exact numbers);
- monitor correspondence of controlled values to required values;
- set the value of a regulated parameter (when the indicator points to a desired number or position);
- track or follow a target;
- display one’s position in a plane or space (e.g., navigational instruments).

Multifunction displays typically are used to increase the efficiency and reliability of parameter monitoring. Crewmembers can request that the screens of such displays represent information either in alphanumeric or symbolic form. One of the first such instruments aboard Soviet spacecraft was a combined CRT display that could both display data and operate as a video monitor for the exterior television cameras. The data-display mode was used to display quantitative data on the status of various systems, atmospheric parameters, data on the approach process, and so on.

Technological progress in the production of small, high-capacity, reliable computer hardware and the development of appropriate software has given computers the leading role in storing, processing, and analyzing information on board spacecraft. Computer displays are becoming an ever more important part of the arsenal of devices for depicting information in onboard monitoring and control systems, management information systems, and data transmission systems.

Nevertheless, the use of computers poses technical and human-engineering challenges for developers. According to one U.S. expert on human-computer interactions, the successful system is designed to enhance operator capacities and confer the feelings of control, mastery, predictability, and clarity.[16] Elements to be considered in such designs include:

- interface style (commands, menu, templates to fill in, direct manipulation)
- how information is configured on the screen (graphic design, strategy for using windows);
- devices and techniques for inputting information;
- facilitation of perception and understanding;
- the use of color, animation, graphics, sound, and tactile feedback;
- the physical design and ergonomics of work station; and
- the response time.

A broad range of issues associated with human factors in “user-computer” systems, and specifications for information representation and software, are discussed in Reference 12.

In addition to indicators and computer displays, liquid-crystal displays (LCD) are used to depict visual information on board spacecraft. LCDs generally are combined in signal-reception matrices as shown in Fig. 1. These matrices allow crewmembers to reproduce a great deal of information, and to monitor the input and progression of control commands through the systems.

Auditory presentation of information is used:

- for danger signals, since hearing, unlike vision, cannot unintentionally be “deactivated”;
- when the visual channel is overloaded;
- when the operator is performing work that demands movement, especially head movement; and
- when environmental conditions make visual perception difficult (e.g., dim or very bright ambient light, hypoxia, high acceleration, and so on).

Distinctions are made among sound, noise, and speech signals, and recommendations for selecting among them for auditory signals are provided in References 10, 12, and 17. Sound or noise signals are used to transmit isolated messages that are brief, that require immediate action, or when the operator is overloaded with verbal signals. Speech signals are preferable over other acoustic signals when information must be exchanged quickly, or in stressful situation in which the operator might forget the acoustic code for sound and noise signals.

2. Coding Information

In modern systems, much information reaches the operator in coded rather than natural form. The concept of coding information refers to methods by which arbitrary signals or symbols are identified with an actual (physical) feature of information (velocity, pressure, temperature, etc.) Here, the issue of coordinating machine outputs and human inputs becomes especially important.

The ideal code will maximize the speed and reliability with which the operator receives and processes information. Characteristics of various coding methods are compared in Table 1.[12,13] Selecting the best coding method requires consideration of the nature of the tasks to be performed by the operator, including:

- human psychophysiological capacities;
- the associative significance of the code symbols;

- the code's accuracy and ease of understanding;
- the compatibility of the code with the form of the coded information;
- the space needed to implement the code;
- the amount of information that could or must be coded with the given method.

Color coding is often used in “search-and-identify” tasks. Because red, yellow, and light blue can be identified the most accurately, these colors are used frequently for color coding. The use of this technique, however, must account for the fact that color perception depends on the size, distance, and position of objects in the operator's field of view. Chromatic objects that are far away or at the periphery of the visual field are perceived as achromatic. When an object subtends a small visual angle (10–20 angular minutes), colors tend to be perceived as either red (warm colors) or blue (cool colors). Moreover, visual fatigue when working with colored representations leads to increasingly bright and long-lasting retinal afterimages, which limit the potential use of color displays.[10]

Alphanumeric coding, another common way of presenting information, overcomes the inherent limitations imposed by the fixed length of an alphabet. The shape or style of the numerals and letters plays a critical role in their perception; with clear outlines, good contrast, and adequate illumination, letters and numbers can be recognized at substantial distances and subtending small visual angles (on the order of 10 angular minutes). Using modified fonts such as the Mackworth or Berger series can further improve the reliability with which numbers are read.[6]

Information coded with icons is perceived and processed the fastest and the most reliably when simple, geometric forms are used, and when the elements in those forms are easily associated with the coded objects. Information also can be coded by using correlations between the size of the sign (symbol) and a given characteristic of the object. However, if a symbol is presented in three sizes, the tendency is to overestimate the size of the smallest and underestimate the largest. Size also can be linked to number of alphanumeric characters; however, using more than 4 alphabetic characters makes comparing the middle sizes to the extreme difficult, and when more than five figures are used, errors in identifying all of them increase. Analogous relationships also hold when information is coded by line length.

Another type of code involves the spatial orientation of a figure or line. For asymmetrical figures, a change in orientation is signaled by rotating the figures in the operator’s field of vision. For symmetrical figures, the coordinate axes can be rotated or one of the contour lines can be thickened. The threshold of perception for deviations from the coordinate axes appropriately is about 1–2 degrees.

A flashing signal is fairly effective in making that signal stand out against a background of other sources of information. Visual evaluation of flash numbers is quite accurate at a 2.5 Hz flash frequency, and decreases as that frequency increases. The threshold for direct visual evaluation of flash frequency is 5–6 Hz. To prevent visual fatigue, no more than 2 or 3 signals can be flashing simultaneously in the operator's field of view. To avoid distortions in the perceived outline of a sign, having a part of the sign flash is preferable to having the whole sign flash.

Reliable recognition of one-dimensional signals is possible for humans only if the difference between each pair of signals exceeds threshold by several hundred percent, which limits the permissible length of the code alphabet. Another limitation reflects the typical drop in accurate identification of signals by humans as the number of those signals increases. Information regarding the recommended lengths of various codes is presented in Table 1 and in References 6 and 10.

Multidimensional codes can be quite effective for transmitting complex messages, as long as the limitations described above are borne in mind. The most important characteristic of the object must be associated with the coding category that fosters maximum understanding, thus improving the likelihood that the task will be completed. One of the most widespread methods of coding complex message is the formulary—compact groups of aggregated letters, numerals, and conventional symbols—to provide information about an object. A caveat for the use of formularies is the tendency of the recipient to perceive information at the ends of a formula (string) more accurately than that in the middle. The most important information, therefore, should be placed at the end(s) of the string.

C. Controls

Controls exist to transmit control actions from an operator to a machine. Their design and placement in the work station are based on the characteristics of the object (or system) of control, the content of the tasks performed by the operator, the anthropometric, biomechanical and psychophysiological characteristics of humans, and the working conditions.

In general, humans can use their hands, feet, or voices for control. Advances in computer technology have allowed limited use of acoustic signals to control machines; however, voice-control technology is not expected to be ready for use in controlling spacecraft in the near future. The overwhelming majority of onboard controls are manual, with the possible exception of landing-control systems in Shuttle-type spacecraft. For this reason, the following material is confined to considerations of the ergonomic characteristics of manual controls.

Selecting the type of control to be used for a particular function requires consideration of:

- the function of that control in the system, i.e., its correspondence to the operations performed (input of commands, regulation of parameters, etc.);
- the control’s importance and frequency of use;
- the requisite range of displacements or number of positions required of the control organ;
- the accuracy, speed of adjustment, and forces that must be applied to the control;
- the ease of recognition of the control itself and its positions in its working mode;
- the ability to lock the control in specified positions if necessary; and
- the feasibility of using the control while wearing special clothing.

The direction in which the control is displaced should correspond with the expected response of the controlled object or dial. This association is best supported if it is based on habitual sensorimotor habits, those motor patterns that have developed over the course of a person’s life. Table 2 lists some controlling motions that typically are associated with one or more system or object responses.[11,12]

A variety of coding methods are used to ensure that controls can be recognized quickly and reliably. Some of these methods, used singly or in combination, involve shape and size, which improve visual and tactile recognition; labels; and color. Although labeling can be effective, labels do require space on the control, adequate illumination, and some standardization of the label codes. One typical example of standardization is the use of the color red for emergency controls or to indicate ‘stop.’

The amount of force needed to move the control must account for both the crewmember’s abilities and working conditions (weightlessless, fatigue, wearing spacesuit, etc.). The resistance offered by the control to a force exerted on it should be selected to support the requisite accuracy and speed of manipulation, as well as its smoothness of movement, the ability of the operator to sense its position, its protection against being activated or displaced accidentally, and its return to a neutral position after the control effort ceases (most characteristic of control handles). Characteristics of the controls used most often in automated systems, including spacecraft, are given in Table 3.[11–13]

Push buttons, push keys, and sensor keys are used when discrete operations must be performed quickly and accurately. The reliability of response can be improved by labeling the surface of the buttons in some way and lighting the buttons from within. Toggle switches and rotary on-off switches are used for rapid activation and deactivation and switching between modes of operation, and are well recognized visually and tactually. Continuous, multiposition, and rotary switches are used for smooth continuous or stepwise adjustment. Thumb wheels in the form of a portion of a rotating wheel protruding above the surface of the body of the control are recommended for digital input of data and switching (discrete operations), or for adjusting and regulation (continuous operation). Handles that are rotated or displaced linearly can be used for stepwise switching and smooth dynamic regulation. For multidimensional regulation, 2- and 3-coordinate control handles (joysticks) are used.

Controls for continuous processes usually are designed to respond to the degree of displacement of the control, the force applied to the control, or combinations of both. For controls of the first type (isotonic), the signal level is determined by the deviation of the handle from the neutral position, which can be perceived by the operator by sight or touch. For controls of the second type (isometric), the signal output level is a function of the amount of force exerted on the control. Although the latter type of control may withstand damage or interference from acceleration or impact, its use, especially in microgravity, requires practice. The advantage of combining control modes (i.e., using both isotonic and isometric types) would be the multiple, simultaneous feedback from the position of the handle and the effort applied to it.

In the variety of tasks they perform, crewmembers use not only controls, but also tools that have been specially developed and adapted to working conditions in microgravity. These tools include hammers, wrenches for screwing and unscrewing screws and nuts, instruments for cutting metal, as well as hoses, cables, punches, chisels, and so on. The definitive requirement for such instruments is the near-absence of reactive forces and moments during their use. For example, the maximum torque on the spindle of a universal power device manufactured by the U.S. firm Martin-Decker is 67.5 Nm, but the reactive moment of its handle is only 0.006 Nm. An analogous device with a set of replaceable tools is used for repair work by Russian cosmonauts. General recommendations for tool design, especially tools to be used in EVAs, are discussed in References 18–20. Fig. 2 shows the exterior of one of the tool boxes used aboard Mir.

D. Work Stations

A work station is defined as a space that contains ways of depicting information, consoles and controls, seats, and other equipment needed by an operator or group of operators to perform tasks. Work station design must take into account the specific content (structure and algorithms) of the operator tasks; the anthropometric, biomechanical, psychological and physiological characteristics of the operator; sanitary and hygienic norms and specifications; safety; and technical aesthetics. The work station itself must provide the following:

- sufficient space for equipment to be placed and serviced; work tasks to be performed, and operators to move;
- the necessary physical, visual, and acoustic connections between the operator(s) and the equipment;
- a clear view of the information displays and accessibility to controls;
- permissible (standard) values of ambient variables, and protection from harmful effects of industrial factors, if any;
- conditions for rapid occupation or abandonment of the work station in emergencies; and
- measures to prevent or minimize premature fatigue or excessive psychological tension in the operator, thus minimizing the likelihood of errors.

In geometrical computations regarding work-station components and reach of controls, the range of values chosen for various anthropometric variables traditionally has been from the 5th to the 95th percentiles.[10–13] As more women and people of various nationalities take part in space flights, this range has been adjusted to accomodate a broader range of anthropometric characteristics. As discussed in Volume II, Chapter 7, spacecraft designed for international crews should accommodate crewmembers ranging from 5th percentile for Japanese women (smallest) to the 95th percentile of U.S. men (largest). Moreover, computations of volumes, distances, areas of visibility, reaches, and other factors should consider the effects of space flight factors on static and dynamic human characteristics, especially the relative positions of the head, arms, legs and other parts of the body in weightlessness. Traditional anthropometric criteria should be modified for space operators to account for differences in motor activity and work positions in weightlessness vs on Earth.[21–23]

Working in microgravity requires measures to aid crew locomotion, as well as ways of maintaining the body in various working positions and of fixing equipment, tools, and documentation during the work. Special plates, clamps, straps, belts, and velcro fasteners are used to attach tools and equipment. For operator locomotion and fixation within the spacecraft, clamps, handrails, belts, limiters, straps, and design features of the interior (projections, handles, brackets, etc.) are used (Fig. 1). Aleksandrov et al.[19] identified five means of fixating crewmembers in standing positions for performance of relatively simple operations (Table 4). All five fixation methods require at least three points of attachment to the body.

Designs for more complex fixation systems must ensure that the system can handle the reaction force to the maximum force developed by a working crewmember (up to 600 N in all directions). Such a system also must allow quick (< 10–12 s) and easy ways of fastening and unfastening, and provide protection against accidental unfastening. Finally, the system should enhance labor productivity and operator mobility (within spherical angles of up to 45 degrees).[19]

The main advantages of fixing operators at the feet are that that mode allows a broad range of working positions and frees the operators’ arms. The Skylab station used such a system, which involved triangular openings on grid surfaces and special boots with the corresponding shapes on the heels. Astronauts could fix themselves firmly to any surface by placing their heels into selected grid openings and rotating the boots. This system allowed the astronauts to move in various directions and perform work that involved considerable forces and moments.

During EVAs, crewmembers move and fix themselves manually through the use of stationary and movable handrails, including telescopic types. Bracket-type foot-fixation devices are located at specific places on the station surface; crewmembers slip their boots under the brackets and tighten the brackets with clamps (Fig. 3). This method of fixation maintains crewmembers in a stable position while allowing them the use of both arms. Devices such as these with a panel that rotates around an axis also are used on the U.S. Space Shuttles.

With regard to seating, the main purpose of onboard chairs and couches is to ensure crew safety during launch and descent. (Details of seat design for this purpose are beyond the scope of this chapter.) During the orbital portion of flight, seats and straps are used occasionally as means of crewmember fixation. However, experience from space stations has shown that chairs have no advantages over other fixation devices; the metabolic cost of maintaining a standing position is nearly the same as that for maintaining seated positions in microgravity. Moreover, the potential range of movement and locomotion from a standing position are much greater than from a seated position.[19]

The main functional component of the work station is the control console. Guidelines for placing information displays and controls on the console are based on the principles of *priority*, *grouping*, and *relatedness.* The priority principle reflects the role of displays and controls in the functioning of the entire system. Considerations for placing controls and displays with respect to priority include the frequency and extent of their use; the accuracy and speed at which information can be read out, and controls can be set; and the significance of potential errors in read-out or delays on the reliability and safety of the system's operation.

Grouping can be done on the basis of function or sequence of use. Functional grouping of displays and controls is based on either conjoint use in performing specific tasks, or belonging to a single component of a system (or a module or device). Sequential groupings reflect the order in which controls and displays are used by the operators, as determined by algorithms of operator performance. Functionally related displays and controls should be placed close to each other, if possible, and configured so that the operator’s hands do not block the display during manipulation. The instrument panel should be divided into sections, rows, and groups, but these divisions should not distract the operator.

Maintaining appropriate relationships between work-related movements of the operator and the direction in which the controlled object moves, or changes in relevant variables, can improve reaction and decision times and reduce the incidence of accidental activation of controls (“reverse errors”). In considering relationships among movements, the natural, direct relationships between directions of motion should be exploited as much as possible (Table 2). Also, the direction of motion of the controls should be considered in relation to the location and orientation of the operator with regard to both the controls and the controlled object. For displays and controls on tilted control consoles, this relationship includes the vertical and horizontal planes as well. Consoles that are tilted from the vertical by less than 45° are considered vertical, and those tilted by a smaller angle are considered horizontal.[11,13]

Creating control consoles for spacecraft should take into account differences in human posure in microgravity. For example, the normal line of sight in microgravity is tilted downward by an angle of 14.7±2.0° relative to that on Earth[12]; for this reason, the main displays should be lower on spacecraft consoles than on ground systems. The neutral posture during orbital flights tends to be intermediate between sitting and standing, with the shoulders and arms somewhat elevated; this posture also requires modification of standards developed for ground consoles. Controls on a console must be sufficiently well separated so that they can be manipulated freely by operators in spacesuits. Those controls for which accidental manipulations cannot be allowed must be protected by recessing, protective clamps, covers, or other means.

In general, consoles intended for controlling the same type of system should have the same or similar configurations of the most important, frequently used, and emergency controls, displays, and information input devices. Consoles must not have superfluous components, i.e., those that cannot be justified by functional purpose, or sharp projections or edges that could injure the operators. Light must be reflected diffusely from the console surface in order to preclude glare in the operator's field of vision. Finally, consoles may need to be equipped with movable cases for storing documents, clipboards for making service notes, and places to put auxiliary and portable instruments.

II. Methods of Evaluating the Ergonomics of "Crew-Spacecraft" Systems

The high cost of eliminating problems made in the development of technology for human space flights, and the limited opportunities for modifying that technology while it is in use, make it absolutely essential to evaluate "crew-spacecraft" systems as early as possible in the development process. The most complete evaluation of a system generally would be obtained through experimental studies of that system's prototype conducted by specially trained operators. Unfortunately, this approach largely precludes comparing alternative design versions or introducing changes, since by the time a prototype is created, usually the final decisions about its structure have already been made. For this reason, the specific methods used in ergonomic evaluation of human-machine systems depend on the stage of development of those systems. For example, during the early stages of system design, when the feasibility of various design configurations for work stations is being assessed, priority is given to computer modeling and use of scale models. At later stages, when information is available on equipment composition and dimensions, full-scale cabin mock-ups can be used.

A. Mathematical Modeling

At present, no universal mathematical model has been developed that can be used for a wide range of human-machine systems. Specific models are developed for specific instances, and each model takes into account the features of a particular system, the reliability of initial data, the need for accuracy of results, and so on. In other words, the development of models requires profound knowledge of the essence of the process being modeled as well as mathematics and programming.

In general, the process of mathematical modeling of such systems includes:

- studying and formally describing the goals, objectives, characteristics, and conditions of system function;
- analyzing the model using the selected mathematical approach and computer technology
- obtaining results generated by the model;
- evaluating the appropriateness of the model;
- experimenting with the model; and
- improving and updating the model on the basis of new data obtained.

Details of how to construct models, and their properties and characteristics, are reviewed in References 1, 13–15, and 24–36. We will merely note here that mathematics derived from theories of information processing, reliability, queuing, operations research, and others can be used to solve problems of ergonomic design such as providing rationales for the structure of a human-machine system, allocating functions among its components, and developing rational algorithms of operator tasks.

However, analytic evaluation methods are not without limitations, some of which include the small number of variables that can be analyzed, insufficient attention to dynamic interactions among systems components, and the stochastic nature of human characteristics. The use of simulation models can avoid such problems. To paraphrase Shannon,[26] the term "simulation" can be defined as a process that includes constructing a model of an actual system and then designing experiments to study the behavior of the system or to evaluate various strategies for its functioning. A simulation model of a human-machine system must have the following properties:

- encompass a functionally complete set of the tasks performed by the system;
- account for the stochastic nature of the processes of its functioning;
- reflect the group and individual characteristics of the human components of the system;
- resemble the actual processes;
- be sufficiently relatible so that decisions can be made on the basis of modeling results; and
- be simple and convenient to use.

Development of simulation models also requires selecting an appropriate means of analyzing and describing the processes and functional relationships of the system. At present, the most extensively used methods are discrete, continuous, and combined (discrete-continuous) simulation.

In addition to models that simulate the behavior and activity of an individual operator, other models can be used to describe the interaction of the entire set of components of the system (personnel, equipment, communications, etc.).[36] Such models are particularly useful for problem-solving.

The structure of one possible model for evaluating and predicting the reliability of crew performance is outlined in Fig. 4.[37] For this purpose, we define reliability as the probability of the flight program being accomplished with the necessary quality (accuracy, lack of error, timeliness) under specific living conditions. We contend that this definition encompasses the stochastic nature of system characteristics (through the element of probability inherent in the concept of reliability) and the effects of space flight factors on those characteristics (through consideration of living conditions).

The flow sequence of the model illustrated in Fig. 4 begins in block 1, where the sequence of tasks stipulated in the flight program is formulated. If some crewmembers are free at a given moment, or if the selected task is given higher priority than others being performed, then the selected task is performed (block 2). If not, then performance of that task is postponed (or, if it is of low priority, precluded) and the flight program is adjusted accordingly (arrow to block 12). The identification of each task accepted for performance (type, requirements on operators, etc.) occurs in blocks 3/1, 3/2, ... 3/n, and the selection of operators to perform the task is shown in block 4. In block 5, the "functional capacities" of the selected operator(s), i.e., their readiness and ability to perform the task, are evaluated. Individual and group characteristics of operators are modeled in blocks 14 and 15, respectively, and their interaction is shown by arrows. The function of block 17 includes simulation of how these individual and group characteristics of operators are affected by combined exposure to such factors as flight duration, flight stages, and health status (simulated in block 21), as well as ambient factors (e.g., danger from meteorites and radiation), equipment failure, and the effect of the ground control group (blocks 18, 19, and 20). The effect of the last group of factors is shown by arrows from block 16 (the work environment) to block 12 (operational effects) and block 17 (psychogenic effects). In turn, the characteristics of the microsocial climate on board the spacecraft may affect the degree of completion of the flight program and the interactions with the ground control group (arrows from blocks 14 and 15 to blocks 12 and 20).

If the functional capacities of the selected operator(s) correspond to the task requirements, the performance of the tasks is simulated, as indicated within the block outlined by a dotted line in the lower right of Fig. 4. If they do not, after all possible selection variants are considered (blocks 9 and 4), then the message that the task cannot be performed at the given moment is sent to block 12.

In block 6, the operations constituting each task (type of operations, equipment needed, organization of communications, etc.) are identified. The sequence of operations for each operator is formulated in blocks 7/1, 7/2, ... 7/n. The model accounts for the presence of deviations from the nominal work-performance algorithm. The list and nature of these deviations are determined on the basis of preliminary analysis of data from actual flights, and occurrence of deviations is determined randomly in block 11/1. Deviations may lead to either changes in the accuracy or time characteristics of operations (arrow to block 7/1), or to the inability to perform them, which is determined in block 13. If the deviation leads to the impossibility of performing the task as a whole, then the appropriate command is sent from this block to block 12.

Variables of operator performance are determined in blocks 8/1, 8/2, ... 8/n, and control then goes to block 10 for evaluation of the quality of task performance. If operations and tasks can be performed more than once, or are of low quality, they are simulated again (arrow from block 8/1 to block 7/1 or from block 10 to block 6, respectively). The success or failure of task performance with regard to individual and group characteristics of operators are indicated by the arrows from blocks 10 or 13, respectively, to block 17. When the modeling of all operations is complete, a command is sent from block 10 to block 1 concerning the completion of the task.

Finally, variables describing accuracy, error rate, and time required to perform tasks, numbers of performed, not-performed, and postponed tasks, and enumeration of other variables describing the reliability of crew performance are recorded in block 22.

B. Simulation Modeling and Flight Tests

Later in the design stages of human-machine systems, simulation models are preferable over mathematical models. In this form of simulation, the content of the operator's work and the devices used to support the operator's performance are as similar as possible to actual conditions, but the operator interacts with a computer-implemented model of the controlled object rather than the object itself. Thus, simulation modeling occupies a position intermediate between mathematical modeling and field studies.

Despite the considerable time needed to obtain statistically significant results and the expense of creating complex simulators, simulation modeling has several advantages, among them the opportunity to evaluate representative systems, to optimize operator-performance algorithms, and to identify skill requirements and ways of training operators. The simulators used for these purposes must be flexible enough to allow the configuration of work stations to be changed, and also must include ways of simulating control of the operation of systems and devices, producing various visual environments, and representing information and controls. References 38 and 39 describe methods for implementing and using the simulation-modeling method for studying and optimizing manual-control systems for piloted spacecraft.

Another aspect of the simulation modeling used for ergonomic evaluation of “crew-spacecraft” systems is the training simulators (trainers). Although the main purpose of training programs is to train crewmembers to perform the tasks stipulated by the flight plan, training programs also can facilitate the development or modification of spacecraft. As experience with cosmonaut and astronaut training has shown, training simulators are often combined with tests and evaluations of spacecraft systems and onboard equipment.[40] The detailed reproduction of flight tasks provided by training simulators allows accurate evaluations of information support techniques, the time spent performing operations, the configuration of work stations, and many other factors.

In general, a training simulator consists of a full-size mock-up of the working area or work stations of a spacecraft, equipped with standard information displays, consoles, and controls, actual components or simulations of onboard systems, devices for simulating the visual environment and space flight factors, computers, monitoring and recording equipment, and control consoles for operating the simulator and implementing training schedules.

Other training systems recently added to these self-contained training simulators are those that include elements for both individual and shared use.[41] In systems such as these, one or more operator work stations are connected to a centralized system; this connection allows both simulation of the task being mastered by the crewmember and the control of training. After training is completed, this channel is reconfigured and the shared software and hardware can be used for supporting training on other tasks.

Such a training system is used in the Gagarin Cosmonaut Training Center, and allows up to 12 independent complex and specialized trainers to be organized efficiently. Cosmonauts use the complex trainer for the Mir station and Kvant module (Fig. 5) to master a wide variety of dynamic operations, e.g., navigational tasks, refueling operations, monitoring, servicing, stowing and destowing onboard systems, and training for scientific and technological experiments. Examples of specialized trainers that function within this system are the Soyuz-TM spacecraft trainer and the trainer for mastering control of personal extravehicular mobility units, in which the visual environment as seen from the EVA suits is simulated with a collimator device and electronic image synthesis.

Equipment and tools to be used during EVA can be evaluated during crew training in microgravity simulations such as neutral buoyancy. As described in Chapter 2 of this volume, microgravity operations can be practiced under water, in large tanks that contain full-scale mock-ups of objects with which the crew will work during EVAs (Fig. 6). The cosmonauts train in suits similar to the ones used during actual EVAs; these suits are made neutrally buoyant with a system of weights tailored to each individual. Although this simulation cannot mimic the effects of microgravity on the vestibular system, and includes hydrodynamic forces and moments not present in space, this method has been used widely in Russia and the U.S. because of the opportunity it provides for mastering performance of a broad range of tasks, as well as the safety and relatively low cost of underwater training relative to that on laboratory aircraft flights.

In summary, the number of indicators, variables, and conditions to be evaluated during space flight is enormous, and essentially constitutes the entire “crew-spacecraft-ground control” system. Crewmembers evaluate their work stations, characteristics of their equipment, special clothing, and aspects of planning and control of the flight by the ground-control services. In turn, the ground control center evaluates crew training in terms of how well the crew performs their tasks and by the operational conditions on board the spacecraft. Considering the enormous flow of information circulating in the system, it has been proposed that “deviations from the norm” be used to analyze the system’s functioning.[42,43] Deviations, in this sense, mean any lack of correspondence between the actual properties of the system and the stipulated, required, or anticipated properties that are noted in the onboard and technical documentation, the flight program, or other regulatory documents. Issues of classification and practical applications of results from error analyses—which also can be considered deviations—are discussed in References 42–45.

III. Conclusions

Further development of the space infrastructure will be accompanied by an increase in the amount of work assigned to the crewmembers, as well as by redistributions of the amounts of time spent in various types of activities. Even now, cosmonauts aboard Mir use and maintain more than 100 standard systems and a variety of scientific equipment. Operations such as deploying and replacing equipment on the spacecraft exterior, inspecting and repairing satellites, and controlling manipulators and extravehicular mobility units are already a reality.

During the assembly and use of still longer-term space stations, some of the functions now carried out by the ground control center will be transferred to the crew, mostly in the control of assembly and installation operations. Later, crewmember functions will expand still further to include short-term planning as well as calculating resources for and supporting flights of crewed and robotic spacecraft launched from the station to other spacecraft.

Nevertheless, allocation of functions among the crew, the onboard facilities, and the ground facilities should represent a balance between the number and variety of crew tasks and the limited size of the crew. Imbalances can produce a sense of overwork, diminishment of performance capacity, and errors in task performance. Today's agenda therefore must address the creation of a balanced structure that unites the crew, the onboard systems, the flight control center, and the ground users. Such a structure will decrease the workload on the crew and perhaps encourage their creative potential.

Incorporation of telemonitoring and telescience technologies in the near future can significantly improve the efficiency of scientific research by curtailing routine work by crews, allowing effective allocation of financial resources, and allowing ground personnel to participate directly in remote sensing, controlling payloads, and processing and analyzing information. As more artificial-intelligence technology is incorporated in onboard systems and equipment, the focus in organizing interactions will shift more and more toward integration and complementarity of human and machine capacities. According to one prediction,[46] up to 45% of work operations on flights in the near future may become automated, with that proportion increasing to 75% after 2005. At the same time, the degree of automation on very long and distant flights such as those to Mars demands particular attention, since excessive automation may lead to the development of monotony and decreased vigilance on the part of the crew.

Clearly, collecting data on human behavior and performance in space flight is critical to solving problems in the design of "crew-spacecraft" systems. One technique for obtaining information such as this is a form of simulation modeling that uses both ground-based and onboard means[47] (Fig. 7). This method allows cosmonaut performance under actual space flight conditions to be reproduced and replicated safely. We have used this technique to obtain data on how adaptation to microgravity, training schedules, and other factors affect cosmonauts' ability to control docking.

Unfortunately, goal-directed studies of this kind have been neither frequent nor systematic, and often involve administrative, methodological, and technical problems. For this reason, we and others have relied mostly on ground-based results on how the human operator functions in human-machine systems (e.g., Reference 12). Nevertheless, extreme caution must be used in extrapolating data obtained on Earth—and the standards developed from those studies—to the design of space systems, since specific flight factors may require significant adjustments. For this reason, we contend that crewmembers, as the "end-users" of spacecraft systems, must be involved as much as possible in direct design of the systems with which they and their colleagues must work.

Our hope in presenting this review of techniques for supporting the professional performance of space crews is to help the reader focus on some of the challenges of ergonomic design, the solution of which will increase the efficiency of "crew-spacecraft" systems. Some of the tasks requiring resolution include:

- increasing the reliability of data on crew performance and psychophysiological capacities through the goal-directed collection of information during flight;

- standardizing ergonomic specifications and standards to be used in designing equipment and work stations aboard spacecraft;
- developing appropriate simulation models that reflect specific features of “crew-spacecraft” system functions, including sociotechnical aspects; and
- improving simulation complexes for experimental study by optimizing the interactions between the crewmember-operator and technology.[48]

As these challenges are met, with data from ground sources and from space flights, attention can be turned toward the future, with such tasks as creating additional complex automated systems for piloted spacecraft, and standardizing parameters of the human-machine interface (e.g., consoles, controls, displays) in those spacecraft. The latter task has become increasingly important in light of international collaboration in space exploration and development.

Acknowledgment

The authors deeply appreciate the invaluable help of Cosmonaut Gennadiy M. Manakov in preparing this chapter.

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Table 1 Characteristics of various coding methods [Refs. 12,13]

Coding method	*Numbers of Coding Symbols* Maximum	Recommended	Subjective evaluation	Notes
Colored light signal	10–11	3	Good	Rapid detection, small space; ambient illumination not important; recommended for quantitative coding
Colored surface	50	9	Good	Same factors, but ambient illumination is important
Alphanumeric	Unlimited	—	Good	Requires little space with good contrast and resolution; time to detect longer than for color coding
Geometric shapes	15	5	Satisfactory	Requires little space with good resolution; some shapes are hard to recognize
Icons	30	10	Good	Opportunity for direct associations; requires high resolution
Area/dimensions of figure	5–6	3	Satisfactory	Requires more space than others; time to recognize is longer than for color or shape coding
Line length	4–6	3	Satisfactory	Same as above
Angle of inclination (orientation)	24	12	Good	Recommended method for quantitative evaluation and for depicting spatial position of object
Brightness	4	2	Poor	Inadequate contrast decreases the visibility of weaker signals
Stereoscopic depth	4	2	Poor	Rarely used; technically difficult to implement
Flash frequency	4–5	2	Satisfactory	Recommended for attracting attention; difficult to distinguish among several frequencies

The maximum length of the code refers to individuals highly trained in the coding method who make ≤ 5% errors.
The recommended values refer to conditions that support high accuracy of recognition.

Table 2 Association between controlling movements and reactions of the controlled object [Refs. 11,12]

Reaction (state) of the controlled object	Controlling motion[a]
Activate, start, increase, open, up forward, to the right	Upward, to the right, forward (from the operator), clockwise, pull toward the operator
Deactivate, stop, decrease, close, down, back, to the left	Downward, to the left, backward (toward the operator), counterclockwise, push away from the operator

[a] Selected through considering the type of control and its orientation in the vertical and horizontal plane

Table 3 Characteristics of widely used controls [Refs. 11–13]

	Push button	Sensor keys	Toggle switch	Rotary on-off switch	Sliding switch	Contin-uous rotary switch	Multi-position rotary switch	Finger wheel	Handle	Joystick
Choosing from 2 alternatives	●	●	●	●	●	●	●	◉	●	●
Choosing from > 2 alternatives	○	○	◉	○	●	●	●	◉	●	●
Prolonged regulation	○	○	○	○	●	●	○	●	●	●
Accuracy of setting	○	○	○	○	●	●	●	●	●	●
Speed of setting	●	●	●	●	◉	◉	○	◉	◉	◉
Tactile recognition	○	○	●	●	○	○	●	○	◉	◉
Visual recognition	○	○	●	●	●	○	●	○	◉	◉
Protected against being turned on accidentally	○	◉	○	●	◉	◉	◉	◉	○	○

● use is recommended
○ use is not recommended
◉ equal possibility for use or non-use

Table 4 Methods of fixing/restraining crewmembers for various types of operations [Ref. 19]

Body parts fixed	Means of fixation	Points of fixation	Type of operations allowed
Hand	Clamp, hand rail, interior design components	1	Switching controls (keys, toggles, etc.); readout from displays, communications
Feet	Semirigid straps, clamps	2	Opening/closing hinged panels and doors, housekeeping, medical studies
Torso	Belt with two elastic attachment straps	2	
Feet+hand	Straps+hand rail	3	Unstowing and stowing equipment, using cameras
Torso+hand	Belt+handrails	3	
Torso+feet	Belt+straps	4	Reloading recording devices, assembling or disassembling modules of moderate size using moderate force
Torso+feet+hands	Belt+straps+hand-rail	5	Assembling/disassembling standard threaded connections or large modules, working with navigational equipment and control handles

Figure Captions

Fig. 1 Interior of the Mir core module, in "transport" mode, with a view of the central control post. 1, hatch to the access module; 2, central control console, with spacecraft control system displays in the center, signal-reception matrices left and right, and input pads underneath the signal-reception matrices; 3, wide-angle optical sight; 4, work chair; 5, cycle ergometer (stowed). Handrails and straps are shown on the walls. Photo courtesy of 'Energiya' Rocket Space Corporation.

Fig. 2 Toolbox used on board Mir. 1, socket wrenches; 2, multipurpose power driver; 3, adaptors and accessories for the power tool; 4, elastic cables for fixation (bungee cords). Photo courtesy of Energiya Rocket Space Corporation.

Fig. 3 Cosmonaut S.Ye. Savitskaya works on the exterior of Salyut-7, with her boots fixed by means of brackets. From *Cosmonautics of the USSR,* edited by L. A. Gilberg and A. A. Yeremenko, Mashinostroyenie, Moscow, 1986, 496 pp.

Fig. 4 Flow chart of a simulation model for evaluating and predicting the reliability of task performance (see text for explanation). [Ref. 37]

Fig. 5 A high-fidelity mock-up of Mir and the Kvant module used for training simulations. The stairway and platform lead to the core module. Photo courtesy of the Yu. A. Gagarin Cosmonaut Training Center.

Fig. 6 Cosmonauts practicing EVA operations underwater in the HydroLab at the Yu. A. Gagarin Cosmonaut Training Center. Photo courtesy of the Yu. A. Gagarin Cosmonaut Training Center.

Fig. 7 Structural diagram of a simulation complex that includes ground-based and space flight components.

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Chapter 11

Psychological Analysis and Monitoring of Crew Performance

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Work performance has been defined as actions taken upon the world in order to attain specific goals related to the creation of socially valued products and the assimilation of beneficial experience.[1] According to this definition, psychologists who study any type of work performance must focus on those psychological factors and processes that evoke, maintain, and regulate the work-related activities of an individual, as well as the personality traits that modulate these activities.[2,3]

For cosmonauts and astronauts, one critical factor of this type is the extensive communication that takes place between a space crew and various ground-support groups (launch, maintenance, and landing crews, Mission Control Center, and others) and between the crew and components of the automated mission-control system. Some ergonomic aspects of these kinds of communications are examined in Chapter 10. From a psychological perspective, these communications provide crewmembers with information of professional and personal significance that enables them to orient themselves in their environment, make prompt and rational decisions regarding controlling and servicing spacecraft systems, and maintain their awareness of developments on Earth. This receipt of information in turn is instrumental in maintaining the emotional and professional readiness of crewmembers, and prevents the development of deprivation effects that can result from long-term exposure to space flight factors.

One feature unique to space crews that must be included in analyses of their performance is the unusual environment in which that performance takes place. Space flight involves exposure to a unique combination of factors such as weightlessness and a remote, closed living environment maintained by life support systems. As discussed at length in Volume III of this series, these factors affect the physiological functioning of crewmembers as well as their performance and even their health.

In the terminology of engineering psychology and ergonomics, space stations such as the Skylab, Salyut, and Mir are macrosystems with automated control. The hierarchy of components, and the relationships among them, are more complex in this “human operator-hardware” system than in other classical systems of this type. The relationships among the components of these systems are subject to the simultaneous, not always compatible effects of physical, social and technological factors, which ultimately determine the reliability and efficiency with which the entire human-operator system functions.

The reliability of the hardware components of a macrosystem, of course, depends on the design and production of those components. (However, even the best-designed system will become less reliable with age.) The reliability of the human-operator component of this class of macrosystems is limited by the destabilizing effects of weightlessness as well as heavy workload, information overload, and time pressure, all of which place stress on psychological and physiological functions and deplete reserves. Thus, enhancing the reliability and efficiency of a “crew-spacecraft” system clearly requires optimizing crew performance.[4]

The successful achievement of optimal performance depends mostly on understanding the most critical component of the human operator-hardware system—the individual cosmonaut and his or her social and psychological needs, concerns, and capabilities. The creation of crews whose members have developed and mastered the requisite professional skills is addressed in large part through selection and training techniques. The next steps, i.e., optimizing cosmonaut productivity, performance, health, and professional longevity, as well as the safety and reliability of the “crew-spacecraft” system, depend on appropriate allocations of functions among different crewmembers, between human operators and hardware systems, and between the crew and Mission Control Center. As discussed in Chapter 10, the most informative criteria for evaluating the reliability of such complex systems are integral performance indicators such as crew errors, variables of professional and psychological performance, and signs of psychophysiological stress during task performance.

Planning is of crucial significance in optimizing crew performance. A clear and well-organized plan stipulating the amount and nature of work to be done must be based on an analysis of working conditions, an understanding of the future course of the process being controlled, an evaluation by the operator of his or her own capacities, and the best use of reserves through rational work and rest schedules.

This chapter provides a review of results from psychological performance analyses of space crews conducted in the course of supporting long missions on Skylab, Salyut, and Mir. The authors hope that the material presented will prove useful not only for supporting current flights, but also for planning future space exploration projects such as those being discussed by space agencies in Russia,[5] the United States[6,7] Europe,[8,9] and other nations.

I. Human-Factors Evaluation and Algorithmic Analysis of the "Crew-Spacecraft" System

From a human-factors perspective, the operative performance of cosmonauts and astronauts during flight is best assessed in the context of the "crew-spacecraft" system. For such analyses, Salyut- or Mir-type space stations can be grouped with other very large systems that include automated control of railroad, air, or other transport vehicles.[10] Such systems contain an enormous number of subsystems and components with complex functional interfaces, involve a high degree of automation, and entail the participation of large groups of operators. These systems involve information interfaces of various types, e.g., "human operator-hardware," "human operator-hardware-human operator," and "human operator-hardware-environment" types. The complexity and variation of these interfaces require that crewmembers participate in extensive exchanges of information.

The automated control system aboard Mir, for example, is a hierarchical structure that is based on interactions between controlling and controlled subsystems.[11,12] In this system, an automated control system sends flight control commands to the spacecraft in the form of radio broadcasts, operational commands, and so on, and receives feedback as to the status of spacecraft systems, spacecraft orientation in space, and flight program status. An onboard control complex[13] in turn sends controlling information (in the form of commands or programs) to controllable onboard systems, which then return feedback on their status to the onboard control complex (Fig. 1). In this scheme, the mission-control system and the crew interface via an onboard electronic subsystem; the crew serves as a controlling element that interacts with onboard systems through peripheral (input/output) devices such as controls and displays.

The successful ground-based mission-control function must meet at least three requirements. First, commands to onboard subsystems must be issued promptly; second, assessments of real-time operation or the status of onboard systems must be accurate; and third, directions regarding actions that the crew should undertake must be clear and unambiguous. These requirements, in turn, can be met if the crew can receive and transmit information in real time, make correct decisions promptly, and provide unambiguous inputs to the spacecraft systems. For the crewmember, the most important abilities, the ones that most directly affect the efficiency and reliability of the "human operator-hardware" systems and space flight safety, are the ability to assess the status of all onboard subsystems simultaneously, and the ability to maintain continuity of the control process.

A space crewmember plays many roles on board, including pilot, analyst, and researcher. Crewmembers also are responsible for a broad range of operator functions, e.g., monitoring and controlling experiments in many areas of science and technology, and performing applied scientific and industrial tasks up to and including space manufacturing.[14] Types of functions and activities performed during flight are summarized in Table 1.

The heterogeneity—and difficulty—of task assignments cannot help but affect cosmonaut performance. Meeting mission objectives comes at considerable psychological cost. For example, processes that must be controlled move at a great range of speeds; some are subject to intense time pressure, and others are marked by monotony and long absence of meaningful signals. Nevertheless, cosmonauts must perform tasks that have different objectives simultaneously, which requires processing a great deal of information in different modalities quickly. In combination with the complex changes in physiological functions that result from space flight factors, the work environment for space crews can be extremely difficult and stressful.[15] All of these issues underscore the importance of ensuring crew-member reliability within the "crew-spacecraft" system.

II. Operator Reliability Within the "Crew-Spacecraft" System

The concept of reliability that originated from theories of automatic regulation subsequently was extended to those who service the machines.[16] Reliability can be considered an integral performance indicator that depends on the speed and accuracy of the human operator, as well as a variable that reflects the probability that this operator will accomplish some requisite task during a given period and under given conditions. Defining reliability as an individual's ability to maintain stable performance is a particularly appropriate approach for long space flights, which carry a high probability that the "crew-spacecraft" system will become less efficient and less reliable over time. Factors contributing to this probability include diminished functional capacities during adaptation to an unaccustomed physical environment (microgravity); various occupational hazards; gradual deterioration of skills for infrequently performed operations; physical symptoms; various extreme contingency situations; and high levels of work-related and psychological stress, especially during extravehicular activities (EVA). Prolonged mobilization of latent functional reserves often leads to episodes of asthenia (debility).

Another factor to consider with regard to operator reliability is the prestige associated with being a cosmonaut or astronaut. The constant drive to excel, even if risks are involved, can lead to erosion of a healthy sense of self-preservation. Although most space crewmembers are aware of the significance of good health in their careers, they often sacrifice it in the interest of meeting mission objectives. This phenomenon is becoming increasingly common as space exploration progresses, with workloads increasing and new problems continually emerging. New responsibilities are constantly being added, e.g., equipment installation, expansion, and repair; maintenance and operation of additional space station systems of various designs and operating principles; implementation of increasingly complex scientific investigations, and so on. The number of EVAs performed during space flights is increasing. The cosmonaut training process also is becoming more intense, largely because of the expanding nature of its subject matter. All of these factors combine to increase the stress, effort, and psychological investment in being a cosmonaut or astronaut.

Psychological changes observed in cosmonauts on long flights also can be considered a risk factor that contributes to less-reliable “crew-spacecraft” systems. The combination of microgravity conditions, social and ecological constraints, and mandated work-rest schedules in space, in conjunction with a relatively impoverished range of external stimuli, give rise to a kind of deprivation response. This response is expressed as psychological exhaustion and decreases in perceptual thresholds. We believe that combatting sensory deprivation on long space flights is another critical aspect of psychological support for space crews.

Finally, our concept of operator efficiency and reliability must include not only the ability to adapt to the space flight environment and to achieve goals of a stipulated quality under particular conditions, but also the need to maintain occupational health while doing so.[17] Moreover, health and professional skills must be maintained not only during flight, but also before and after flight as well. The long, comprehensive crew-training process carries its own set of stress factors, the negative effects of which are apparent in the illnesses present in the cosmonaut corps. Over the current 15- or 16-year active working life of the cosmonaut, the predominant illnesses are essential hypertension, ischemic heart disease, ulcers, other systemic and local circulatory disorders, autonomic- and endocrine-regulation disorders, and disorders of the central nervous system. Morover, the second most common cause of crew attrition is psychosocial maladjustment of various types, e.g., on-the-job conflicts or family problems.

III. Psychological Analysis of Crew Errors in Flight

In the previous section, we have dwelt on the psychological, social, and occupational aspects of operator reliability in “crew-spacecraft” systems because we believe that all of these factors can cause crew errors, which of course can affect space flight safety. Statistical analysis of a sample of flight incidents (potential accidents) has shown that more than 30% of these incidents reflect diminishments in the reliability of the human factor of the spacecraft-control system.[18]

For our purposes, errors can be defined as failures of an individual to perform assigned tasks to stipulated criteria of accuracy, sequence, and time. A time-and-motion study conducted on the three U.S. Skylab missions showed no significant degradations in performance quality. Indeed, some measures of performance improved with increasing time spent on board.[19] Soviet researchers, on the other hand, have identified three patterns of error dynamics by cosmonauts on the Salyut and Mir stations.[20] The first and most common pattern involves the most errors taking place during the first 3 or 4 weeks of a flight, with fewer errors thereafter. The second pattern reflects a tendency for errors to increase slightly during the last 1 or 2 weeks of flight. The third, least typical pattern is for errors to be distributed relatively homogeneously throughout the flight. Examples of error distribution for three flights are shown in Fig. 2.

Possible explanations for the first pattern of errors are as follows. First, the initial phase of flight is, of course, the period during which acute adaptation takes place; according to one report, 51.3% of all cosmonauts experience illusions, difficulty in time estimations, and spatial disorientation during that time.[21] Another reason for errors during this period is the difficulty of the tasks involved in docking the Soyuz transport module with the space station. Third, the lack of accustomed contact with supporting surfaces in weightlessness disrupts motor coordination, resulting in time pressure. Finally, the presence of more errors early in flight could result from the difficulty and psychological tension associated with launch and orbital insertion, particularly for those tasks involving the electronic and radiotelemetric systems. Other difficult tasks include scientific experiments, which require performing demanding scientific operations while simultaneously controlling the spacecraft.

Increased numbers of errors during the last 1 or 2 weeks of flight, on the other hand, could reflect general fatigue, either from prolonged habitation of the closed environment, or from the need to perform a great deal of work during that period. Dissimilar tasks often must be performed simultaneously, under some time pressure. Finally, errors during this period may reflect partial loss of skills for tasks that have not been performed for a long time, even for individuals with stable job skills and good understanding of the theory of “crew-spacecraft” system control.[22] All else being equal, the third error pattern may be associated with inadequate crew training on mission tasks.

We assessed several objective variables (amount, time and quality of the work performed, number and nature of errors, performance style and behavior in standard and contingency conditions, ability to recover after errors, and others) and used those results to characterize dynamics of crew psychological status and performance on the Salyut and Mir stations.[23] Quantitative analysis revealed decreases in crew errors from Salyut-6 (0.46 arbitrary units per day) to the more technologically advanced Salyut-7 and Mir stations (0.32 and 0.30 units/day, respectively). This finding is thought to reflect not only improvements in the performance and selection of onboard equipment, automation, and assumption of some crew operations by the Flight Control Center, but also training crewmembers in error analysis, decreasing the work hours during acute adaptation to weightlessness, and granting days off after performance of particularly difficult tasks.[20] Also, error variables are associated with the total size of the work environment and number of tasks performed. For example, the average number of errors per day during the first portion of Mir flights was 0.09 per day; as the station grew by docking with the Kvant, Kvant-2, and Kristall modules, the error rates increased to 0.13, 0.27, and 0.29 per day, respectively.

Finally, this error analysis would be incomplete without mentioning cosmonaut performance capacity, which several experts in ergonomics and industrial psychology believe characterizes the ability of individuals to do their jobs, with the necessary quality, in a given time.[24–26] This definition, of course, is quite similar to that of reliability.

IV. Methods of Evaluating Performance

In space psychology and medicine, performance capacity is evaluated in two ways, first by how well cosmonauts or astronauts perform tasks in experimental simulations, training simulators, and in space flight,[27,28] and second by the time needed for one or two crewmembers to learn and perform various types of tasks, e.g., destowing and deploying hardware, preparing meals, and other in-flight operations.[19]

As noted earlier, no correlation was found between performance ability and duration of residence aboard Skylab. During the first part of the flights, the time needed to complete any task requiring several coordinated operations was always greater than on Earth. This finding was interpreted as reflecting the stress of last-minute flight preparations, the onset of microgravity, and the caution and care taken in performing flight tasks. However, performance improved quickly in weightlessness; by the second trial, 50% of all task elements were completed as quickly in flight as before flight, especially for tasks that had been practiced during preflight training.[19] Diminishments in performance attributable to space motion sickness lasted 1 day or less.[29]

In another study, cosmonauts aboard Salyut and Mir were tested with an onboard training simulator. For the first 3–7 days of flight, their ability to control a simulated berthing was significantly degraded in terms of disrupted work style, decreased concentration, and changes in response time. Performance characteristics and the state of tension gradually returned to normal over subsequent trials, and returned to baselines after 4 or 5 trials.[22] The drop in performance quality during this period was thought to result from disruption of motor coordination and the inefficiency of Earth-learned motor skills to control the spacecraft in weightlessness. This inefficiency was manifested by frequent, jerky motions instead of smooth controlling motions. Later in flight, allowing more than 30 days to elapse between trials produced further decrements in simulated berthing and docking skills, with the degree of decrement directly related to the duration of the interval.[22] The greatest declines were present in accuracy and time; after more than 30 days, operators tended to forget components of the performance algorithm as well. However, another study revealed no change in logical or computational ability, nor in complex sensorimotor reactions during flight.[30] Cosmonauts and astronauts were able to process a great deal of information under time pressure; to discriminate between similar signals; to shift attention rapidly; to recognize problems promptly; and to implement appropriate solutions. Thus, humans in space flight retain their ability to perceive, comprehend, and think, can understand their surroundings, and can anticipate the need to perform critical actions quickly and efficiently.

Human actions are known to be accompanied by activation of the central and autonomic nervous systems.[31] Signs of this activation, e.g., changes in heart rate, blood pressure, perspiration, muscle tone, and other indicators, have been used to develop an integral measure of psychophysiological stress.[32] This measure, quantified in arbitrary "stress units," is closely linked to the difficulty of the task being performed. As an example, Fig. 3 portrays the dynamics of psychophysiological stress in a cosmonaut before and during an EVA on a Mir mission. This cosmonaut's stress level during Earth training (Fig. 3, Panel A) was roughly comparable to that before EVA (Fig. 3, Panel B), ranging from 0.07–0.15 stress units. Stress levels increased substantially once that cosmonaut reached the station exterior (Fig. 3, Panel C). Mounting a tethered platform produced a stress level of 0.3; installing a deployable antenna increased this value to 0.65, which in simulation experiments on Earth is considered a marked stress response. More passive activity, i.e., observing the Earth from the spacecraft exterior, reduced the stress level to about 0.25. Later peaks in the stress indicator were associated with the cosmonaut freeing himself from the tether anchor (0.5) and getting out of the suit quickly, before its life support system resources were exhausted (0.75).

Another concept showing great promise for psychological analysis of cosmonaut performance is that of an onboard multipurpose psychophysiological complex (Fig. 4) like that planned for Medilab.[33] The configuration of that complex facilitates the solution of many problems, such as:

- acquiring, processing, analyzing, and storing psychophysiological information;
- issuing commands to select and present the operator with test material and various types of operator tasks;
- creating a data bank and expert system representing a set of programs, allowing diagnostic information to be used to predict operator reliability and "crew-spacecraft" system efficiency;
- simulating work tasks for monitoring, supporting, and recovering skills for controlling the spacecraft and evaluating crew performance;
- implementing and optimizing the state of the operator with biofeedback and psychotherapy techniques; and
- supporting conditions for embedding test information in game or work-simulation forms, which substantially increases the motivation to perform well on psychological tests.

The psychophysiological complex also provides confidentiality in data collection, a dialogue mode, graphic representation of results, and other features necessary for its effective use. This concept has met with the support and approval of several discussion groups, including one held in March 1991 with the European Space Agency.

V. Enhancing the Efficiency of the "Crew-Spacecraft System" During Its Design, Production, and Use

From a mathematical perspective, efficiency is a scalar quantity representing the quality of crew performance divided by expenditure of time and resources. The efficiency of a "crew-spacecraft" system can be associated with the probability that the crew will perform some stipulated function(s) during a period defined by the flight program. Other considerations can include the quantity of products or quality of the services performed by the crew in a given time.

At the current state of crewed space flight, enhancements of the efficiency of the "crew-spacecraft system" can be grouped into 5 major categories: (a) optimal allocation of functions between the spacecraft and ground-control crews, between the crew and the onboard spacecraft hardware, and among crewmembers; (b) appropriate design of the spacecraft layout and interior according to ergonomic principles and functional comfort; (c) well-organized and planned in-flight work schedules; (d) the use of selection and training to create crews that have the most important qualities for work performance; and (e) psychological support measures to ensure the readiness (i.e., reliability) of crews during flight. Aspects of these 5 categories are discussed further below.

A. Allocation of Functions

Allocation of functions in human-machine systems is an extraordinarily complex issue. Aspects of this problem are addressed from an ergonomics/engineering perspective in Chapter 10, and from a psychological point of view in the following paragraphs.

One example concerns whether the balance of spacecraft-control functions are allocated to the flight control center on Earth vs. to the spacecraft itself. On the one hand, centralizing flight control (i.e., transferring the control functions of the automated spacecraft-control system to the flight control center) offers the potential for experts to analyze very large amounts of data and use complex simulation systems and computers during the flight, which presumably would increase the rationality of the decisions made. On the other hand, decentralizing that process (i.e., assigning flight-control functions to the spacecraft crew) allows control commands to be controlled and issued on-line, which facilitates problem solving during high-speed operations and contingencies during flight. Decentralized flight control also is needed when the spacecraft is out of radio contact with Earth, whether from orbital pattern or from problems with the communication lines. The importance of decentralized flight control in maintaining the efficiency of the “crew-spacecraft” system has been amply demonstrated throughout the history of crewed space flight.

Allocation of functions among members of a flight crew is based on principles of command authority, collegiality, and specialization. Within a crew, the commander is responsible for the safety of the crew and orbital complex, as well as the completion of the flight program. The commander generally controls the motion of the orbital complex (i.e., relative center of mass and center of mass in the inertial coordinate system). The flight engineer is responsible for the use and maintenance of the onboard systems. Mission and payload specialists, if present, are responsible for specified tasks and the use of associated hardware. Responsibilities among crews are alloacated and defined as the orbital complex is being planned. While onboard systems and methods of controlling them are being developed, functions are allocated to crewmembers in more detail, at the level of flight operations and modes of operation of onboard systems. More detailed allocations take place both while the crews train with the training simulators (see Chapters 2 and 10) and during actual work according to individual strengths and skills.

From a psychological perspective, the role of human operators in the current “crew-spacecraft” system is less than ideal. Space-hardware developers strive for maximum automation of all functions, following the principle that all the major flight operations should be performed automatically, without crew involvement. Crews, as a rule, are assigned secondary functions, and serve as a back-up for automated operations. This situation diminishes the active participation by crews and as a consequence decrease their readiness to act in cases of equipment failure or other emergencies.

Effective interactions among crews and hardware can be fostered through an integrated systems approach to spacecraft design, which substitutes the design of a unified “human operator-hardware” system for the design of individual hardware components. In this approach, the crew is treated as the major, active, defining component of the system, and the spacecraft systems controlled by the crew are treated as passive components.

For operational tasks and control functions that do not affect crew safety, crew-hardware functions can be allocated on the basis of cost effectiveness, i.e., to minimize expenses during the flight. For control functions that do affect crew safety or could threaten the operation of the spacecraft, this principle is not acceptable. All available resources should be used to provide maximum reliability, which in some cases means maximizing the level of automation. Special training methods and programs are now being developed that can support active crew involvement with highly automated station control.

B. Spacecraft Architecture and Interior Design

Another way of enhancing the efficiency of the crew-spacecraft system is to improve the “functional comfort” or habitability of working conditions for its human operators. Such improvements, based on principles of architectural and interior design, aim to provide variety in volumes, forms, and colors of working and living modules, compartments, areas interiors, panels, and work stations. Ideally, these areas could be reconfigured as needed over the course of a flight.[34,35]

From the standpoint of functional comfort, the interior architecture and configuration of Mir is greatly constrained, being determined by the configurations of the spacecraft hull. Mir belongs to the corridor or gallery type of configuration. Major elements of its interior are illustrated in Fig. 5.

From both psychological and architectural perspectives, Mir is a highly dynamic and symmetrical living environment that is densely saturated with specialized equipment. In general, its design represents an appropriate balance between hardware and working conditions for the crews in terms of maximizing productivity, maintaining crew health, and allowing the development of human potential (including spiritual needs). The success of this balance is demonstrated by the reliability and efficiency of the “crew-spacecraft” system during missions lasting up to 1 year.

C. Planning Mission Tasks

Planning can have an enormous influence on the efficiency with which a wide variety of tasks are performed on board a spacecraft. Appropriate planning organizes the work of the crew (both temporally and spatially), defines the direction of that work, and establishes the amount of effort needed to complete the work so as to meet the goals and objectives of the mission.

In a sense, planning is part of the cyclic process by which space flights are controlled. The essence of planning is the identification of a sequence of actions that will achieve mission objectives through transforming information about the status of the spacecraft and the environment. During the process of planning, the order of flight operations and their temporal relationships to each other are established. The result of the planning process is the creation of a flight plan by which mission objectives are achieved and the safety of the crew is maintained.

In the Russian space program, three levels of planning correspond to three types of plans: the overall flight plan, the detailed flight plan, and the schedule of flight operations. The overall flight plan for crewed space stations covers periods lasting 10–12 days, and includes the list and sequence of flight operations performed on each day. The detailed flight plan covers 24-hour periods and provides a schedule for crew activities (see Section D below), operation of onboard systems, and exchanges of information between the crew and other components of the flight control system (e.g., Mission Control Center or other spacecraft). The schedule of flight operations contains instructions on how to monitor the operation of onboard systems and how to change the activity schedule if contingency situations arise.

Flight planning begins at the phase of spacecraft design and continues until the flight is completed. The extent to which crews are involved in planning during the course of the flight depends on the autonomy of the spacecraft and the allocation of this function between the crew and the Mission Control Center.

D. Work-Rest Schedule

As described above, planning is one way in which both the efficiency of the “crew-spacecraft system” and crew performance can be enhanced. The latter goal is achieved only if planning is not limited to the technology of human-hardware interfaces, but also considers the full range of ergonomic factors. In this way, planning can directly or indirectly determine the potential for improving working conditions, supporting performance, and increasing productivity.[36]

One ergonomic factor that definitely affects cosmonaut performance is the daily work schedule. Russian research using simulations and space flights led to the development of recommendations for space crew schedules. Used to create rational plans for crew work during long flights,[37] these recommendations define the specifications for the content, organization, planning, and monitoring of the work-rest schedule. Specifications covered include the optimal duration of workdays, best numbers of work shifts per week, ideal rest periods after work shifts, and so on. From the standpoint of ergonomic requirements, this type of work-rest schedule allows workloads to be standardized, while simultaneously protecting the health and performance capacity of the crew.

Cosmonauts’ daily routines are divided into working hours, personal time, and sleep period. Typical activities within these periods are shown in Table 2. Meals and exercise sessions are scheduled with particular care. Four meals are planned per day, with 3- to 6-hour intervals between them; two 1-hour exercise sessions are scheduled for each day, to take place no earlier than 2 hours after meals and no later than 2 hours before bedtime. As noted above, the overall work-rest schedule is a component of the overall flight plan, and the crewmembers themselves help to develop it as much as possible.

The flight week is divided into 5 work days and 2 days off. The schedule for the first day off allows up to 1.5 hours of work on mission tasks and up to 2 hours of housekeeping tasks. Routine daily operations (see Table 2) also are allowed on the second day, but most of this day is devoted to individual recreation, e.g., radio and televised sessions with families, friends in the cosmonaut corps, specialists, and representatives of science, culture and art; entertainment broadcasts are provided as well.

Both the daily and weekly work cycles, and their relationship to time schedules on Earth, are flexible, and can be changed according to the needs of the individual crewmembers and the flight program. For example, many crewmembers, especially those on their first space missions, experience psychosensory discomfort, sleep disorders, and psychological tension during the acute adaptation period. Because these symptoms can interfere with the ability to complete the flight program in the stipulated time, the crew's workday for the first 14 days of flight is limited to 50% of that expected later (although it never drops below 1.5 hours per day). As another example, the workday during the hectic final 2 weeks of flight is shortened by 2 hours, so that the crew (typically fatigued) can use this time for countermeasures. During these 2 weeks, crews are not allowed to work at night, nor to attempt to shift the sleep-wake cycle, nor to perform difficult operations not associated with docking with Soyuz.

1. Visiting Crews

Daily work routines for visiting crews can be adjusted so that workdays last up to 10 hours, for no more than 7 consecutive days. These routines also can be amended as needed with regard to the health of the crewmembers.

2. EVAs

During preparations for EVAs, the crew's schedule is based on the premise that EVAs entail risk and intense psychological and physical demands. Thus, medical specialists take great care in assessing the health status of the crewmembers at that time, with consideration of the duration of the EVA, the time of day, the nature and difficulty of the planned operations, and previous experience with EVAs and the specific tasks. The preparation period for an EVA can last as long as 10 days. On the day before an EVA, crews are given an additional rest period of at least 4 hours. The total duration of the work day that includes the EVA can last 12 to 14 hours, of which 5 or 6 hours are spent working on the spacecraft exterior.

The crew's work-rest schedule during an EVA also depends on the orbital path of the spacecraft. If the EVA takes place at night (i.e., during the normal sleep period), then the stress factors include up to 8 hours without food. After completing EVAs, crews are encouraged to sleep for as long as needed to restore their functional reserves. Two or more consecutive EVAs are separated by a day of rest between each; during this time, crews are allowed to perform tasks to maintain the suits (e.g., drying, verifying life support system, etc.).

3. Sleep Shifting

Occasionally, flight tasks require that the crews shift their sleep-wake cycles for up to 12 hours. The intervals between such shifts must be no shorter than 2, and no more than 6 shifts can take place during even long space flights (i.e., up to 12 months long). After the tasks that required the displacement are completed, the crew is given 2 days of rest. As the crew is sleep-shifting, and again as they return to a normal schedule, the length of their workdays are shortened, with the exact duration determined on the basis of the crew's physiological status. Subsequent increases in the workday to its normal duration depend on the rate at which crewmembers adapt to the working conditions.

On brief space flights (i.e., those lasting 7–10 days or less), crew workdays can last for 10 hours. On such flights, neither days off nor exercise sessions are allotted, and scheduled sleep periods do not exceed 8 hours.

Several variants of work-rest schedules have been tested during long space flights between 1971 and 1992. Three schedules that involved sleep-wake displacement have been attempted on Salyut: an inverted work schedule in which the sleep period was displaced by 12 hours (prime crew 4 on Salyut-6); a multistep displacement of the sleep schedule (prime crew 1 on Salyut-5, see Fig. 6); and a progressive displacement of the sleep period by 30 minutes (prime crew 1 of Salyut-6). Other variants were a work-rest schedule with a 9- to 10-hour workday (prime crew 2 of Salyut-7), and a work-rest schedule with a 24-hour diurnal cycle closely tied to Moscow time (Mir crews).

One way of judging how well the various schedules work is by how many work hours (beyond the 8.5 hours typically scheduled) are needed to complete the assigned tasks. For example, on the 1158-hour Soyuz-21/Salyut-5 flight cited above (and shown in Fig. 6), the sleep-shifting periods were associated with increases in the length of the workday beyond the allotted time. In other words, the planned proportion of 30% work to 37% personal time to 33% sleep was actually 44% work to 30% personal time to 26% sleep. This increase in the time spent on work has been present in other flights as well, and typically exceeds the scheduled allottment by 6–16%. Converting these percentages into absolute number of days, revealed that crews on Salyut-3, -4, -5, -6, and -7 worked 12–37 extra days (i.e., beyond that stipulated in the flight plans). In contrast, the Mir crews worked no extra days after the schedule was optimized (except for prime crews 7 and 8, who worked between 4 and 6 extra days).

In summary, the 24-hour diurnal cycle seemed to be the best in terms of supporting productive work by the crews. Nevertheless, work-rest schedules continue to be a critical issue for space psychology and medicine, and requires additional attention. We contend that two general problems remain to be addressed in order to maximize the effectiveness of structured work-rest schedules. The first issue concerns minimizing fluctuations in crew workload. Particular attention should be paid to avoiding increases in the duration of workdays—and the corresponding decreases in time available for other activities—and eliminating unjustified displacements of the sleep-wake cycle and disruptions of meal and exercise schedules. These efforts should improve crews' use of the entire set of countermeasures. The second issue concerns the number of crewmembers present on spacecraft, and requires adjusting the size of crews so that they correspond to the amount of work on board modern research stations.

E. Psychological Support Factors

All of the measures described above will help to increase flight safety. However, optimizing safety also requires considering the work-related personality traits of each crewmember, which in combination with experience and mastery determine that person's psychological reliability.

A cosmonaut's psychological reliability in space is determined by the stability of his or her basic psychophysiological functions (see Volume III, Chapters 19 and 20) as well as the stage of development of professionally significant traits. The latter are defined as those traits that ensure an individual's ability and desire to perform a certain type of work. Some of the more heterogeneous personality traits can be professionally significant in the context of a specific task.[38] However, our research suggests that those traits that are most significant for successful work are: appropriate anxiety; tolerance of stress; psychophysiological resistance; motivation to learn and improve; physical fitness; high behavioral-activity level; general flexibility; realistic self-evaluation and ambition; balanced motivational structure; high self-actualization; and well-developed operator-task skills. Stepwise discriminant analysis of these traits, weighted appropriately, revealed that the 4 factors most important for maintaining professional achievement and health are (1) appropriate levels of anxiety, (2) psychophysiological resistance to harmful factors, (3) capacity for self-actualization, and (4) motivation to learn and improve.[39] For the first of these factors, anxiety as a trait (i.e., the tendency to anxiety responses) should be distinguished from anxiety as a state, i.e., anxiety experienced at a specific moment that serves as an appropriate psychological signal of danger. The second factor, psychophysiological resistance, refers to the association between psychological activity and its physiological basis. Psychological tension is closely associated with anxiety, and fosters the maintenance of functional resistance in difficult living conditions. The third factor, capacity for self-actualization, refers to the ability to understand one's self, including one's strengths and weaknesses. Self-actualization is related to the selection of life goals and the formation of a value system that accords with those goals. Finally, the motivation to learn and improve is a set of psychological traits that are conducive to successful performance of a task. Preconditions for this ability are thought to be determined genetically, at least in part, and involve the speed and strength with which temporal associations are formed, ability to differentiate and concentrate, mental capacity, and others.

The Russian psychological-training program includes means of developing professionally significant traits in space crews. This system, described in detail in Chapter 2 of this volume, consists of four general parts:

- development of personality traits, such as powers of observation, ability to concentrate and shift attention, reaction time, temporal sense, memory, mental and volitional discipline, and self-control;
- self-improvement by means of optimizing interpersonal relationships, and actively creating a microsociety in which human beings feel accepted, appreciated, and understood by others;
- development and improvement of professionally significant traits, by means of flight, parachute, survival, and endurance training under extreme conditions; and
- instruction in autogenic and autofeedback skills for psychological self-regulation and controlling initially involuntary autonomic functions.

Of course, the initial prerequisite for successfully developing personality traits and skills in a crew is appropriate psychological selection. This topic also is discussed at length in Chapter 2. In brief, the psychological selection involves identifying professionally significant traits for cosmonauts, especially the absolute and relative contraindications for mastery of the profession; and evaluating candidates both individually and as members of teams.

In summary, the formation and development of the personality of a cosmonaut is a complex, permanent process in which the tendencies of the individual and the strength of their internal professional motivation are decisive for maintaining psychological health, physical safety, and active professional longevity.

VI. Conclusions

Space flight represents one of the most intimate types of contact between human beings and state-of-the-art technology. Entrusting humans with the kind of power represented by modern spacecraft and space stations is associated with some risk of human error as well as the potential for developing psychological disadaptation, which in turn becomes a risk factor for the efficient, reliable operation of the “crew-spacecraft” system. Psychological analysis of contingency situations arising on flights of Soyuz, Salyut, and Mir has shown that 40% were attributable to crew error. Further improvements are needed in the systems by which crew performance can be enhanced.

One of the most effective ways to reduce human error is to approach the design, production, and use of space technology on the basis of coordinating the physical and psychophysiological capacities of humans with performance characteristics of the spacecraft. Underestimating the importance of human factors can lead to development of inappropriate technology and diminishment of the performance of the human-machine system.[40]

Nonetheless, trying to optimize performance of a crew-spacecraft system by focusing solely on the ergonomic requirements of the spacecraft systems ignores the vast potential of human productivity and resources. Productivity and longevity can be enhanced in many ways, not the least of which is by developing and strengthening human traits of the cosmonauts. Our understanding of the principles governing human adaptation to space flight conditions is closely associated with this problem. Indeed, the efficacy of adaptation cannot be considered apart from the physiological shifts that provoke adaptation. Hormonal and other mediators that participate in these shifts also affect the mechanisms that trigger and support psychological and emotional states.

The environment in which space crews live has independent significance in terms of the efficiency and reliability of the crew-spacecraft system. Our definition of environment includes not only the living and working conditions of the crew, but also the psychological climate, interpersonal relationships, moral value systems, and other psychological factors. This definition allows the use of many approaches to the study of crew-spacecraft reliability. These approaches allow us to evaluate the medical (i.e., mental health) and psychological (i.e., performance efficiency) aspects of crew reliability; to participate in rational allocation of functions among space crews and ground support teams; and to design efficient work schedules that account for the structure of tasks, the state of skills, and architectural aspects of the spacecraft interior.

Supporting the professional and psychological reliability of space crews requires a complex approach and the use of advances in many related disciplines, e.g., space medicine and psychology, psychophysiology, sociology, and ergonomics, as well as a sense of technical aesthetics. An integrated approach to the psychological analysis of work performance is especially critical during what one author has termed “the new space era.”[41] Current astronautics is no longer limited to issues regarding human flights in near-Earth space, but instead is directed toward expanding the sphere of human life beyond that biosphere to which we have linked functionally and structurally throughout our evolution.[42]

Acknowledgments

The authors thank V. P. Zavalnyuk and V. F. Nesterov of the Yu. A. Gagarin Cosmonaut Training Center for their contributions to the section on work-rest schedules.

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Figure Captions

Fig. 1 Diagram of the onboard control complex of a crewed spacecraft. Solid lines indicate transmission of control information from the spacecraft control system to the onboard electronic complex, crew, peripheral devices, onboard systems; dotted lines represent feedback from these information sources to the automated spacecraft control system.

Fig. 2 Crew error patterns during flights on the Mir complex. A, error pattern during 52-week flight; B, error pattern during 30-week flight; C, error pattern during 19-week flight.

Fig. 3 Dynamics of psychophysiological stress in a Mir cosmonaut (A) during baseline studies on Earth, (B) before EVA, and (C) during EVA. [Ref. 32]

Fig. 4 Diagram of a multipurpose onboard psychophysiological complex. AWS, automated work station. [Ref. 33]

Fig. 5 Spatial layout of the Mir complex during flight. [Ref. 42]

Fig. 6 Work-rest schedule, with stepwise displacement of the sleep period during the 49-day Soyuz-21 mission. Day 1, Soyuz-21 was launched; Day 2, Soyuz-21 docked with Salyut-5; Day 50, Soyuz-21 landed. Dotted lines indicate the sleep period; A, B, C, scheduled times for breakfast, lunch, and supper, respectively.

Table 1 Types of professional activities and tasks performed by space crews during flight

Type of function	Nature of task
Planning	1. Identification of a sequence of actions to attain mission objectives 2. Allocation of functions among crew members, considering their professions, work styles, psychophysiological status, workload, and status of onboard systems
Monitoring	1. Monitoring operation of onboard hardware 2. Monitoring the correspondence between the actual modes of the monitored system and flight program 3. Analyzing contingencies and developing recommendations to address them
Repairs and preventive maintenance	1. Replacing malfunctioning or worn out components of onboard systems 2. Installing spare components 3. Repairing failed components 4. Inspecting hardware 5. Testing hardware 6. Adjustments 7. Decontamination and dust removal
Manually controlling spacecraft motion (orientation, approach, berthing, docking)	1. Evaluating flight parameters 2. Controlling onboard systems 3. Controlling center of mass 4. Guidance control; attitude assessment and angular maneuvering
Controlling onboard systems	1. In real time, controlling and implementing programmed flight sequence; conducting astrophysical, geophysical, technological, engineering, medical, biotechnological and other experiments
Autonomous (unassisted) navigation	1. Identifying reference points 2. Calculating trajectory 3. Making navigational measurements 4. Processing navigation data 5. Computing the magnitude, direction and timing of correction burns
Extravehicular activities	1. Operating the manned maneuvering unit (MMU) 2. Monitoring and controlling MMU variables and monitoring self 3. Controlling MMU maneuvering system 4. Conducting maintenance and repair tasks in outer space
Communicating with Earth	1. Radiotelephone communications 2. Transmitting data files 3. Video communications
Supporting crew performance, psychological climate, and group interactions	1. Physical exercise 2. Hygiene 3. Food preparation and meals 4. Compliance with medical recommendations 5. Leisure and rest (viewing videotapes, reading, sleeping, etc.) 6. Instruction and training 7. Personal needs
Controlling manipulators and manipulator-robots	1. Evaluating position of manipulator in space 2. Evaluating status of manipulator and control system according to information model 3. Controlling manipulator motion

Table 2 Time allocations during a typical in-flight work-rest schedule

Components of daily routine	Time, hours:minutes
Work day	
Routine daily operations, e.g., station inspection, maintenance, communications, visual observations, food preparation, etc.	3:45
Major operations, e.g., preparing and implementing experiments, working with visiting crews, conducting EVAs, unloading *Progress* cargo vehicle, repairing or maneuvering spacecraft	4:45
Personal time	
Morning ablutions	0:30
Meals	2:00
Exercise	2:30
Free time	1:30
Sleep	9:00
Total	24:00

Space Biology and Medicine
Volume IV: Health, Performance, and Safety of Space Crews

Chapter 12

General Requirements for Flight Safety

Georgiy Petrovich Shibanov

Ensuring the safety of human crews aboard spacecraft becomes both more critical and more difficult to attain as space flight missions become more complex. Space flight safety depends not only on the reliability of the spacecraft and the systems within, but also on how well crews are trained, the compatibility between the crew and the spacecraft's hardware systems, the nature and severity of the adverse conditions to which crewmembers are exposed, their reactions to those conditions, the structure of their training and work, flight control, and numerous other factors. In other words, space flight safety presents a series of complex interrelated problems to be solved. Steps to be taken in solving these problems include the following:

- develop scientifically based general requirements for space flight safety;
- evaluate the effects of adverse space flight factors on crew safety;
- develop methods for evaluating safety levels and establishing acceptable risk levels;
- classify and analyze hazards specific to various spacecraft and develop countermeasures to combat these hazards;
- formulate general simulation principles and improve general algorithms with which to simulate emergency situations; and
- find ways to localize or deal with emergencies with minimal losses.

Moreover, implementing comprehensive, integrated process analyses to ensure the safety of space flights must be preceded by establishing terms and definitions for international use, i.e., terms that can be interpreted in the same way by specialists from different countries working in different areas. The concepts expressed by these terms must be reflected in criteria for flight safety, in methods of analyzing flight safety, and in principles used to predict, contain, and prevent situations that could lead to impaired crew health, injury, or death. Some recommended terms and definitions are listed in Table 1.[1–3]

Technical, operational, and economic constraints preclude absolute guarantees that flights can be completed without any possibility of crew health impairment or death. Some of the environmental factors associated with space flight cannot be eliminated (see Table 2); also, the possibility of illness or injury to the crew cannot be precluded in the course of maintaining spacecraft systems and conducting extravehicular activities (EVAs). Contingency events that have complicated in-flight performance and threatened crew health typically have occurred as a result of problems with spacecraft hardware (about 70%) or from adverse environmental factors (12%). Significantly fewer contingencies have resulted from errors in design or manufacture of spacecraft and boosters (6%), problems with ground-based hardware (< 5%), crew error or problems with flight planning (< 4%), errors in ground control (2%), or crew illness (about 1.5%). Consequences of contingencies such as these in the U.S. and Soviet space programs are described in Chapter 13, Table 1.

Risks to the crew associated with various adverse factors generally are estimated on the basis of the severity of consequences.[3–10] The European Space Agency (ESA) identified four levels of risk associated with in-flight situations: *insignificant* (i.e., does not lead to illness or injury); *limited* (involves minimal illness or injury that is not disabling); *critical* (causes illness or injury that temporarily disables but is not life-threatening); and *catastrophic* (causes illness or injury that is permanently disabling or life-threatening).

Thresholds of "acceptable risk" adopted for the now-cancelled German "Hermes" space plane project are presented in Table 3; the risk of catastrophic (lethal) outcomes from various ground-based activities are compared in Table 4.[10] The concept of "acceptable risk" forms the basis for developing general safety requirements for environmental control systems for crewed spacecraft[1]; criteria and methods for analyzing space flight safety[2,3]; and methods for estimating risk.[11–16] The remainder of this chapter describes the Russian approach to developing safety requirements, standards, and assessment methods during the 1980s. Another perspective on these topics is presented in Chapter 13 of this volume.

I. Safety Requirements for Environmental Control Systems on Crewed Spacecraft

The complexity of environmental control systems for spacecraft intended for human use dictates that components of those systems that are critical to flight safety must be identified before safety requirements can be developed.[17] For expedience, design specifications for safety can be applied to those components that are related to the spacecraft and its systems[18–25]; to protecting the spacecraft from adverse environmental factors[26,27]; to crew performance on board the spacecraft and ground support of this performance[6,28,29]; to requirements for safety equipment on board the spacecraft[30–32]; to support crew health[10,33–35]; and to crew selection and training.[36,37]

A crewed spacecraft must include the following safety requirements:

- design components that are free from safety hazards;
- ways of preventing loss of pressurization, explosions, fires, accumulation of toxic substances, and electric shock, and means of protecting crewmembers if such hazards occur;
- ways of ensuring the safety of powered portions of the flight (injection into orbit, maneuvering, docking, descent, and landing) and the safety of crew egress from the descent module;
- backup for all systems for which failure could lead to emergency situations;
- ability to make repairs during flight;
- availability of emergency supplies and consumable items; and
- compliance with physiological, hygienic, and ergonomic standards related to crew living and working conditions, and ways of monitoring those conditions so as to support the health and performance of crewmembers in space.

Protecting the spacecraft from adverse effects of the environment requires designs and procedures with which to provide protection from lightning, adverse meteorological conditions, ionizing radiation, ultraviolet radiation, and micrometeorites.

Safety requirements regarding crew performance aboard spacecraft stipulate that crews must be able to perform operations like monitoring, maintaining, and controlling onboard systems according to flight documents, work and rest schedules, and current conditions. Crewmembers must interact closely with each other and with ground-control personnel. The most important requirements provide redundancy for major functions of both the crew and ground personnel, interchangeability of crewmembers, and functional backup for onboard operations. Requirements for informational support of crew tasks stipulate that the performance of onboard systems, occurrence of emergency situations, and deviations of flight data from stipulated variables must be monitored by the crew (using information displays and emergency warning systems) and, to the extent possible, should be confirmed by ground control personnel. Crew actions in emergencies must accord with onboard documentation.

Types of safety equipment required on spacecraft intended for human use is described in Chapter 13; in brief, this equipment includes:

- an emergency escape system for use at the launch site and during powered portions of the flight;
- devices to protect individual crewmembers or crews as a group from depressurization, fire, radiation, and other risks associated with emergency situations;
- equipment for making repairs on board (spare parts and tools);
- signals and survival equipment for descent modules, in case those modules land in uninhabited or remote areas; and
- a rescue spacecraft for emergency use.

Requirements associated with supporting crew health must:

- ensure that each crewmember's initial condition conforms to appropriate health standards through preflight medical measures (e.g., examinations, prophylactic treatments, and observations);
- ensure that the living environment and working conditions meet hygienic, psychological, and ergonomic standards;
- provide means of monitoring crew health and living conditions in flight;
- provide preventive measures and interventions as needed to improve the living and working environment of the crew; and
- provide search-and-rescue, therapeutic, and rehabilitative measures after return.

Requirements associated with the selection and training of space crewmembers are discussed in detail in Chapters 1 and 2 of this volume. Briefly, guidelines in these processes can be classified as medical, psychological, or professional. All are directed toward ensuring that crew health meets medical standards; that psychological compatibility is fostered; and that crewmembers attain adaptive capacities and master the skills associated with being a cosmonaut. The latter skills include those needed during emergencies and other extreme situations, and those needed to interact effectively with fellow crewmember(s) crew and with ground-control staff.

II. Methods of Analyzing Flight Safety

Of the many available methods with which to analyze flight safety, logical probability is used most widely to analyze flowcharts of spacecraft function,[1] failure trees,[9] diagrams of structural reliability,[3] simulation models,[4] flow diagrams of system function,[12] and area classifications.[11] Descriptions of these methods constitute the remainder of Section II.

A. Logical Probability

Use of this method involves deriving a logical function to represent conditions under which a space flight either can be continued safely or must be aborted. Assumptions made to allow the use of this method include the following: that failures occur instantaneously; that failures of different systems are independent; that the structure of the object remains constant within the bounds of the design interval; that the onboard systems operate constantly; and finally that the moment of failure of all onboard systems can be reduced to a single time within the bounds of the design interval.

The sequence of operations used in this analytical method is as follows. First, the entire system (spacecraft and equipment, humans, environment) is divided into components of independent significance (e.g., functional systems, crew, ground control personnel, and environmental conditions). Second, the flight of the spacecraft is divided into stages (prelaunch preparations, injection into orbit, orbital flight, and descent and landing) (see Fig. 1), which in turn are divided into substages (e.g., injection into orbit includes first, second, and third booster substages). Next, the elements of the entire system are linked with the processes of spacecraft functioning for each flight stage and substage. The purpose of this exercise, i.e., dividing spacecraft functioning into stages and substages, is to allow the assumption that each has constancy in structure, mode of operation, and principles governing changes in the major variables of the whole system being considered, as well to consider the possible states of its elements, the relations and interactions among those elements, and the outcomes.

The next step involves analyzing possible emergency situations at each flight stage or substage associated with the system-component functioning, and developing methods of dealing with these emergencies. These emergency events are identified and labeled as resulting in either successful (event S) or failure (event F) outcomes. Specific outcomes from S or F events include the following:

- S_1 refers to the state of the spacecraft after some failure that does not impair the operation of a vital system; examples would be failures in individual communications channels or in an electrical component in the switchboard of the telemetric system.

- S_2 describes the state of the spacecraft when some failure leads to impaired functioning of a vital system, but does not require immediate measures or emergency landing; an example would be problems in the thermoregulatory system.

- F_1 indicates a spacecraft state that requires either immediate measures to eliminate a dangerous situation or terminating the flight; examples would be depressurization of the inhabited modules, failure of the water supply system, or some acute illness or serious injury that could not be treated effectively during flight.

- F_2 refers to a catastrophic state aboard the spacecraft that occurs as a result of sharply impaired operation of a vital system with possible fatal outcome for the crew; an example would be failure of the air regeneration system.

The final step in the logical-probability analytical method is to use the identified flight stages and substages and the distribution of hypothesized events among them to derive a diagram depicting the chance of success or failure of the spacecraft during flight (cf. Figs. 1 and 2). The probability of occurrence for various events linked to the different flight stages, and with the projected time and sequence of their occurrence are used to compute the likelihood of different flight outcomes.

If events S_1 and S_2 are independent, then the following formula can be used to evaluate the occurrence of event S during flight stage i:

$$P(S_i) = P(S_{i2} \Delta S_{i2}) = P(S_{i1}) + P(S_{i2})$$

where Δ is the sign of disjunction (logical addition).

However, the probability of an event occurring at the i^{th} stage depends on previous occurrences and on the successful completion of previous flight stages. Thus, in the first (prelaunch preparation) stage, i.e., when $i = 1$,

$$P(S)_{1j} = P(S_{11}) + P(S_{12})$$

where $j = 1, 2$ (events S_1, S_2).

During the second flight stage (injection into orbit), three outcomes are possible: (a) successful completion of the second stage given the successful completion of the first stage (event S_{21}); (b) lack of completion of the second stage due to emergency completion of the first stage (S_{12}); or (a) an emergency flight abort during the second stage after successful completion of the first (event S_{22}). Thus, the probability event S occurring can be derived as a logical sum:

$$P(S) = P(a) + P(b) + P(c)$$

where $P(a) = P(S_{21} \wedge S_{11}) = P(S_{11}) \infty P(S_{21} / S_{11})$; $P(b) = P(S_{12})$; and $P(c) = P(S_{22} \wedge S_{11}) = P(S_{11}) \infty P(S_{22} / S_{11})$, and $\wedge$ is the sign of conjunction (logical multiplication).

In summary,

$$P(S) = P(S_{11})\, P(S_{21} / S_{11}) + P(S_{12}) + P(S_{11})\, P(S_{22} / S_{11})$$

Next, the formulae can be written for the conditional probabilities of events S_1 and S_2 associated with all four flight stages (1, prelaunch preparations; 2, injection into orbit; 3, orbital flight; and 4, descent and landing). With respect to these stages, 5 final “S” states are possible (I–V) (see Fig. 1), the probabilities of occurrence of which are equal to:

$$P(S_I) = P(S_{41} \wedge S_{31} \wedge S_{21} \wedge S_{11})$$
$$= P(S_{11}) \infty P(S_{21} / S_{11}) \infty P(S_{31} / S_{21} \wedge S_{11}) \infty P(S_{41} / S_{31} \wedge S_{21} \wedge S_{11})$$

$$P(S_{II}) = P(S_{12})$$

$$P(S_{III}) = P(S_{11}) \infty P(S_{22} / S_{11})$$

$$P(S_{IV}) = P(S_{21} \wedge S_{11}) \infty P(S_{32} / S_{21} \wedge S_{11})$$

$$P(S_V) = P(S_{31} \wedge S_{21} \wedge S_{11}) \infty P(S_{42} / S_{31} \wedge S_{21} \wedge S_{11})$$

The probability of events S_1 and S_2 occurring at all stages of flight is determined on the basis of the probability of the final state S_I, S_{II}, S_{III}, S_{IV}, and S_V:

$$P(S) = [P(S_{11}) \infty P(S_{21} / S_{11}) \infty P(S_{31} / S_{21} \wedge S_{11}) \infty P(S_{41} / S_{31} \wedge S_{21} \wedge S_{11})] + P(S_{12}) + [P(S_{11}) \infty P(S_{22} / S_{11})] + [P(S_{21} \wedge S_{11}) \infty P(S_{32} / S_{21} \wedge S_{11})] + [P(S_{31} \wedge S_{21} \wedge S_{11}) \infty P(S_{42} / S_{31} \wedge S_{21} \wedge S_{11})]$$

The probability of catastrophic-failure (type F) events occurring in each flight stage can be analyzed analogously. Because type S events and type F events are independent,

$$P(S) + P(F) = 1 \qquad (1)$$

Because type F events are abortive (i.e., their occurrence leads to the end of a flight), the formula for the probability of occurrence of event F for various flight stages is written in the form:

$$P(F) = P(F_{i=1}) + P(F_{i=2} / S_{11}) + P(F_{i=3} / S_{21} \wedge S_{11}) + P(F_{i=4} / S_{31} \wedge S_{21} \wedge S_{11}) \qquad (2)$$

As alluded to above in the definitions of S and F events, group F_1 events (symbolized by F_{i1}) are assumed to occur during a normal routine flight, and F_2 events (symbolized by F_{i2}) during emergencies (see also Fig. 2).

A formula from probability theory is used to evaluate the probability of a combination of events occurring:

$$P(F_i) = P(F_{i1}) + P(F_{i2}) \pm P(F_{i1} \wedge F_{i2}) \qquad (3)$$

Substituting Eq. (3) for Eq. (2) generates an expanded formula that can be used to evaluate catastrophic consequences during the four stages of flight:

$$P(F) = P(F_{11}) + P(F_{12}) \pm P(F_{11} \wedge F_{12}) + P(F_{21} / S_{11}) + P(F_{22} / S_{11}) \pm P[(F_{21} \wedge F_{22}) / S_{11}] + P[F_{31} / (S_{21} \wedge S_{11})] + P(F_{32} / S_{21} \wedge S_{11}) \pm P[(F_{31} \wedge F_{32}) / (S_{21} \wedge S_{11})] + P[F_{41} / (S_{31} \wedge S_{21} \wedge S_{11})] + P[(F_{42} / (S_{31} \wedge S_{21} \wedge S_{11})] \pm P[(F_{41} \wedge F_{42}) / (S_{31} \wedge S_{21} \wedge S_{11})].$$

Using Eq. (1), the probabilities for the first stage of flight (i=1, prelaunch preparations) are:

$$P(S_{11}) + P(S_{12}) + P(F_{11}) + P(F_{21}) = 1$$

and for the second stage of flight (i=2, launch and orbital insertion):

$$P(S_{21} / S_{11}) + P(S_{22} / S_{11}) + P(F_{21} / S_{11}) + P(F_{22} / S_{11}) \pm P[(F_{21} \wedge F_{22}) / S_{11}] = 1$$

and for the third stage of flight (i=3, orbital flight):

$$P[S_{31} / (S_{21} \wedge S_{11})] + P[S_{32} / (S_{21} \wedge S_{11})] + P[F_{31} / (S_{21} \wedge S_{11})] + P[F_{32} / (S_{21} \wedge S_{11})] \pm P[(F_{31} \wedge F_{32}) / (S_{21} \wedge S_{11})] = 1$$

and for the fourth stage of flight (i=4, descent and landing):

$$P[S_{41} / (S_{31} \wedge S_{21} \wedge S_{11})] + P[S_{32} / (S_{31} \wedge S_{21} \wedge S_{11})] + P[F_{41} / (S_{31} \wedge S_{21} \wedge S_{11})] + P[F_{42} / (S_{31} \wedge S_{21} \wedge S_{11})] \pm P[(F_{41} \wedge F_{42}) / (S_{31} \wedge S_{21} \wedge S_{11})] = 1$$

Analogous expressions can be used for larger numbers of flight stages.

Calculations of outcome probabilities associated with flight stages and substages can be used to construct new methods of eliminating contingency situations (including emergencies) and new diagrams describing the success and failure of the spacecraft during flight; to compute new probabilities for the different outcomes; and to select ways for dealing with contingency situations that cost the least while conferring the greatest benefit.

B. Failure Trees

As a rule, the "failure tree" method is used to analyze the probability of failure of individual spacecraft systems and contingency situations that affect flight safety. Construction of a "failure tree" involves using logic to establish cause-and-effect relationships between individual events and possible states of the system. To some extent, the construction process is heuristic, and requires an in-depth understanding of how the system functions and which major factors can negatively affect it. The failure-tree method involves the following steps.

Each specific type of system failure treated as a complex event (called a head event) is broken down into simpler events that may induce this type of failure (cause). For example, failure of the manipulator arm located in the Space Shuttle payload bay and controlled remotely from the crew cabin is treated as a head event that can be broken down into simpler events that represent causes of the failure. Events such as these can include structural deformations of the manipulator or malfunction of its components, e.g., depressurization of the hydraulic drive, jamming or destruction of its mechanical components, short circuits in the power lines to the pumps and electric valves, faults in the onboard computer, "bugs" in software programs, or false signals. Each of these "simple" events can be selected for further analysis and treated as a head event. For example, faults in the onboard computer can be attributed to the occurrence of other simpler events, such as failure of control devices, arithmetic units, input/output devices or interfaces with the controlled object, long-term or working memory, or power source.

Relationships between head events and their causes are established by using logical operators of the “and” and “or” types, after which certain causes for the occurrence of the head event are selected for more detailed study. As noted earlier, each cause is treated as a head event for the purpose of further analysis. The events considered and the relationships among them are represented by a “tree” system to graphically represent the events and the logical operators and relationships relating them. The entire process is repeated until all events that need to be analyzed in detail are considered, and only elementary (initial) events remain. Thus, analysis is complete when one of three conditions is met: (a) when an event needs no further analysis because all of the necessary information is available, e.g., when the cause of a computer failure has been established unambiguously; (b) when an event proves to have an insignificant effect on the analyzed head event, e.g., when a manipulator failure was caused by a random misfire of the computer, with a recurrence probability of nearly zero; or (c) when no information is available on the event, e.g., the cause of false alarms cannot be established from existing information.

At this point, the “tree” is then analyzed qualitatively to identify dangerous vs not-dangerous failures of system elements, to determine significant values for monitored system variables, and to establish sets of dangerous vs. not-dangerous forms of system failure. Next. probability parameters are generated for the type of failure being considered. Formulas are used to link the probability parameters to the corresponding head event, with elemental events being treated as source data for computation. In general, these formulas take the form of sums of derivatives and derivatives of sums, and are derived by expressing the probability parameters of output events (outcomes) as a function of the probabilities of a sequence of input events related by logical operators, beginning with the event(s) most remote from the head event.

The following probability relationships are used to link output events with input events:

for “or” operators,

$$Q_0 = 1 \pm \prod_{i=1}^{m} (1 \pm Q_i)\,;$$

and for “and” operators,

$$Q_0 = \prod_{i=1}^{m} (Q_i)$$

where Q_o is the probability of occurrence of the output event of the operator; Q_i is the probability of occurrence of the input event of the operator; and m is the number of input events of the operator.

Modifications proposed to prevent or decrease the probability of failure are evaluated as follows:

- if a proposed modification changes the cause-and-effect linkage of the head event being considered, a new failure tree is constructed to correspond to the situation once that modification is implemented.
- if implementing a proposed modification changes only the probability parameters or the characteristics of some or all of the elemental events, then the probability parameters are modified in the original failure tree.
- new values for the probability parameters of the failure being considered are generated for each modification proposed.
- ways to eliminate or minimize the probability of occurrence of the failure under consideration are selected so as to produce the lowest cost/benefit ratio.

C. Reliability Diagrams

Reliability diagrams are used to determine possible modes of system failure that result from the state of that system’s components. This method is particularly effective for analyzing systems that fail only as a consequence of component failure, as well as systems in which failures associated with disrupted physicochemical and other processes are not relevant. One such system is that which controls the attitude and motion of crewed spacecraft.

Constructing and analyzing block diagrams takes place as follows. First, block diagrams of a system’s reliability are constructed for the various failure modes of its components. The effects of various modes of failures of individual components and groups of components on system function are considered in turn. Subsets of dangerous and not-dangerous failures are identified, as are ranges of values for specific modes of system failure. Then, the structural-reliability diagram is sequentially reduced to a combination of basic types of connections between components, and appropriate mathematical relationships are used to determine the probability parameters and characteristics of the system.

Analytical results are used to reduce the probability of system failures through identifiying ways of increasing system reliability, with new structural-reliability diagrams constructed as needed and new probability parameters and systems characteristics generated. Again, techniques are sought that increase reliability while producing the lowest cost/benefit ratio.

D. Simulation Models

The great advantage of using simulations to assess system safety is that they can be applied to the most complex systems and components, during nominal or a variety of contingency conditions. One example of such a system is the automaticall controlled regenerative life support system for a crewed spacecraft, which consists of functionally independent closed subsystems for air, water, and waste recycling. The disadavantages associated with use of simulation models are the difficulty in obtaining precise, statistically reliable results; lack of clarity in the relationship between final results and source data; and the need for large amounts of source data for the modeling process.

When this method is used, the analysis proceeds as follows. First, a model of the occurrence of contingency situations is constructed that simulates the following features:

- the nature and hypothesized frequency of failures, and the operating schedule of the spacecraft system and the entire spacecraft complex during flight;
- the crew composition, work schedules, probability of crew error while working with each spacecraft system, and probability of illness and its associated effect on spacecraft systems;
- the communication sessions scheduled between the spacecraft and Earth, and the probability of errors by ground-control personnel and their effects on specific spacecraft systems;
- the nature of environmental factors and their temporal effects on the spacecraft during flight, and probability of their causing failure in each spacecraft system; and
- the changes over time in predicted likelihoods of contingency situations during a given flight, the causes and sources of their occurrence, and the time required for these situations to develop (while accounting for interactions among these situations and the interdependence of all relevant adverse factors).

Next, a model of the process of coping with contingency situations is constructed to simulate the following:

- the spacecraft flight program;
- the ability of the spacecraft automated systems, the crew, and the ground-control center to recognize and detect contingency situations (accounting for communication sessions and work/rest schedules);
- the time needed to identify and detect contingency situations by each of the above “system components”;
- the ability and time needed for decision-making as to how to deal with the emergency by the crew and ground-control center (accounting for ability to interact via communications sessions);
- possible ways of dealing with contingency situations and the time needed for each; and
- the differences between general algorithms for crew and ground support control operations in dangerous and not-dangerous contingency situations, the potential overlap between contingency situations, the presence of time pressure, and the differences in significance of contingencies with respect to their potential danger to the crew.

Next, the data from the simulated contingency situation is input to a simulated process for dealing with that situation, and the operation of both models is synchronized. A module is developed to process data obtained from the operation of the two models, a module that accounts for the benefits associated with routine flight and the cost of contingency situations, and whether the situation has been dealt with successfully (including the time required for the situation to develop and the time required to deal with it), and temporary and stochastic aspects of space flight safety. Source data for the flight being considered are input into the model and the level of safety attained and a flight-efficiency value are evaluated.

At this point, the effects of various technical and procedural measures on the efficiency and safety of the flight are analyzed and the appropriate source data are input to the model. For example, if an automated system is adopted to identify contingency situations, or if communications sessions are made more efficient through the use of a relay satellite, then the likelihood and time needed to identify contingencies are changed in the model. The most effective measures are selected on the basis of efficiency, safety, and cost.

E. Flow Diagrams of System Functioning

This method is used to analyze spacecraft systems that have variable structures. One such system is the energy supply system, which modifies its structure when power demand varies, or reconfigures itself automatically when certain blocks of the spacecraft computer system fail.

The first step in using this analytical method is to construct a flow diagram of how the system functions. First, the nominal program of system functions is broken down into a sequence of nonoverlapping sections, so that when some elements of a section fail, the system shifts to a new structure. The nominal portion of the flow chart reflects the sequence of segments associated with this program. Each segment of the diagram shows all the components functioning or ready to function during the appropriate portion of the program in the sequence of their operation, as determined by the schedule.

Next, the non-nominal portion of the flow chart is constructed in the form of a set of branches for each component of the system at each segment of the nominal portion of the system. Each branch corresponds to a potential failure (associated with failure of that component in that section) for which the system can shift its structure to maintain nominal functioning of the program, and represents a sequence of segments for performing the remainder of the nominal program after the structure has been changed. When secondary failures of system components occur while the system is functioning in a non-nominal mode (i.e., in the non-nominal portion of the diagram) where further alterations of system structure are possible, additional branches are constructed from the segment of the non-nominal diagram until all possible routes for completing the nominal program, or all possible potential failures of the system, have been exhausted.

“Local” values are computed for the likelihood of system failures in various sections of the functional program. Formulas for computing these local values are derived from a diagram of system state in these sections. These values also can be computed in the same way as those for an analogous system with unchanged structure, given that the system is ready to function the moment the section begins. This kind of analysis can be used to assess the probability that the entire system fails, or the probability of failure-free function of the entire nominal sequence.

F. Area Classification

The technique of “area classification” involves defining operational hazards in terms of the potential for their being present in a particular area. In Earth-based petrochemical and allied industries, where the area classification technique is used frequently, the hazards typically take the form of combustible gases, vapors, or dust produced in the course of processing materials. The primary source of risk in closed environments such as spacecraft, by contrast, would be the life support system. With regard to life support systems, hazard categories in addition to those noted above might include explosive dusts; combustible, toxic or corrosive liquids or solids; mechanical damage; and radiation. Examples might include ignition of dust in ventilation ducts due to static charge; confined vapor-phase explosions; short-circuits in electrical equipment; gas leaks; charcoal combusting in trace-contaminant control units; experiment chemicals leaking or spilling; loss of cabin pressure from micrometeoroid impacts; and external radiation that can trip all onboard detectors.[11]

Area classification can be used as a basis for analyzing risks to crewmembers before launch and during various mission stages. Areas that could pose potential hazards, such as a module or a particular work station, would be identified, and specific recommendations provided to reduce the hazard in these areas. Such recommendations may include:

- increasing ventilation in areas where the amounts of a flammable gas could approach maximum acceptable concentrations;
- relocating equipment that could catch fire because of high surface temperatures or sparks;
- segregating ignitable sources from potential hazards by physical means;

- developing special fail-safe equipment that can function normally in potentially hazardous areas; and
- restricting or eliminating the use of flammable materials aboard crewed spacecraft.

Nevertheless, the use of regenerative life support systems, particularly on long, remote missions, will always carry some risk. One way of minimizing this risk would be to define “hazard zones” (e.g., flammability, toxicity, and breathability) for spacecraft. The first such zone, that or flammability or fire, would include areas around water electrolysis and CO_2 reduction units (hydrogen), trace-contaminant control units (carbon), and ventilation systems (dust). The second type of zone would encompass areas in which accumulated gases or liquids could pose a toxic hazard to crews. Laboratory areas would be included, as would those near waste-management subsystems. The third type of hazard zone involves areas where normal breathing air would be compromised, e.g., low-pressure storage areas, CO_2 “flood zones,” and perhaps plant growth units.

III. Criteria and Techniques for Safety Assessments

One of the most difficult tasks in ensuring the safety of space missions is to evaluate, both qualitatively and quantitatively, how well space missions can comply with safety requirements. Successful completion of this task is largely a matter of selecting the best criteria and methods with which to analyze mission safety. These factors ultimately determine the quality of the safety measures selected for use, the appropriateness of emergency supplies expended during flight, the objectivity of comparisons among different spacecraft system designs, and the overall efficacy of the mission safety program.

Mission safety must be evaluated at each phase in the life of the “crew–spacecraft–environment” system. During the development of technical proposals and the production of prototype designs, a set of safety methods and models typically are used to evaluate the project’s overall safety. Safety issues are dealt with at length at the stage of engineering design, when the structure, components, and features of the “crew–spacecraft–environment” system become more defined. During this stage, analysis is directed toward:

- evaluating the design and configuration of the entire space complex, as well as its systems and subsystems, to determine whether they meet safety requirements;
- allocating major functions between the crew and automatic systems for all portions of the mission;
- allocating suffient resources to ensure the reliability of onboard systems and enough contingency supplies and safety measures to maximize mission safety;
- assessing possible contingencies with respect to the risks associated with their potential consequences;
- assessing the course of contingencies in terms of measures to address them; and
- developing a safety program for the “crew–spacecraft–environment” system during final development and tests of the space complex (considering contingency modes and long-term operation of subsystems).

While the space station complex, spacecraft, and components are being tested, safety procedures include:

- optimizing and validating the selected safety devices and measures;
- analyzing test results and validating design estimates and features prescribed by safety requirements; and
- assessing the optimization of the space complex and the readiness of all project designs to be implemented.

Test results obtained during this stage are not particularly reliable, since the numbers and durations of tests are limited. Most safety evaluations are conducted during design verifications (i.e., with the crew on board) and during actual space flights. Integrating the schedules associated with safety with those for spacecraft development is critical, both for formulating safety requirements and for effectively monitoring compliance with those requirements.

Quantitative analysis of space missions is the natural continuation of qualitative analysis, and establishes the degree to which a project meets the mission safety requirements. These requirements often are represented by a quantitative criterion or set of criteria that reflect the most essential relationships and crucial variables of system function, as well as the constraints for the proposed mission safety program. These criteria must have clear meaning; must be determinative and consistent with the chief mission objective; must account for the chief fixed and stochastic factors that define the level of mission safety; and must reflect the scope of the use of safety measures within the safety program.

In general, criteria must account for essential aspects of the crewed spacecraft, such as configuration, mission program, sequence of operations and activation of individual systems, onboard supplies, and so on. The quantitative value of such criteria depend on the one hand on the major determinate design parameters of the crewed spacecraft, and on the other on the stochastic variables that reflect the reliability of the engineering systems, the human operator(s), and the effects of the space environment. In other words, because the criteria reflect both determinate and stochastic factors, they have a stochastic component. However, the use of stochastic criteria does not exclude the use of specific criteria expressed in terms of natural units of measurement.

We contend that addressing general safety problems requires a single generalized criterion, but addressing narrower problems requires several specific criteria that are components of a generalized criterion. From the concepts of generalized criteria used in operations research, reliability theory, feasibility analysis, and other disciplines, we propose the following classification scheme for these types of safety criteria:

- *general or integral criteria,* which allow the fullest evaluation of the "crewmember–spacecraft–environment" system overall (e.g., the total cost of creating a system with a given safety level);
- *conditional (indirect) criteria,* which reflect some feature of a system by comparing it with some ideal variable (e.g., average time of system operation per failure);
- *relative (standardized) criteria,* which compare one measure with another (e.g., the relative increase in efficiency associated with a certain safety measure); and
- *specific criteria,* which are used to assess constituents of an integrated criterion of system quality (e.g., a criterion for radiation safety).

The remainder of this section constitute examples of these types of criteria, and discussions of how they can be used to assess aspects of mission safety for crewed space flights.

One traditional criterion for mission safety is safe return of the crew (P_σ), which can be expressed as:

$$P_\sigma = P_s + P_e$$

where P_s is the probability of a successful mission program with a safe return and P_e is the probability of an emergency mission abort with a safe return. (Any space mission can have one of three independent outcomes—successful with safe return (s), abort with safe return (e), or abort with loss of life (ℓ); moreover, $P_s + P_e + P_\ell = 1$.)

The P_σ criterion (safe return of the crew) was used during the development of the Apollo spacecraft, and was applied to the entire mission program, starting with insertion into near-Earth orbit through landing of the descent vehicle on Earth. No provisions were made for premature abortion of the flight resulting from damage to the spacecraft by micrometeoroids, exposure to solar flares, or crew error. The mission safety specification for this particular project set the probability of safe return to Earth at 0.999.

In another paradigm, mission safety can be identified by the probability of not more than one failure (in not more than one spacecraft subsystem) occurring during the mission. This definition would preclude the occurrence of a failure while the flight is operating in emergency (contingency) mode, which of course would have resulted from a failure that occurred during nominal operation.

According to the criterion-classification scheme presented above, one example of a general (integral) criterion would be the expected number of [catastrophic] accidents during the lifetime of a crewed spacecraft, which can be estimated as:

$$\overline{N} = nP_\ell^{(1)}$$

where $P_\ell^{(1)}$ is the probability of abort with loss of life during a single mission, and n is the planned number of missions for spacecraft of this type.

Other criteria include the probability of a safe crew return as being part of the successful accomplishment of the program, and account for all the conditions that the crew could be exposed to, e.g., mission control error, failures of engineering systems, radiation, and micrometeoroid impacts. The associated probabilities can be calculated as:

$$P_\sigma = 1 \pm \sum_i \infty \sum_j \infty \sum_k (P_\ell)_{ijk}$$

where $(P_\ell)_{ijk}$ is the probability of an accident at an i^{th} mission phase due to a failure of a j^{th} onboard system or a k^{th} external effect such as a micrometeoroid impact. In this case, the primary failure that causes the spacecraft to fly an emergency-descent trajectory would determine the probability of an accident.

The second classification of safety criteria, conditional or indirect, includes variables that are directly or indirectly related to mission safety. For example, the probability that some number of crewed spacecraft will accomplish the mission program (P_s) is an indirect definition of mission safety risk, since P_s is one component of the probability of a successful crew return:

$$P_s = \prod_j P_j = \prod_i P_i$$

where P_j is the reliability of a j^{th} onboard system (i.e., the probability of fail-safe operation of that system during a routine mission) and P_i is the probability of fail-safe operation of the spacecraft during an i^{th} mission phase.

$P_\ell^{(1)}{}_{max}$ is a similar criterion that defines the highest probability of a catastrophic accident $(P_\ell)_{ijk}$ during one crewed spacecraft mission. Generally, the probability of an accident at an i^{th} mission phase is computed as an emergency $(P_e)_i$ at that phase, or as a failure of an onboard system or an adverse external effect Q_i:

$$P_\ell = (P_e)_i \infty Q_i$$

The third class of safety criteria (relative criteria) defines mission safety in terms of the availability and effectiveness of rescue aids on board the spacecraft. These criteria include measures such as the time during which crew survival or rescue (using onboard aids) is possible relative to the duration of the entire mission, and the percentage increase in mission safety that results from introduction of some safety system.

The fourth class of safety criteria (specific criteria) represent components of the general mission safety criterion, and include the probabilities of:

- safe launch and insertion into orbit;
- radiation safety (expressed as either not exceeding the maximum allowable dose or some expected in-flight dose);
- depressurization of living quarters, vessels, or thermoregulation coils caused by micrometeoroid impacts during flight; and
- catastrophic outcome at some point in the mission that would dictate safety limitations for certain spacecraft elements (e.g., the probability of a catastrophe during descent and landing, which would affect requirements for the descent vehicle).

General criteria are easily modified to account for various types of spacecraft modules that are launched separately and meet while in orbit. For example, if an orbital station is launched without a crew, and crews are delivered to it by several transport vehicles, two mission-safety criteria can be used. The first is the probability of safe return of all crews during the life of the station. The second is that of the safe return of a single crew, and includes safe launch of the transport craft, its safe flight to the station, and its safe descent and landing on Earth. The first criterion defines the overall safety of the rocket and spacecraft system and provides relative assessments of safety at various mission phases and with different systems used during the mission. (According to this criterion, the conditional probability of a safe return of the crew increases for the coming crews because of the potential for cancelling launches if the station malfunctions. In other words, even if a station were absolutely safe, safety would be maximal if transport flights were to be canceled.) The second criterion defines the anticipated hazards a single crew would face to accomplish the mission program. In this event, only the launch, insertion into orbit, docking, joint flight with the station, undocking, deorbiting, and landing phases of the crewed-transport vehicle mission are considered. If different crews spend the same amount of time on the station, if the transport vehicles are the same, and if the failure rate of space station systems is constant, then the safety levels for all crews would be identical.

In summary, integral (general) criteria are more effective for evaluating and comparing different missions and vehicle designs. Conditional and relative criteria are best suited for comparisons among different preliminary designs of crewed spacecraft, and specific criteria are best for analyzing space mission safety.

The considerations listed below can be used to represent results from qualitative and quantitative safety assessments. As discussed earlier in the section on logical probability, the safety of crewed spacecraft missions can be analyzed by flight stage, e.g., prelaunch preparations, launch, insertion into orbit, docking, joint flight with the station, undocking, descent, and landing in the designated area.

If events A_i ($i = 1, 2, 3, .. n$), which constitute the successful execution of each stage, are generally independent, then event A (defined by conjunction) corresponds to successful completion of the entire mission:

$$A = A_1 \wedge A_2 \wedge A_3 \wedge ... \wedge A_n \qquad (4)$$

Since different hardware is used at each mission stage, each event A_i can be expressed by a logical sum of events B_{ij}, indicating that each j^{th} set of main systems activated at the i^{th} mission phase is functioning well. At $i = 1, 2, ... m$,

$$A_i = B_{1i} \Delta B_{2i} \Delta B_{3i} \Delta ... \Delta B_{mi} \qquad (5)$$

where m is the number of possible combinations of systems operating at an i^{th} mission phase.

If each event B_{ji} appears as the occurrence of event G_{hji}, during which the crew-controlled system h in a j^{th} combination at an i^{th} mission phase operates properly, then when $h = 1, 2, ... k$

$$B_{ji} = G_{1ji} \wedge G_{2ji} \wedge ... \wedge G_{kji} \qquad (6)$$

where k is the number of crew-controlled systems in a j^{th} combination at an i^{th} mission phase.

Considering Eq. (4), (5), and (6) in terms of probabilities, Eq. (4) can be rewritten as:

$$P(A) = 1 \pm \prod_{i=1}^{n} \prod_{j=1}^{m} \prod_{h=1}^{k} P(\overline{G}_{hji}) \, P(SFA / \overline{G}_{hji}) \qquad (7)$$

where $P(\overline{G}_{hji})$ is the probability of failure for an h^{th} main crew-controlled system (for example, failure of the power supply system during experiments requiring both alternating and direct current) supporting an i^{th} mission phase in a j^{th} combination of systems; $P(SFA / \overline{G}_{hji})$ is the conditional probability of a space flight accident (SFA) due to the failure of an h^{th} main crew-controlled system such as the previously mentioned power supply system; and P(A) is the probability of ensuring crew safety throughout the whole mission.

Analysis of Eq. (7) suggests the following conclusions. First, since the reliability of current spacecraft technology and systems elements is far less than one, obtaining a probability value of one for P(A) is not possible. Second, since P(A) is less than one, additional systems and devices will be needed on board that can ensure crew safety (1 – P[A]). If the reliability of these additional systems is P(B), then crew safety can be expressed as:

$$P = 1 \pm [1 \pm P(A)] \infty [1 \pm P(B)] \qquad (8)$$

or alternatively, Q, which defines the risk probability for the crew:

$$Q = [1 \pm P(A)] \infty [1 \pm P(B)] \qquad (9)$$

Eq. (9) can be rewritten in terms of Eq. 7, with the relation for P(B) similar to that of P(A):

$$Q = [\, 1 \pm \prod_{i=1}^{n} \prod_{j=1}^{m} \prod_{\hbar=1}^{k} P(\bar{G}_{\hbar ji})\, P\,(SFA / \bar{G}_{\hbar ji})\,] \propto [\, 1 \pm \prod_{i=1}^{n} \prod_{\alpha=1}^{\mathcal{M}} \prod_{\beta=1}^{\mathcal{L}} P(\bar{G}_{\hbar ji})\, P\,(SFA / \bar{G}_{\beta\alpha i})\,] \qquad (10)$$

where α is a combination of auxiliary systems at an i^{th} mission stage; $\mathcal{M}$ is the number of possible combinations of auxiliary systems at the i^{th} stages; β is one of the auxiliary crew-controlled systems in combination α at an i^{th} mission stage; $\mathcal{L}$ is the number of auxiliary systems in combination α at an i^{th} mission stage; $P(\bar{G}_{\beta\alpha i})$ is the failure probability of a β^{th} auxiliary system in combination α, supporting the i^{th} mission stage; and $P\,(SFA / \bar{G}_{\beta\alpha i})$ is the conditional probability of the space flight accident due to the failure of a β^{th} crew-controlled system.

For each mission stage and combination of systems, one can identify μ units and systems that are likely to cause space flight accidents. For the purpose of this identification, we can use a quantitative assessment of the probability that a space flight accident will result from a failure of a given $\hbar^{th}$ (β^{th}) crew-controlled system:

$$P\,(\bar{G}_{\hbar} / SFA) = [\, P(\bar{G}_{\mu})\, P\,(SFA / \bar{G}_{\hbar})\,] / [\, \sum_{\hbar=1}^{\ell} P(\bar{G}_{\hbar})\, P\,(SFA / \bar{G}_{\hbar})\,] \qquad (11)$$

where $P(\bar{G}_{\hbar})$ is the failure probability of an $\hbar^{th}$ crew-controlled system; $P(SFA / \bar{G}_{\hbar})$ is the conditional probability of a space flight accident due to a failure of an $\hbar^{th}$ crew-controlled system; and $P(\bar{G}_{\hbar} / SFA) = \sum_{\hbar=1}^{\ell} P(\bar{G}_{\hbar})\, P(SFA / \bar{G}_{\hbar})$ is the total probability of a space flight accident for all possible failures for a given combination of crew-controlled systems. Here $P\,(\bar{G}_{\hbar})$ is determined by the reliability of an $\hbar^{th}$ crew-controlled system that can be calculated from statistical data on the rate of system failures and errors committed by the crew and ground control staff. $P(SFA / \bar{G}_{\hbar})$ is a function of the ability of the in-flight and ground-based staff to address contingencies; the ruggedness of the system and its ability to “localize” or contain emergencies; and warning systems that provide information on spacecraft systems, the external environment, and other factors.

Values of $P\,(SFA / \bar{G}_{\hbar})$ can be obtained through the use of statistical modeling or mockups. A “space flight accident” is understood to be an intolerable change in at least one hardware or environment variable (temperature, pressure, CO_2 content, pressurization, velocity during rendezvous, and proximity operations), or errors committed by the crew or mission-control staff that can lead to an accident.

If the equation

$$\sum_{\hbar=1}^{\ell} P(\, \bar{G}_{\hbar} / SFA) = 1 \qquad (12)$$

holds true for all possible space flight accidents constituting a complete group of events, then Eq. (11) can be used to rank all systems according to their probability of failure (Fig. 3), and identify those that are more likely to lead to an accident at each stage of a mission.

Eq. (11) and (12) also can be used to plot various probability density functions. One example, shown in Fig. 4, illustrates the function ofspace flight accidents resulting from in-flight hardware failures, including those caused by external factors and by crew errors. Other contingency conditions that can lead to space flight accidents involve environmental changes that can cause failure of spacecraft systems and boosters as well as illness or death of space crews. In general, the number of factors that could lead to accidents can be very large for a set of systems. Fig. 5 illustrates the probability of a space flight accident as a function of emergency factors.

In order to assess safety, it is desirable to differentiate the conditional factors leading to accidents $\psi_{\mathcal{N}}$ by powers; as a function of probable consequence for the first power, $10^{-1} \leq P(SFA / \psi_{\mathcal{N}}) \leq 1$; for the second power, $10^{-2} \leq P(SFA / \psi_{\mathcal{N}}) \leq 10^{-1}$; and so on. After numbering and arranging these factors in the order of regression of $P(SFA / \psi_{\mathcal{N}})$, one can plot distribution diagrams of the conditional probabilities for space flight accidents as caused by all emergency factors (Fig. 6), by a subset of emergency factors, by some emergency situation on board crewed spacecraft, or by those emergency factors that define a specific outcome of an emergency situation.

An emergency situation that is caused by some emergency factor takes some time to develop; during that time, the magnitude of at least one variable reaches its maximum allowed value (for example, the lowest allowable atmospheric pressure in the crew quarters or the highest allowable radiation level). An emergency situation can be addressed by the crew if their response time (t_c) is less than the maximum allowable time (t_a). The crew's response time includes some delay while they assess the situation, reach a decision, and implement it.

Hence, the probability of counteracting the effects of an $\mathcal{N}^{th}$ emergency factor by the crew equals:

$P\ (t_{\psi\mathcal{N}} \leq t_{a\mathcal{N}}) = P\ (\Delta t_{\mathcal{N}} \geq 0)$, where $\Delta t_{\mathcal{N}} = t_{\mathcal{N}} - t_{n\mathcal{N}}$

With regard to safety, accidents are divided into those that require immediate action by the crew ($t_{\mathcal{N}} \cong 0$) and those that do not ($t_{\mathcal{N}} > 0$).

Finally, risks to spacecraft crews from emergency situations can be evaluated in terms of the ways in which those situations can be resolved. Some emergency situations can be addressed by the crew, e.g., through activation of rescue systems or making repairs; others are counteracted automatically without crew input. Some emergency situations can be linked to results from preflight tests of the spacecraft systems; the course of action in situations such as these usually is described in an onboard handbook. A fourth type of situation cannot be foreseen during spacecraft design and testing, but can be counteracted in flight. The fifth type of emergency situation cannot be predicted from the design or test phases, and cannot be counteracted. This type of classification has been incorporated into Russian mission safety-assurance programs for all mission stages. In combination with probability calculations such as those shown in Figs. 3–6, data such as these can be used to quantify the probability of risk to a particular crew on a particular mission.

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Table 1 Space flight safety glossary

Terms	Definitions
Safety risks	Probable situations that can occur in flight and result in deteriorated crew health, trauma, or loss of life
General safety criterion	Set of spacecraft features that allow counteractions to be taken against aggregate factors that lead to deteriorated crew health, trauma, or loss of life
Specific safety criterion	Spacecraft capability that allows it to counteract one of the factors that lead to deteriorated crew health, trauma, or loss of life
"Fail-safe" capability for onboard equipment	Safe operation of onboard equipment under specified flight circumstances during a specified period
Maintenance safety	Means of servicing spacecraft systems, apparatus, and devices so that crew health is not affected during maintenance and repair activities
Technological safety	Means of running a technological process (e.g., life support systems or experimental chemical reactors) safely while still maintaining prescribed parameters of that process during a specified time
Infectious diseases safety	Means by which space crews resist infectious and autoinfectious diseases
Toxicological safety	Means by which the spacecraft and their components resist the formation of toxic substances and harmful effects
Pressure safety	Means by which the spacecraft and their components respond to changes in atmospheric pressure and gas partial pressures that might affect the crew
Radiation safety	Means by which the spacecraft and their components resist the effects of radiation from natural and artificial sources
Psychological/ physiological safety	Means with which the crew withstands psychological and physiological disorders caused by undesirable flight conditions
Explosion safety	Means by which the spacecraft and its components prevent and withstand explosions
Fire safety	Means by which spacecraft and its components resist combustion, provide prompt fire detection, and safeguard the crew from possible burns and traumas
Thermal and humidity safety	Means by which the spacecraft and its components prevent or limit changes in temperature and humidity in habitable areas and in space suits
Microgravity safety	Means by which the crew, spacecraft, flight systems, and onboard aids counteract microgravity and acceleration effects
Micrometeorite safety	Means by which spacecraft and its components withstand micrometeorite impacts and protect the crew
Electrical safety	Means by which the spacecraft and its components protect the crew from possible electrical shocks
Safety measures	Legal, methodological, engineering, and operational measures and activities that ensure specific and general safety
Safety level	A quantitative and qualitative measure for spacecraft and its components that defines the safety of the craft and its crew during flight
Contingency situation	A unexpected condition of the spacecraft and its operating equipment that cannot be predicted from routine operations
Emergency	A condition of the spacecraft or its components that poses an immediate threat to crew health or life

Table 1 Space flight safety glossary, continued

Terms	Definitions
Safety aids	Aids that allow detection, warning, abolishment, and localization of emergencies for crews
Emergency abolishment	Abolishing the causes and effects of an emergency
Emergency localization	Eliminating an immediate threat to crew health and life without removing the underlying cause(s) of an emergency
Analysis of an emergency situation	Identifying the indications, causes, and possible outcomes of an emergency situation, and defining its temporal characteristics, probability of occurrence/recurrence, associated hazards, and possible ways of overcoming it
Emergency failure	Failure of spacecraft components that leads to an emergency situation during flight
Emergency error	An error in documentation with failure to act (or mistake) by the space crew or ground support staff that leads to an emergency situation during flight
Emergency change in the environment	A change in the state of the environment that affects the spacecraft or crew and leads to an emergency situation during flight
Emergency factor	A factor that can lead to death of crewmembers if special safety measures are not taken
Space flight accident	An accident that causes the spacecraft or space complex to enter a state marked by the presence of an emergency situation
Spacecraft damage	A space flight accident not involving injury or death of the crew in which restoration of spacecraft function is possible and economically feasible
Spacecraft emergency	A space flight accident not involving death of the crew in which restoration of spacecraft function is not possible or economically feasible
Spacecraft catastrophe	A space flight incident involving the death or loss of at least one crewmember
Crewmember loss	An event marked by the impossibility of establishing the whereabouts of a space crewmember
Crew survival capacity	Ability of a crew to survive, with the use of aids, under various adverse (extreme) climatic and geographic conditions from the time of landing or splashdown until first aid and evacuation can take place
Safety analysis	A set of measures designed to determine whether actual safety status meets prescribed safety requirements
Crew safety assurance	The process of planning and implementing engineering and medical measures to achieve, maintain, and monitor prescribed safety requirements during flight

Table 2 Health hazards for space crews

Physical and mechanical
- weightlessness
- electrical currents
- noise and vibration
- atmospheric composition
- atmospheric pressure
- ambient temperature
- radiation
- decompression
- G load, angular acceleration
- explosion, fire
- vapor, particulates, dust
- impact with surfaces or edges

Chemical
- toxins in food, air, water

Biological
- illness
- working and living conditions
- lack of food, water

Social and psychological
- impairments in biological rhythms
- psychological incompatibility
- emotional stress

Table 3 Maximum allowable safety risks for the European “Hermes Space Plane” [Ref. 10]

Safety risk	Frequency of the event	%
Minor	1	100
Maximal allowable	10^{-4}	0.01
Critical	10^{-5}	0.001
Catastrophic	10^{-6}	0.0001

Table 4 Risk of catastrophic (lethal) outcome for Earth-based activities relative to a 90-day space flight [Ref. 10]

Activity	*Equivalent risk* Event frequency	%
Work in industry	9×10^{-5}	0.009
Riding in a car	3×10^{-3}	297
Traveling by rail	9×10^{-4}	.0090
Civil aviation	1×10^{-4}	153
US Marine aviation (1982–1986)		
• Aircraft	6.6×10^{-2}	6.660
• Helicopters	1.6×10^{-1}	16.660
Space flights	9.9×10^{-4}	0.099

Figure Captions

Fig. 1 Diagram showing fluctuations in favorable flight conditions for crewed spacecraft. I, II, III, IV, and V, outcomes or final states; S, current (safe) state; i, flight stage; and T, time.

Fig. 2 Diagram showing fluctuations in undesirable flight conditions for crewed spacecraft. i, flight stage; S, current (safe) state; F, failure/contingency state (see text); T, time. Curve labels: 1, hazardous situation; 2, flight continuation; 3, emergency descent; 4, scheduled descent; 5, safe landing; 6, catastrophe.

Fig. 3 Classification of crew-controlled space flight systems as a function of their failure risk. $P(SFA / \bar{G}_{h})$, conditional probability of flight event G in the event of failure of system h controlled by the crew; ℓ, number of crew-controlled systems.

Fig. 4 Probability density functions of causes underlying flight accidents for system h as a function of $\mathcal{N}$ emergency factors. $P(\bar{G}_{h} / SFA)$, probability of flight event G occurring because of failure of crew-controlled system h; $\sum_{h=1}^{\ell} P(\bar{G}_{h} / SFA)$, integrated probability of flight event in the event of failure of n systems (n=1, 2, ... ℓ) or crew mistakes equivalent in their consequences to these failures.

Fig. 5 Classification of emergency factors as a function of hazard to the crew. P(SFA), probability of a flight event; N, code number of emergency factor.

Fig. 6 Distribution of conditional probabilities for all emergency factors related to the spacecraft environmental control system. $P(SFA/\psi_{\mathcal{N}})$, conditional probability of flight event in the event of emergency factor $\psi_{\mathcal{N}}$; N, code number of emergency factor. Stage I, $10^{-1} \leq P(SFA / \psi_{\mathcal{N}}) \leq 1$; Stage II, $10^{-2} \leq P(SFA / \psi_{\mathcal{N}}) \leq 10^{-1}$; Stage III, $10^{-3} \leq P(SFA / \psi_{\mathcal{N}}) \leq 10^{-2}$ (see text for explanation).

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Chapter 13

Emergency Escape and Rescue

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As humans have ventured further from their terrestrial surroundings to explore the seas and the air, means of escape and rescue from specialized craft have evolved apace. From the first use of a shipboard lifeboat to the present-day aircraft ejection seats, escape systems have advanced with developing technology and experience. High-performance aircraft have prompted the development of elaborate, high-technology escape systems that have proven effective in preserving the lives of pilots and crewmembers in otherwise unsurvivable events. Human space flight has presented a particular challenge through the addition of new elements of environmental extremes, remoteness, and inaccessibility. Nevertheless, the basic premise endures—that exploration is a uniquely human adventure, and the value of a human crew cannot be justly calculated. This premise, along with the high visibility and formidable commitment of the human space program, calls for careful consideration of escape-and-rescue procedures and systems.

More than any other exploration effort, space flight encompasses several diverse phases and environments, each associated with unique perils. The ground phase involves the risks of explosion, fire, and toxic release, among others, during both simulations and prelaunch procedures. During the launch and ascent phase, added hazards include systems failures that could prompt mission abort and extremes of dynamic pressure and temperature. Once an orbit, or a translunar or transplanetary trajectory, has been established, the risks of radiation, orbital debris or micrometeoroid impact, failure of the life support system, and crewmember illness or injury may necessitate spacecraft evacuation or early return. During descent and reentry, a crew that has been physiologically deconditioned by space flight faces temperature extremes, sustained acceleration forces, and spacecraft impact. The postlanding environment may vary from a well-trafficked runway to a sea splashdown to a wilderness-survival situation. Mishaps have occurred in all of these phases of crewed space flights to date, resulting in early returns, injuries, and fatalities. With ambitious new programs underway (the U.S.-Russian Shuttle-Mir Program) or in the planning stages (the International Space Station and other advanced space exploration efforts), the duration and frequency of exposures to these hazards will increase.

This chapter summarizes the historical aspects of the development of emergency systems and the mishaps that have occurred in crewed space flight; outlines the rationale for escape systems and discusses the types of hazards and events that might prompt escape procedures; discusses escape and rescue from low Earth orbit (LEO), emphasizing the Space Shuttle Program and the planned International Space Station; reviews the international considerations of space rescue; and briefly considers lunar and planetary escape-and-rescue scenarios.

I. Historical Aspects

A. Development of Launch-and-Entry Escape Systems

The early history of the development of spacecraft escape systems is characterized by the adaptation of aircraft safety technology. During the risky launch-and-ascent phase, when the major concern is fire and explosion, the philosophy is to remove the pilot or crewmember quickly from the proximity of the mishap. For any prelaunch event, this has to be a “zero-zero” system, that is, one that will remove the crew from a vehicle with zero-horizontal and zero-vertical velocity. For the single-occupant Mercury program, this was accomplished with an escape rocket mounted atop the capsule (Fig. 1). This solid-rocket motor, which could be activated manually by the astronaut during a launch or prelaunch emergency, provided 250 kN of thrust to blast the capsule free of the Atlas or Redstone booster and attain an altitude safe for parachute deployment and descent.[1] The escape-rocket ascent profile involved acceleration forces on the pilot of up to 20 +Gx,[2] which could be tolerated in terms of risk of injury but does not allow any control input by the crew. Thus, the process was fully automated once activated. The escape rocket was jettisoned from the spacecraft shortly after a nominal launch.

Vostok, the first spacecraft to carry a human into orbit, and the two-person Gemini spacecraft incorporated pyrotechnic ejection seats into the crew capsules. These seats could be used from the zero-zero conditions of before launch to the 7000 to 8000 m level of ascent phase for Vostok[3] and the 18,300 m level of ascent for Gemini.[2] To accommodate physiologic needs at this altitude, Gemini seats incorporated a source of positive-pressure oxygen, and crewmembers of both spacecraft wore pressure suits. The ejection seats also served as a backup landing system in the event of parachute failure or landing over land.

With the Apollo and Soyuz programs, ejection seats gave way to a top-mounted solid-rocket escape system. Ejection seats for three crewmembers, with supporting pyrotechnics and hatch modifications, would have added considerable weight to the capsule. Further, a ground explosion of the magnitude that would have been generated by the massive Saturn-V booster could not have been escaped by the state-of-the-art ejection systems of that time. Acceleration forces for the aborted reentry profile of the Apollo escape rocket were reduced from that of the Mercury program to a maximum of 16.2 +Gx.[4] To date, neither escape rockets nor ejection seats have had to be used for contingency vehicle egress in the U.S. space program. However, their efficacy was verified in 1983 during the pre-ignition launch-pad fire of the Soyuz T-10A. Seconds before a massive explosion destroyed the booster and pad, cosmonauts V. Titov and G. Strekalov were separated from the vehicle via their escape-rocket system. The crew landed several kilometers away and suffered only minimal injuries.

The U.S. Space Shuttle, which made its first flight on April 12, 1981, and Russia's Buran shuttle represent departures from the traditional vertical-stack configuration of boosters and crew compartments. Rather than being a separate module in a "high-ground" position amenable to an escape-rocket system, the crew cabin is part of a much larger spacecraft near the projected center of a vehicle fire and explosion. An escape rocket capable of pulling the entire orbiter free of a launch-pad explosion would be much larger than practical. Independent crew capsules that can be separated from the orbiter and ejected, such as the FB-111, were considered for the Space Shuttle Program. However, they were deemed too large and complex, and would have reduced the maximum allowed weight of orbital payloads by 9090 kg.[1] The early Shuttle missions thus relied on ejection systems.

During the first four Shuttle flights, known as the orbital flight test (OFT) missions, only a commander and pilot were on board. Modified SR-71 ejection seats provided emergency escape from the launch pad to an ascent altitude of 24,400–30,500 m, limited by the spin stability of the person-plus-seat combination. The seats were set on rails on the flight deck, at a slight angle from the vertical, because of their size and shape. Concern was expressed over the theoretical possibility that this position would produce adverse yaw forces on the ejecting crewmembers; acceleration forces could exceed acceptable Gy limits, which in turn could preclude safe ejection. Analyses of the ascent profile revealed an area of concern between 3000 and 9100 m, where plume heating from the main engines might exceed survival limits for the suited crewmembers. In addition, aerodynamic heating limits ejection velocities to Mach 2.5 to 3.0 because of the sensitivity of synthetic materials used in the suit and the possibility of heat injuries.[3] Thus, although ejection theoretically was possible up to 30,500 m, crew survival was questionable.

Although the Buran shuttle has yet to fly a crewed orbital mission, its escape system warrants comment. The escape approach is based on the sophisticated, highly capable K-36RB ejection seat. This seat accommodates crew escape from zero-zero prelaunch conditions to ascent and descent altitudes of 30,000 m and velocities up to Mach 3.[3] Complex subsystems allow multiaxial trajectory to be controlled within tolerable limits. The K-36RB has been tested successfully from high-performance aircraft platforms.

Ejection seats were removed from the Space Shuttle Program on the fifth U.S. Shuttle mission (STS-5, launched November 10, 1982). The STS-5 mission carried a crew of four; shortly thereafter, Space Shuttle crew sizes averaged 5 to 7 members. Accommodating the simultaneous ejection of such large crews called for extremely complex seat and hatch designs. Thus, no escape system was available for the crew during flight; only emergency ground egress was possible until modifications resulting from the *Challenger* accident were implemented.

During the four OFT flights, Shuttle crewmembers wore full SR-71 pressure suits that could be pressurized to 24.1 kPa. These suits were intended to protect crewmembers against loss of cabin pressure, thermal heating, and freezing temperatures that might be experienced during a free-fall descent. In the event of a bail-out over water, the suits also would provide some thermal protection during water immersion. After STS-4, pressure suits were replaced with regular flight suits and a launch-and-entry helmet, which had a face seal that provided a positive flow of 100% oxygen when activated. This suit also was replaced after the *Challenger* accident.

Several launch-abort profiles have been developed for the orbiter after burnout and separation from the solid-rocket booster (Fig. 2). The use of a given option is decided primarily by the time of failure in the flight sequence. For example, in the event of main engine failure within the first 4 min 20 s of flight, a return to launch site (RTLS) abort is implemented. The orbiter and attached external tank continue downrange under the power of the remaining main engines, orbital-maneuvering system engines, and aft-maneuvering rockets. A change in pitch of 5°/s orients the orbiter back toward the launch site at an altitude of 122,000 m. The external tank separates after the propellants have been exhausted (about 600 km downrange), and the orbiter glides back to the launch site. The RTLS scenario cannot be attained if a failure takes place from 5 min 46 s to 7 min 7 s of flight; during this period, the transoceanic-abort landing (TAL) option is used. TAL sites consist of contingency-landing facilities in Europe and North Africa equipped with emergency services and hardware. Selection of a particular TAL site depends on launch azimuth and ascent profile; possible sites include Zaragoza and Moron, Spain; Ben Guerir, Morocco; and Banjul, The Gambia.

After 7 min 7 s of flight time, the “abort once-around” mode becomes an option. Upon failure of one or two main engines, all remaining engines are used to attain an altitude and speed that can maintain suborbital flight to deliver the orbiter to Edwards Air Force Base, California or White Sands Space Harbor, New Mexico. The final option, available for failure of the main engine after 7 min 18 s, is to abort to orbit. Firing the remaining engines produces a stable—albeit lower than nominal—orbit, which affords time to effect alternate mission plans and a more leisurely deorbit. An abort-to-orbit took place during the launch of STS-51F in 1985 when a main engine shut down because of dual transducer failures. An orbit lower than planned was achieved, but a productive mission was completed.

After a contingency landing, the crew leaves the vehicle through the middeck crew-entry hatch. Should this route be inaccessible or unusable, the left-overhead flight-deck window can be removed to allow egress from the top of the orbiter. This option requires the crew to use thermal blankets to protect themselves from the orbiter’s high skin temperatures and to lower themselves with a rope.

Throughout the history of human space flight, the possibility has been recognized that a spacecraft crew could be returned during a contingency essentially anywhere within the latitudes of its orbital inclination. From the outset, Russian and U.S. space crews have undergone extensive land-and-water survival training before flight. Returning spacecraft are equipped with such survival aids as food and water rations, protective exposure and flotation garments, and signaling devices. The Shuttle vehicle carries survival equipment designed to sustain a crew of 7 for 48 hours. In addition, emergency medical service teams and search-and-rescue forces are made available for launches and landings, either as activated units or on “alert” status. Crew recovery times generally have ranged from several minutes to several hours in both the U.S. and Russian space programs, but have rarely exceeded 24 hours.

B. Experience With Spacecraft Mishaps

Hazards, both known and unknown, have been inherent in the preliminary steps of human space flight. Identifying such hazards and creating highly reliable protective systems has been the goal of both the Russian and U.S. space programs. However, the small incidence of system failures and mishaps that has occurred is an expected consequence of space flight. With each incident, corrective actions were taken to prevent recurrence. Table 1 summarizes some of the major mishaps in Russian and U.S. space flight history, particularly those that implied a direct risk or those with an adverse outcome on crew safety. Three of the incidents, the Apollo-13, Soyuz T-10A, and *Challenger,* represent different phases of the mission sequence and are discussed below.

1. Apollo-13

Apollo-13 was launched on April 11, 1970, and was to have been the third human landing on the moon. All proceeded as planned until 56 hours into the flight, when 300,000 km from Earth an oxygen tank in the service module (SM) exploded.[5] This explosion apparently had been caused by a failed electrical circuit that led to increases in temperature and pressure within the tank. The resultant loss of oxygen to generate electrical power and to breathe in the service and command modules created an emergency situation. Apollo-13 was committed to its trajectory, with the earliest possible return to Earth some 90 hours away. Fortunately, the crew was not injured during the explosion, and the lunar module’s systems were undamaged. The command module was “powered down” to conserve resources, and the crew transferred to the lunar module. The latter was designed to provide an environmental control and life support system (ECLSS) for two crewmembers; as a “lifeboat” for three, its resources were adequate for less than 40 hours.[2] Through the efforts of the crew and ground-support teams, contingency plans were quickly formulated and applied. Fundamental to this effort was the redundancy of the ECLSS between modules. The lunar-module systems were inadequate to remove metabolically produced carbon dioxide (CO_2) from the breathable atmosphere. However, with guidance from ground engineers, the crew was able to adapt lithium-hydroxide cells taken from the command modules for this task. With this approach, CO_2 partial pressures did not exceed 15 mm Hg. The cabin became uncomfortably cold, with temperatures ranging from 10 to 13°C (nominal is 24±2.8°C), and one crewmember developed a urinary-tract infection. However, the lunar module was jettisoned successfully 1 hour before reentry, and the crew of Apollo-13 splashed down safely 6 days after launch.

2. Soyuz T-10A

The Soyuz T-10A spacecraft was to have launched two cosmonauts from Baikonur to the Salyut-7 space station on September 26, 1983. Crewmembers had entered the vehicle and were ready for launch when at T-minus-90 seconds, a fuel spill flooded the pad at the base of the vehicle.[6] Sometime after T-minus-60 seconds, but before the engines started, the fuel spill caught fire. The Soyuz does not allow crew-initiated abort, and communication cables had already been damaged when ground controllers commanded an escape-tower abort. A backup radio-command system was activated, and the escape tower's solid-rocket motors were ignited approximately 20 seconds after the abort attempt. The crew module separated from the launch stack, which was engulfed in flames. Six seconds later, the booster and pad were consumed in a massive explosion.[7] During the 5-second firing of the escape tower's solid-rocket motors, the cosmonauts experienced acceleration forces between 10 and 17 +Gx[7,8] before the air brakes and smaller attitude-control engines could be deployed. The module separated from the escape tower, parachutes were deployed, and the crew module landed approximately 4 km downrange. The launch pad was completely destroyed. Both cosmonauts walked away from their unplanned landing site with only minor injuries. Without question, this event was a spectacularly successful launch-abort escape.

3. Challenger

The Apollo-13 and Soyuz T-10A missions serve as harsh reminders of the potential consequences of mishaps during space flight. At the same time, they demonstrate the adaptability of human crewmembers and their spacecraft in survival situations that might otherwise have ended badly. Lessons learned have provided valuable input to the design of ECLSS and emergency systems and the development of contingency procedures.

A less forgiving event was the January 28, 1986 *Challenger* accident, in which failure of the solid-rocket booster's joint seal led to destruction of the entire vehicle and loss of the crew 73 seconds into the flight. A panel of outside experts (only one member of which, Dr. Sally Ride, was employed by NASA) was assembled within a week of the event to investigate the accident and formulate recommendations. This group, headed by Secretary of State William P. Rogers, was known as the Rogers Commission.[9] NASA simultaneously assigned internal teams to review escape procedures and present their recommendations within 5 months. After extensive testimony from involved personnel, experts, and astronauts, the Commission concluded that escape from this particular type of incident was not possible with known emergency systems. Emphasis was placed on preflight safety procedures. Of the 9 recommendations proffered by the Rogers Commission, the seventh deals directly with crew escape: "In regard to launch abort and crew escape, every effort should be made to increase the range of conditions under which an emergency landing can be successfully made, and to provide a crew-escape system during controlled, gliding flight."[9] It became NASA's goal to meet this requirement and add other safety refinements to the Shuttle program.

Ejection-seat systems were reevaluated and again discarded because of complexities in accommodating several crewmembers. Escape solutions focused on manual escape from the orbiter during stable, gliding flight. Studies using wind tunnels demonstrated that crewmembers were likely to strike the leading edge of the orbiter's wing during manual egress at the slowest stable flight configuration (200 knots, 11° angle of attack). A mechanism was required to impart a downward velocity sufficient for the crew to clear the wing. Tractor rockets could provide the necessary clearance with acceptable acceleration loads on the crewmembers. However, because of their weight and the additional hazard of pyrotechnics in the crew cabin, tractor rockets were rejected in favor of a telescoping pole that would guide the crewmembers' egress. With this system, a bail-out profile would begin at about 12,200 m, when the orbiter cabin would begin equalizing pressure with the ambient atmosphere. Between 9150 and 6100 m, egress procedures would be begun by blowing the left-side hatch with pyrotechnic systems followed by sequential egress down the pole. Each crewmember would attach a lanyard to a sliding ring on the pole and roll forward out of the hatch. With the pole extending in a downward arc from the orbiter's left-side hatch, crewmembers would be routed beneath the wing (Fig. 3). Flight tests at the China Lake Naval Weapons Center with instrumented mannequins and Navy parachutists have demonstrated the feasibility of this system from a C-141 aircraft.

Parallel efforts produced a parachute to be integrated as the seat back, a personal life-raft integrated into the seat kit, and a partial-pressure suit known as the launch-and-entry suit (LES). The LES, pressurized to approximately 19.3 kPa, replaces the standard flight suit plus launch-and-entry helmet from earlier flights (Fig. 4). The LES provides some protection against rapid cabin decompression on ascent or descent; the risk of incapacitating decompression sickness during the 35 to 45 minutes required to accomplish a TAL abort is about 10% per crewmember. In the event of a bailout, the LES provides 100% oxygen from two high-pressure (12,400 to 15,160 kPa) bailout bottles to protect the wearer against hypoxia during descent or against fire and smoke after ground egress. The thermal insulating properties of the LES are designed to protect the wearer from hypothermia for 6 hours during water immersion or for 24 hours in the life-raft. Studies in 4°C water suggest that survival for these periods is a reasonable expectation in the LES/raft combination.[10] Cooling fans also are used to circulate ambient air to the suits to protect the crewmembers from thermal loads while they await launch.

A further safety enhancement is the addition of an inflatable slide (similar to those used by commercial airliners) to the left-side hatch of the orbiter for ground egress. This replaces the emergency side-hatch bar, which required crewmembers to drop 3.2 m to the ground.[11]

Escape capabilities during the prelaunch period also were upgraded after the *Challenger* accident. In the event of an emergency on the launch pad, the crew access arm can be repositioned in approximately 15 seconds. Five 3-person slide-wire baskets were added that allow the crew to escape to an underground bunker 375 m away, from which they can be transferred to another evacuation site by armored personnel carriers. Crewmembers or rescue personnel contaminated by toxic substances (such as propellants) are decontaminated at this site and delivered to a medical team for treatment or transferred to a medical care facility.

High-risk areas for emergency rescue during the launch phase have been identified as the launch site itself and the first 370 km (200 nautical miles) of the downrange ground track.[12] Launches from the Kennedy Space Center in Florida involve operations over water and are covered by refuelable search-and-rescue helicopters. Lower-risk areas are the TAL sites and within 50 nautical miles (93 km) of the planned end-of-mission sites. Areas requiring expanded search-and-rescue and medical capability are the three continental U.S. landing sites (Edwards Air Force Base, California; Kennedy Space Center, Florida; and White Sands Space Harbor, New Mexico) and the TAL sites. During the launch and ascent phases, resources are positioned at the launch site (Kennedy), the primary TAL site, and an abort once-around site. For landing, resources are positioned at the planned end-of-mission site.

C. Events Prompting Escape and Rescue Scenarios

Any cogent discussion of accidents, failures, injuries, and other events that could lead to an escape or rescue situation must combine past experience with a rational analysis of specific risks. Not all life- and spacecraft-threatening contingencies can be anticipated; however, with proper consideration, planning, and simulation, the most likely events can be reasonably prepared for. Table 2 lists the incidents most likely to be encountered, independent of the launch and landing phases, and emphasizes response time and medical implications. Any one of these incidents could lead to repair, selective evacuation, or abandonment of a space platform. Selected events are discussed in turn below.

1. Loss of Pressure

Depressurization of a spacecraft's habitable volume is most likely to result from a collision with orbital debris or a failed mechanical system. Response time and medical implications are dictated primarily by the rate at which pressure is lost, which is determined by the size of the breach; the initial module pressure and volume; and the ability of the environmental control system to compensate. From a physiological standpoint, threshold limits of atmospheric pressure and partial pressure of oxygen (ppO_2) must be established to formulate response plans. For a loss-of-pressure event during the early phase of the International Space Station, in which the nominal ambient pressure is 70.3 kPa at 28% O_2, the crew must don portable breathing apparatus and evacuate the station if the pressure drops below 52.4 kPa.[13] At this pressure in a 28% O_2 atmosphere, the ppO_2 is 14.7 kPa, which equates to an alveolar pO_2 (pAO_2) of approximately 47 mm Hg without the protective breathing device. Loss of pressure secondary to failures of systems or seals would be unlikely to result in rapid depressurization of a module. Depressurization is expected to be detected and annunciated by onboard alarm systems in time to allow corrective action or evacuation. However, collision with orbital debris or a meteoroid fragment may lead to a sudden catastrophic event.

Orbital debris from fragmenting satellites, spent upper stages, and other space vehicles pose a threat to both humans and equipment in LEO. The permanent presence of crews on space stations increases the possibility that a large impact may be life-threatening. Both U.S. and Russian spacecraft have collided with debris on orbit, which has induced micrometeoroid damage to solar arrays, pitted windows on the Shuttle and Salyut, and minor structural damage to Shuttle surfaces. In July 1983, the Soyuz T-9 crew aboard Salyut-7 began evacuation procedures afrer hearing a loud impact. Procedures were aborted when the module's pressure was verified as stable. A viewing window had sustained an impact resulting in a 3.8 mm-wide crater.[14]

Ground-based radar systems can detect and track objects as small as about 10 cm; as of 1987, more than 6000 such objects were identified, with a calculated mass of approximately 2,000,000 kg.[15] The estimated mass of natural meteoroids at altitudes below 2000 km is less than 250 kg. Evidently an object that is slightly smaller than the radar-detection threshold could induce considerable damage to a pressurized module at encounter velocities (near 10 km/s). The primary event could produce injuries from blast forces, burns and flash injuries from heat and explosive oxidation,[16] and trauma from projectiles. Secondary events may include module decompression, fire, and disruption of vital systems.

In the event of rapid decompression, successful rescue, whether by oneself or with the aid of another, will depend in large part on the time-of-useful consciousness, i.e., the interval between loss of pressure and loss of crewmember function. Time-of-useful consciousness is a measure of the time of effective physical and cognitive performance in which a crewmember might take corrective action like donning an oxygen source or transferring to a pressurized module. Table 3 shows times-of-useful consciousness associated with rapid decompression to varying final pressures, beginning from a sea-level-equivalent atmosphere.

The values shown in this table were calculated primarily for healthy air crews during studies in an altitude chamber, measuring the time until the crew was no longer able to don an oxygen mask or perform other functions relevant to the aviation environment. Presumably, an astronaut who is transferring to a different module and accessing emergency equipment during loss of pressure would have greater physical and cognitive requirements than a seated aviator. Physical exertion is known to reduce time-of-useful consciousness considerably.[17] Also, crewmembers' age and underlying physical condition will vary widely. Perhaps most importantly, the deconditioning expected with prolonged space flight could further influence time-of-useful consciousness. For example, an increase in cardiac output is a compensatory mechanism to enhance tissue oxygenation during hypoxic exposure. Cardiac stroke volume has been noted to decrease during prolonged space flight; however, the effect this might have on the hypoxic response has yet to be clarified.

Whatever the cause of pressure loss, contingency operations and supporting hardware must be activated easily by the crew. Portable oxygen supplies must be widely distributed, and the options to exit quickly into an adjacent module or isolate the damaged area must be available. The safe-haven concept, applicable to many types of contingencies, provides a free-standing pressurized volume equipped with a backup supply of consumable items and medical gear. Such a haven might be another module or docked spacecraft that could serve as a refuge while repairs are being completed (while crewmembers wear pressure suits) or while the crew awaits rescue. Ideally, a safe-haven module also would have a docking adapter to accommodate the rescue vehicle. Calculations generated for Space Station Freedom showed that crewmembers would need 106 seconds to transfer from the most distant pressurized module to the docked orbiter. For a drop in pressure from 70.3 kPa to 55 kPa, the hole causing the decompression could be no larger than 5.3 cm in diameter to allow egress within this time.[13]

2. Fire and Explosion

Only minor combustion events have occurred in spacecraft thus far, e.g., during Space Shuttle flights STS-6 (April 1983) and STS-28 (August 1989). In these cases, overloaded electrical circuits led to the smoldering and burning of a small amount of insulation. Major fires or explosions might result from pockets of oxygen enrichment in the habitable atmosphere; inadvertent release of volatile, flammable substances; or direct heating of combustible material. Preventive steps are taken to preclude these events, and automated or manual fire-suppression systems are integral to all spacecraft that house human crews. In formulating a response to onboard fire and explosion, two major medical implications must be kept in mind. First, the possibility of direct injuries (such as burns and blast trauma) requires the inclusion of medical equipment adequate for first-response care. Second, any combustion event should be regarded as able to produce smoke and other volatilized toxic substances (such as hydrogen cyanide and carbon monoxide). The medical capability in the primary spacecraft or rescue vehicle should include supplemental oxygen and respiratory equipment.

As is true for an explosive impact with debris, the first response should include exiting and isolating the module if possible. A safe haven may be needed while rescue is awaited. For a single-cabin spacecraft, crewmembers would don portable oxygen supplies or pressure suits. Once a fire is controlled, the onboard environmental-control system will require some time to scrub carbon dioxide and other contaminants from the atmosphere. Alternatively, an uncontrollable fire could be extinguished and its toxic byproducts eliminated by depressurizing the module. A larger and more damaging fire may prompt reentry (in the case of the Shuttle) or evacuation (from an orbiting space station).

3. Toxic Substance Release

Aside from thermodegradation and pyrolysis products, toxic substances also can be encountered from breach of a containment vessel or conduit, experimental mishap, or exposure to an extravehicularactivity (EVA) suit inadvertently contaminated with a propellant (such as hydrazine). Stored chemical constituents of concern in the orbiter are nitrogen tetroxide (propellant oxidizer), hydrazine and monomethyl hydrazine (propellant), ammonia (coolant), and Halon 1301 (fire suppressant).[18] Several volatile organic and other substances also are present in lesser quantities. As noted in Table 1, exposure of the Apollo-Soyuz crew to nitrogen tetroxide during atmospheric reentry led to hospitalization of all three crewmembers for pulmonary edema.

The recurring themes of access to emergency equipment, exiting, isolating, and repairing the module, and safe haven all apply to toxic-release events as well. As is the case for pressure loss or fire, circumstances dictate whether a crew remains on orbit and performs repairs and clean-up operations, awaits rescue, or initiates an emergency return.

4. Primary Medical Event

Astronauts and cosmonauts are selected and screened to the greatest extent possible to produce a minimal incidence of in-flight illness. As yet, no crewmember has required medical evacuation for a chronic illness or a condition that predated astronaut or cosmonaut selection. However, the possibility of developing an acute condition such as appendicitis, respiratory or other infection, or anaphylaxis cannot be eliminated. This was demonstrated during the Soyuz T-14 mission in 1985, which was terminated early when a cosmonaut required medical evacuation for persistent high fever,[6] later diagnosed as prostatitis. More significantly, the space flight environment is one of occupational risks. Possible events leading to illness or injury include electrical shock, hypoxia, hypercapnia, hypothermia, and decompression disorders (decompression sickness, aeroembolism, ebullism from EVAs or loss of pressure), trauma, and exposure to toxic substances. In addition, prolonged space flight induces electrolyte and other physiological changes that potentially could render the cardiac-conduction system more susceptible to rhythm disturbances. Of note, in July 1987, a Russian cosmonaut was returned early from a mission because of cardiac dysrhythmia, which had not been observed before flight. This abnormality seems to have been an asymptomatic, stress-induced supraventricular tachycardia that resolved completely after landing.[6,19]

Response to a medical event will depend primarily on 4 factors: the severity of the illness or injury; the capability of the onboard medical system; the skills of the crew medical officer, and the ease and feasibility of return or evacuation. Stated goals of the space station’s health maintenance facility are to provide medical treatment to ill and injured crewmembers in flight, prevent evacuation if possible, and increase the likelihood of success in the event that evacuation for medical reasons is indicated. The continued presence of a return vehicle will influence the capability of this facility. For example, medical supplies to support long-term patient care would be de-emphasized. Since an off-nominal return is not without its own inherent risks, the above factors must be weighed carefully. The concept of returning ill and injured crewmembers will be amplified in a following section.

5. Radiation Exposure

Several sources of radiation are present in space, particularly beyond Earth’s protective atmosphere. Charged particles geomagnetically trapped by the Van Allen belts and background galactic-cosmic radiation are chronic sources of radiation from which space crews should be shielded by vehicle and mission design. Acute exposures that might lead to an escape scenario could have several potential origins. Solar-particle events, which often accompany solar flares, generate dangerous levels of high-energy protons. Earth’s magnetic field affords considerable protection for spacecraft in LEO, especially low-inclination orbit, so that transit through the South Atlantic Anomaly (where the Van Allen Belts extend into LEO) is minimal. However, spacecraft in high Earth orbit, geostationary-Earth orbit, or a translunar or transplanetary flight trajectory, or inhabited outposts on the moon or Mars, may be particularly susceptible to these occurrences. Solar particle events are predictable to some degree, correlating with sunspot activity, and usually are heralded by increased solar emissions of light, radio frequency, and X-ray radiation. These activities warn orbital space crews to take shelter in a radiation-shielded safe haven or to evacuate before peak activity. Evacuation is not practical for spacecraft and bases beyond Earth's orbit, and thus crews in these habitats must rely on a shielded refuge.

Payload-experiment mishaps involving radioactive materials could contaminate crewmembers or the habitable volume. Also, failure of a nuclear-power system, planned for lunar and Mars bases, may lead to the release of radioisotopes and subsequent contamination. Finally, ground or orbital detonation of a nuclear device could subject crews to sudden dangerous levels of radiation. Crew evacuation could be prompted by habitat contamination or radiation-induced illness that exceeds the capabilities of the onboard medical facilities. To minimize the morbidity and mortality associated with radiation exposure, high-level supportive medical care is required.

6. Other Events

A failed thruster on the Gemini-8 mission resulted in loss of attitude control, which induced a peak axial tumbling rotation of 50 rpm to the spacecraft.[20] Such a rotation rate is highly disorienting, and will produce centrifugal forces that impair manual-control inputs. This event was stabilized by the reaction-control system. Large orbiting space structures such as the International Space Station and Mir are designed to minimize the likelihood of asymmetric thrust leading to loss of attitude control and uncontrolled spin. However, in such an event, failure of corrective actions may prompt crew evacuation. A relatively low rotation rate may mandate evacuation from the space station; disorientation and partial-*g* effects must be factored into egress timelines.

Malfunctioning of the environmental and life support systems from mechanical failure or accident could affect the spacecraft or station habitat and crew. This situation was encountered during the Apollo-13 mission described above, and later aboard the Russian Salyut-7 station in June 1985 when the primary power failed. In the latter case, the mission was preserved by crewmembers Dzhanibekov and Savinykh, who completed repairs successfully under harsh conditions.[6,21] Inability to make such repairs is likely to prompt an early return or station evacuation.

Nominal launch services and schedules can be interrupted for a variety of reasons ranging from accidents to social and political factors. Both the U.S. and Russian space programs have experienced interruptions lasting from 18 to 32 months after fatal events. The delay of a return mission from Mir because of political events in the former Soviet Union (now the Russian Federation) demonstrate that social forces could influence launch or recovery operations. These events suggest that autonomous return capability may be needed for human space missions.

II. Escape and Rescue From LEO

From a practical standpoint, LEO is defined as the space bordered by the mechanical boundary of the atmosphere below 200 km and the Van Allen belts above 1000 km, depending on latitude. Atmospheric drag is sufficient to preclude sustained orbit below 200 km; even at higher altitudes, periodic reboosts are required for spacecraft with a significant cross-sectional area. Spacecraft penetrating the Van Allen belts must be able to provide adequate radiation shielding for human occupants and sensitive avionics, implying a substantial weight penalty. For the foreseeable future, LEO will remain the primary staging ground for short-term missions and permanently occupied space platforms, and will provide stable "parking" orbits for access to higher orbits and translunar and transplanetary missions.

A. Short-Term LEO Missions

Missions lasting 20 days or less generally involve a single spacecraft and crew. Minor in-flight mishaps during U.S. and Russian missions have prompted early returns and affected mission timelines, but none have stranded a crew in orbit as of this writing. A backup rescue vehicle and crew is a tremendous commitment of resources, but this concept has gained some acceptance. Throughout the Soyuz program, a second Soyuz spacecraft and crewmember have stood ready at each launch to embark on a rescue mission.[3] Rescue-team readiness is reduced once the mission is established on orbit, but still can be launched within 10 to 15 days. Early in the U.S. Space Shuttle program, vehicle turnaround was high, enabling a rescue mission to be launched with an additional orbiter should the primary vehicle become incapacitated. Current estimates are that 45 days will be needed to launch a rescue mission to the International Space Station. This relatively long period has provided the impetus for developing an on-site rescue vehicle.

After a rescue mission is launched, the next phase is to rendezvous and transfer the crew from the disabled spacecraft to the rescue vehicle. This normally would be accomplished through the use of docking adapters. If the lack of docking hardware, or damage to it, precludes docking, or if circumstances preclude equalizing the spacecraft atmosphere (in a toxic-release situation), EVA transfer would be necessary and thus crewmembers would need pressure suits. An EVA-suited crewmember might be transferred from an orbiter, for example, to another vehicle by using the remote manipulating system (RMS) arm, or a maneuvering unit or its equivalent. Transferring an entire crew would require either several pressure suits or suit-swapping among the crewmembers. An alternative in the Shuttle program is the personal-rescue sphere (PRS). The PRS is an inflatable fabric enclosure 86 cm in diameter that weighs 11.3 kg[5] (Fig. 5). It is used in conjunction with a portable oxygen system, which provides a high-pressure oxygen supply as well as controlling CO_2 and humidity. A crewmember assumes a fetal position and is zipped into the enclosure, which is then pressurized with the oxygen system. The PRS can be transferred to a rescue vehicle by a suited crewmember with an maneuvering unit or conceivably by the RMS. The PRS also could serve as a final refuge in the event of a pressure loss or a mandatory decompress due to toxic release or fire. To date, the PRS has not been flown, primarily because of the low probability of launching a rescue orbiter.

Once the decision has been made to deorbit and return, recovery options must be weighed carefully. The number of possible landing sites, the cross-range capability of the vehicle, and the availability of search-and-rescue and recovery forces all are important factors in the success of a contingency return. If the emergency calls for an immediate deorbit, it may be necessary to rely on suboptimal landing facilities with inadequately staffed and equipped recovery teams. Recovery operations should be simplified to the extent possible to accommodate untrained rescue worders. Potential landing sites are numerous for a water landing, but the implications for search-and-rescue forces involved in an unscheduled ocean return are formidable. The orbiter, with its cross-range capability of approximately 1770 km, is more flexible in terms of selecting a landing site in acceptable conditions (daylight, favorable weather) with facilities to meet its immediate needs, such as a definitive medical care facility. A greater number of potential landing sites, particularly on a global scale, equates to a shorter period for deorbit and return. Aside from its primary landing and TAL sites, the orbiter has over 30 emergency landing sites in the continental U.S. and around the world.

B. Permanently Occupied Space Stations

Several approaches to returning orbiting space station crews in emergencies have been analyzed over the years, particularly with regard to the trade-offs between Earth-based vs. space-based systems. Earth-based rescue vehicles are severely constrained by launch site, preparation time, and launch-window considerations. A dedicated on-station vehicle provides ready escape but also can be disabled because of its proximity to a potential catastrophic event such as fire or explosion. Another alternative is a nonjoined space vehicle, which might either be co-orbiting or in a higher orbit, that could reach several low Earth orbital stations on short notice. Launch and weather constraints would not be a factor, and rendezvous and docking procedures could be highly automated. This alternative would remove the option of immediate station evacuation. International opinion has held that no single system can cover all possible contingencies, but a dedicated on-site vehicle seems to offer a solution to the greatest number of scenarios.[22–25] Russian space crews always have been able to return immediately via a docked Soyuz vehicle, and cosmonauts have performed evacuation drills on the Salyut-7 and Mir space stations.

NASA’s assured crew-return vehicle (ACRV) project, in support of the International Space Station, represents the most highly developed analysis of emergency-return concepts and provides a useful framework for discussing the generic attributes of an escape vehicle. The 3 stated goals of the ACRV project are designated “design reference missions” (DRM):

- DRM 1—Return one disabled crewmember from the space station during reasonable medical emergencies.

- DRM 2—Return crew from reasonable accidents or from reasonable failure of station systems.

- DRM 3—Return crew during interruption of scheduled Shuttle or Soyuz launches.

Notably, incidents leading to each of these scenarios have occurred in either the U.S. or Russian space program. Operational status of the International Space Station, with a 3- to 6-person permanent crew, and continued occupation of the Russian Mir station will increase the likelihood of repeat events in the future.

Each DRM scenario imparts unique requirements for the ACRV. Moreover, as a permanently available vehicle, it must be long-lived and reliable with relatively low-maintenance demands to support the 10-year planned operational lifetime of the International Space Station. To facilitate rapid crew escape, a "shirt-sleeve" environment is required. The vehicle must be equilibrated with the station's ambient atmosphere, i.e., must be compatible in terms of pressure, respirable gas mix, and thermal control. Performance requirements of the ACRV call for isolating the vehicle from the station within 2 minutes of the beginning of crew entry, and separating from the station within 3 minutes of crew entry.[26] Evacuation of the entire crew must be accommodated (cf. DRM 2). Depending on the sizes of the crew and vehicle, two vehicles may be needed. Because an escape vehicle is expected to be used infrequently, a high degree of pilot proficiency cannot be assumed. Separation, deorbit, and landing will be automated to the greatest extent possible, and will require minimal control input.

To meet DRM-1 conditions, the ACRV must evacuate and transfer a critically ill or injured crewmember to a definitive medical care facility. Any contingency deorbit and recovery will have its own inherent risks; thus, the decision to transfer must result from careful consideration of the patient's condition, the medical treatment capabilities on board, and the skills of the onboard medical officer. ACRV return and recovery present considerable logistical challenges in deploying search-and-rescue and medical forces, which must be considered in the decision to transfer. Ideally, the patient would be maintained on station as long as possible to allow an optimal landing site to be selected and search-and-rescue vehicles to be deployed. Once the decision is made to evacuate, the ACRV's design requirements specify a maximum of 24 hours from declaring the patient appropriate for transfer and arrival at a definitive medical care facility. Further breakdown of mission timelines calls for a maximum of 6 hours from ACRV separation to arrival at the definitive medical care facility, including 3 hours for on-orbit loiter and reentry, 1 hour from landing to crew recovery by search-and-rescue forces, and 2 hours for transporting the ill or injured crewmember to the selected care facility.

An emergency return vehicle, like an ambulance, also must accommodate any equipment needed to support the medical transport. This equipment will consist of modular items that can be used in various combinations, and will be transported with the patient from the station's medical care facility. Medical hardware items to be accommodated in the ACRV include a cardiac monitor/defibrillator, a pneumatically driven ventilator, an intravenous infusion pump, and an advanced life support pack. These items will require volume, power, and for the oxygen-powered ventilator, an overboard dump system in order to avoid enriching the cabin atmosphere with expired oxygen. Recovery personnel must be familiar with these items.

The costs associated with having recovery teams available continuously during space station operation are prohibitive. However, search-and-rescue forces may be need to be deployed on relatively short notice. The number of available landing sites significantly influences the speed, ease, and overall success of emergency return and recovery, and this may control the design of the ACRV's landing configuration. A lifting-body design with considerable cross-range capability, limited reentry *g*-loads, and the ability to land on a runway affords the most flexibility, but is the most complex and costly. Final decisions on vehicle type are pending, but NASA's test-bed models have resembled the Apollo capsules.

The next decision concerns whether to plan for landing on land or in water. For the planned 51.6° orbital inclination of the International Space Station, splashdown sites near U.S. or its allies are abundant and should allow at least one return opportunity per orbit. This was the preferred method of return for U.S. spacecraft before the Space Shuttle program. However, recovery operations for water landings are complex and hazardous. Landings on land should simplify the recovery process and enhance the success of the medical mission. Although sites within the U.S. are limited compared to the vast Russian steppes, improvements in guidance and global-positioning satellite technology should allow highly accurate landings. The possibility of a dual-mode lander also exists. The Soyuz lander, which nominally returns on land via parachutes and impact-attenuating retrorockets, can also land in water; in fact, the Soyuz-23 spacecraft landed in Lake Tengiz 8 km from shore in 1976.[6] Conversely, the Apollo capsule, which nominally landed in water, was designed to land on land during contingencies. Crew couches were attached to the capsule infrastructure via telescoping struts filled with crushable aluminum in a honeycomb matrix to minimize impact.

If an orbiter is docked to the space station, the orbiter will be the emergency return vehicle. Health maintenance and transport hardware will be designed to interface with orbiter systems, and to accommodate the transport of a medical patient.

C. Medical Concerns Associated With Atmospheric Reentry

Both the Russian and U.S. space programs have returned crews safely after long periods on orbit, particularly from the Mir space station, where missions have lasted more than a year. However, medical evacuation from space prompts consideration of the influence of illness or injury, as well as the effects of space flight deconditioning, on tolerance to the acceleration forces of reentry. No adequate body of data exists to define the risks of orbital reentry for a critically ill patient. Guidelines for ACRV reentry-acceleration limits were based on the responses of normal and deconditioned subjects to acceleration forces and data from appropriate animal studies.

The physiologic effects of sustained acceleration on normal subjects are discussed in detail elsewhere in this series (Volume III, Book 2). Briefly, human tolerance of acceleration forces is determined primarily by interference with normal hemodynamic relationships, mechanical impedance of respiration, and displacement and deformation of internal organs. Significant factors that affect human resistance include magnitude, duration, the force/time relationship, the direction of the force, and body position with respect to the force vector. Environmental factors like the use of restraints, countermeasures, and other protective systems also are contributory. Individual resistance is determined by age, training, underlying physical condition, and any additional compromising factors such as injury.

From a hemodynamic standpoint, the +Gx direction (chest-to-back) is the optimal axis for tolerating acceleration in spacecraft; crews on Apollo and Soyuz spacecraft have been oriented in this way during return to Earth. Specific physiologic effects of +Gx acceleration (for healthy subjects) are summarized in Table 4. Ground-based studies and actual space flight experience have shown that the hypogravic state effectively reduces tolerance to +Gx acceleration commensurate with duration of exposure.[34–36] Kotovskaya has reported that returning cosmonauts exposed to an average +Gx value of 3.6 after flights lasting less than 30 days showed 48% increases in heart rate and 62% increases in respiratory rate compared with preflight centrifuge values.[37] After longer flights (2–11 months), 95% increases in heart rate and 92% increases in respiratory rate were noted. From the assumption that these effects would be additive to some illness or injury, models of diffuse lung injury and hemorrhagic shock have been studied under varying profiles of +Gx representative of spacecraft reentry.

Pulmonary compromise can result from infectious disease, trauma with associated acute respiratory-distress syndrome, or inhalation of toxins. To evaluate the combined effects of resulting pulmonary compromise and sustained +Gx acceleration, a model of lung injury was created by investigators at the University of California by infusing oleic acid intravenously into Rhesus monkeys.[38] This procedure induced a diffuse injury pattern, with significant impairment of pulmonary gas exchange. Two reentry profiles reflective of designs being considered for the ACRV were simulated in a centrifuge (Fig. 6). The high-*g* profile, representative of a ballistic reentry capsule, peaks at approximately 7.8 +Gx, with a total of 180 seconds over 1.0 *g;* the low-*g* profile, representative of the Apollo reentry, peaks at 3.3 *g* with a total of 390 seconds over 1.0 *g*. A wide array of cardiopulmonary variables were measured in lung-injured and control monkeys. Preliminary results show that centrifugation of control subjects produced the expected increase in heart rate and respiratory rate, decrease in tidal volume (V_T), and hypoxemia, with nearly complete recovery after exposure. Lung-injured monkeys demonstrated significantly more hypoxemia and deterioration in pulmonary function, which was most marked in the high-*g* profile. With cessation of *g*-exposure, the degree of hypoxemia in lung-injured subjects returned to near precentrifuge values.

These results suggest that the effects of lung injury and +Gx exposure are additive, and that a crewmember with respiratory compromise will require more aggressive treatment measures during reentry. For example, a medical officer may opt to intubate and mechanically ventilate an otherwise stable patient with a toxic-inhalation injury before reentry so as to ensure normoxemia and airway integrity during high +Gx acceleration.

With regard to trauma, hemorrhagic shock can result from open wounds or from internal hemorrhage due to injury from a blunt object. Using the same two reentry profiles, Hamilton and others investigated the combined effects of Class II (20%) and Class IV (40%) hemorrhage with +Gx in a primate model.[39] Assessment of multiple cardiovascular and pulmonary function variables demonstrated that sustained +Gx and hemorrhage were additive in inducing deterioration of cardiopulmonary function. Of note, mixed venous oxygen (MVO_2) was influenced significantly downward by both +Gx and hemorrhage, but the decline in cardiac output depended primarily on the degree of hemorrhage. As was the case for the lung-injury model, the detrimental effects attributed to +Gx are increase with acceleration magnitude and generally are reversed upon cessation of exposure.

Aggressive fluid resuscitation using the station's medical facility and judicious use of respiratory support will be needed to stabilize hemorrhagic shock before the patient can be transported from the space station. Thus, neither of these proposed reentry profiles seems to contraindicate transport; early evacuation and transfer of a critically ill patient to a definitive medical care facility will take priority over maintaining the patient on station. The lower-*g* profile is the more desirable option since a lesser degree of cardiopulmonary deterioration is incurred.

Another consideration for reentry is angular acceleration, or spacecraft spin. A nominal reentry and return normally involves some spin about the x-axis, with minimal combined input from other axes. Most subjects can tolerate up to six rotations per minute (rpm) with no untoward effects.[40] Above 6 rpm, however, gradual disorientation and declining performance become problems. The deconditioned neurovestibular systems[41] of returning space crews render them particularly vulnerable to disorientation induced by rotational forces. Nausea and emesis in a patient with a degraded level of consciousness may lead to catastrophic aspiration. Finally, wind-induced swinging of the capsule on its parachute shrouds may introduce a component of radial acceleration, which would contribute further to disorientation and unwanted neurovestibular effects.

During the increased accelerations associated with reentry, the medical attendant's ability to offer physical aid to a patient will be severely impeded. At 3 *g* and greater, lifting an arm or leg becomes extremely difficult. Therefore, the patient must be stabilized so that minimal aid is needed from the medical attendant during reentry. The patient and any accompanying medical hardware must be well secured to avoid the need for positional adjustments during reentry, and to counter any differential shear forces that might adversely affect the position of an artificial airway or dislodge an intravenous catheter. However, the patient should remain within reach of the medical attendant, and the medical attendant should be able to view displays of medical hardware (such as the cardiac monitor) with a minimum of head movement.

Current performance standards specified for the ACRV limit the sustained reentry-acceleration forces experienced by occupants to 4 *g* in the ±Gx direction, 1 *g* in the ±Gy direction, and 0.5 *g* in the ±Gz direction. Spin is limited to 5 rpm or less.[26]

D. Medical Concerns Associated With Impact

Tolerance to impact forces has been explored and some experience obtained with regard to aircraft ejection seats. This information and ongoing test data have been applied successfully in the past to U.S. and Russian spacecraft. Detailed discussions of the human response to impact can be found in Volume III, Chapter 14. The development of the ACRV, with its mission being to return ill or injured crewmembers from the space station, adds another dimension to defining impact limits. The possibility of compromising medical conditions and the effects of space flight deconditioning must be considered when setting G-limits for impact. A dedicated medical seat or couch may be needed to afford additional protection to an ill or injured crewmember (which invariably translates into a weight penalty). The design of such a seat or couch must attenuate impact forces more completely compared with other crew positions.

The human body can tolerate high acceleration forces for brief periods (0.2 seconds or less[42]); limits can be expressed conveniently in terms of peak acceleration force and duration alone. However, the full description of an impact event on the human body depends on several variables, all of which must be considered to predict associated medical risk. These variables include:

- Peak vehicle acceleration
- Acceleration history before the event
- Acceleration pulse shape
- Magnitude, direction, and duration of velocity change
- Characteristics of the impacted subject
- Subject's contacts and attachments to the vehicle (internal restraint system)

Brinkley and others[43,44] have developed a mathematical model, the dynamic response (DR) model, to predict the risk of major injury from simple descriptions of the impact event. The DR approach uses characteristic physical responses of the human body, which can be modeled by mass, spring, and damper. The model assumes that acceleration forces have their greatest deleterious effect at a certain critical point, and this becomes a reference point to mathematically describe the body's response to impact. The model was developed originally to estimate the probability of spinal compression fractures from ejection-seat forces (+z direction). A single-axis model was verified and used to design and test the ACES-II ejection seat. Subsequent operational experience and laboratory testing have improved characterization of the body's tolerance to impact and provided input to enable the model to be used to evaluate the effects of linear-acceleration components acting in the three orthogonal axes (x, y, and z).

A detailed description of the DR model is beyond the scope of this chapter. To summarize, Newtonian equations of motion are applied to the spring deflection and acceleration of the critical point, and the DR value is calculated as:

$$DR = \omega_n^2(\xi) / g$$

where ω is the undamped natural frequency of the system, ξ is the deflection of the mass with respect to the critical point, and g is acceleration of gravity. The system frequency ω also equals $(k/m)^{0.5,}$ where k is the spring constant and m is the mass.

A DR value for each orthogonal axis thus can be calculated from the deflection of the system spring, and the calculated maximum DR value is compared to an established DR limit value to assess risk. An Injury Risk Criterion ß is generated based on DR values for the three axes and their DR limit values (xL, yL, zL):

$$ß = [\ (DRx/DRxL)^2 + (DRy/DRyL)^2 + (DRz/DRzL)^2\ ]^{0.5}$$

The Injury Risk Criterion ß is calculated for low (0.5%), moderate (5%), and high (50%) risks of injury. A given risk level is defined as ß < 1.0. If ß > 1 for a given risk level, then that risk level has been exceeded and ß is calculated for the next risk level. For example, if a ß value of 0.78 is obtained for the low-risk level, the model predicts an injury risk of 0.5% or less. If ß for the low-risk level is 1.26 but for the moderate-risk level is 0.98, an injury risk of 5% or less is predicted. Risk refers to major injury, defined as bone fracture (other than fingers and toes), damage to internal organs, or cardiovascular shock.

The DR program outputs thus become:

- Time histories for critical point accelerations in graphic form
- Angular acceleration of the critical point
- DR values for each orthogonal axis
- Injury risk criterion ß for low, moderate, and high risk; the subject is considered to have exceeded specific risk if ß > 1.

The estimates of coefficient values such as natural undamped frequency and damping coefficient are derived from experimental studies, accident investigations, and expert consensus where usable data are lacking. As might be expected, the strongest estimates are available for the low-risk levels, from the large samples of controlled, experimentally derived data. In other words, the greatest confidence of the DR model lies with the low-risk ß values.

The DR model provides a useful quantitative frame of reference with which to deduce how crewmembers in various physical conditions would react. Since the DR model was developed around a healthy U.S. Air Force population, some consideration must be given to the effects of prolonged space flight and how those effects might influence impact tolerance. These considerations will affect the impact profile of the overall vehicle. Limits for the medical couch also must account for the influence of injuries. Because spacecraft impact is a transient mechanical event, the most significant adverse effects would be conditions or injuries involving a mechanical interface susceptible to short-duration acceleration forces. Visceral shear occurs in the frequency range of 2 to 3 Hz, a relatively low frequency compared to any of the proposed impact profiles. Induced low-frequency vibrations in the body stemming from a short impact pulse will be predicted and precluded by the DR model. Skeletal fractures become a concern in light of microgravity-induced loss of bone mass as well as preexisting fractures incurred on orbit that might be worsened as a result of impact.

The Russian Voskhod and Soyuz landers have returned space-deconditioned cosmonauts after prolonged flights, and crewmembers have not incurred fractures or other significant injuries associated with impact forces at landing. The impact profile for Voskhod, involving a peak +Gx acceleration of approximately 4 *g* over 0.4 seconds on the crew couch (Fig. 7), has been subjected to the DR model (Fig. 8), and has been shown to be within the limits for the low-risk category. This and other analyses have led to the idea that adjustments to the DR values for healthy deconditioned crewmembers are not recommended when the low-risk category (0.5% risk of injury) is used. Other factors (muscle atrophy, fat padding, and external restraint of the body) will influence fracture risk. Sex and age also can influence impact tolerance. The incidence of vertebral fractures associated with ejection is known to increase when pilots enter their late thirties and early forties. However, data are not sufficient to recommend altering DR limits for returning space crews on the basis of sex or age, again assuming that the low-risk category is baseline and that maximal impact forces will be in the +x direction.

Injuries and conditions that could occur on an orbiting station, require evacuation, and affect impact tolerance due to mechanical interfaces include the following:

- Foreign bodies (in the airway, for example) that could move independently;
- Retained foreign bodies involved in a penetrating trauma also are potentially unstable, and could cause further injury during impact;
- Visceral injuries, lacerations, or ruptures;
- Fractures, specifically of the skull, thorax (especially “flail chest,” which could be particularly compromising in +Gx impact), femoral (could induce significant hemorrhage), or any spinal injury with possible cord compromise;
- Closed head trauma, in which impact could induce or exacerbate hemorrhage; and
- The stability of “therapeutic foreign bodies,” such as endotracheal tube or central intravenous line, could be compromised.

Other conditions such as aortic dissection, aortic aneurysm, and prosthetic implants could be compromised further by impact events, but should be effectively excluded among space station crews by the medical-screening process. Crush injuries, which could be incurred by an arm or leg between a large moving orbital-replacement unit and a bulkhead, are always possible. Injury to the cervical—or other areas—of the spine are highly unlikely without gravitational forces; indeed, most of the forces that produce terrestrial fractures are driven by gravity and impacts (e.g., motor-vehicle accidents) that will not be encountered on orbit.

Assessments of medical evacuation events in analog populations, such as Antarctic station crewmembers[45] and U.S. Navy submarine crews,[46] have shown the occurrences of these types of injuries to be extremely low. Despite the inherent risk of extrapolating these results to the space station environment, the subset of events and conditions requiring medical evacuation that might affect impact tolerance seems much smaller in space flight. Some degree of adjustment seems prudent, however. Therefore, the ACRV medical couch should include a margin of 25% applied to the existing DR limits for the low-risk category.

Current DR limits are given in Table 5. Overall, incorporation of the DR model should afford designers more latitude, since multiple combinations of peak Gs and pulse widths may fall within acceptable DR limits. The model undoubtedly will undergo refinements in the future as additional experience is accrued with crewed-spacecraft impacts. Finally, the DR model could be applied to any situation involving spacecraft that undergo abrupt onset of short-lasting, high-acceleration forces, such as launch aborts and launch-vehicle staging.

E. Medical Concerns Associated With the Postlanding Phase

The period immediately after landing, regardless of the spacecraft used, involves readaptation as physiological systems are once again exposed to Earth’s gravity. The major physiological systems to be considered with regard to human performance are cardiovascular, with subsequent orthostatic intolerance due to deconditioning; musculoskeletal, with disuse atrophy and diminishing available strength and endurance; and neurovestibular, with disorientation induced by head movements and postural instability. Some adaptation occurs during space flights of any length. However, upon landing, crewmembers are susceptible to adverse effects. For example, crewmembers returning from the 237-day Soyuz T-10B mission (Salyut-7) reportedly were unable to lift their arms to unbuckle their lap belts.[23] Even after short flights, Space Shuttle crewmembers occasionally have been incapacitated by neurovestibular symptoms for more than an hour; others have been unable to complete a 5-minute cardiovascular “stand test” because of orthostatic intolerance for up to 2 hours after landing. Some degree of postural instability may persist for several days after landing.[41] Conversely, many crewmembers are sufficiently readapted to extricate themselves from landing vehicles and walk within 10 to 20 minutes of touchdown.

At best, the level of functioning of returning space crews is highly variable. In the event of a contingency return from LEO, nominal countermeasure protocols, such as fluid loading before deorbit, may not be observed. Also, as previously mentioned, an entire crew may suffer from injuries related to the evacuation event (such as smoke inhalation). With this in mind, a dedicated emergency return vehicle should require only limited physical performance by deconditioned crewmembers in the period immediately after landing. In particular, tasks that involve upright posture, deploying a heavy load, or multiple head movements must be minimized. Also, the medically evacuated crewmember should not be expected to help himself or herself immediately after landing.

The recovery team and search-and-rescue personnel should be fully cognizant of the effects of space flight deconditioning, with realistic expectations of the returning crewmembers' ability to help in the rescue operation. Ideally, search-and-rescue forces would be briefed en route to the recovery site on the circumstances leading to the return, the severity of injuries, the duration of the mission, the medical-hardware items used during transport, and other salient facts. Direct communication between crewmembers and search-and-rescue personnel would enhance readiness upon arrival. As stated earlier, widely dispersed, dedicated recovery teams will not be available for the ACRV program. Therefore, efforts must focus on making the rescue process as simple as possible. Fig. 9 shows a simulated rescue drill involving an ACRV design for a potential landing on water**.** These and other simulations will provide important design specifications as methods are identified to streamline the processes of crew recovery.

III. International Aspects of Space Rescue

This is a unique time for human space flight. The world's two major space powers, Russia and the U.S., have accumulated sufficient experience to confidently consider and plan such projects as the International Space Station and a crewed mission to Mars. LEO is becoming less an area for exploration and more a workplace. At the same time, several other space agencies have demonstrated launch capabilities and plans for ambitious crewed programs of their own. Global tensions among industrialized nations have eased and with current trends toward world trade and industrial codependence, the stage is set for unprecedented international cooperation in space.

The hazards faced in space flight endeavors are common to all nations. Given the tremendous investment of capital and resources to support an active space program, international joint ventures are inevitable. Multinational cooperation is a logical "countermeasure" against global economic overhead, particularly with regard to low-use contingency hardware and procedures like emergency rescue vehicles. Cooperation implies compatibility of systems and approaches, and these considerations should figure prominently in the early design phases of new programs.

To date, four rendezvous-and-docking operations have been completed between U.S. and Russian spacecraft, one in the Apollo-Soyuz Test Project in 1975 (Fig. 10) and three in the Shuttle-Mir program in 1995–1996 (Fig. 11). These efforts involved the development of specialized docking mechanisms, complex coordination of mission-control centers from different nations, and joint training of astronauts and cosmonauts. As early as 1963, however, J. W. James had advocated development of a universal docking and coupling mechanism.[47] Throughout the history of human activities in space, consideration has been given to international aspects of rescue through formal conferences and publications. The Association of Space Explorers, a society of astronauts and cosmonauts, has been influential in advocating the development of an international space-rescue policy.[48] In addition, several formal treaties have outlined or referenced policy for international rescue efforts. One such treaty was the broad Outer Space Treaty of 1967. Article V of this document builds on wording from a 1963 United Nations resolution[49]:

> States Parties to the treaty shall regard astronauts as envoys of mankind in outer space and shall render to them all possible assistance in the event of accident, distress, or emergency landing on the territory of another State Party or on the high seas. When astronauts make such a landing, they shall be safely and promptly returned to the State of registry of their space vehicle.
>
> In carrying on activities in outer space and on celestial bodies, the astronauts of one State Party shall render all possible assistance to the astronauts of other States Parties.
>
> States Parties to the Treaty shall immediately inform the other States Parties to the Treaty or the Secretary-General of the United Nations of any phenomena they discover in outer space, including the Moon and other celestial bodies, which could constitute a danger to the life or health of astronauts.

The Outer Space Treaty was followed by the “Agreement on the Rescue of Astronauts, the Return of Astronauts, and the Return of Objects Launched into Outer Space.” Signed by 44 nations on April 22, 1968, this document focuses specifically on humanitarian concerns, particularly with regard to crews making emergency landings on foreign soil and areas not under the jurisdiction of any State, such as the high seas and outer space. As international space policy matures, treaties such as these can continue to be refined.

Once accepted, the goals of international space rescue must be translated into a cogent, workable plan. Feasibility studies must address search and rendezvous capabilities including universal communication frequencies, compatibility of docking mechanisms, cabin-atmosphere parameters, and operational procedures. Development of a universal docking hatch would be a major milestone in this process. Standardized hardware and connectors will simplify any operation (such as allowing a rescue vehicle access to power and data channels) involving spacecraft from different countries. Ideally, astronaut training would include orientation to international systems relevant to a rescue or escape operation.

To present the greatest number of options, world launch capabilities should be integrated into a multinational network with the constraints of orbital mechanics in mind. To fully use the Earth’s rotation in attaining orbit, launches primarily are directed due east, which results in an orbital inclination approximate to the latitude of the launch site. A site near the equator affords the greatest flexibility in selecting a range of inclinations; conversely, a high-latitude site is more restricted. Transition of orbital inclinations or planes on orbit requires enormous energy and subsequent fuel penalties. The orbital inclination of space flights launched from the U.S. has ranged from 28.5° (roughly the latitude of Kennedy Space Center in Florida) to 57°. Russian crewed launches from the Baikonur Cosmodrome uniformly attain a 51.6° inclination and thus could not reach most U.S. orbiting vehicles. A rescue vehicle launched from the European Space Agency’s launch site Kourou, French Guiana, at a latitude of 7° could serve future flights of all known or planned crewed programs.[48]

With regard to escape and Earth-return scenarios, increasing the number of possible landing sites dramatically enhances the flexibility, timelines, and expected success of reentry and landing. The international implications are obvious. Spacecraft-recovery personnel, stationed during their nominal duties near selected landing and splashdown sites, could be trained and activated as needed for a contingency return. Again, universal communication frequencies and rescue procedures would require formulation. Conceivably, generic spacecraft-recovery training will include data common to all returning vehicles (e.g., effects of space flight deconditioning, toxic hazards associated with propellants, etc.) as the number of users of LEO increases. An increasing number of medical personnel will become familiar with specific medical problems common or unique to the orbital environment and enhance the immediate medical care available to crews returned in emergencies.

IV. Conclusions and Future Directions

Continued occupation of the Mir space station and the operational status of the International Space Station will be accompanied by missions of other nations in LEO as world access to space widens. During this time, an experience base will be accumulated that will define and characterize spacecraft mishaps, including the incidences of illness and injury, and allow predictions to be made on the basis of empirical evidence rather than extrapolation from analog scenarios. Future human space activities will see the advent and development of more reliable launch, landing, and orbital systems that will minimize the occurrence of emergency escape-and-rescue situations. At the same time, exploration activities are expected to carry human crews to even more remote locations, such as geostationary Earth-orbit platforms, the moon, and Mars, that progressively limit the capability for immediate return.

The means for rapid emergency transport from the International Space Station will influence onboard medical capability, generally diminishing the capacity to care for long-term or chronic medical problems. The opposite will be true for lunar or Mars bases. Emergency medical transport from a lunar habitat is likely to require 3 days with favorable orbital alignment. At its most distant point from Earth, the 99.8 million km journey from Mars effectively precludes any medical return. This leaves two options: accept greater level of risk to crew health from a lesser level of medical care on an exploratory mission, or increase the capability of medical facilities to ensure crew health and contribute to mission success. Given the many known hazards, the largely unknown risks, and the enormous commitment of resources involved in sending human crews to Mars, the latter approach is more logical operationally. To maximize autonomy, medical facilities should have at least a limited capability for surgical procedures and moderately long-term critical care, and the crew should include a physician of skill equal to or exceeding the capability of the medical hardware. Calculations of maximal distances from Earth have been used to determine that medical consultations with ground personnel from an orbiting Mars base or surface station may require up to 5.5 minutes transit time (one-way), and extended communication outages could occur because of unfavorable orbital alignments.

In the event of a catastrophic failure (such as fire or toxic release) that renders a lunar or Mars habitat uninhabitable, first-line rescue will consist of retreating to a safe haven. If repairs are not possible, the crew must await a scheduled return or rescue vehicle, or evacuate with a vehicle at hand. Emergency and rescue scenarios thus significantly influence amounts and storage space for consumable items. Program structure will dictate these needs as the operational plan unfolds. A Mars habitat, for example, might well be served by an orbiting Mars station (with a more capable medical facility) and simple surface-transfer vehicles. This also would form a second-line point of escape in the event of a habitat catastrophe.

Inherent in their grand scale, such endeavors as travel to Mars and permanently staffed lunar and Mars habitats are particularly amenable to international participation. Methods and approaches to space rescue and escape will evolve in step and become a focal point for cooperation. The entire world has shared in the accomplishments of human space activities on an individual level; the burden of rescuing a human crew, the “envoys of humankind,” from a distressed space vehicle also will be shared on a global scale and with a sense of world unity. Envisioning these scenarios does not require great leaps of imagination; this future is well within our grasp.

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Figure Captions

Fig. 1 Solid-rocket motor escape-towers for the Gemini (left) and Apollo (right) crew capsules.

Fig. 2 Space Shuttle abort and normal mission profiles. MECO, main engine cutoff; OMS, orbital maneuvering system; ATO, abort to orbit; AOA, abort once-around; RTLS, return to launch site; ET, external tank; SRB, solid-rocket booster.

Fig. 3 Path of egress from the Space Shuttle during controlled gliding flight. The bail-out pole routes the crewmember beneath the leading edge of the wing.

Fig. 4 The launch-and-entry suit (LES) and support equipment worn during Space Shuttle launch and return.

Fig. 5 The personal-rescue sphere, a single-occupant pressurized fabric enclosure for emergency transfer of crewmembers.

Fig. 6 Apollo and high-G reentry profiles proposed for the ACRV.

Fig. 7 Voskhod and Soyuz landing-impact profiles as measured at the crew couch.

Fig. 8 Dynamic response profile for the Voskhod crew-capsule impact measured at the crew couch.

Fig. 9 Sea rescue and egress simulations using a mockup of the ACRV are performed in a wave-generating tank.

Fig. 10 The Apollo-Soyuz Test Project rendezvous.

Fig. 11 The U.S. Space Shuttle docks with the Russian space station Mir (NASA photo no. STS-071(s)072).

Table 1 Mishaps in human space flight

Launch date, duration of flight	Crew	Mission	Event
21 Jul 61	Grissom MR-4	Mercury	Suborbital flight. Upon splashdown, capsule hatch opened 16 min prematurely and flooded capsule and suit. Astronaut barely escaped drowning; capsule lost.
18 Mar 65	Belyayev Leonov	Voskhod-2	Reentry abort due to failure of attitude-control system. Eventual 26 h 2 min manual reentry and landing 2000 km off-target in snow. Crew spent night in capsule.
16 Mar 66 10 hr 42 min	Armstrong Scott	Gemini GT-8	Attitude-control system malfunction while docked to Agena. Reaction-control system activated to stabilize; prompted early reentry.
27 Jan 67 Ground Simulation	Grissom White Chaffee	Apollo-1	During a launchpad simulation, fire broke out in the 100%-oxygen atmosphere. Hatch could not be opened quickly; entire crew killed.
23 Apr 67 27 h	Komarov	Soyuz-1	Failure of reentry control system. Parachute did not deploy, capsule impacted at terminal velocity. Cosmonaut killed; capsule destroyed.
11 Apr 70 142 h 52 min	Lovell Swigert Haise	Apollo-13	Mission abort prompted by explosion of oxygen tank in service module. Completed lunar circumnavigation by using lunar module life support system and power; returned safely.
1 Jun 70 17 days	Nikolayev Sevastyanov	Soyuz-9	Failure of telemetry switchboard made communications between mission control and crew difficult.
6 Jun 71 23 days	Dobrovolsky Patsayev, Volkov	Soyuz-11	Accidental cabin depressurization during reentry. No crewmembers wore pressure suits; all were killed.
26 Aug 74 2 days	Sarafanov Dyomin	Soyuz-15	Failed to dock with Salyut-3; crew landed at night in remote area.
5 Apr 75 21 min	Lazarev Makarov	Soyuz 18-1	Launch vehicle did not separate from stage; launch aborted. Crew exposed to sustained 20-G reentry force, landed in Siberian wilderness, and were rescued the next day.
15 Jul 75 9 days	Stafford Brand Slayton	Apollo-Soyuz	Crewmembers accidentally exposed to nitrogen tetroxide during reentry. All hospitalized with chemical lung injury.
6 Jul 76 49 days	Volynov Zholobov	Soyuz-21	Crewmember illness prompted early return from Salyut-5.
14 Oct 76 2 days	Zudov Rozdestvensky	Soyuz-23	Failed to dock with Salyut-5 station. Landed in ice-covered Lake Tengiz. Rescue team could not recover spacecraft and crew for several hours.
8 Oct 77 2 days	Kovalenok Ryumin	Soyuz-25	Failed to dock with Salyut-6; crew landed at night in remote area.
10 Apr 79 2 days	Rukavishnikov Ivanov	Soyuz-33	Main engines failed on orbit. Excessive backup engine retrofire led to ballistic reentry with up to 10 +Gx.
26 May 80	Kubasov Farkash	Soyuz-36	Soft-landing engine malfunctioned; vehicle landed at high velocity and impact acceleration. Use of emergency shock-attenuation system protected crew from major injuries.
27 Sep 83	Titov Strekalov	Soyuz-T10A	Launchpad fire 90 seconds before launch. Escape rocket was fired by ground crew just before massive explosion; crew landed safely several km away.
29 Jul 85 8 days	Fullerton Bridges, Henize, England, Acton Musgrave, Bartoe	STS 51-F	Transducer failures prompted single main-engine shutdown during ascent. ATO[a] option exercised; remained in low Earth orbit with minimal effect on mission.

Table 1 Mishaps in human space flight, continued

Launch date, duration of flight	Crew	Mission	Event
17 Sept 85 64 days	Vasyutin Grechko A. Volkov	Soyuz-T14	Crewmember illness prompted early return from Salyut-7.
Feb 85	Dzhanibekov Savinykh	Salyut-7	Failure of solar cells and power-supply system left then-unmanned station without power or attitude control; Soyuz-T13 crew effected repairs under extreme environmental conditions.
28 Jan 86	Scobee Smith, Onizuka, Resnik, McNair, Jarvis, McAuliffe	STS 51-L	Entire crew of *Challenger* killed when solid rocket booster failed at 73 s after launch, causing explosion and destruction of launch vehicle.
6 Feb 87	Romanenko Laveikin	Soyuz-TM2	Crewmember illness prompted early return from Mir.
29 Aug 88 10 days	Layakhov Mohmand	Soyuz-TM6	Horizon-sensor malfunction shut down engines during reentry. Two restarts were terminated; fourth attempt at reentry was successful.

[a] ATO, abort to orbit.

Table 2 Events prompting escape-and-rescue scenarios

Event	Potential causes	Emergency procedures	Medical consequences
Loss of pressure	Debris/meteoroid impact Systems failure Seal/hatch failure	*Seconds to hours* • Don O_2 masks, pressure suit • Repair • Evacuate	Decompression disorders Hypoxia Trauma (secondary projectiles)
Fire/Explosion	Electrical circuit overload Volatile material release Rupture of pressurized container	*Seconds to minutes* • Don O_2 masks, goggles • Extinguish fire • Evacuate immediate area *Minutes to hours* • Effect repairs • Evacuate	Burns Smoke inhalation Blast trauma
Release of toxic substance	Rupture of containment line or vessel	*Seconds to minutes* • Don O_2 masks • Evacuate affected module • Stop toxic release *Minutes to hours* • Decontamination, cleanup procedures, gloves, etc. • Evacuate	Toxic inhalation Lung injury Hypoxia
Primary medical event	Decompression sickness Electrical shock Infectious disease Isolated trauma	*Seconds to minutes* • Emergency care, CPR • Stabilize for treatment or transport *Minutes to hours* • Treat with available medical facilities • Evacuate ill or injured	Per primary event Cross-infection of crew Rapid use of medical consumables
Exposure to radiation	Solar flare event Nuclear power system failure Experimental mishap Artificial event (ground or orbital nuclear detonation)	Seconds to minutes • Evacuate radiation area • Safe haven, shielding • Stop release if possible *Minutes to hours* • Decontamination, cleanup procedures • Treat radiation-injured crew • Evacuate some or all crew	Acute radiation syndromes • Gastrointestinal • Central nervous system • Hematologic effects Long-term exposure factors • Risk of future malignancies • Career-limiting doses
Loss of attitude control	Guidance/navigation system failure “Stuck thruster”	*Seconds to minutes* • Correct problem • Power-down spacecraft *Minutes to hours* • Correct problem • Evacuate	Trauma Neurovestibular Disorientation
Failure of environmental/ life support system	Mechanical failure Electrical failure Loss of consumables	*Seconds to minutes* • Halt further damage or loss of consumables • Treat medical conditions *Minutes to hours* • Repair damage • Evacuate	Hypoxia Hypercarbia Hypothermia Hyperthermia Dehydration
Interruption in nominal launch services	Accident Safety stand-down Social/political	*Hours to days* • Extend consumables • Evacuate	None specific

Table 3 Time-of-useful consciousness (TUC) for rapid decompression events

Pressure, kPa	Equivalent altitude, m	TUC
50.8	5486	20–30 min
42.7	6706	10 min
37.3	7620	3–5 min
32.0	8534	2.5–3 min
30.1	9144	1–2 min
23.7	10,668	0.5–1 min
18.8	12,192	15–20 s
15.9	13,106	9–12 s
11.6	15,240	9–12 s

Assumes starting pressure of sea-level equivalent, pressure = 101.3 kPa, oxygen concentration = 21%.

Table 4 Physiologic effects of sustained +Gx acceleration [Ref. 39]

2–3 +Gx	Mild visual disturbances, slight spatial disorientation (improves over time). At 3 *g* (breathing 100% oxygen), vital capacity decreases 18%,[27] expiratory reserve volume decreases 45%, tidal volume decreases 33%. After 5 minutes at 3.5 *g*, heart rate increases 25%, cardiac output increases 26%, mean arterial pressure increases 22%.[28]
3–6 +Gx	Progressive chest discomfort, difficulty breathing, loss of peripheral vision. At 5 *g*, vital capacity decreases 54%,[29] respiratory frequency increases 50%, minute volume increases 20%, oxygen consumption increases 16%.[30] Arterial oxygen saturation (breathing air) at 4 *g* decreases to 90% after 2 minutes; at 5.4 G, decreases to 80%.[31] Right atrial pressure increases threefold to fourfold, stroke index reduced by 25% at 4 *g*.[32] Premature atrial contractions noted at 5 *g*.
6–9 +Gx	Further increase in chest discomfort, shallow respiration; progressive vision loss; inability to lift limbs. Vital capacity decreased 86%, minute volume increased by 50%, oxygen consumption increased by 66% at 8 *g*.[30] Increased frequency of premature atrial contractions at 7 *g*.[33]
9–12 +Gx	Respiration extremely difficult; marked chest pain, fatigue, vision loss. Progressive inequalities in pulmonary ventilation-perfusion.

Superscript numbers refer to reference citations.

Table 5 Impact design limits generated with the dynamic-response model for the NASA assured crew return vehicle (ACRV) [Ref. 26]

	Healthy, deconditioned crewmembers, 0.5% risk of major injury	*Ill/Injured crewmembers, 0.5% risk of major injury*
+Gx	35	26.3
–Gx	28	21
Gy	14	10.5
+Gz	15.2	11.4
–Gz	9	6.8

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Chapter 14

Terrestrial Benefits From Space Exploration

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In the 40 years since the first human space flight, both the technologies developed for use in space and the scientific knowledge gained with regard to living in space have been applied to an impressive range of uses on Earth. Many of the constraints inherent in conducting space missions, e.g., the limitations on weight, volume, and power available to payloads and the remoteness of missions from Earth, have forced the development of innovations that have significantly advanced technology. Technologies for communication, miniaturization, automation, and development of new materials conceived for space are now used routinely in Earth-based applications.

The application of space-developed technologies to medicine in particular has proven extraordinary valuable. To date, medical technology spin-offs have created more than $2 billion in sales of medical equipment in the U.S. alone. Advances in miniaturization for space hardware have been used to develop circuitry for implantable devices such as cardiac pacemakers. The high-resolution, bidirectional telemetry needed for space flight operations has been adapted and applied for use in medical monitoring in both ambulatory and critical care settings. Micropumps invented for space use have been adapted for use in chemotherapy, so that people can receive appropriate dosages without having to be admitted to hospitals. Space-developed alloys are used routinely for prosthetics and for joint replacement. The use of transdermal patches for parenteral drug dosing was pioneered in the space program. Another significant cost savings comes not from technology but rather from the use of bed rest as an experimental model to mimic space flight conditions on Earth. Even the healthiest individuals, when confined to bed for long periods, can experience undesirable changes in function, a finding that led to current recommendations for making confinements—in bed or in hospitals—as brief as possible. In general, the application of research results generated through space investigations can play a significant role in containing the cost of providing health care, and in many cases can expand its availability.

In addition to technological breakthroughs, space-based research has proven to be an important supplement to traditional biomedical research by providing a new perspective on the ancient profession of medicine. Traditional Earth-based medicine focuses primarily on treating abnormal conditions in normal environments. Space medicine and physiology, on the other hand, focus on the reactions of normal, healthy individuals exposed to an abnormal environment. Comparing and contrasting the philosophical differences between these two approaches allow a far more complete understanding of the human organism and its function than can either approach alone. As discussed at length in Volume III of the *Space Biology and Medicine* series, investigations of physiological function in space, regardless of whether they focus on cardiovascular, neurosensory, immunological, metabolic, or other systems, allow a new perspective on human functioning by examining how healthy humans react to stimuli that are unfamiliar and that cannot be completely duplicated on Earth. The insights derived and discoveries made during the course of these investigations often are applicable to treating or preventing disease on Earth as well as in space.

As discussed at length in this volume, humans clearly can live and work productively in space (Fig. 1). Ongoing studies directed at clarifying the complex, integrated physiological processes that underlie human adaptation to the space flight environment, and at developing means of protecting people from the negative aspects of that hostile environment, have generated results that are useful for a broad range of Earth disciplines. Some of the applications specific to medicine that have been derived from space activities are the subject of this chapter. The paragraphs that follow constitute a brief review of how the principles used in designing equipment for the spacecraft environment can be beneficial for Earth-based settings. That discussion is followed by descriptions of some of the many benefits accrued in the development of imaging, communications, and robotics technologies; materials science; and biotechnology. Next is a brief section on potential commonalities between aging and space flight exposure in terms of bone loss and postural control. Finally, the conclusion underscores the need to continue enhancing the exchange of emerging technologies between space programs and commercial industries.

I. Principles for Designing Analytical Equipment for Use in Space: an Overview

Equipment designed for use aboard spacecraft must meet strict requirements in terms of size, weight, volume, power, ease of use, and reliability in addition to being able to function without the influence of gravity (Fig. 2). Although few devices meant for operation on Earth were designed to operate independently of gravity, the other constraints on spacecraft hardware, especially portability, ease of operation, and ease of interpreting results, have led to the development of equipment that expands some capability in Earth settings as well as in space. Moreover, automation, the goal of which for space activities is to minimize the need for intervention by busy crews, also can reduce the need for labor-intensive, time-consuming procedures on Earth, and can extend clinical capability far beyond traditional service points such as hospitals or laboratories.

Many research tools for space flight applications began as off-the-shelf equipment that was modified to reduce the size of the component systems. A prototype clinical chemistry analyzer, for example, evolved from a large stand-alone device to a small bench-top unit, and from there to a device the size of a toaster. Another example is a tiny ear oximeter-transducer, developed at Ames Research Center, to measure blood oxygen saturation, blood pressure, pulse rate, and pulse pressure during space flight.[1]

Other aspects of the spacecraft environment aside from size can drive the development of entirely new analytical techniques. For example, when the need for measuring blood electrolytes during space flight first became apparent in the early 1970s, the analytical methods of that time required the use of flammable gases. Since flammable materials are prohibited aboard spacecraft, another approach was required, and new analytical instruments were developed that used ion-specific electrodes to measure individual electrolytes. The first commercial clinical laboratory instruments capable of measuring more than one electrolyte—in this case sodium and potassium—were a direct result of this work. The evolution of portable clinical blood analyzers has continued well into the 1990s; one current device being assessed for routine use in the U.S. space program is designed to measure sodium, potassium, ionized calcium, glucose, pH, and hematocrit, all from an 85 µL “finger-stick” blood sample.[2,3]

Another application conceived to meet spacecraft safety requirements that has proven useful on Earth is a water-treatment device that quickly and easily disinfects drinking water.[4,5] This “regenerable biocide delivery unit” (U.S. Patent 5176836) is a self-replenishing resin bed that imparts biocidal amounts of iodine to recycled drinking water. The device, designed in collaboration with NASA, is an attractive alternative to conventional water-treatment technologies like chlorination, because it does not require hazardous gases or electricity, cannot “overtreat” the water, and can be stored safely for long periods. This water-treatment device is especially useful for treating water supplies that may have been contaminated through floods or other natural disasters.

A final example, an automated microbial analysis system, represents a particularly elegant combination of miniaturization, speed, automation, and ease of use. Traditional methods of screening biological samples for potential pathogens can take up to 4 days. Speeding up this process can reduce hospital stays by allowing infectious agents to be identified more quickly, as well as reducing the indiscriminant use of antibiotics to treat unidentified infections. Inventors of another system devised for use in space[6,7] have miniaturized and automated the process by which microbial pathogens are identified and their susceptibility to antibiotics tested. Tiny samples of body fluids are injected onto disposable credit-card sized microplates. Each plate contains 16–30 wells that hold chemical substrates for microbial growth or inhibition, which are chosen so that a positive reaction generates a change in color or turbidity in the well. The treated cards are placed in trays, which in turn are placed in a reader/incubator module. The system scans each well for chemical reactions every 60 minutes, and compares the reactions taking place with those in a computerized database of identified microorganisms. Once an organism is identified, the sample is tested in the same way for susceptibility to several antibiotics. The entire process takes between 4 and 13 hours, compared with two to four days for traditional culture preparations. This system allows Earth-based microbiology laboratories to provide guidelines for antimicrobial treatment within one day of specimen collection. Other advantages include the minimization of human error, reductions in technician time, and increases in laboratory output. This system also has broad applicability beyond medicine, such as in food processing; identification of biological indicators or contaminants in sterilization processes; and in-plant environmental testing.

II. Imaging And Image-Processing Technologies

Advances in electronics, computers, and miniaturization technologies developed in the course of space exploration have proven particularly valuable for imaging applications. The potential scope of these applications is enormous; the nondestructive testing and visualization allowed by X-ray imaging, for example, can be used for everything from production and quality-control testing to ensuring security at buildings or airports. The diagnostic utility of X-ray imaging in medicine is well known. Spin-offs from X-ray astronomy applications at NASA’s Goddard Space Flight Center have yielded two X-ray imaging devices for medical applications, the LIXISCOPE and the FluoroScan. The LIXISCOPE, a small, portable, low-intensity X-ray imaging device, was designed by Goddard engineers for use at the site of medical emergencies, e.g., accident scenes or sporting events. A modified version of the LIXISCOPE, the FluoroScan (marketed by HealthMate, Inc.), incorporates a variable-power X-ray tube instead of the LIXISCOPE’s isotopic penetrating source, and is safe to use without lead aprons or other traditional safety barriers. The FluoroScan also allows images to be created in real time, so that visible structures can be monitored continuously.[8,9]

The development and use of sophisticated imaging techniques and systems has revolutionized the field of microscopy, and in combination with advances in computer technology continue to produce many new applications every year. Among the most exciting applications of imaging technology in medicine are its uses in microscopic diagnosis, surgery, and other forms of treatment. Some space-related applications of computed tomography (CT) and magnetic resonance imaging (MRI) technologies adapted for use in surgery and in the diagnosis of breast cancer and cataracts are described briefly in the next paragraphs. Next are described two additional imaging applications, designed to aid people with visual impairments. The final component of this section on uses of imaging and image-processing technologies focuses on the use of global geographic images to track patterns of disease transmission around the world.

A. Surgical and Diagnostic Applications

Two relatively recent types of imaging applications, computed tomography (CT) and magnetic resonance imaging (MRI), have changed the course of medical diagnosis and treatment, particularly surgical treatment. Both CT and MRI are based on digital signal processing, a means of computer-enhancement of images that was pioneered in the 1960s for the Apollo Lunar Landing Program.[10] Since that time, CT and MRI techniques have greatly reduced the need for exploratory surgery, and in combination with other techniques have minimized the destructive and invasive nature of many surgical procedures.

The advent of CT (also known as computerized axial tomography), which generates cross-sectional images from thousands of X-ray images collected in a given plane, represented a quantum leap from single-view roentgenograms. A particularly powerful application of tomographic technology is that of positron or single-photon emission computed tomography (PET or SPECT, respectively). In these techniques, patients are given short-lived radionuclides that emit photons when they react with active tissues; computers are used to trace the path of these particles and to produce composite images of metabolic and physiological functions in those tissues.

Another sophisticated use of CT technology was developed jointly by investigators at NASA’s Ames Research Center and the Stanford University Medical Center in Palo Alto, CA. Using software originally developed for space research, members the Biocomputation Center (NASA) and the Department of Reconstructive Surgery at Stanford designed a system with which laser images are integrated with CT scans of a patient’s head to create detailed three-dimensional images of the face and skull.[11,12] This “virtual workbench” system allows images of the cranial exterior and interior to be manipulated freely. The system can be used for “phantom surgery,” which allows physicians to plan—and safely practice—various surgical approaches. It also allows patients to see the potential results from complex craniofacial surgery before that surgery is begun.

The development of MRI represents another giant step forward in imaging technology, through improving contrast among adjacent tissues while eliminating the need for radiation. This type of imaging depends on the reaction of hydrogen atoms in tissue to harmless radiofrequency pulses, and can generate extremely detailed images of the human body.

Another more specialized use of image-processing technology forms the basis of percutaneous transluminal or “balloon” angioplasty. In this type of surgery, cardiologists use a digital cardiac imaging system, originally developed for Earth-resources survey satellites, to manipulate images to guide their progress during angioplasty and to compare vessel patency before and after the procedure.[13]

Those patients who cannot withstand the balloon angioplasty procedure may benefit from another type of microsurgery that also represents a spin-off from space technology. In this type of microsurgery (“excimer laser angioplasty”), a tiny fiber-optic probe that contains a laser beam, light source, and camera lens is threaded through a stenosed (constricted) artery. Areas of atherosclerotic plaque formation are visualized and then excised or reduced with short bursts of ultraviolet light, which generates considerably less heat than conventional thermal lasers. Precise control of the laser pulse is made possible by a system of magnetic switches originally developed at the Jet Propulsion Laboratory to measure gases in Earth’s atmosphere.[14,15]

1. Mammography

Astronomy and breast-cancer detection share several common imaging requirements. Both require high resolution, so that minute details can be visualized, and both must be operable over large ranges of illumination.[16] New combinations of digital detection technology and computer-aided diagnosis and image processing are proving useful in improving mammographic technology.

Digital mammography has several advantages over film-based X-ray imaging systems for detecting breast cancer early and reliably. Digital images are not only more easily stored, transmitted, and displayed than film exposures, but images that are collected with electronic sensors such as charge-coupled devices (CCD) also are of superior quality over film in their linearity, dynamic range, and sensitivity. Difficulties in expanding the image format from the previous limits of about 3 cm by 3 cm to a more practical 18 cm by 24 cm led the U.S. National Cancer Institute to join forces with NASA and other agencies to speed the development of digital mammography.[17,18]

CCDs used as light sensors in the Hubble Space Telescope have already been adapted for use as imaging sensors in a stereotactic breast biopsy system.[19–21] The "Advanced Breast Biopsy Instrumentation" (ABBI) system,[22] already in use throughout the U.S.,[23,24] allows targeted lesions to be located with high accuracy (within 1 mm) and removed in their entirety at the time they are located, while the patient is under local anesthesia. This system represents substantial improvements in accuracy over excisional or core-needle biopsy techniques, and eliminates the need for general anesthesia during the biopsy procedure.[24] In addition to being less traumatic for the patient, this form of biopsy is much less expensive than traditional surgical biopsy techniques.

Other aspects of the technology developed for the Hubble Telescope also are being used to expand the image format to a size useful for imaging the entire breast. Diagnoses then could be made more easily by comparing a baseline image taken of a healthy breast with images of the same breast collected over the course of subsequent examinations. For the "Stratospheric Aerosol and Gases Experiment" ("SAGE III"), appropriately sized images were created through the use of an array of CCDs. In this technique, the array is moved across a target area, multiple images are collected, and the final image is reconstructed with computer software.[25] Clinical prototypes of a large-area, high-resolution mammography imaging device are being developed by a team of investigators at NASA Langley Research Center, the National Cancer Institute, and the University of Virginia.[26] Clinical testing is planned for late 1997 and 1998.[25] Another effort, based on research funded by NASA, the U.S. Army, and the Ballistic Missile Defense Organization, focuses on using miniature silicon pixel detectors, a form of sensor that couples CCDs and their required electronics on a camera on a computer chip,[27] to detect breast cancer at early stages. The "Brigit" device, being developed by investigators at the Lawrence Livermore National Laboratory, Fischer Imaging Corporation, and the University of Toronto, includes an X-ray source that can be tuned to various wavelengths, which in combination with its unique detector design is expected to produce superior image quality with significantly less radiation exposure than conventional mammography units.[19]

Other aspects of digital mammography that have been targeted for development involves developing and validating new algorithms, neural networks, and other forms of machine intelligence for computer-aided diagnosis.[18] Here, too, NASA technology has formed the basis for several ongoing projects. In one such project, members of the Space Telescope Science Institute are adapting image-processing algorithms used for various experiments with the Hubble Telescope for detecting clusters of microcalcifications within the breast, an early indication of possible malignancy. Another project underway at Bilkent University in Turkey is focusing on automating the detection and enhancement of microcalcifications from digital mammogram images.[28–30] Additional information on related efforts can be obtained from members of the U.S. National Institutes of Health/National Cancer Institute (NIH/NCI) National Digital Mammography Development Group.[31]

2. Cataract Detection and Monitoring

In addition to X-ray, CT, and MRI technologies, another means of creating images—laser-light scattering—is being applied for medical purposes: detecting the formation of cataracts in vivo. A dynamic laser light-scattering probe, developed at NASA Lewis Research Center to characterize fluid-particulate dispersions in microgravity experiments, also can be used to follow the agglomeration of protein crystals in the lens of the eye, an early sign of cataract formation (Fig. 3).[32] Information about the size and location of these crystalline agglomerates can be presented on a three-axis grid, or in color images dubbed "cataractograms." These images provide a quick means of detecting and tracking the formation of unhealthy crystalline masses in otherwise healthy lens tissue over time. The probe device was demonstrated in the October 1996 meeting of the American Academy of Ophthalmology as one of 15 technologies judged likely to affect the practice of ophthalmic care in the next century. Preliminary tests of the probe in anticipation of clinical trials are underway at the U.S. National Eye Institute (NEI) as part of an interagency agreement between the NIH and NASA. The inventors of this device hope to be able to expand its capabilities to produce color images of the vitreous body as well as the lens, which will aid in the diagnosis and study of diseases affecting this part of the eye.

B. Vision Enhancement Applications

1. Low-Vision Enhancement System (LVES)

Other types of imaging technologies used for space applications have given rise to at least two types of devices that can help visually impaired individuals on Earth. One of these devices, the Low-Vision Enhancement System (LVES, pronounced “Elvis”), was introduced to the commercial marketplace in 1994 by a large development team that included NASA, the Wilmer Eye Institute of The Johns Hopkins University, the U.S. Department of Veterans Affairs, and Visionics Corporation. Based on NASA technologies for processing satellite images and for head-mounted vision-enhancement systems, the LVES, manufactured by Visionics, is a video magnification device consisting of three miniature cameras mounted in a helmet, inside of which are two miniature viewing screens (Fig. 4). The unit can zoom from two inches to infinity, can provide up to nine times magnification at distance and up to 25 times at near, and is completely portable. The cameras feed video images to a computer, which corrects for the individual’s particular vision problem, and forwards the images to the video display in the goggles. “Zoom-in” and contrast-enhancement features allow “close-up” focus that allows users to read, watch television, and use personal computers. The LVES is available through prescription only; each device is programmed and fit for each person’s particular visual needs. The potential market for the LVES includes people whose vision has been impaired by diabetes, glaucoma, multiple sclerosis, macular degeneration, retinitis pigmentosa, and other ocular ailments or injuries.[33,34]

2. Optacon and Optacon II

The original “Optacon” device, marketed by TeleSensory, Inc., was introduced in the 1970s as a print-reading device for blind people. The underlying optical scanning technology was used by Ames Research Center and the Stanford Research Institute for the “Viking” series of Martian-surface explorers. The user passes a small camera over a printed page with his or her left hand; a control unit processes the image and translates it into a vibrating tactile image of the words the camera is viewing, and the user touches the vibrotactile pin array to “read” the words (Fig. 5). This system can be used with nearly any alphabet or language, and is in use in more than 70 countries. A greatly enhanced second-generation spin-off, the Optacon II, was introduced in 1989 by TeleSensory and Canon, Inc. The new device uses the same basic technique of converting printed information into a tactile image, but connects directly to a desktop computer and allows the user to read graphic images as well as text. The new device also is completely portable, and can be run on battery power for up to 8 hours. Further improvements to this and related devices are expected to include haptic representations in addition to tactile images.[35–37]

C. Using Remote Sensing and Computer-Based Geographic Information Systems to Track Vector-Borne Infectious Diseases

The international medical community has become concerned over the recent global emergence and reemergence of infectious disease (Fig. 6).[38] Techniques developed in space for observing geographical and environmental factors on Earth (Fig. 7) have numerous applications in disease control, especially with regard to vector-borne illnesses. Vectors, i.e., invertebrate animals such as ticks, mosquitoes, flies, and others that can transmit an infectious agent among vertebrates, require specific living conditions in which to reproduce and transmit the infection. Key environmental elements such as elevation, temperature, rainfall, and humidity influence the presence, development, activity, and longevity of pathogens, vectors, zoonotic reservoirs of infection, and their interactions with humans.[39] The type and distribution of vegetation also are influenced by these variables, and can be expressed as landscape elements that can be sensed remotely and their interrelationships modeled spatially.[40]

Previous research involving the use of remote-sensing (RS) data to study disease has focused on identifying and mapping vector habitats, or assessing environmental factors related to vector habitat quality.[41–47] More recent studies focus on investigating how RS and spatial analysis techniques can be applied in identifying and mapping those landscape elements that collectively define the vector and human population dynamics related to the risk of disease transmission.[48–57]

The use of geographic information systems (GIS) has many implications for landscape epidemiology, because it provides to users the ability to store, integrate, query, display, and analyze data from the molecular level to that of satellite resolution through their shared spatial components. Field observations on environmental conditions, including vegetation, water, and topography, can be combined in a GIS to interpret RS data directly and to facilitate characterization of the landscape in terms of vector and pathogen prevalence. The associations between disease risk variables (e.g., vector, pathogen, and reservoir host abundance and distribution) and environmental variables can be quantified by using the spatial analysis capabilities of the GIS. Landscape pattern analysis, combined with statistical analysis, allows us to define landscape predictors of disease risk that can be applied in larger regions where field data are unavailable. This makes RS/GIS a powerful set of tools for disease surveillance, predicting potential disease outbreaks, and targeting intervention programs.[58]

RS/GIS technologies have been used to monitor and predict outbreaks of malaria, Lyme disease, schistosomiasis, filariasis, and other diseases.[54,55,59] The following descriptions are taken largely from an overview of the Ames Research Center's Center for Health Applications of Aerospace Related Technologies (CHAART) program.[59] Additional information is available from the participants in that program.

1. Malaria

Beginning in 1985, investigators at Uniformed Services University of Health Sciences, University of California at Davis, Centro de Investigacion de Paludismo at Chiapas, California State University at Fresno, University of Texas Health Sciences Center, and University of Texas at El Paso joined forces to apply RS/GIS technologies for malaria surveillance. The first phase of this effort involved developing landscape models to follow the dynamics of the *Anopheles albimanus* Wiedemann mosquito, an important vector for malaria, in California rice fields. Results from this effort verified that high-anopheline-producing fields could be identified with more than 90 percent accuracy two months before peak anopheline production.[54] Next, this landscape model was extended to Chiapas, Mexico, along the Pacific coastal plain, with the goal of modeling malaria vector/human contact risk within villages in this region. The proportions of transitional swamp and floodable pasture in these areas were found to be the best predictor of mosquito abundance within a village.

Other applications of RS technologies for malaria control are underway in Belize, Brazil, and Nigeria, where the incidence of malaria has been increasing. RS technology will be used to define the temporal and spatial distributions of environmental factors that themselves determine the presence and abundance of mosquito vectors. These factors, in combination with demographic data, will provide specific predictors of which locations are at high risk for human malaria. Ultimately, the predictive model will direct how the various types of vector-control interventions can be used for maximum effectiveness.

2. Lyme Disease

Lyme disease is currently the most commonly reported vector-borne disease in the U.S., with more than 80% of reported cases occurring in the northeast. Residential development within recently reforested suburban areas has brought increasing numbers of people into closer contact with the tick vector, *Ixodes scapularis,* and consequently to the Lyme disease agent, *Borrelia burgdorferi.* This species of tick and its natural hosts (e.g., deer and rodents) are associated with particular landscape features, e.g., forested habitat. High densities of white-tailed deer, the most important host of the adult-stage tick, are supported by the residential-forest landscape, which contains preferred forage in an abundance of edge habitat and ornamental plantings. Mice and other small vertebrates are common hosts of the juvenile stage of the tick, and many of these hosts also serve as reservoirs of the disease.

RS/GIS technology has been used to identify and map landscape characteristics related to exposure risk for Lyme disease in two separate studies in Westchester County, New York. Another similar study is underway in the north central U.S. (from the upper peninsula of Michigan to northern Illinois). The eventual goal of this research is to develop a satellite RS/GIS model for predicting the risk of Lyme disease that can be used by public health agencies to reduce disease incidence. This approach will increase the efficiency with which limited resources are targeted to those places where they are most needed.

3. Other Diseases

Investigators at Ain Shams University in Cairo, Egypt, are using RS/GIS to explore the spatial patterns of filariasis in the Nile delta. This disease, caused by infection with nematode parasites, is transmitted by the mosquito *Culex* *pipiens*. Data from the Landsat Thematic Mapper satellite, which coincided with epidemiologic field data from this region, were converted into indices of vegetation and moisture, and classified with respect to type of landcover. Statistical analyses are being used to compare landcover variables with the spatial distribution of microfilaria in 201 villages in 10 communities.

Another CHAART project, this one headed by the School of Public Health at the University of California, Berkeley, involves a GIS analysis of schistosomiasis in relation to the drainage network surrounding a village in southwestern Sichuan Province, China. The goal was to develop a hydrologic model that could be used to identify risk factors for disease transmission. The GIS database included topography, irrigation networks and natural drainage systems, demographics, location of residences and work areas, snail habitats and night-soil storage sites, snail population densities, and disease incidence. Risk was found to depend mostly on age and housing location. Future efforts will focus on using remote sensing data to extend the village model to the Anling River watershed.

Other collaborative programs planned include investigations of how environmental and climate changes affect the spatial and temporal distribution of the *Aedes* mosquito (a carrier of dengue fever and other human diseases), the Africanized honeybee, and carriers of the new Bengal strain of cholera.

III. Communications

A. Telemedicine

Another broad-reaching application of space technology is *telemedicine,*[60,61] i.e., the practice of medicine through the exchange of information, data, images, and video across large distances via telecommunications networks (e.g., telephone lines, satellites, microwave, the Internet, and so on). Ongoing improvements in telecommunications technology, which allow information to be transferred and accessed at previously unheard-of speeds, can greatly enhance access to medical information as well as the delivery of medical care.[62] Spacecraft and space habitats, of course, are the most remote of outposts. The extent to which crews that inhabit those outposts will rely on telemedicine for their medical care is expected to increase as both the duration of missions and the remoteness of those missions increase. The following paragraphs describe some of the philosophies and instruments developed for telemedical applications, first for space crews and next for terrestrial populations.

1. Space Telemedicine

The U.S. space program relies on telecommunications to conduct routine medical operations. Two-way voice communications, and one-way video and data downlink, constitute the communications capabilities for telemedicine. Biomedical variables and aspects of the cabin environment are monitored via telemetry, and private medical conferences (PMC) are held daily between the crew surgeon in the mission control center and each individual aboard the spacecraft. This communication has become increasingly important during long missions such as those aboard space stations.

A device developed to support biomedical research via “telemetry” was the portable dynamic fundus instrument (video fundus camera), which was first developed to decrease the time needed to train astronaut crews to take photos of the retina for a flight experiment that examined the effects of microgravity on retinal blood vessels. Since the video images were of excellent quality, the video device was used in addition to a 3 mm film version. Overall, the instrument was flown on 6 U.S. Space Shuttle missions, and video images of the retina were downlinked in July 1992 on STS-50.

A more extensive system developed for space flight telemedicine aboard the International Space Station (ISS) is a portable telemedicine instrumentation pack[63] (Fig. 8). This system, envisioned as a portable diagnostic clinic, is being designed to link the patient (or astronaut) with Earth-based consultants (the flight surgeon and others) via video, audio, and data communications.[64,65] The flight surgeon uses a voice channel in the spacecraft communications system to instruct the TIP operator as to which instruments to use, and to request information needed to assess the patient’s condition. Video signals are used to transmit information on overall appearance and that of the skin, ear, nose, throat, and eyes, as measured with macro zoom lenses, otoscope, rhinolaryngoscope, ophthalmoscope, and fundus camera. Audio signals are measured with an electronic stethoscope, and include heart, lung, and bowel sounds. Data signals to be measured and downlinked include electrocardiography waveforms, heart rate, and blood-oxygen saturation, the latter to be assessed with a pulse oximeter.

2. Terrestrial Applications

The same high-quality communications technology that link spacecraft with mission-control centers can be used to link remote locations on Earth to large medical centers, thus providing opportunities for specialty consultations that otherwise might not be possible. In this way, telemedicine can provide a cost-effective way of delivering high-quality health care to remote areas, such as disaster sites, and to traditionally under-served populations. An overview of NASA involvement in terrestrial telemedicine applications is shown in Table 1.

Medically underserved areas. Telemedicine technologies can be used by physicians and other health care practitioners to extend medical care to populations that are medically underserved, i.e., have inadequate access to primary-care providers and facilities. One example of such an application was the “Space Technology Applied to Rural Papago Advanced Health Care” or “STARPAHC” project, conducted in the 1970s. NASA and the Indian Health Service conducted a 2-year telemedicine project on the Papago Indian Reservation near Tucson, Arizona. This project involved mobile health units linked to the Indian Health Service hospital via a microwave communication system. Nonphysician medical personnel conducted medical examinations aboard the mobile health units and the video, audio, and data signals were transmitted to the hospital staff for review. This project’s major benefit was in providing health care resources not previously available in the local area.[66]

Telemedicine also can benefit the delivery of health care to other locations as well, such as work sites; correctional facilities (prisons); accident, battle, or natural-disaster sites (see below); and homes.[65] Occupational medicine clinics at work sites can use telemedicine to consult with specialists without the patient having to leave the site. The use of telemedicine at prisons or jails could reduce the need to transport inmates to secondary or tertiary care facilities. An example of the latter is a recent contract between the Texas Department of Criminal Justice and the University of Texas Medical Branch in Galveston. The Galveston hospital system plans to use telemedicine to help reduce the cost of caring for incarcerated individuals.[67] Teleradiology and telemedicine is used in emergency and military medicine sites around the world.[68–71] Projects in development to improve battlefield survival range from a wristwatch-type device for monitoring soldiers’ vital signs to a mobile telerobotic surgery system.[72] Telemedicine also could be used to help with triage in the event of industrial mishaps or accidents, especially for isolated or remote worksites (e.g., offshore drilling or maritime industries). Finally, the need for home health care in managing chronic disease is expected to increase greatly in the U.S. as the average age of the population increases.[65] Home health care workers can use aspects of telemedicine to monitor patients’ recovery from illness, injury, or surgery at home, which may reduce the length of time patients need to remain hospitalized.

Disaster relief. As shown in Table 1, NASA has provided satellite communications for several telemedicine projects on Earth. The first Applications Technology Satellite (ATS-1) and the subsequent ATS-6 satellite were used to provide “teleconsultation services” during telemedicine experiments in central Alaska in the 1970s.[73] NASA, the American Red Cross and the Pan American Health Organization (PAHO) worked together via the ATS-3 satellite to coordinate disaster-relief efforts after an earthquake struck Mexico City.

This concept was expanded after another earthquake struck the Republic of Armenia in December 1988, leaving much of the health care delivery system there in ruins. Under the auspices of the US/USSR Joint Working Group on Space Biology and Medicine, American and Soviet space agencies established a “Spacebridge” of satellite-based communications networks that linked Armenia with medical centers in the United States (Fig. 9).[74] Over the 3 months that the Spacebridge was in operation, 247 Armenian and Russian and 175 American medical professionals participated in 34 clinical sessions dealing with a variety of clinical disciplines (Table 2).[74] Clinicians reviewed 209 cases of injuries sustained in the Armenian earthquake and burns sustained in a gas explosion in Ufa, Russia, one month after the Spacebridge was implemented. Diagnostic and therapeutic decisions were made in “real time” across 11 time zones. Several satellite networks for distant interpretation of images and data are now operating in the United States and other countries.

More recently, Russia and the U.S. completed a collaborative telemedicine demonstration, Spacebridge to Moscow.[75] A follow-on to the Spacebridge to Armenia, the Spacebridge to Moscow, linked several U.S. medical centers with a hospital in Moscow via a dual-hop satellite network. It provided real-time, full-motion color video for medical consultation. Experience in telemedicine and communications technologies has helped promote the practice of telemedicine across the globe. Both Spacebridge projects[75,76] clearly demonstrated that existing telemedicine systems can be easily deployed and used to support medical consultation in the aftermath of natural disasters.

NASA Headquarters and the Pan American Health Organization recently extended the disaster-preparedness concept by establishing an Internet-based network. This network provides links between offices and agencies in several Central and South American countries, with the goal of strengthening disaster management, preparedness, and response. In this way, the Internet can be used as a cost-effective tool to support training for disaster-response personnel in the host country.[77]

Global health care education and training networks. Several efforts are underway to extend telemedicine and Internet and World Wide Web (WWW) communications capabilities still further, to encompass medical education and training activities. One such effort is the Global Health Network (GHNet), a WWW-based source for disseminating information on medicine and public health. A joint venture between NASA and the University of Pittsburgh, the GHNet also is envisioned as becoming a virtual university, providing interactive collaborations and communications to support medical education.[77]

Another large-scale effort is the “Spacebridge to Russia” project, a telemedicine test bed that links academic and clinical sites in the U.S. and Russia via the Internet for clinical consultations and medical education.[75,77,78] Component sites in this effort include the LDS Hospital in Salt Lake City (Utah), Fairfax Hospital in Falls Church (Virginia), Yale University School of Medicine in New Haven (Connecticut), the Clinical Hospital of the Medical Department of the Ministry of Interior in Moscow, and the Space Biomedical Center for Training and Research at Moscow State University. The telemedicine studio is located at the Clinical Hospital of the Medical Department of the Ministry of Interior in Moscow. Medical diagnostic equipment at this site is being integrated with the workstation and the telemedicine studio. Each site has a UNIX-based Indy™ workstation (Silicon Graphics, Inc.) with a graphic user interface, which provides the capabilities for acquiring patient information including an electronic patient record containing medical images, heartbeats, and diagnostic movies as well as text. Each workstation can initiate real-time multicast videoconferences, support MIME-compliant e-mail, and access the WWW.[78] Several hundred clinical consultations are planned between the clinical sites in the U.S. and Russia. Clinical consultations are prepared at each site by using a standard format, which includes motion video, data transfer, still photography, and video teleconferencing capabilities. Cases are stored in a relational database that is made available to the reviewing hospitals through a WWW server.[78]

NASA’s Johnson Space Center is working with the Baylor College of Medicine in Houston and with Moscow State University to use the Spacebridge to Russia infrastructure to provide lectures on medical topics. Lecture material is provided via a graphical user interface on the WWW.[77]

B. Sensors and Feedback Technologies: Monitoring Biomedical Functions

Ensuring the health, safety and productivity of crewmembers in space, and studying their responses to being in space, requires keeping a close watch on crewmembers’ physiological functions during flight. Tracking heart rate, blood pressure, temperature, and other variables involves using biosensor technology to collect the data, and telemetry to relay that data back to Earth by means of radio signals.

In the late 1980s, NASA initiated the “Sensors 2000” program to develop new, noninvasive monitoring technologies designed to meet space biomedical research requirements while interfering as little as possible with crewmembers’ activities during flight. These noninvasive biosensor and biotelemetry systems are small, lightweight, and easy to use; some can be implanted or consumed. Thus far, the program has produced several implantable biotelemetry systems, and sensors that detect pH, calcium, and blood gases.[79] These and other similar applications are described briefly in the following paragraphs.

1. Cardiac Pacemakers

Early requirements for small, highly reliable bioelectric signal conditioners for the Mercury astronauts led to the development of a programmable cardiac pacemaker in the late 1970s (Siemens-Pacesetter, Inc., Sylmar, CA, USA).[80,81] That system, marketed under the trade name Synchrony Pacemaker System, represented three significant advances at that time: the first rechargeable, long-life pacemaker battery, based on technology for spacecraft electrical power systems; the first single-chip pacemaker, a product of space microminiaturization technology; and the first pacing system to use bidirectional telemetry, a NASA-developed technology for two-way communication with satellites. The pacemaker system, now in its fourth generation,[82] includes a unique sensor that responds to the degree of body movement by either slowing or speeding the heart rate. After the pacemaker is implanted, the associated control system is used to reprogram and fine-tune the device to the individual's particular needs, thus avoiding the need for further surgery to adjust the device's function. The bidirectional communication system allows both control commands and system queries to be delivered to the pacemaker; for example, the physician can send signals to the pacemaker to change its rate, and also can receive signals from the implanted device regarding the status of its interaction with the heart tissue. The inclusion of 28 pacing functions and thousands of programming combinations in the control unit frees users of the Synchrony device to jog, swim, dance, and participate in other strenuous activities. The microprocessor unit can record and store pertinent pacemaker data for up to one year.

Other related spin-offs have included rechargeable batteries and devices to detect and abort cardiac dysrhythmias, which can save the lives of an estimated 50,000 cardiac patients in the U.S. each year. Bidirectional telemetry also is used to monitor physiological functions of patients in ambulances, intensive care units, and coronary care units.

2. Baroreceptor Monitors

Another device designed to test regulation of blood pressure during space flight is useful for terrestrial studies of people with congestive heart failure, chronic diabetes mellitus, and other conditions in which baroreceptor control mechanisms may be affected. Findings from studies using a neck-cuff device during the SLS-1 Shuttle mission in June 1991[83] may clarify the mechanisms underlying orthostatic intolerance after space flight—or long periods of bed rest.

Interest in using a similar device to test baroreceptor function in Earth-based subjects led to development of the commercially available "Baro-Cuff" device.[84] Since the arterial pressure sensors in the carotid arteries are more accessible than those in the aortic arch, the Baro-Cuff is designed to be worn around the subject's neck. The cuff is used to deliver pulses of positive or negative pressure that are similar to natural changes in blood pressure, but span a slightly larger range. The precise relationship between arterial pressure and heart rate in a variety of conditions can be explored by comparing the pressure applied by the cuff with the reflexive changes in heart rate triggered by that pressure, which is recorded with an electrocardiograph.[85,86]

3. Thermometers

Several types of thermometers have been developed from the infrared radiation technology used to measure temperatures of distant stars and planets. Perhaps the most familiar of these applications is the aural infrared thermometer, which provides a digital display of body temperature in less than 2 seconds by measuring the heat emitted from the tympanic membrane (eardrum).[87] One such device, the Diatek Model 7000 (San Diego, CA),[88] weighs 8 ounces (226 g) and can be operated with one hand without disturbing the patient (Fig. 10). This device provides both substantial time savings over traditional oral temperature measurements, and significantly improved comfort over rectal measurements. Moreover, since the infrared probe does not come in contact with mucous membranes, and is covered with a disposable plastic tip, the risk of cross-infection between patients is minimal.[89]

Another type of thermometer is an ingestible capsule that measures the subject's internal (core) body temperature.[90,91] The subject swallows a 3/4-inch (2 cm) capsule that contains a telemetry system, a microbattery, and a quartz crystal temperature sensor. The sensor reads the internal temperature and telemeters the information to a receiving coil outside the body, from which the signal is relayed to a computer. The system, marketed under the name CorTemp (Human Technologies, St. Petersburg, FL), can record temperature every 30 seconds during the 24 to 78 hours it takes for the capsule to traverse the alimentary tract. This system was developed jointly by The Johns Hopkins University Applied Physics Laboratory and Goddard Space Flight Center. Originally intended for treatment of hypo- or hyperthermia, this type of thermometer also is useful for monitoring circadian rhythms, fertility cycles, incubators, and some aspects of surgery. The Applied Physics Laboratory is working on an advanced 4-channel capsule that will simultaneously monitor temperature, heart rate, internal pressure, and acidity.

A third type of thermal-sensing technology that is proving useful for medical applications is infrared thermography.[92] Thermographic devices convert infrared radiation into voltage signals that can be displayed in various forms. Shifts in skin-temperature patterns can offer important clues for diagnosing disease or functional anomalies, and can be used to follow the progress of healing or therapeutic interventions as well. For example, localized areas of warmth on the skin can indicate inflammation, and cold areas can reveal poor blood circulation.

Asymmetrical temperature patterns on the body surface can serve as a visual indicator of pain; mapping dermatomic areas (i.e., those areas supplied by a specific spinal nerve) allows accurate measurement of nerve dysfunction. Sensory nerve impairments in the lower back can be detected by a difference in temperature from one extremity to another of only 1°C. Thermography also can be a valuable as a screening tool, in that it can provide information that eliminates the need for more invasive tests. Thermal imaging also can verify a patient's progress through therapy and rehabilitation, and is finding special utility in determining the extent of sports injuries.

4. Fetal Monitors

A team consisting of representatives from NASA Ames Research Center and the University of California-San Francisco (UCSF) Fetal Treatment Center is adapting space biosensor and biotelemetry technology to monitor fetuses in utero.[93,94] The original biotelemetry technology was used in the joint U.S./Russian "Bion" biosatellite program to monitor the physiological responses of the monkeys on these missions.

The UCSF Fetal Treatment Center has pioneered the use of sophisticated surgical procedures to correct certain congenital defects in human fetuses before they are born. This group, and others like it, sought a way to continously monitor fetal heart rate, intrauterine pressure, and other variables both during and after the surgery. The ideal device would be small, portable, and unobtrusive enough so that pregnant women could wear it as needed outside the hospital.

With these needs in mind, this team developed the Implantable Biotelemetry System, which is now used during in utero surgical treatment of diaphragmatic hernia. In this condition, displacement of the abdominal organs into the chest cavity leaves insufficient room for pulmonary growth and expansion; left untreated, about three-quarters of children born with diaphragmatic hernia die. Moreover, conventional treatment for fetal diaphragmatic hernia can be extremely expensive (up to $1 million), and involve a hospital stay of up to six months. The new fetal surgery procedure involves incising the uterus as if for a caesarian section, surgically correcting the flaw, and implanting a biosensor and telemetry transmitter under the skin of the fetus or in the uterus (Fig. 11). Information on fetal heart rate, temperature, and intrauterine pressure is transmitted to an external receiver and the fetus's health status is monitored for the remainder of the pregnancy. After the infant is born and his or her condition is judged to be stable, the device is removed. This fetal surgery procedure costs only slightly more than a standard caesarean section and requires only a two-week hospital stay for the infant.

Future improvements to the monitoring system for fetal-surgery applications are expected to include a sensor to measure blood pH, which may be a more reliable early indicator of fetal distress than the variables currently monitored, and expansion of the telemetric capability that would allow pregnant women to live outside the hospital during the course of monitoring.[95] Other biosensors of interest for space applications include those that measure calcium and glucose.

5. Implantable Drug Delivery System

Biotelemetry developed to monitor space crews also served as the basis for another spin-off, this one a device that can be programmed to administer precisely controlled doses of medications to ambulatory patients according to those patients' needs.[96,97] Two versions of this system, one that is implanted and the other worn externally, were created by a team from the Applied Physics Laboratory at The Johns Hopkins University, NASA Goddard Space Flight Center, and MiniMed Technologies (Sylmar, CA, USA). Both the pump and the telemetry whereby the drug delivery schedule is controlled were based on NASA technology. The implantable system consists of a refillable drug reservoir, a pump mechanism, a catheter leading from the pump to the patient's intestine, a microprocessor, and a lithium battery, all encased in a 8 cm by 2 cm titanium shell. After the rate at which the drug is to be administered is calculated, the schedule is implemented by digital telemetry; preprogrammed codes allow the physician—or the patient—to adjust the infusion rate, add supplemental doses, or generate records of the pump's performance as needed. The reservoir can be refilled with a hypodermic needle, without surgery. The external version of this system, marketed as the MiniMed 504, consists of a microprocessor, battery, and syringe reservoir in a package the size of a credit card, which can be clipped to the wearer's clothing. The syringe is connected to an infusion set consisting of flexible plastic tubing with a small needle at the end. The drug dosages are calculated and programmed into the system in the same way as for the implantable version. However, the external system allows the user to dose him- or herself subcutaneously, usually in the abdomen, according to the preprogrammed dose schedule. Early versions of these systems were designed to deliver insulin[96,97]; however, this technology also could be used to deliver anticoagulation drugs, chemotherapeutic agents, or other kinds of drugs as well.

6. Autogenic Feedback Training System

Other forms of monitoring technology have proven useful for learning to modify one's responses to a variety of environmental stressors. The Ames Autogenic Feedback Training System (U.S. patent pending) was originally developed by NASA to facilitate astronaut adaptation to the space flight environment.[98] In this system, subjects undergo a 6-hour training program during which they wear an ambulatory monitoring and feedback system, which sends physiological signals to a PC-based display system. Interactive software allows real-time display of cardiovascular variables such as cardiac output, blood pressure, vagal tone, and total peripheral resistance.

Autogenic feedback training is highly effective in treating motion sickness in crews aboard high-performance aircraft, and has many other potential applications as well. This type of training can be used to reduce physiological arousal, improve individual psychomotor performance, and improve coordination and communication among crews. It can be used to modify the effects of sleep deprivation on cognitive performance and to facilitate sleep, thereby reducing disturbances in circadian rhythmicity. Autogenic feedback training also can be useful in the treatment of hypertension, dysautonomia, autonomic neuropathy, and chemotherapy-induced nausea. Other possible applications include alleviating low blood pressure in people with diabetes, spinal cord lesions, or generalized somatic paralysis; and modifying central nervous system activity in epilepsy, attention deficit disorder, and mild head trauma.

7. Speech Aids

Space technology also has played a part in developing two speech aids. The first, the Resnick Speech Teacher™ (marketed by Dynamed Audio, Inc., Natrona Heights, PA), is a feedback system that provides visual cues to people who cannot hear, in order to help them modulate the tone and volume of their speech. Words spoken into the Speech Teacher's microphone are electronically processed and displayed in combination with an “optimal” voice tone pattern; the speaker then can adjust his or her voice to match the optimal pattern. This device is available in two forms, a desktop model and a wrist-mounted version.[99,100] The second device, the Resnick Tone Emitter I™, is a miniaturized electronic system for use by people who have lost their larynxes. The components of this system, a microchip, microcircuitry, power switch, speaker, and rechargeable battery, are built into a denture consisting of three or more artificial teeth. Like a normal larynx, this device produces a tone that can be shaped into words by the tongue, teeth, lips, and palate.[99,100]

IV. Robotics

The scope of potential medical applications for space-developed robotics technology is immense. On one level, robotic attachments such as those designed for the Space Shuttle remote manipulator arm (Fig. 12) have found useful application for limb prostheses. Research at NASA Marshall Space Flight Center has led to the development of several upper-limb prosthetic aids. One such device, a rotationally actuated prosthetic “helping hand” (U.S. Patent No. 5,021,065), contains a clamping mechanism that is opened and closed by rotating the lower arm. This design is more durable, more comfortable, and easier to use than other kinds of artificial limbs.[101] Other types of prostheses for lower-arm amputees are designed to expand the wearer's ability to manipulate small objects or work with tubular or bar-shaped objects (U.S. Patent No. 5,163,966).[102] Another device is a simplified elbow joint (U.S. Patent No. 5,314,500) that allows the wearer to lift and manipulate heavy objects. The new design has far fewer parts than existing designs and is less expensive to manufacture. All metal parts in this small joint are covered by a rubber sleeve, the color of which can be changed to approximate the wearer's skin color. The sleeve can be peeled back easily to gain access to the joint for maintenance and repairs, most of which can be performed with a screwdriver.[103]

Robots also can allow finer control of movements than is possible with manual manipulations by humans. For example, one surgical-assist device now undergoing clinical trials at several U.S. hospitals (Fig. 13) is designed to hold a laparoscope during endoscopic surgery and move it precisely in response to commands delivered via foot pedal, hand control, or buttons on the unit.[104,105] This device, nicknamed “AESOP” (Automated Endoscopic System for Optical Positioning), both provides finer control than is possible for a human assistant, and allows the surgeon to control the endoscope directly.

Perhaps the greatest potential for robotics in medicine, however, lies in its combined use with medical computer vision, virtual reality, and computer-assisted therapy and surgery. The ability to create “virtual environments,” in which human operators can perceive a robot’s environment from the robot’s point of view as well as from that of an observer, has proven extraordinarily valuable in medicine, especially in surgery.[106] “Biorobotics” may well revolutionize the practice of medicine in the next few decades.

Robotics already is in use for several types of endoscopic surgery (also called “minimally invasive surgery”) on the vascular, pancreatic, urological, and gynecological systems. The German aerospace agency DLR is applying space robotics technology to developing visual tracking systems, forceps equipped with physical sensors, and telesurgery systems.[107] NASA is building on its success in designing computer-controlled devices for endoscopy by creating robotic instruments to be used in microsurgery. Like the AESOP device, these instruments improve surgical accuracy by using computer-compensated movement control,[108] but they also pave the way for the next innovation: “smart” surgical tools. Inventors at NASA Ames Research Center have combined hardware and software to create a revolutionary probe system designed for microneurosurgery.[109,110] The primary hardware is a robotically controlled microprobe that includes at its tip a fiber-optic imaging system and sensors that measure tissue density and blood flow. The real power of this device, however, lies in its use of sophisticated “neural network/fuzzy logic” software. Laboratory results from biopsies are used to “train” the software, which “learns” to recognize differences among various types of tissue (e.g., blood vessels, healthy neural tissue, tumors). Theoretically, the system can automatically recognize and identify abnormal tissue in real time, as it traverses the brain, and provides immediate feedback to the surgeon in a graphical three-dimensional virtual view.

Many more applications of robotics can be expected as computer technology, imaging systems, and neural-network software become still more sophisticated. Biorobotics research can help clarify the complex mechanisms by which humans control motor and sensory functions. Such information in turn could be used to develop ways of helping disabled people regain control of lost or impaired functions.[111]

V. Materials Science And Biotechnology

The potential benefits of materials science and biotechnology research to Earth-bound biology and medicine are only beginning to be tapped. In these fields, the unique nature of the microgravity environment is used to study the fundamental states of physical matter (solids, liquids, and gases) or biological processes as they operate independently of gravity. Materials science focuses on understanding the relationships between the formation, structure, and properties of physical materials; biotechnology, on the nature and function of living materials. The improved understanding that comes from such “basic” research can then be used for more “applied” purposes, such as finding ways of improving production methods and materials on Earth.

The journal *Trends in Biotechnology* defines the term biotechnology as “the integrated use of many biological technologies, from molecular genetics to biochemical engineering ... [to translate] novel research into applications ... [ranging] from medical products to devices to entirely new ways of applying existing technology toward the solution of a problem.” In practice, considerable overlap exists between microgravity materials science and biomedical or biotechnological applications. Current research in space materials science focuses on fundamental properties of glasses and ceramics; metals and alloys; polymers; and electronic materials.[112] To use examples presented in this chapter, the properties of polymers, such as those used in various prostheses, and electronic materials, such as those used in computers, communication systems, and X-ray detection systems, all depend on crystalline structure and purity. These properties also are central to biotechnological concepts such as microencapsulation and macromolecule formation (see below).

From the biomedical perspective, two of the most commercially successful applications of space-based materials science have been the development of plastic lenses and protective coatings for eyeglasses, and the development of microsphere technology. Brief descriptions of these applications are given in the next paragraphs. After these reviews follow mention of two particularly exciting fields in space biotechnology—macromolecule formation and cell culture.

A. Protective Eyewear

Perhaps the most widespread application of space-based material science may be the use of plastic lenses and various protective coatings for eyeglasses. In the Apollo era, during the course of developing water purification systems for spacecraft, investigators at Ames Research Center discovered ways of applying thin, abrasion-resistant plastic coatings to surfaces. Meanwhile, investigators at the Jet Propulsion Laboratory developed a special process for treating welders' helmets that protects the welders from eye injuries. Other advances in polarization technology at that time led to the creation of lightweight plastic lenses that can block glare and harmful ultraviolet light.[113–115] These technologies were brought to the commercial marketplace in the mid 1980s by Suntiger Inc. Biomedical Products (North Hollywood, CA) and the Foster Grant Corporation (Leominster, MA, USA). Their products include polarized plastic lenses, for both prescription and nonprescription use, that block damaging UV rays and reduce reflective glare, which enhance vision and reduce eyestrain in fog, snow, and darkness. Other applications include the Fluorotech™ lens, which blocks the wavelengths emitted by fluorescent lighting and unfiltered computer screens, and inspection glasses, which are designed to protect workers from flying objects, splash hazards, and the harmful combinations of light intensity and color used in some manufacturing processes.

B. Microspheres and Microencapsulation Technologies

As the name implies, microspheres are tiny, uniform spherical particles that can range from 1 to about 400 µm in diameter. Used initially to make carbonless copy paper and novelty "scratch-and-sniff" products, this technology now is being used for a broad range of biological applications. In the 1970s, microspheres made of latex or other polymers were labeled with fluorescent markers and linked biochemically to antibodies or other proteins. These microspheres could be used to track the progress of a labeled marker through various biological processes, or to label particular types of cells or cell-surface receptors.[116–118] Later variants on this concept included the production of magnetic microspheres for use in medical diagnostic tests and chemical processes.[119] The microsphere concept was expanded in the 1980s, when various types of porous microspheres were created in which various materials could be packaged for later release at controlled rates. Many microencapsulated pharmaceutical preparations are in use in the U.S., including taste-masked pediatric medication and once-a-day, timed-release oral dosage forms of various drugs. Other proposed uses for microencapsulation technology include injectable forms of insulin, for the treatment of diabetes; secretory cells (e.g., from the pituitary or other endocrine glands), for treating other hormonal disorders; cells for organ transplantations; or agricultural chemicals for controlled release in the environment.[120] The potential market for this type of technology is nearly limitless, and many more applications are anticipated from the creation and analysis of improved microcapsules and microencapsulation processes in space.

C. Macromolecule Crystallization

Investigations of how microgravity affects the processes by which biological macromolecules (e.g., proteins or viruses) form crystals were begun in the mid-1980s. The quality of crystals that would form in microgravity was expected to be higher than that of crystals formed on Earth because of the elimination of sedimentation and the convective flow inherent in crystallization solutions in microgravity. The goals of these experiments are twofold: first, to define and describe in quantitative terms the chemical and physical mechanisms by which crystal quality improves in microgravity; and second to produce large, high-quality crystals (Fig. 14) for biotechnology and research applications.[121] The higher the quality of the crystal, the better its molecular structure can be visualized with techniques such as X-ray diffraction. A clear understanding of the three-dimensional molecular structure of a virus, for example, could allow biotechnologists to design drugs that will interact specifically with that virus.

The potential applications for this cystallization technology are extremely broad, and range from the treatment of diseases to the development of new agricultural products. The Center for Macromolecular Crystallography at the University of Alabama in Birmingham is working with several large drug companies (e.g., Schering-Plough, Eli Lilly, Upjohn, Smith Kline Beecham, BioCryst, DuPont-Merck, Eastman-Kodak, and Vertex) to produce high-quality protein crystals for new drug development. For example, the Hauptman-Woodward Research Institute of Buffalo, NY and Eli Lilly & Co are using space-grown crystals of human insulin in order to design a drug that will bind specifically to insulin, thereby improving the treatment of diabetes. Structural analyses of reverse transcriptase, an enzyme that the human immunodeficiency virus (HIV) uses to replicate, are expected to reveal ways in which this enzyme can be blocked, thereby slowing or stopping the progression from HIV infection to AIDS. A team of investigators from Argentina, Brazil, Chile, Costa Rica, Mexico, Uruguay, and the U.S. is studying the enzyme trypanathione reductase, a protein critical to the life cycle of *Trypanosoma cruzi*, the parasite that causes Chagas' disease (South American trypanosomiasis). The number of people afflicted by this debilitating disease is estimated at 10 to 18 million, with additional infections arising both from the carrier (various species of the reduviid bug) and from infected blood. Development of a drug that acts at the level of this enzyme could save millions of lives through eradicating this disease.[122] Other drugs being developed for influenza and nonspecific inflammation are based on the structure of crystals of neuramidase and protein factor D, respectively. Finally, a type of alpha-interferon crystal is being assessed for its potential use as a timed-release dosage form for the treatment of such diverse diseases such as multiple myeloma, melanoma, hairy cell leukemia, Kaposi's sarcoma, and some forms of hepatitis.

D. Cell Culture and Tissue Formation

The ability to grow human cells outside the body has greatly enhanced human health through advancing understanding of the physiology and molecular biology of gene expression and regulation in single cells. However, the inherent complexity of three-dimensional extracellular signaling and variations in the composition of the extracellular matrix make it difficult to study these interactions by using conventional cell culture techniques. More advanced methods are needed to culture cells in the context of their native three-dimensional cytoarchitecture and tissue microenvironment.

Traditional culture methods have largely precluded the formation of high-density, three-dimensional human tissues after samples of those tissues have been removed from the body and deprived of their natural sources of nutrients and gas exchange. Although some tissue explants can be maintained for short periods on a supportive collagen matrix surrounded by culture medium, this culture system allows only limited mass transfer of nutrients and wastes through the tissue. Moreover, gravity-induced sedimentation prevents complete three-dimensional interactions among cells and between the cells and the matrix.

Single-cell co-culture techniques have been developed to overcome these problems. These techniques, which include bubble-free oxygenation, porous microcarrier beads, and hollow-fiber and "fluidized bed" bioreactors, provide excellent mass transfer rates and facilitate high-density cell growth. However, because much of the extracellular matrix and cytoarchitecture in a tissue is laid down during embryogenesis, it is impossible to recreate a normal microenvironment by using only collections of well-differentiated cell types.

A cell culture device developed at NASA Johnson Space Center can integrate three-dimensional interactions among cells and their matrices in a low-shear environment that allows effective mass transfer of nutrients and wastes.[123] This "rotating wall bioreactor" consists of a cylindrical growth chamber that contains an inner co-rotating cylinder with a gas exchange membrane. Cells and liquid culture media are placed in the space between the inner and outer cylinders, and the assembled device is rotated about its longitudinal axis. Because of viscous coupling, the liquid inside the vessel accelerates until the entire fluid mass is rotating at the same angular rate as the outside wall, and the cells and microcarrier beads within the vessel are suspended uniformly in the fluid at a given rotational speed. The suspended cells rotate as a solid body, with minimal disruptive shear, and the cells maintain their relative positions for long periods, allowing them to touch one another or to construct bridges between the microcarrier beads that form the intercellular matrix. Rotating the chamber also subjects the cells to a constantly changing angular gravity vector. This constant randomization of the normal gravity vector subjects the cells to a state of simulated free fall, which resembles some aspects of microgravity.

The rotating wall bioreactor was originally intended to protect delicate cell cultures from the high shear forces generated during the launch and landing of the U.S. Space Shuttle. However, ground-based experiments that involved culturing various "suspension" cell lines revealed the formation of cell aggregates and large tissue-like structures.[124] This observation opened the possibility of using the bioreactor to study interactions among multiple cell types, perhaps leading to proliferation and differentiation.[125] Some of the three-dimensional cell models cultured to date in this type of bioreactor include rat bone-marrow stromal cells with microcarrier beads; rat adrenal chromaffin cells with a microvascular endothelial cell line; and human carcinoma cells.[126,127] This bioreactor system also is being used to generate human skin equivalents[126] and endochondral bone.[128–130] Understanding the mechanisms involved in the formation of those tissues would have clinical significance for a variety of human disease processes, such as bone repair, osteoporosis, and osteoarthritis.

The rotating wall culture environment also holds promise for maintaining human tissue explants in ways that preserve their native microenvironment and cytoarchitecture. A commercial company, VivoRx (Santa Monica CA), is using this bioreactor technology to grow large numbers of pancreatic islet cells so that the insulin they produce can be used in clinical trials.[126] Tissue explants also can be used as models to examine the effect of infectious agents or environmental insults on those organs, and assess the effectiveness of proposed treatments. For example, investigators at the National Institutes of Health use cultures of human tonsils, a lymphoid tissue, to explore the effects of HIV infection in this type of tissue, and the effects of azidothymidine (AZT) as well.[131,132] Another group, at the U.S. Army Medical Research Institute at Fort Detrick, is using RWV cultures of human liver, spleen, and lymph nodes in an effort to identify new compounds that could be used to treat people infected with the deadly Ebola virus.[126] Another application, in which malignant prostate epithelial cells are added to cultures of normal prostate tissue, serves as a model for how host cells and tumor cells interact in the human prostate.[126,133] Other cancer-related studies include attempts to isolate the genetic changes that produce preneoplastic forms of bronchial epithelium, and testing possible treatments for ovarian and colon cancers.[131,133,134]

Yet another potential application for this type of bioreactor is in tissue engineering, i.e., for growing and modifying human tissues with the aim of implanting those modified tissues back into the body. Conceivably, genetic modification of explants from various tissues could eventually be used to treat children born with enzyme deficiencies.[126] Gene therapy experiments to date have focused on the use of bone marrow stem cells, to replace defective genes with normal ones that can be expressed in the hematopoietic compartment. However, hepatocytes (liver cells) may prove to be easier to isolate and transfect. Liver tissue equivalents cultured at the Baylor College of Medicine are being used as models for liver diseases such as hepatitis.[135] Explanted tissues such as these, with appropriate genetic engineering and vascularization, could one day be used as a source of transplant organs, or as a means of repairing certain inborn errors of metabolism in human patients.[126]

VII. Aging And Space-Based Research

Less tangible—but no less important—benefits from space research are the improvements in understanding what constitutes “normal” human function that come from observing healthy people in unusual environments. Information gathered from those observations can be invaluable in helping healthy and less-healthy people over the course of their lives.

In February 1997, NASA and the U.S. National Institute on Aging convened a conference to identify commonalities between the effects of aging and the effects of space flight on biological systems.[136] At that meeting, experts in immunology, connective tissue and biomineralization, muscle and motor control, spatial orientation, biological rhythms, and cardiovascular function identified promising research areas for possible joint sponsorship and technologies needed by both agencies. The overall goal was to identify areas in which space technology could be applied to gerontology research and clinical practice.

The following paragraphs are not intended to provide an exhaustive review of these complex issues, but rather to briefly discuss two topics of current interest: bone loss and how physical activity—and inactivity—affect that loss, and balance and gait disorders. The latter topic includes brief mention of a recent Russian study involving use of spacesuits to assess postural stability in children with cerebral palsy. Additional information on how humans react and adapt to the unique environment of space, and what those processes reveal about normal function, can be obtained in Volume III (Books 1 and 2) of the *Space Biology and Medicine* series.

A. Bone Loss

Many similarities exist between the bone loss associated with aging and that associated with space flight.[136,137] Some of the known similarities include the specific physical areas from which bone is lost; changes in calciotropic hormones and calcium metabolism; uncoupling of bone formation from resorption in the remodeling process; less efficient intestinal absorption of calcium; the increased propensity for falls and fractures in both groups; and how ambient light influences vitamin D synthesis. Whether and how bone loss can be reversed also are crucial for both groups. Thus, research topics of interest for both gerontology and space medicine include understanding how loading and exercise can maintain or modify bone mass density; understanding the factors that regulate bone cell function and activity; defining nutritional and environmental factors that maximize bone retention; and developing ways of countering bone loss.

1. Quantifying Physical Activity through Ground Reaction Forces

Exercise, particularly resistive exercise or “strength training,” is well known to increase muscle size and strength; it also can improve bone mineral density.[138–141] Better insight into the relationship between physical activity and bone density, whether in astronauts or in Earth-bound populations, can be used to identify those types of exercise that can best increase bone mineral density and strength—or at least minimize their loss over time. For example, many of the exercise devices designed for use in space flight (e.g., ergometers and treadmills) can provide substantial cardiovascular benefit, but cannot provide the physical loads typical of weight-bearing exercise on Earth.[142,143] As part of a larger effort to assess the effectiveness of new exercise modalities for use in space flight, investigators at Ames Research Center have developed a device that measures musculoskeletal loading on the lower limbs during various activities.

This device, the Ground Reaction Force (GRF)-based Activity Monitor (U.S. patent pending),[143,144] measures, records, and analyzes the forces generated between the subject's feet and the ground. This Activity Monitor consists of an insole force sensor worn in the shoe, a signal conditioner, and a battery-powered digital data-logging system carried in a waist pack. Vertical GRF is sampled continuously at 100 Hz, and the sequence of force minima and maxima is reduced to provide a histogram of the number of cycles of a given magnitude. Cycles that occur with a given load rate, contact time, or stride period also can be visualized. These kinds of data can be processed further to generate indices of overall activity, bone density, and energy expenditure.

The advantage of the GRF-based Activity Monitor over previous methods lies in its ability to quantify the actual forces exerted on each subject's body. Traditional estimates of daily activity level and musculoskeletal loading have relied on activity logs and step-meters, and are inherently imprecise because of differences among people (age, sex, and weight) and in the amount and intensity of their daily activities. (For example, greater reactive forces tend to be experienced during fast walking than during slow walking, even for the same person.) The inventors of the device are working with the Palo Alto (CA) Veterans Administration Hospital and Stanford University to study how daily activity levels and exercise influence bone density in several clinical populations. Further clinical data are expected to substantiate correlations among bone density maintenance, energy expenditure, and other physiological variables.

This monitoring system can be used as a research instrument in many areas, including bone and muscle physiology; gerontology (especially the effects of aging on ambulation, balance, falls, energy requirements, and physical activity); exercise physiology; gait analysis; tests of the efficacy of sports or exercise equipment; and obesity research. Eventually, the GRF-based Activity Monitor will enable the user or clinician to prescribe specific weight-bearing activities that provide the most benefit for that person's age, sex, and weight.

2. Measuring Biomechanical Strength (Bone Stiffness)

Bone mineral density has long been used as an indirect measure of bone strength. According to the U.S. National Osteoporosis Foundation, bone density tests can be used to detect osteoporosis before a fracture occurs; to predict the risk of fractures; to determine the rate at which an individual will lose bone mass; and to monitor the effects of treatment.[137] Density measurements alone, however, are not always sufficient; some bones that are naturally less dense than others can function well without risk of fracture, but other denser bones are more susceptible to breaking.

In order to supplement traditional density measurements, investigators at NASA Ames Research Center and Stanford University developed an instrument for direct, noninvasive measurement of bone strength via its bending stiffness. This instrument, the mechanical-response tissue analyzer (MRTA), was first developed to measure slight changes in bone strength in monkeys after "Bion" missions,[145] and was brought to the commercial market by GaitScan Inc. (Ridgewood, NJ, USA).

The MRTA uses low-frequency vibration to measure bone stiffness, which is the product of the mineral content and the geometric structure of the bone.[146,147] At this writing, the MRTA can be used to measure bending stiffness in the ulna (Fig. 15) and tibia.[147] Potential applications of this device include assessing postflight bone strength in astronauts, monitoring the effects of exercise and rehabilitation in osteoporosis, and monitoring the process by which fractures heal.

B. Posture and Gait Control

Of the many changes in spatial orientation that take place with age and with exposure to the space flight environment, one effect of these changes that may be common to both is postural instability. The enormously complicated system by which humans control their balance, posture, and gait includes contributions from sensory structures and neural pathways; eye movements, including vestibulo-ocular responses and neural storage of sensory information; spatial navigation systems; and sensorimotor integration, including the ability to adapt to changes in sensory and motor conditions, and temporal coordination of complex activities such as reaching or walking.[136] Background information and the state of current research are described in Volume III (Chapter 7) of the *Space*

Biology and Medicine series. The following paragraphs describe two systems, each based on space technology, that are being used on Earth to assess various components of the complex system by which we orient ourselves and move around in our environment.

1. Electromyographic Gait Analysis System

The Gait Analysis Telemetry System[148] represents another spin-off from biotelemetry developed for space flight use. Representatives from NASA, the Children's Hospital at Stanford University, and L&M Electronics Inc. (Daly City, CA) developed this system, based on electromyography, to help diagnose and treat a variety of gait disorders arising from birth defects, disease, or injury. The neural damage underlying the gait disorder can generate muscular spasticity as well as loss of coordination; however, the effects on specific muscles can vary substantially, and are difficult to determine by physical examination alone. The gait analysis system is used to identify the affected muscles so that appropriate treatments can be applied.

Small transmitters, each about 2 cm in diameter, are affixed directly over specific muscle groups in the patient's legs. Each transmitter includes a miniature lithium battery and a pair of sensing electrodes. The electrical activity of the muscle is sensed and telemetered to a computer for analysis and display. The absence of wires in this system represent a substantial improvement over other electromyographic monitoring systems, since the presence of wires between the electrodes and the computer can interfere with the subject's ability to walk as well as distorting the recorded gait pattern.

Hospitals use the system to test the gait patterns of children afflicted with cerebral palsy, congenital disorders such as muscular dystrophy, or injuries. Measurements of muscle activity in the limbs and spine are analyzed to produce illustrations of gait patterns. These patterns help physicians evaluate the potential usefulness of corrective surgery, various types of braces, or physical therapy for improving the child's mobility. This system also is used in a research program at the Department of Veterans Affairs Rehabilitation Research and Development Center (Palo Alto, CA) to investigate the possibility of restoring locomotion to people with spinal cord injuries and severe gait disorders.

2. Space Suits and Cerebral Palsy

Russian investigators are used a modified version of the classic "Penguin" antigravity suit—the ADELI suit—to investigate mechanisms of postural control in children with the "hyperkinetic" [athetoid] form of cerebral palsy.[149] The underlying hypothesis for this study was that wearing the ADELI suit might help stabilize the center of gravity in these subjects by lessening the prominence of muscular hyperactivity, perhaps by lessening the fatigue associated with the athetoid movements.[150] Thirty children (ages 9–12 years) with cerebral palsy, 12 of whom had between 10–90% visual impairment, were examined before and after a series of 20 sessions in which the ADELI suit was worn from 15–90 minutes once daily. Another group of 11 healthy subjects (ages 18–19 years), who did not wear the ADELI suit, served as a control group. Both groups underwent a standard stabilometric assessment, a Romberg (station) test, and tests in which the head was rolled toward the left and right shoulders. Variables measured included the degree of shift in body position (and thus center of gravity) in the sagittal, frontal, and horizontal planes during each of the test conditions.

Treatment with the ADELI suit seemed to reduce the difference between the eyes-open and eyes-closed conditions in terms of shifts of the center of gravity. Most of the test group was able to stand better, with eyes open, after 20 suit-wearing sessions than before; moreover, some of these subjects maintained this improvement two months after the first session. Although variation in the severity of impairment among the test group precluded any firm conclusions, the authors suggest that wearing the ADELI suit may enhance the contribution of the visual system in maintaining posture in cerebral palsy.

VI. Conclusions

Space exploration has and will continue to lead to the development of a vast array of new technologies. As discussed throughout this chapter, space-related technologies can improve the diagnosis, treatment, and prevention of disease, and can increase the independence of people with disabilities.

The infrastructure is well in place to facilitate the exchange of space-generated technology with Earth-based investigators, industries, and universities. In the U.S., each NASA field center has an office organization that deals specifically with transferring technology for commercial use. These offices function as clearinghouses for information; their purpose is to remain abreast of research and engineering activities at that center that could be used in the private sector. Additional information on technology resources available through NASA can be obtained on-line from the NASA Commercial Technology Network at <http://nctn.hq.nasa.gov/>. Introduction of new medical technologies not only improves the quality of life for individuals, but also creates new business opportunities. By developing cutting-edge technologies that have uses both in the aerospace field and in the general economy, the space program pays dividends in the form of new products, new jobs, and new prosperity.

The medical applications of space research are virtually unlimited, as long as the necessary research and commercialization programs are continued and the space program continues to move on to new frontiers. By developing cutting-edge technologies that are useful in both aerospace and the general economy, the space program pays dividends in the form of new products, new jobs, and new prosperity.

The 1990s have brought unprecedented attention to the needs for containing the cost of health care while simultaneously expanding its availability. The engineering feats of the last three decades have benefited communication, miniaturization, image processing, and many other areas; discoveries and practical applications in medicine and human physiology will be no less revolutionary.

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Table 1 NASA Telemedicine Projects [Ref. 77]

1970	1975	1989	1993	1994	1995
Space technology is applied in the Rural Papago Advanced Health Care Program, bringing medical care to the Papago Indian Reservation in Arizona.	NASA's Applied Technology Satellite-6 (ATS-6) used to provide S-band television, education, and support for agriculture and health care in India. Satellite technology (COSPRAS/SARSAT) supports international search and rescue efforts in Canada, France, and the former Soviet Union. NASA's ATS-1 and ATS-3 support Pacific Basin health care education efforts through PEACESAT.	Spacebridge to Armenia/Ufa responds to December 1988 earthquake in Armenia and gas explosion in Ufa.	University of Washington joins Lewis Research Center and Jet Propulsion Laboratory on a teleradiology project that uses Advanced Communications Technology Satellite. Spacebridge to Moscow responds to October 1993 civil disturbances.	NASA collaborates with the University of Pittsburgh, WHO, PAHO, USAID, and World Bank to organize Global Health Network, which provides telepreventive medicine.	Ames Research Center, Trident, Inc., and Cedars Sinai Medical Center, Los Angeles, collaborate on a telemedicine demonstration project.

Table 2 Institutions participating in the Spacebridge telemedicine project [Ref. 74]

Center	Participating institutions	Specialty emphasis	# of participating individuals
ARMENIA Yerevan	Republic Diagnostic Center for Hyperbaric Medicine	Tertiary care, diagnostic imaging	233
	Several Armenian hospitals and clinics	Multiple specialties	
RUSSIA Ufa	Hospital 21	General hospital, burn care	14
UNITED STATES			
Baltimore, MD	Maryland Institute for Emergency Medical Services Systems	Trauma, burns, critical care	18
Bethesda, MD	Uniformed Services University of Health Sciences	Casualty management, psychiatry, epidemiology	64
	National Institutes of Health	Multidisciplinary tertiary care	
	National Naval Medical Center	Multidisciplinary tertiary care	
	Walter Reed Army Medical Center	Multidisciplinary tertiary care	
Houston, TX	The University of Texas MD Anderson Cancer Center	Oncology	45
	Texas Institute for Rehabilitation Research	Rehabilitation medicine	
San Antonio, TX	US Army Medical Center	Burn care	
Galveston, TX	Shriners Burn Institute	Burn care	
Salt Lake City, UT	LDS Hospital	Trauma, critical, & tertiary care	45
	Primary Children’s Hospital	Pediatric trauma, critical care, & tertiary care	
	University of Utah Medical Center	Tertiary care, trauma, burns, critical care	
Washington, DC	NASA Headquarters	Operational medicine, administration	3

Figure Captions

Fig. 1 Joining her new crew mates on the STS-76/Mir-21 mission, Shannon W. Lucid helps conduct an inventory of new food supplies for the Russian station Mir. Commander Yuri I. Onufriyenko is in the foreground and Flight Engineer Yuri V. Usachov is in the background. (Mir was still docked with the Space Shuttle *Atlantis* when this picture was taken.) (NASA photo 76345025)

Fig. 2 Aboard the International Space Station (ISS), Flight Engineer Sergei K. Krikalev (left) and Soyuz Commander Yuri P. Gidzenko work in the stowage-packed Zvezda Service Module. The two Russian cosmonauts, along with American astronaut Bill Shepherd, embarked as the ISS Expedition One crew. (NASA photo ISS01-323-010)

Fig. 3 The second generation of the dynamic light-scattering (DLS) probe consists of two monomode optical fibers and two gradient index (GRIN) microlenses, contained in a stainless steel housing as shown. For three-dimensional scans of ocular tissue, the probe is positioned automatically, an input beam from an helium-neon laser at 50 microwatts is shone into the eye, and the scattered signal is collected by the probe and detected with an avalanche photodiode detector system. [Ref. 32]

Fig. 4 A subject uses a personal computer while wearing the Low-Vision Enhancement System (LVES). [Ref. 33]

Fig. 5 The LED probe, consisting of 144 tiny pinhead-sized diodes, is 9-inches long and about one-half-inch in diameter. The special lighting technology, initially developed for NASA's commercial plant growth experiments in space, is now being developed for photodynamic cancer therapy.

Fig. 6 Worldwide infectious disease patterns in the 1990s. [Ref. 38]

Fig. 7 This Earth observation photo taken from the U.S. Space Shuttle shows India's Ganges River delta, the largest river delta in the world. (NASA photo STS081-ESC00212933)

Fig. 8 The portable telemedicine instrumentation pack.

Fig. 9 NASA's ground-to-ground infrastructure which supports telemedicine.

Fig. 10 The Diatek hand-held aural thermometer. [Ref. 89]

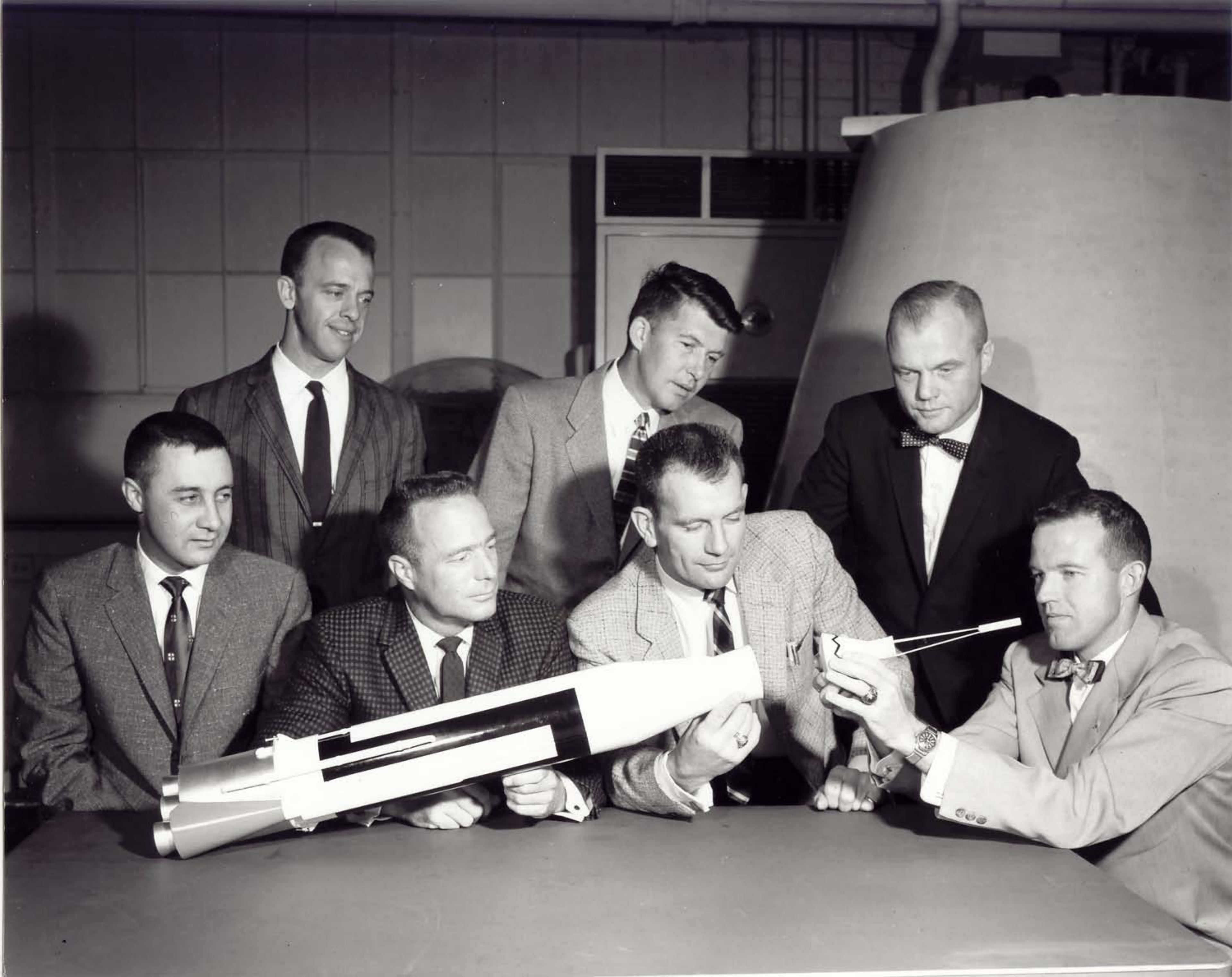
Fig. 11 Preparing to implant the Fetal Health Monitoring System in a fetus in utero. [Ref. 94]

Fig. 12 Lake Winnipeg in Manitoba, Canada forms the backdrop for the Wake Shield Facility in the grasp of the Canadian-built Remote Manipulator System. The image was taken through a window on *Discovery*'s aft flight deck. (NASA photo 20119282)

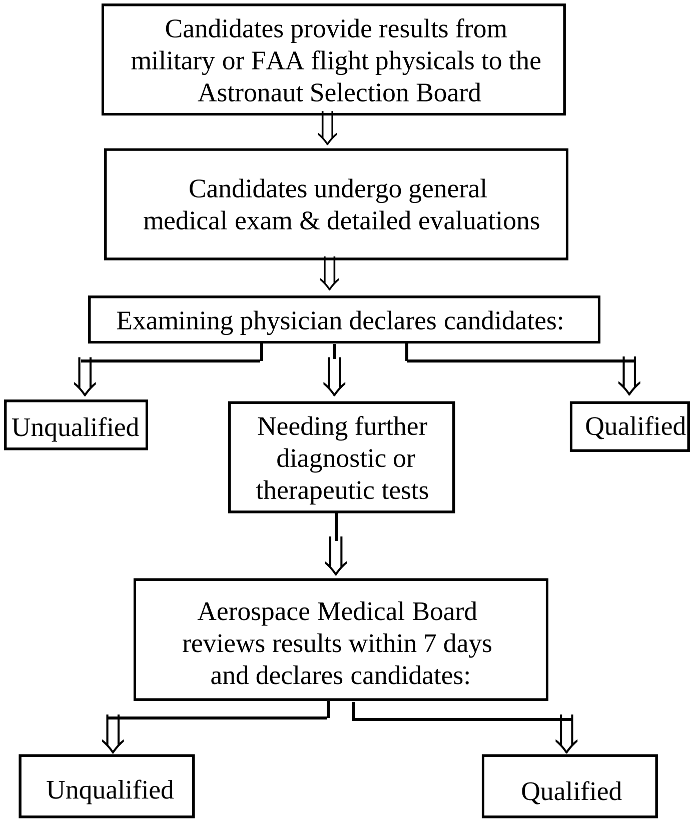
Fig. 13 Surgical assist device used during endoscopic surgery. [Ref. 104]

Fig. 14 An experiment performed on STS-85 produced large crystals of a mutant HIV protease involved in drug resistance complexed with a cyclic urea-based inhibitor. Previous terrestrial crystals were of insufficient size for X-ray analysis. The microgravity crystals were the largest grown to date and provided data to 1.8 angstroms (high resolution). A detailed image of the inhibitor bound to the active site was obtained from the microgravity data.

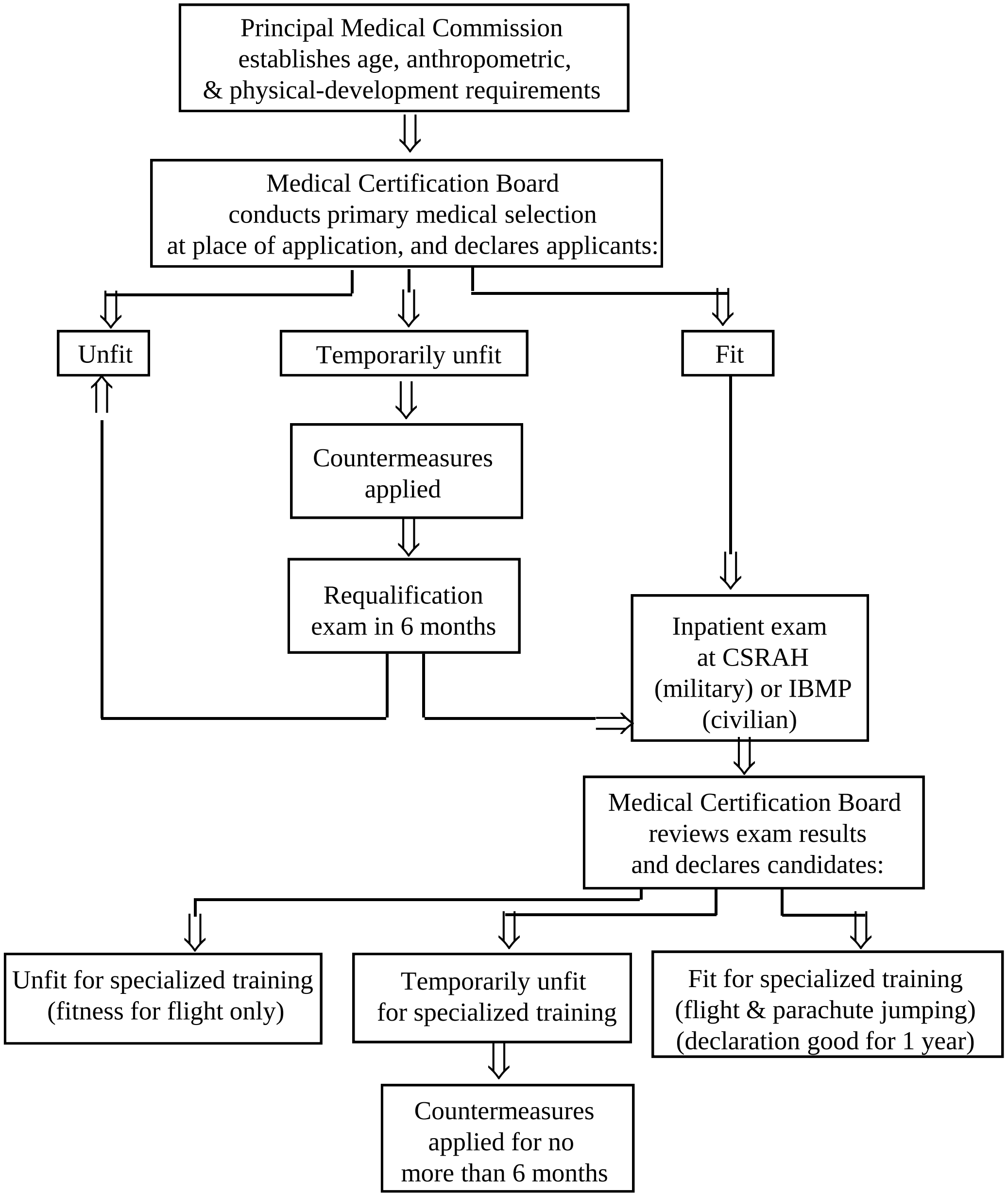
Fig. 15 Using the Mechanical Response Tissue Analyzer (MRTA) to measure bending stiffness of the ulna. [Ref. 147]



U.S. Astronaut Selection Process



Russian Cosmonaut Selection Process

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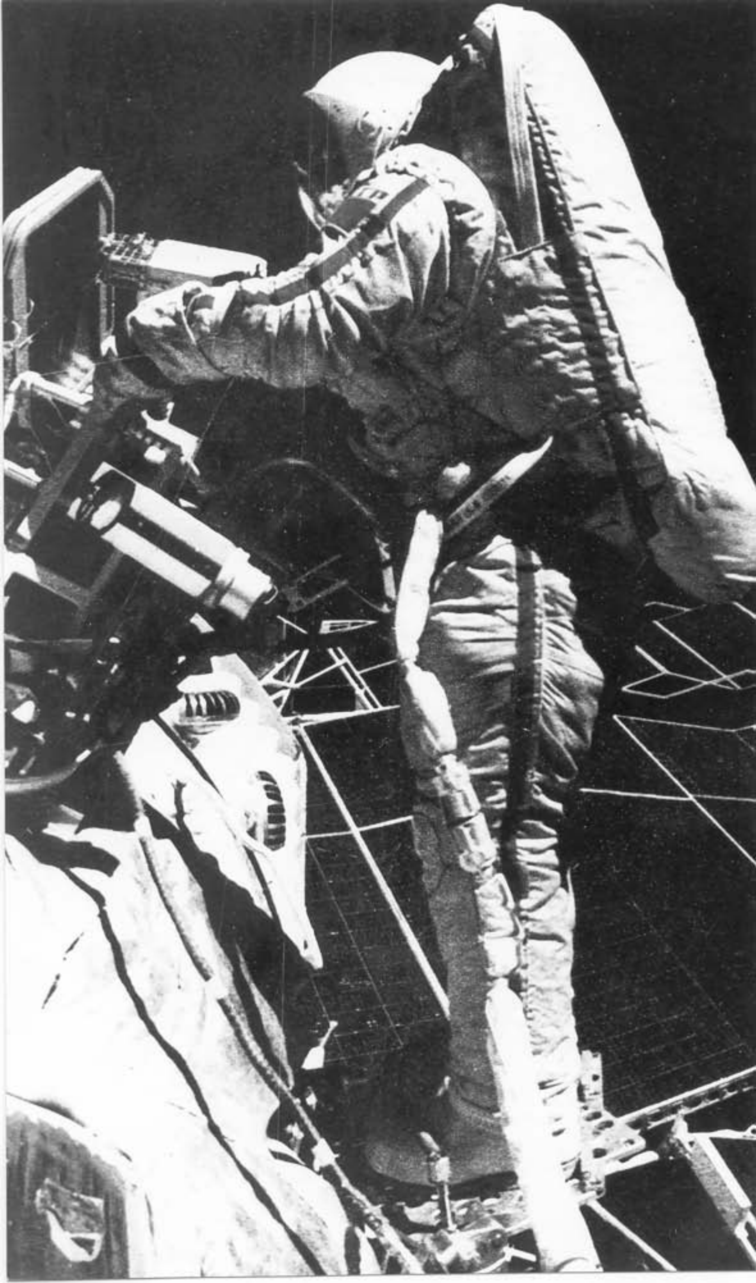
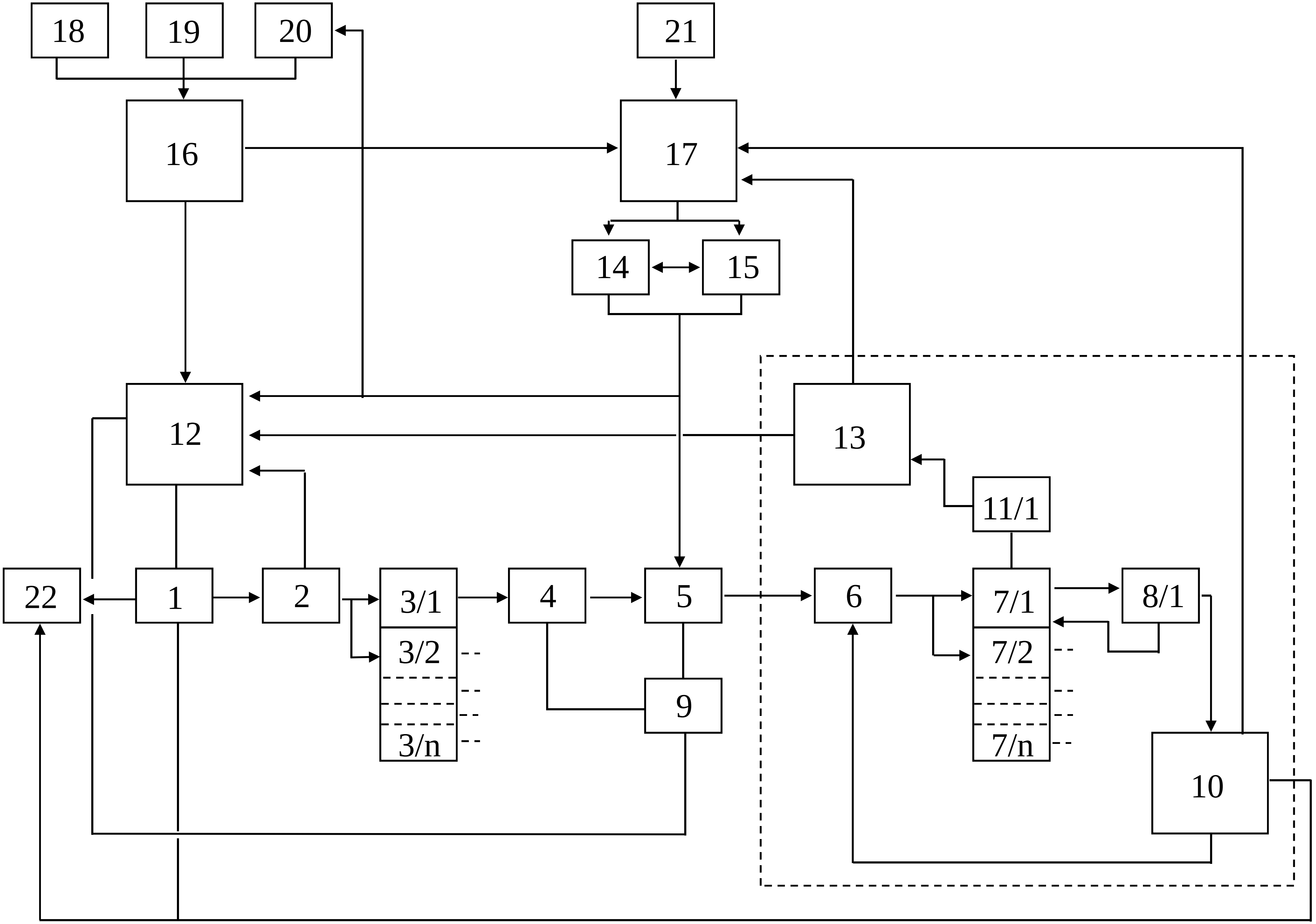
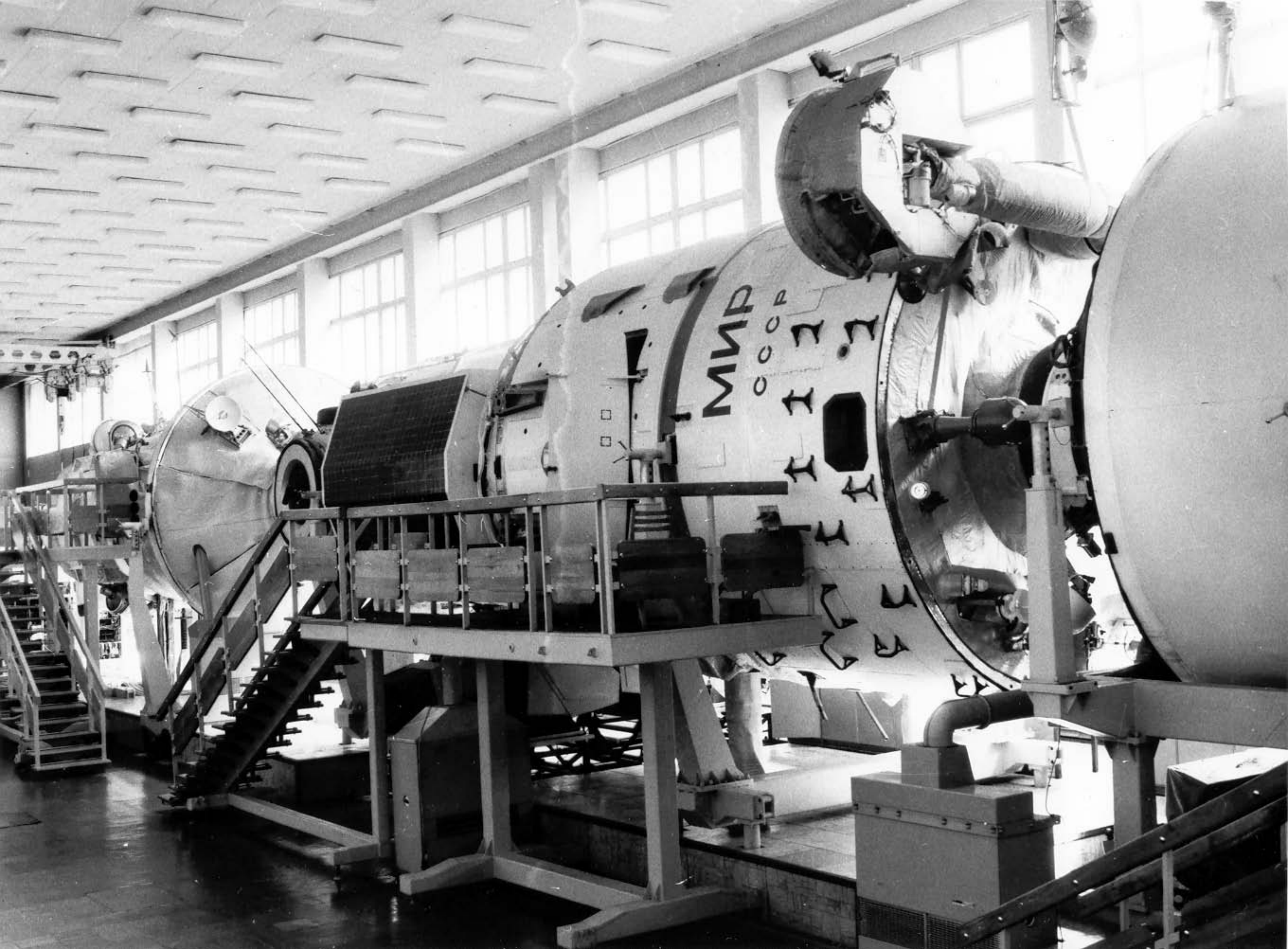
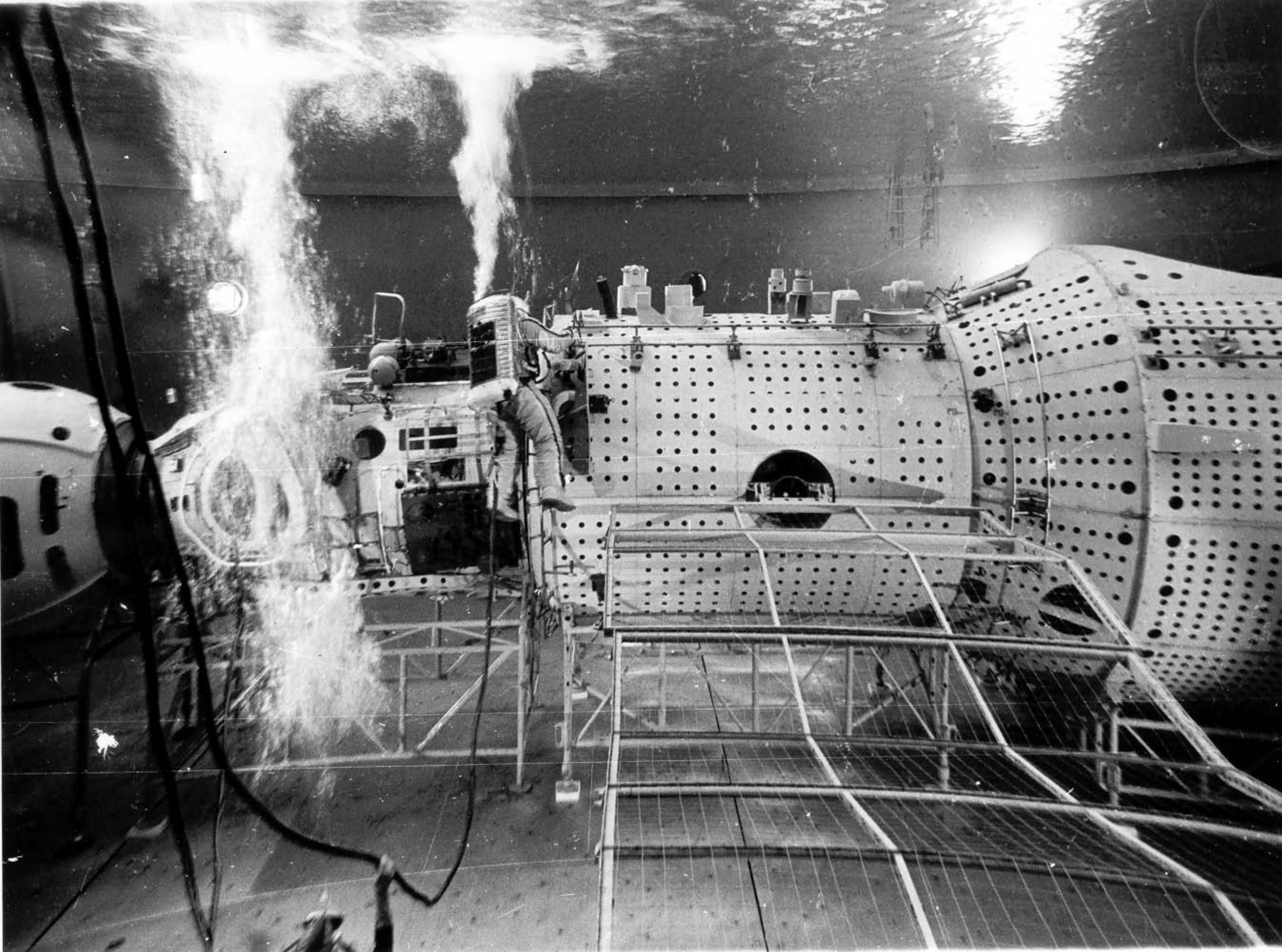
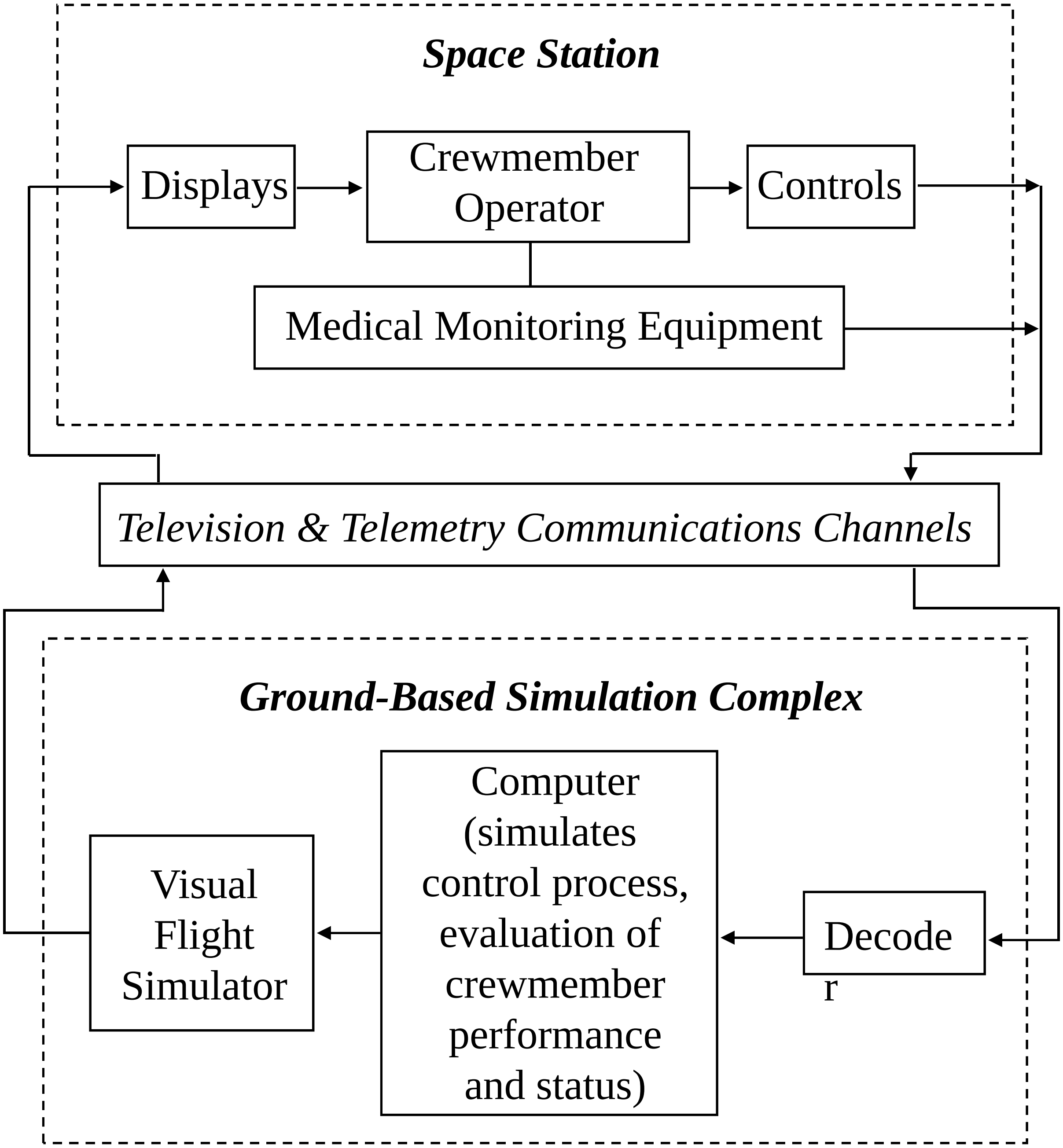
2
038
3
035

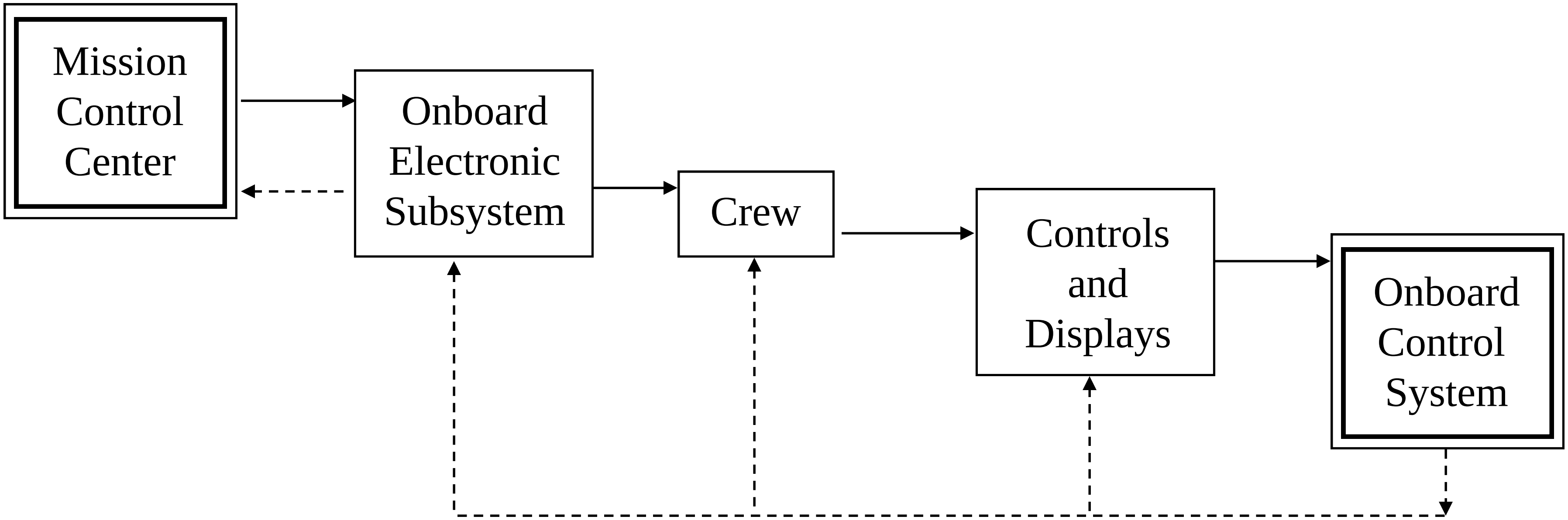


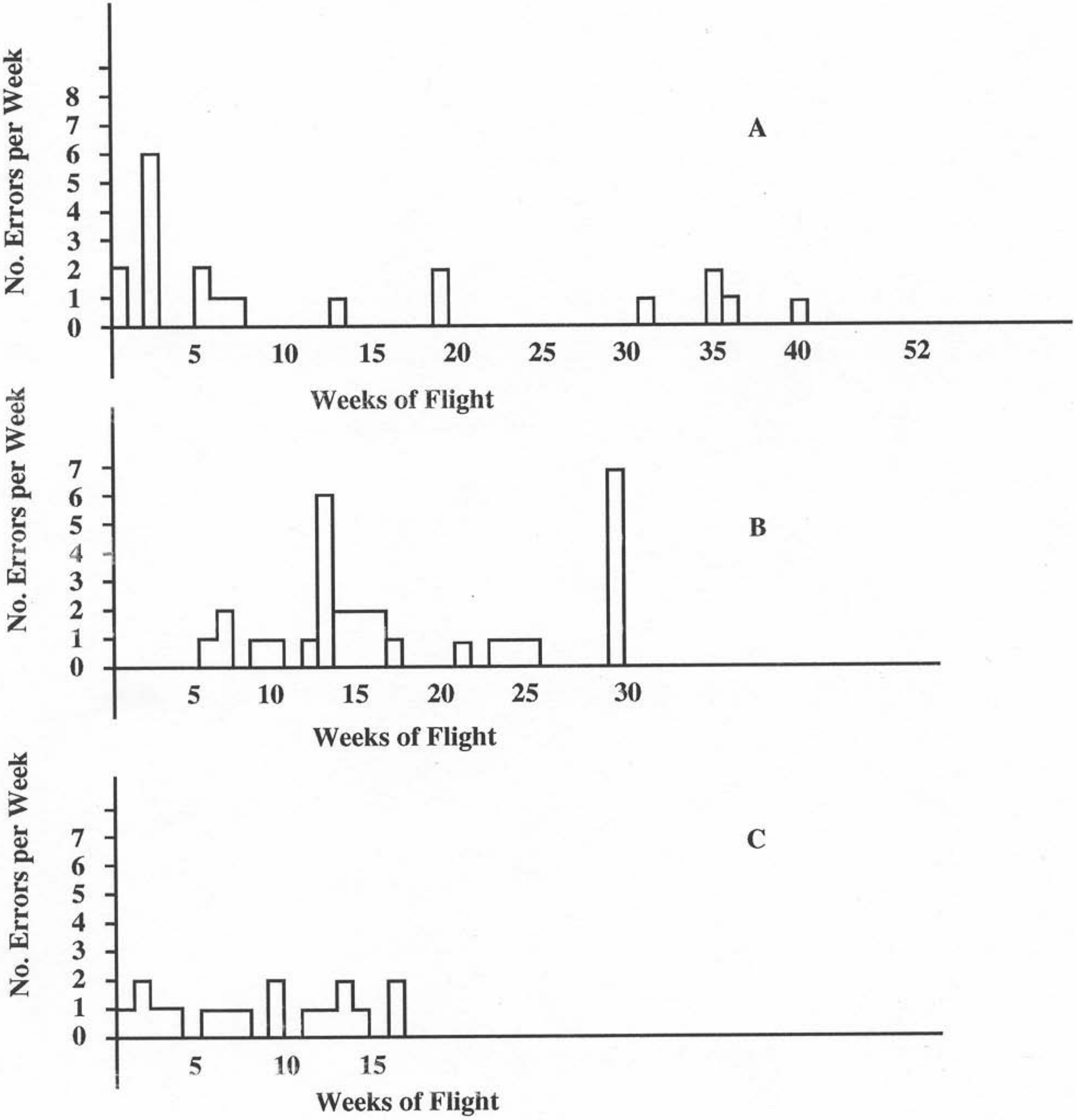

18
19
20
21
16
17
14
15
12
13
11/1
22
1
2
3/1
3/2
3/n
4
5
9
6
7/1
7/2
7/n
8/1
10

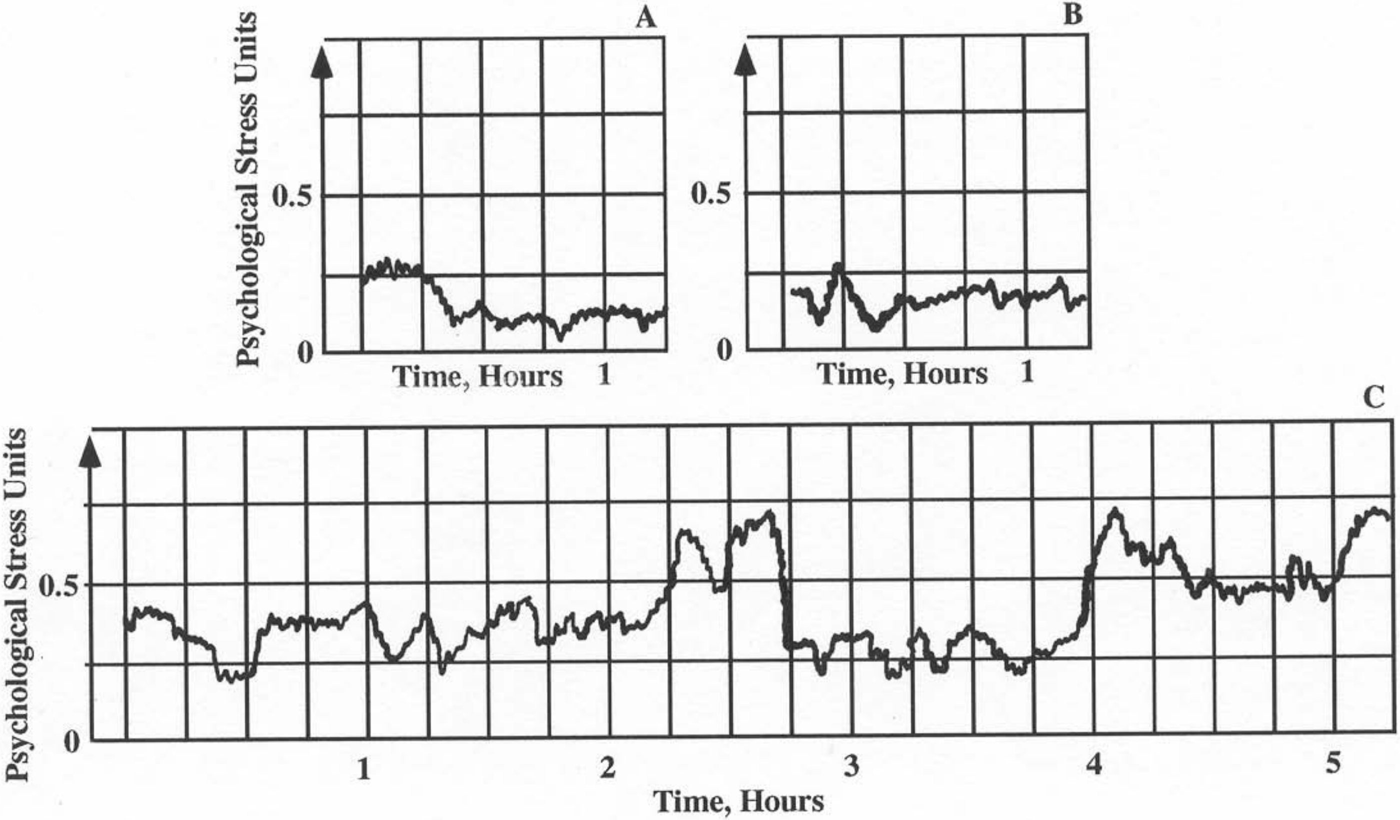

МИР
СССР

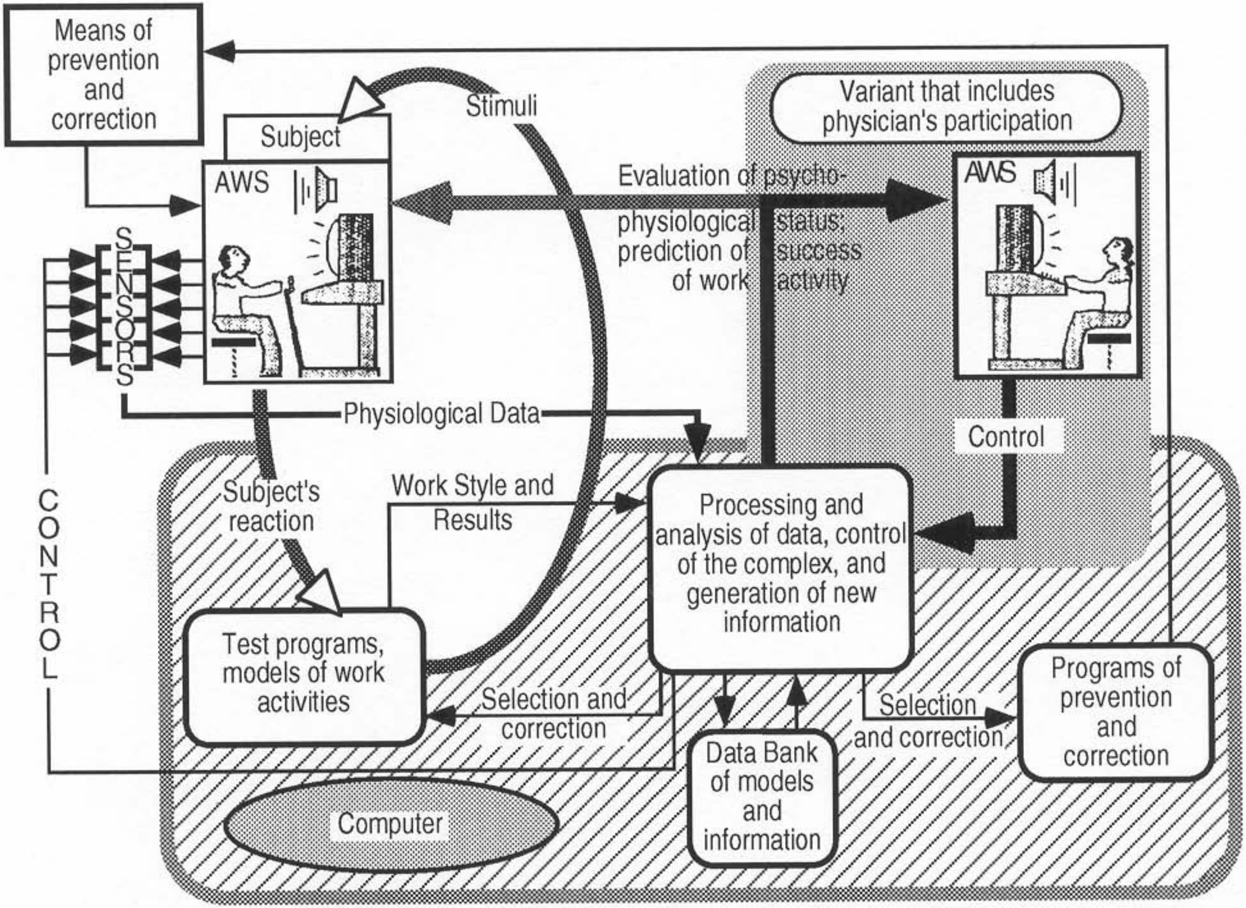


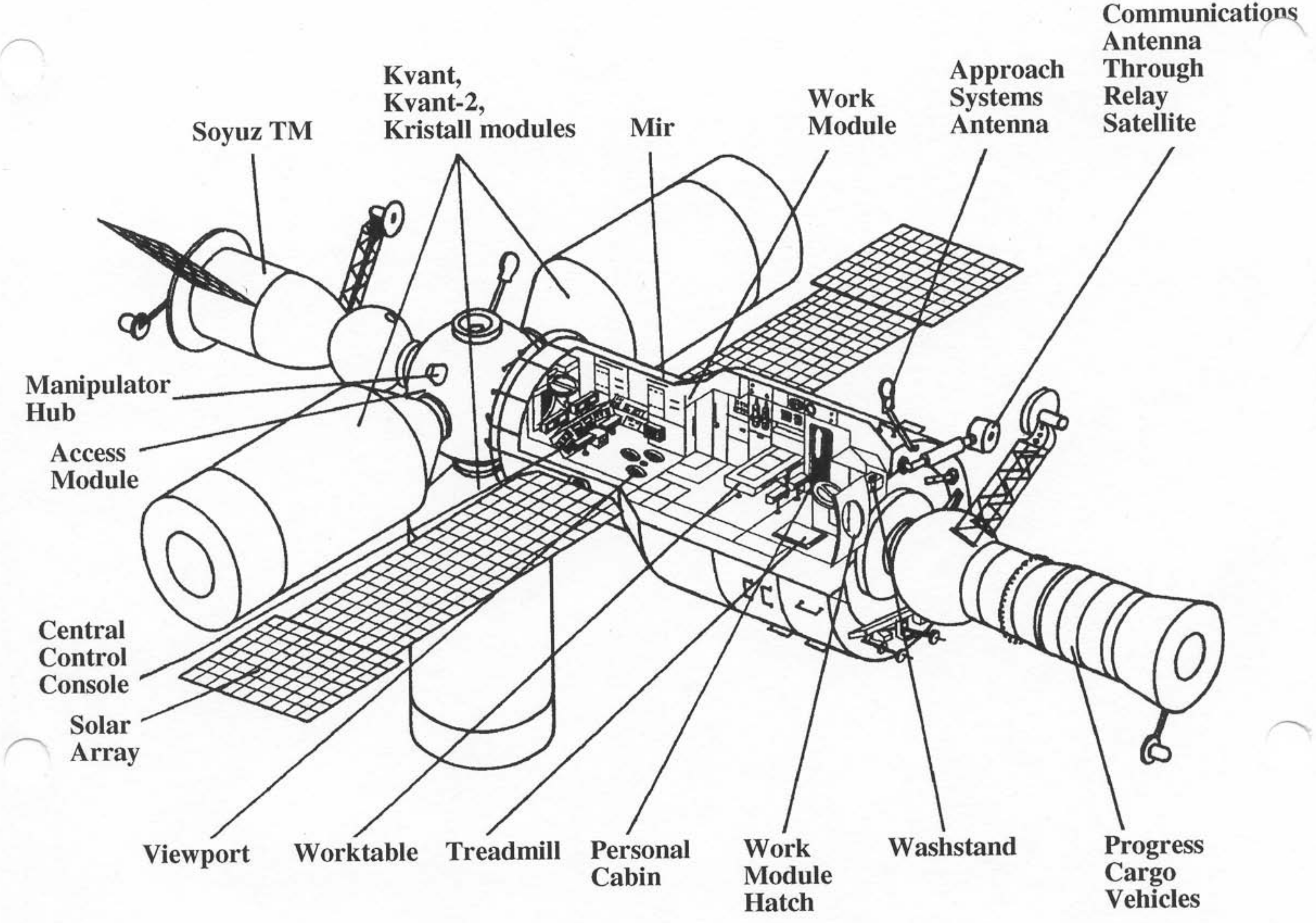

Space Station
Displays
Crewmember Operator
Controls
Medical Monitoring Equipment
Television & Telemetry Communications Channels
Ground-Based Simulation Complex
Visual Flight Simulator
Computer (simulates control process, evaluation of crewmember performance and status)
Decoder

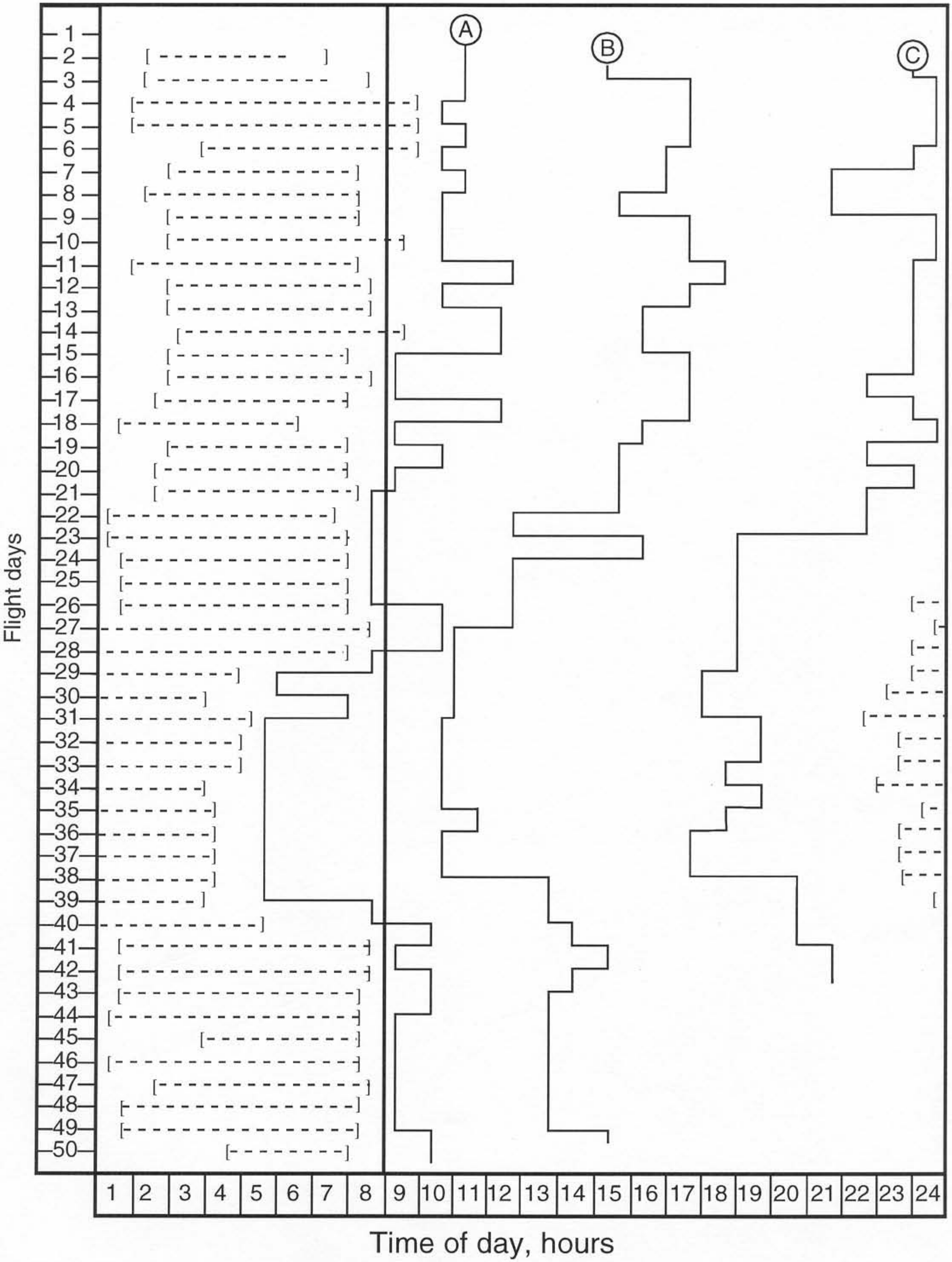

Mission Control Center
Onboard Electronic Subsystem
Crew
Controls and Displays
Onboard Control System

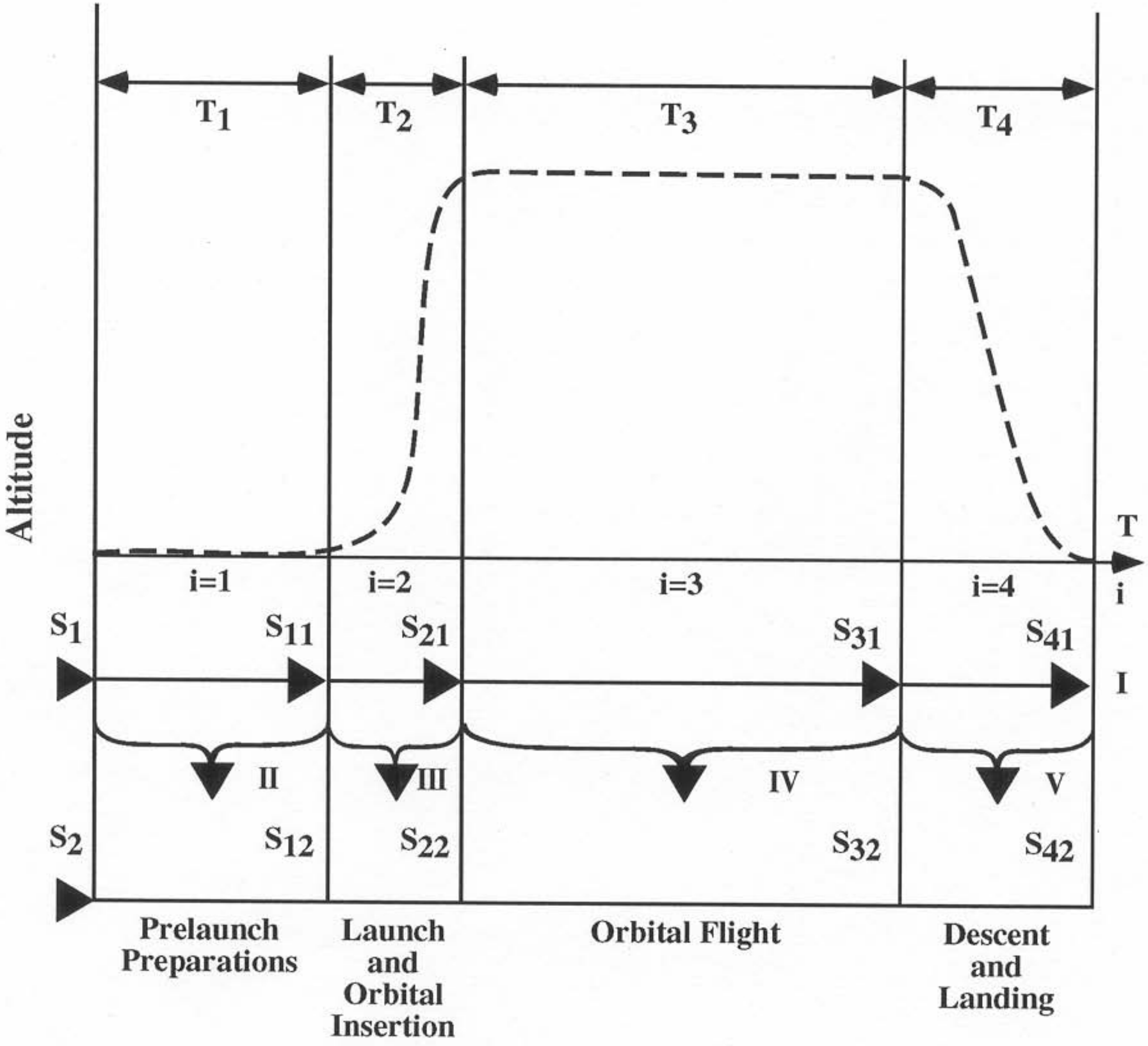

A
No. Errors per Week
0
1
2
3
4
5
6
7
8
5
10
15
20
25
30
35
40
52
Weeks of Flight
B
No. Errors per Week
0
1
2
3
4
5
6
7
5
10
15
20
25
30
Weeks of Flight
C
No. Errors per Week
0
1
2
3
4
5
6
7
5
10
15
Weeks of Flight

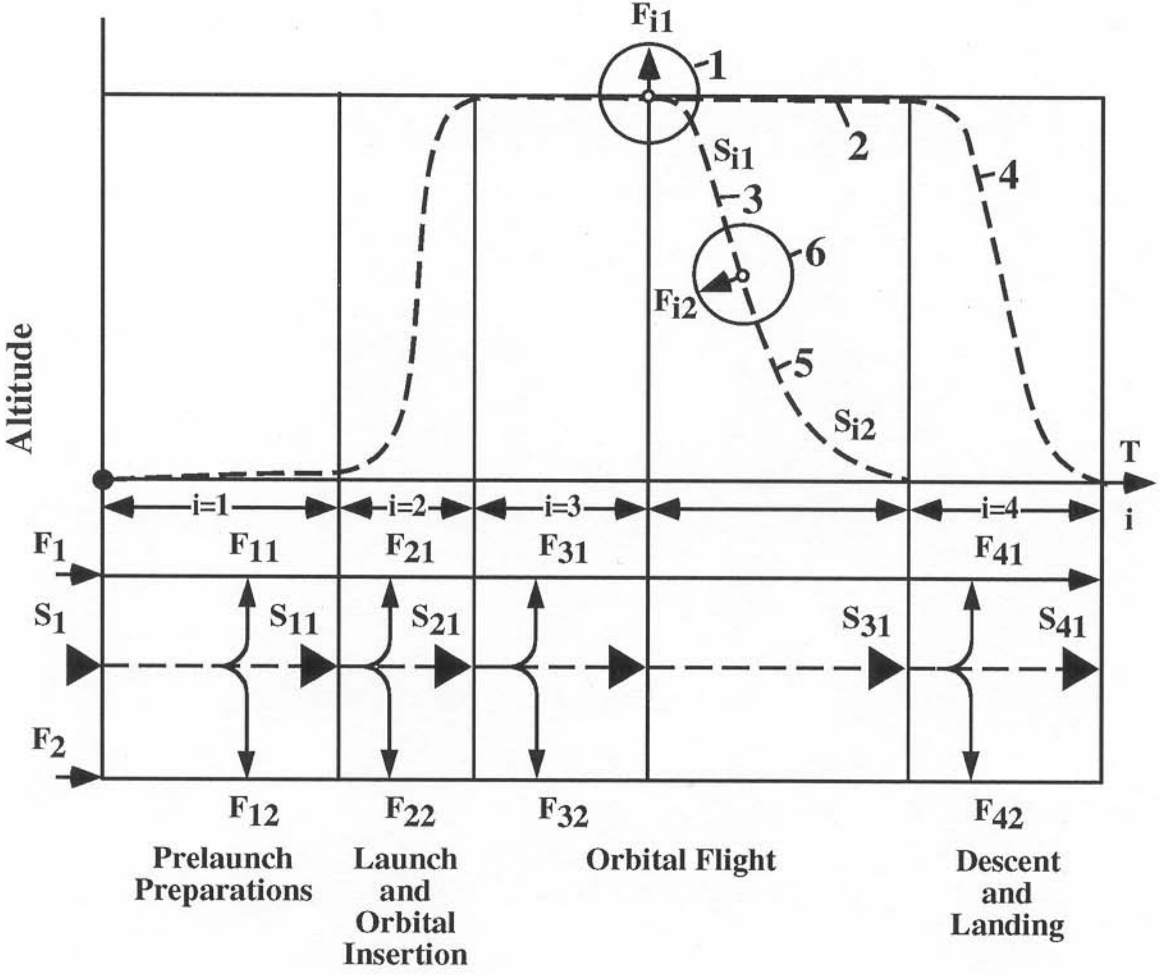

A
B
C
Psychological Stress Units
0.5
0
Time, Hours
1
Psychological Stress Units
0.5
0
Time, Hours
1
Psychological Stress Units
0.5
0
1
2
3
4
5
Time, Hours


Means of prevention and correction
Subject
Stimuli
Variant that includes physician's participation
AWS
Evaluation of psycho-physiological status; prediction of success of work activity
AWS
SENSORS
Physiological Data
Control
CONTROL
Subject's reaction
Work Style and Results
Processing and analysis of data, control of the complex, and generation of new information
Test programs, models of work activities
Selection and correction
Selection and correction
Programs of prevention and correction
Data Bank of models and information
Computer

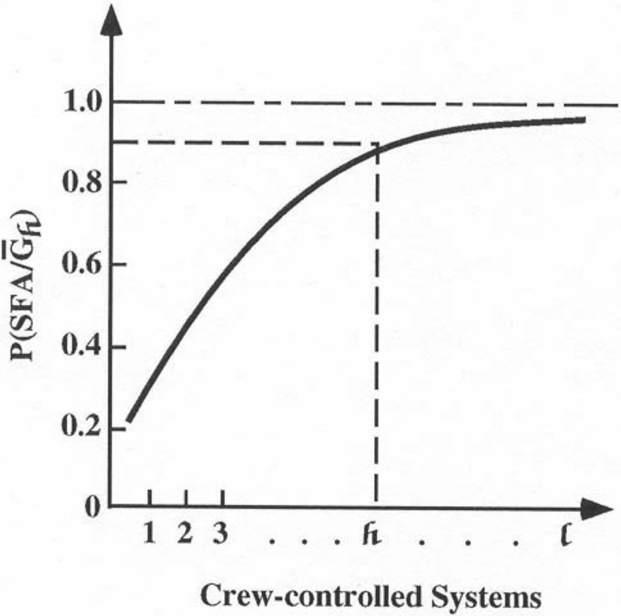

Communications Antenna Through Relay Satellite
Approach Systems Antenna
Work Module
Mir
Kvant, Kvant-2, Kristall modules
Soyuz TM
Manipulator Hub
Access Module
Central Control Console
Solar Array
Viewport
Worktable
Treadmill
Personal Cabin
Work Module Hatch
Washstand
Progress Cargo Vehicles

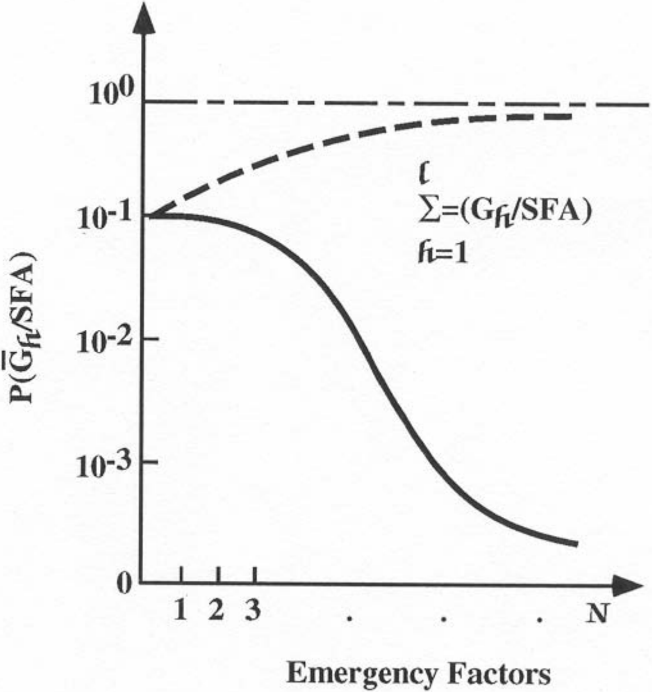
A
B
C
Flight days
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
Time of day, hours

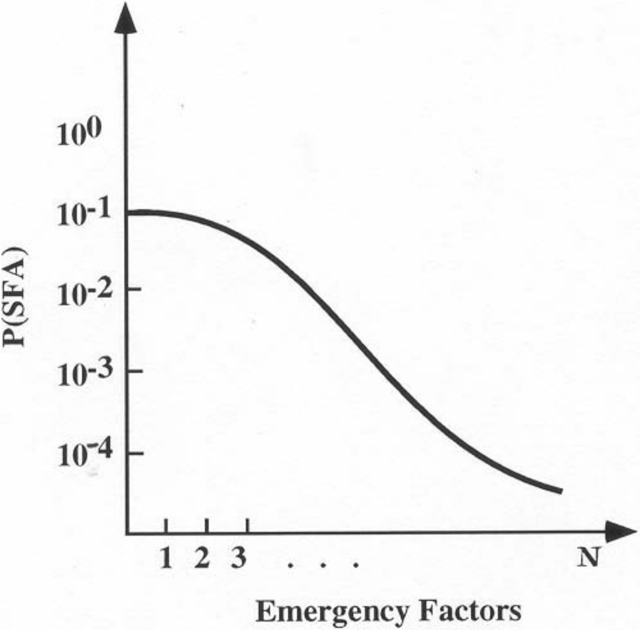

T1
T2
T3
T4
Altitude
T
i=1
i=2
i=3
i=4
i
S1
S11
S21
S31
S41
I
II
III
IV
V
S2
S12
S22
S32
S42
Prelaunch Preparations
Launch and Orbital Insertion
Orbital Flight
Descent and Landing



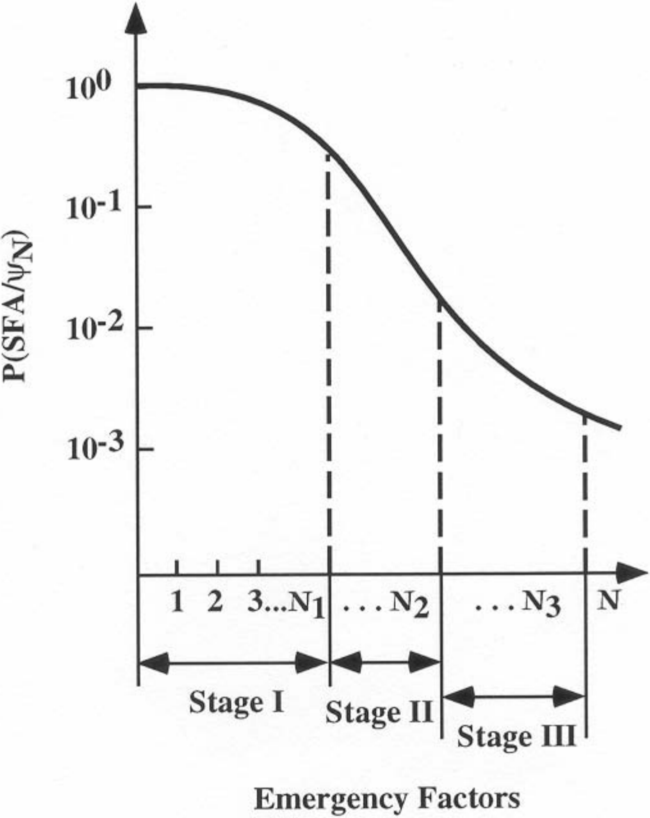
F_{i1}
1
2
S_{i1}
3
4
6
F_{i2}
5
S_{i2}
Altitude
T
i=1
i=2
i=3
i=4
i
F1
F11
F21
F31
F41
S1
S11
S21
S31
S41
F2
F12
F22
F32
F42
Prelaunch Preparations
Launch and Orbital Insertion
Orbital Flight
Descent and Landing


P(SFA/$\bar{G}_h$)
1.0
0.8
0.6
0.4
0.2
0
1
2
3
. . . h . . . . ℓ
Crew-controlled Systems


10^0
10^-1
10^-2
10^-3
0
P(Ḡ_ℓ/SFA)
ℓ
Σ=(G_ℓ/SFA)
ℓ=1
1
2
3
.
.
.
N
Emergency Factors

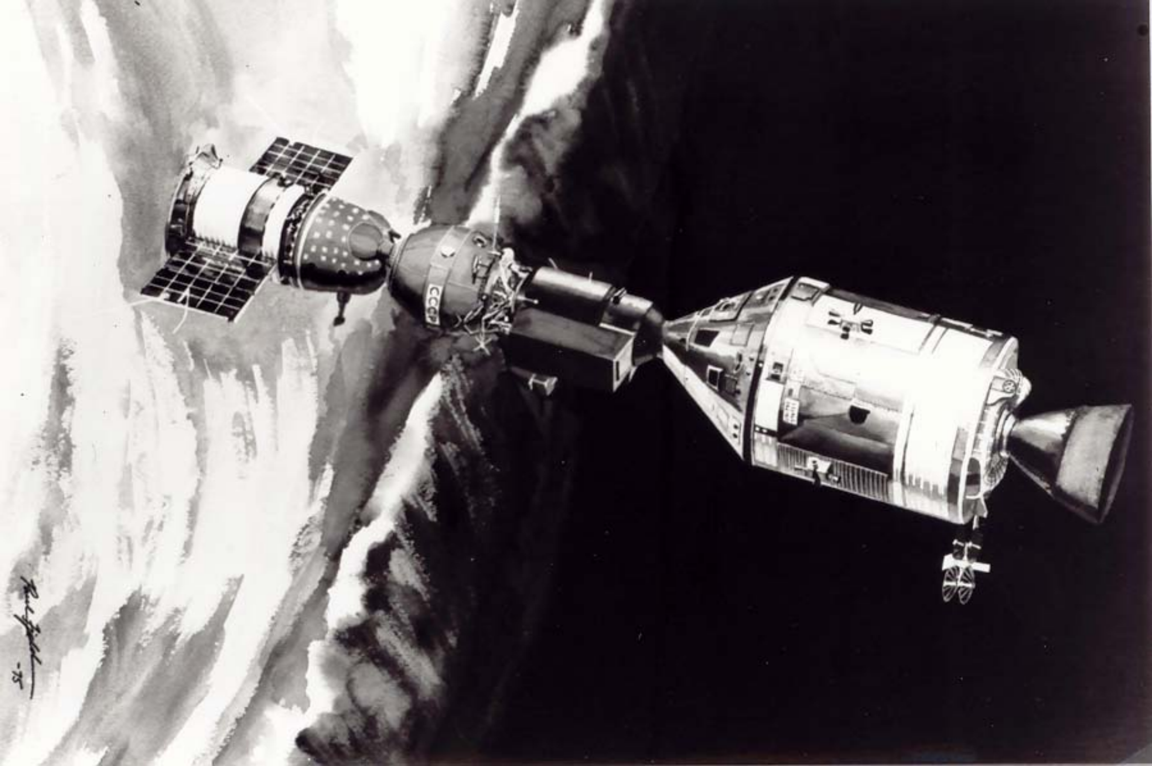


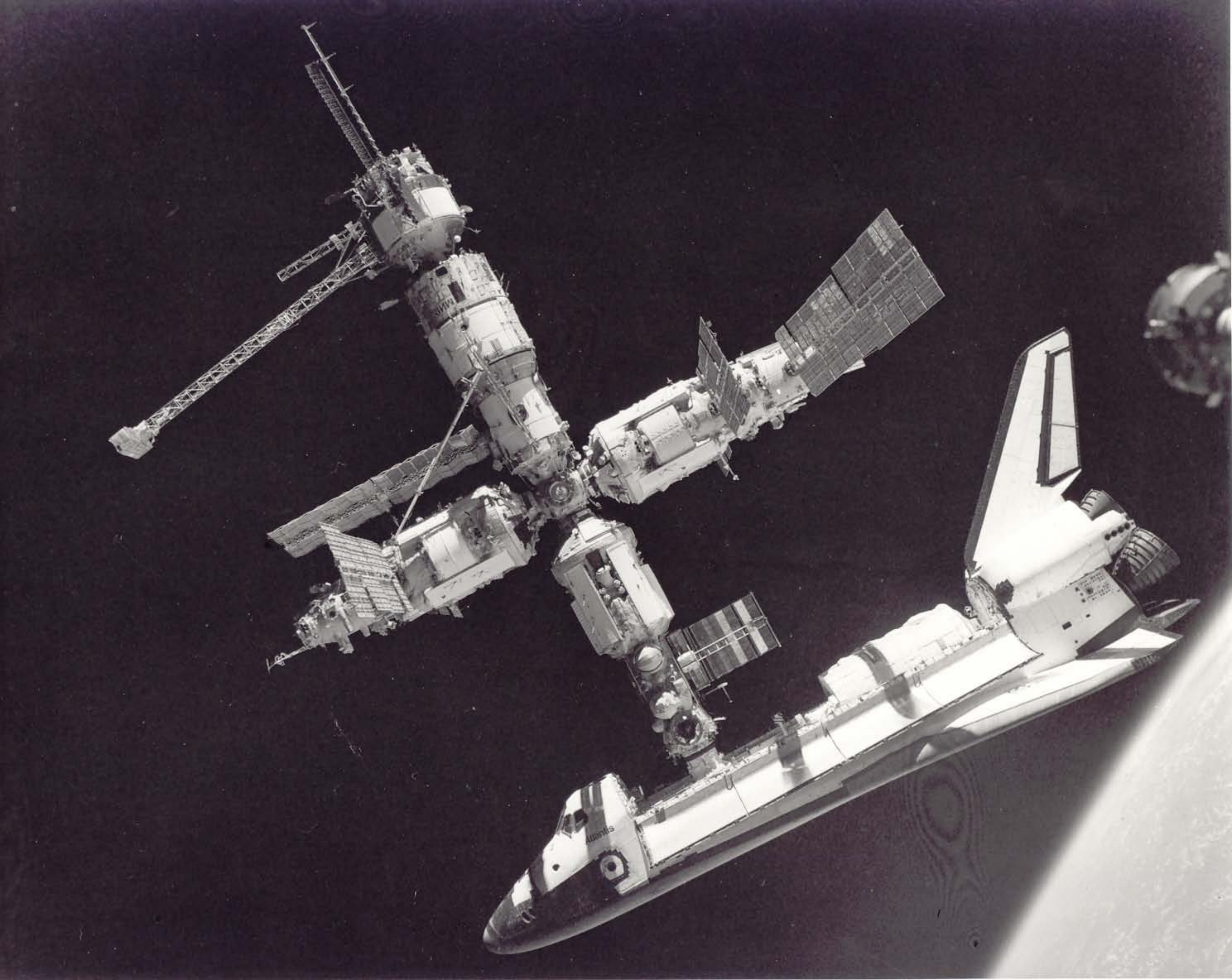
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
P(SFA)
1
2
3
. . .
N
Emergency Factors

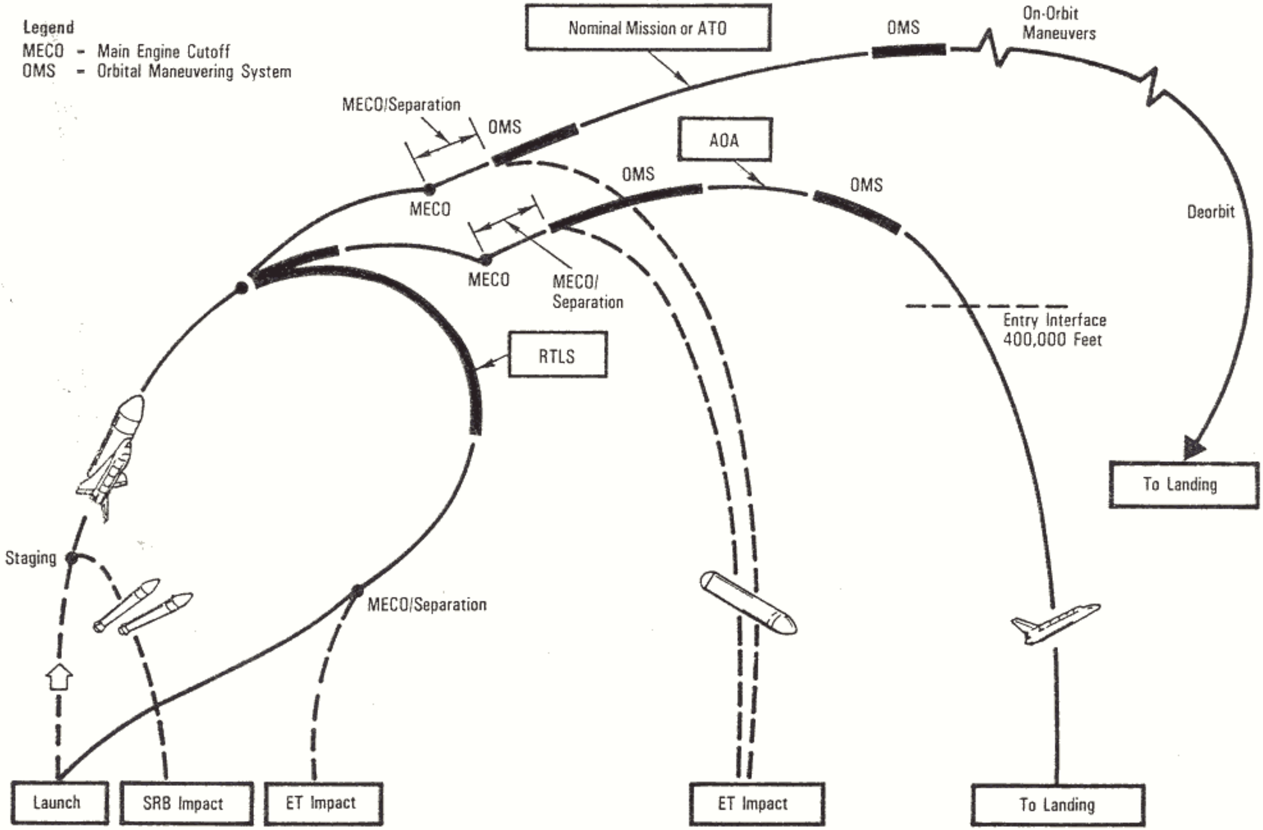


P(SFA/ψN)
10^0
10^-1
10^-2
10^-3
1 2 3...N1
. . . N2
. . . N3
N
Stage I
Stage II
Stage III
Emergency Factors

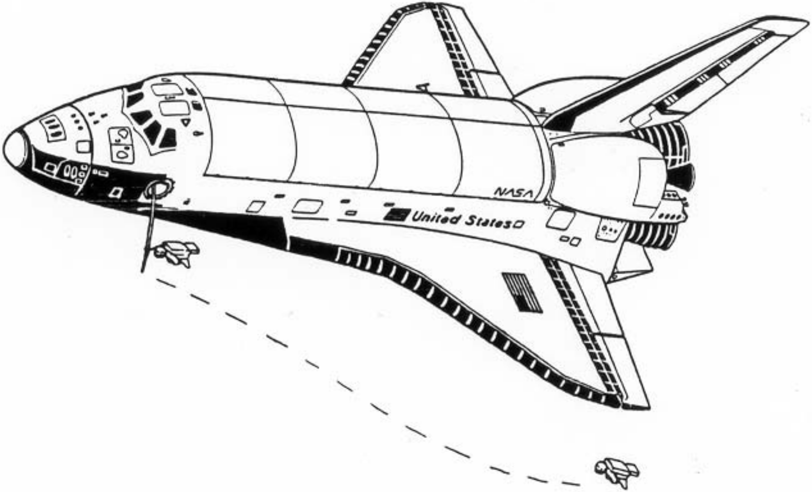
NASA-MSC C.J. COLER 11 FEB 63 S-317-1

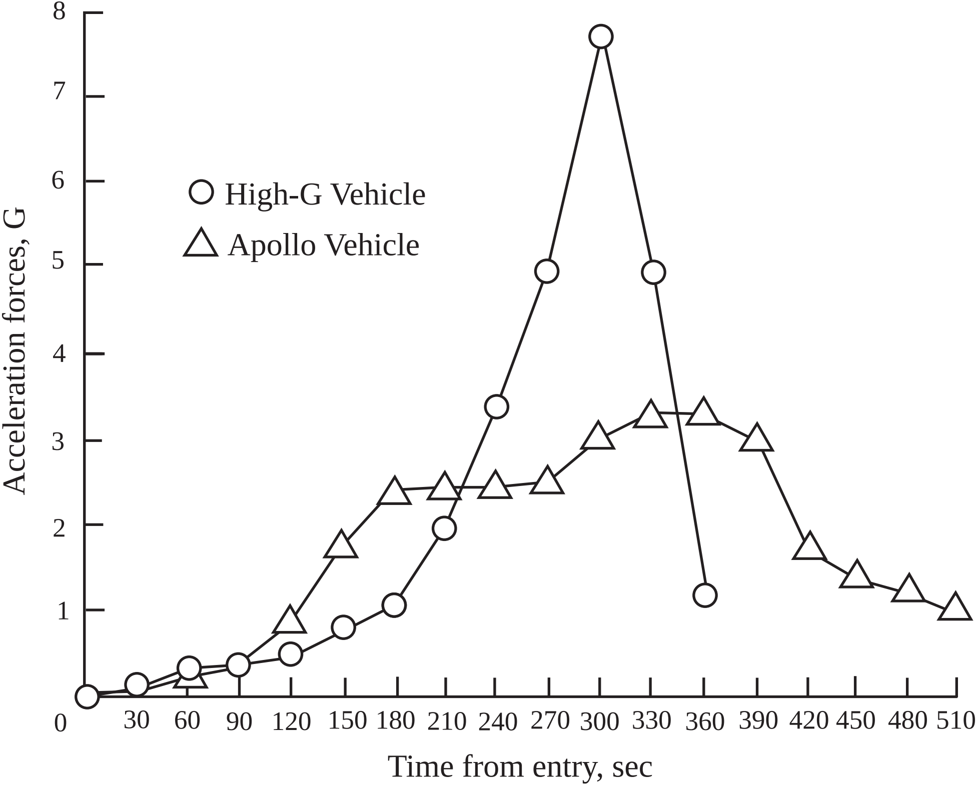

CCCP
-75


Atlantis

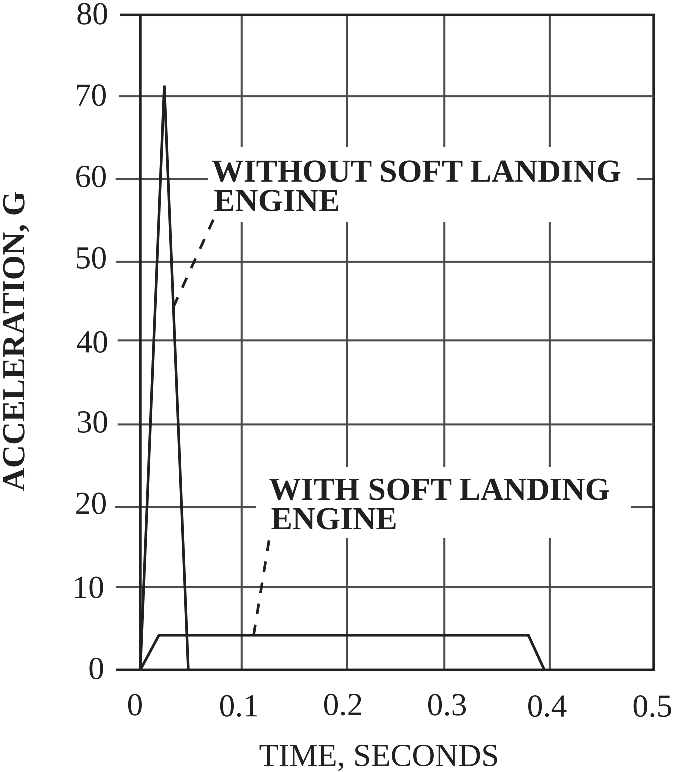

Legend
MECO - Main Engine Cutoff
OMS - Orbital Maneuvering System
Nominal Mission or ATO
OMS
On-Orbit Maneuvers
MECO/Separation
OMS
AOA
OMS
OMS
MECO
Deorbit
MECO
MECO/ Separation
Entry Interface 400,000 Feet
RTLS
To Landing
Staging
MECO/Separation
Launch
SRB Impact
ET Impact
ET Impact
To Landing

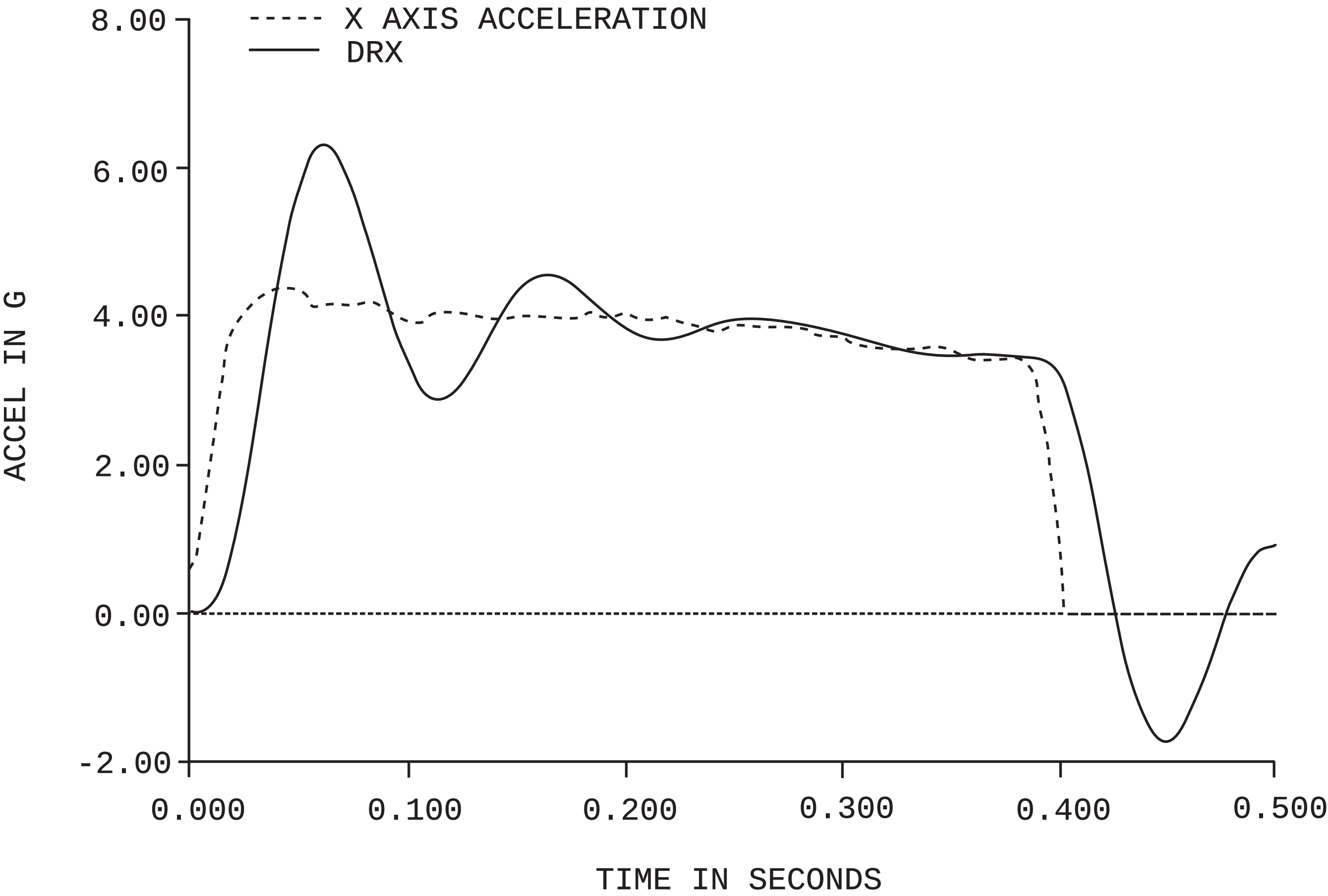
BAILOUT MODE-CREW ESCAPE POLE





8
7
6
5
4
3
2
1
0
Acceleration forces, G
○ High-G Vehicle
△ Apollo Vehicle
30
60
90
120
150
180
210
240
270
300
330
360
390
420
450
480
510
Time from entry, sec

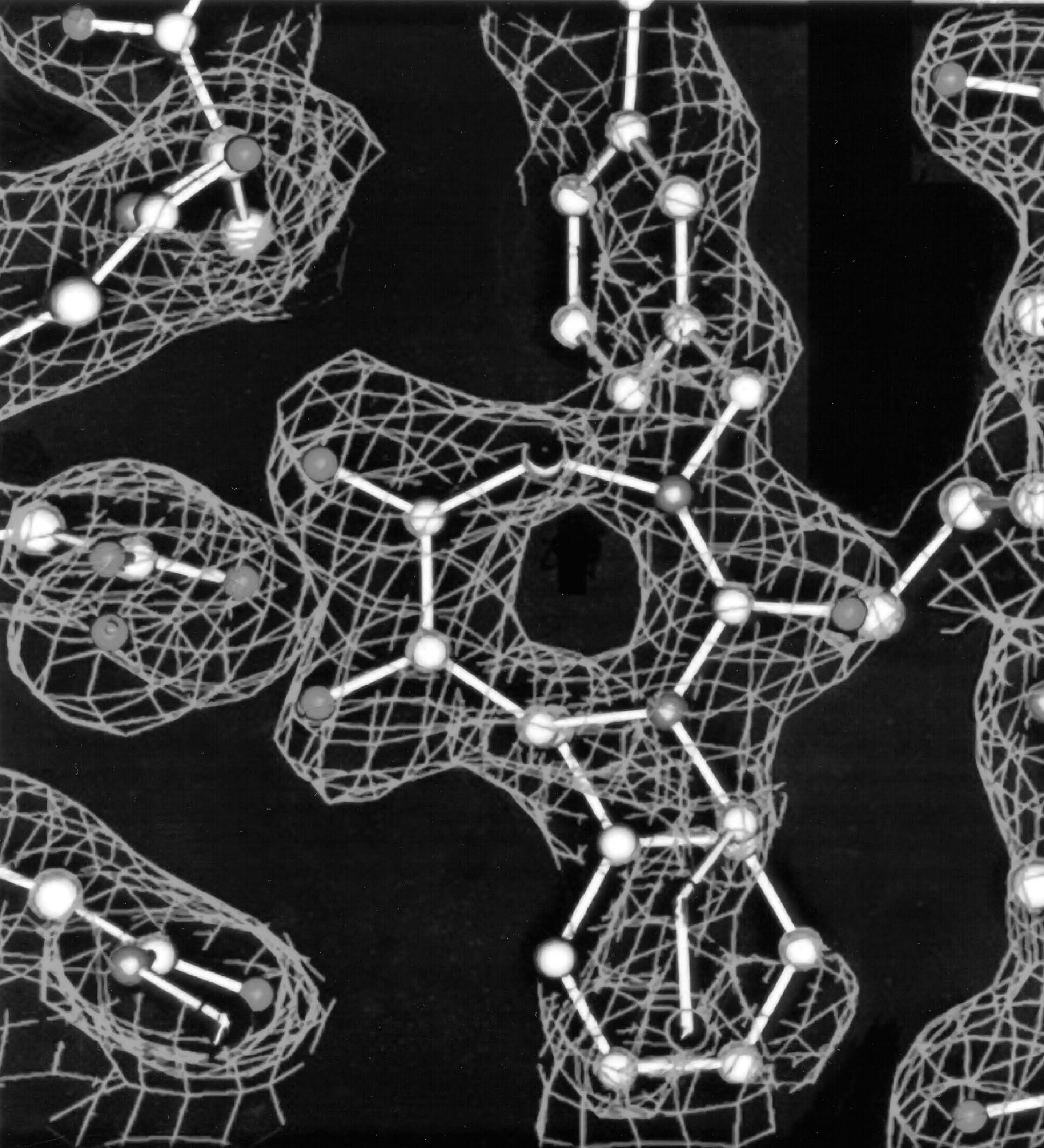

80
70
60
50
40
30
20
10
0
ACCELERATION, G
WITHOUT SOFT LANDING ENGINE
WITH SOFT LANDING ENGINE
0
0.1
0.2
0.3
0.4
0.5
TIME, SECONDS

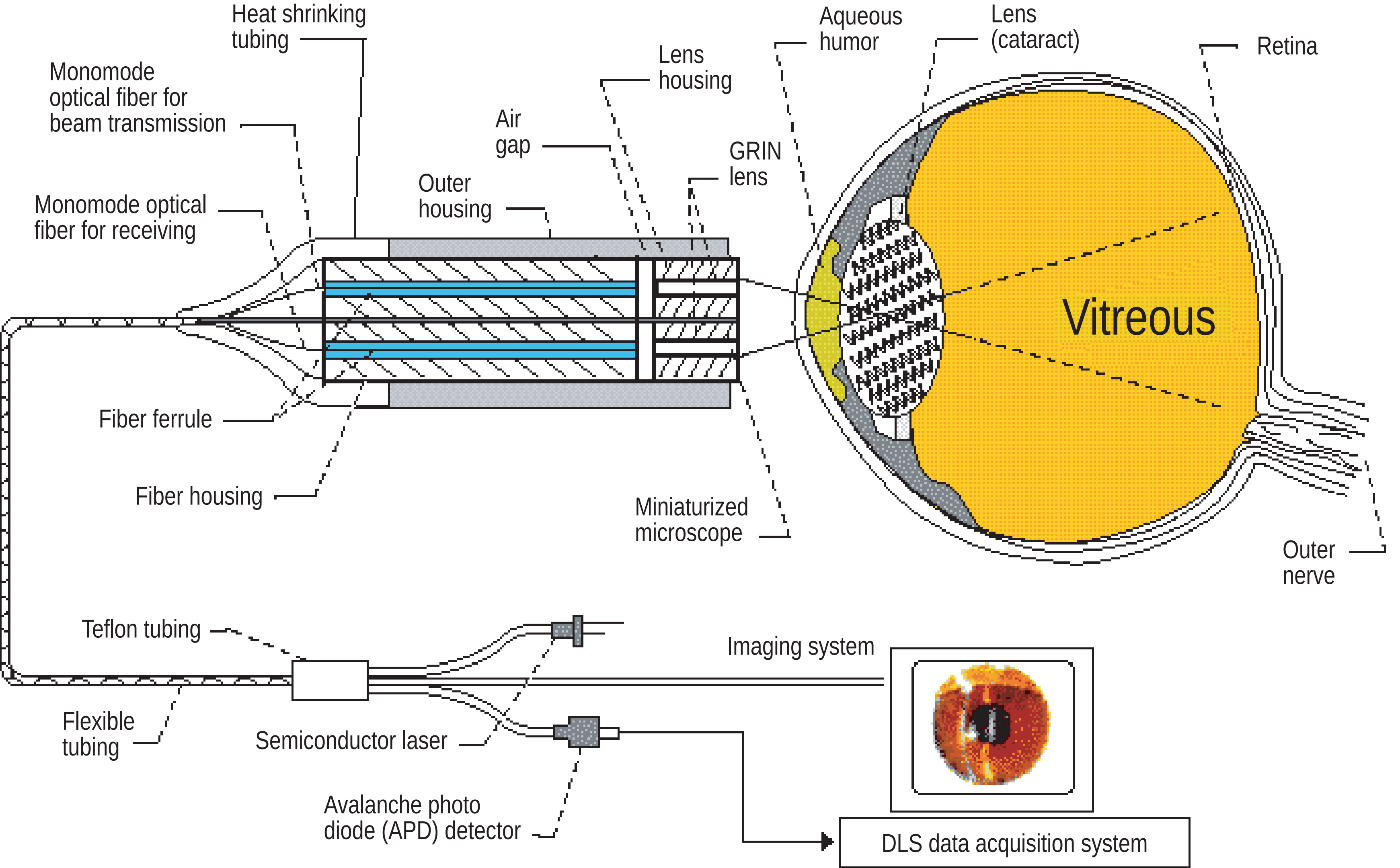


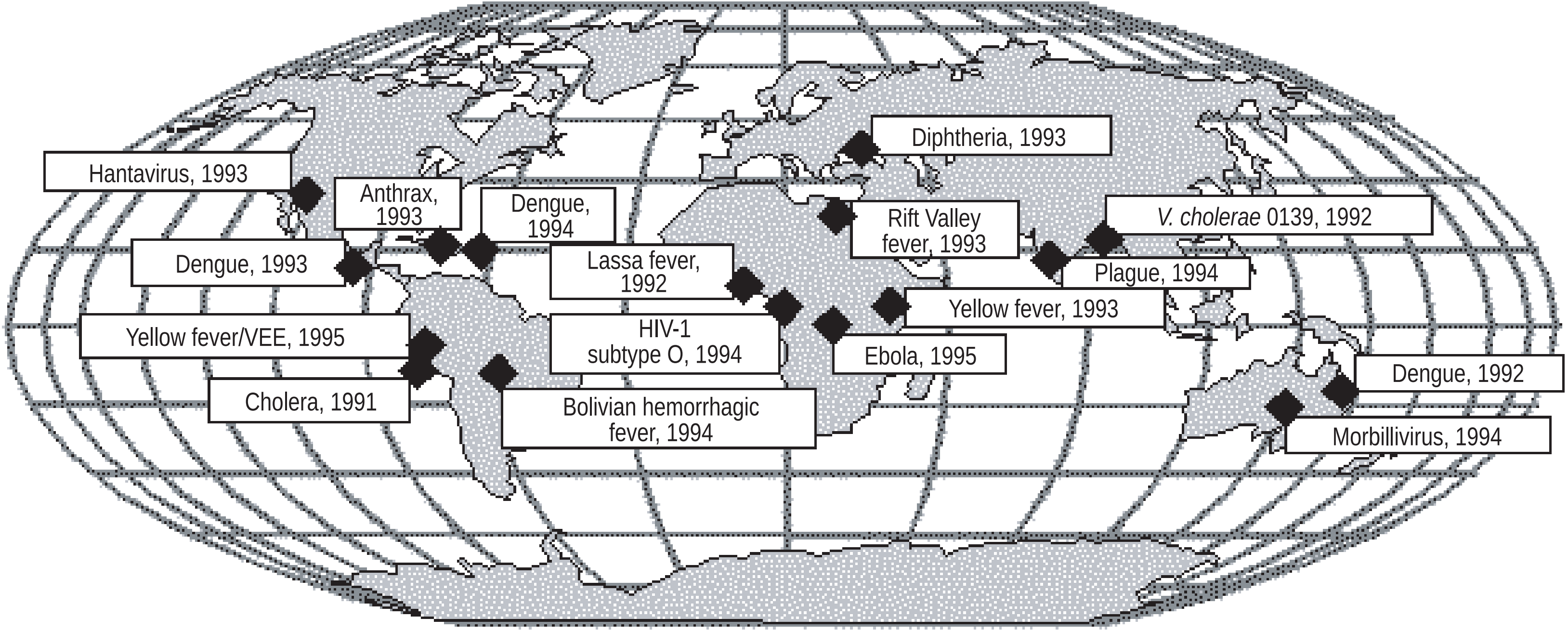
VOSKHOD SPACECRAFT WITH SOFT LANDING ENGINE
DR = 6.32 NAT FREQ = 62.80 RAD DAMP RATIO = 0.200

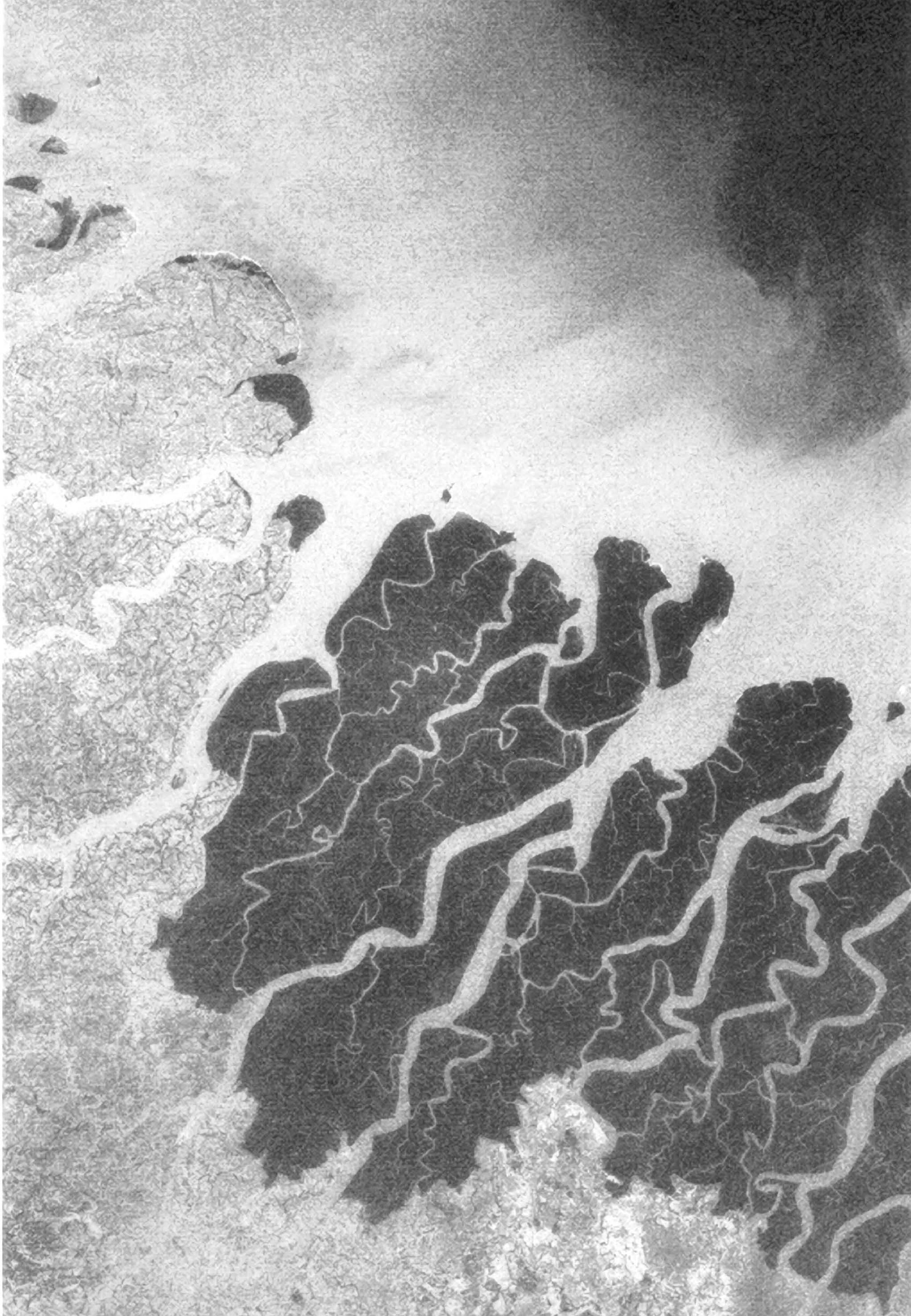

OFFSHORE
TECHNOLOGY
RESEARCH
CENTER
UNITED STATES
ACRV

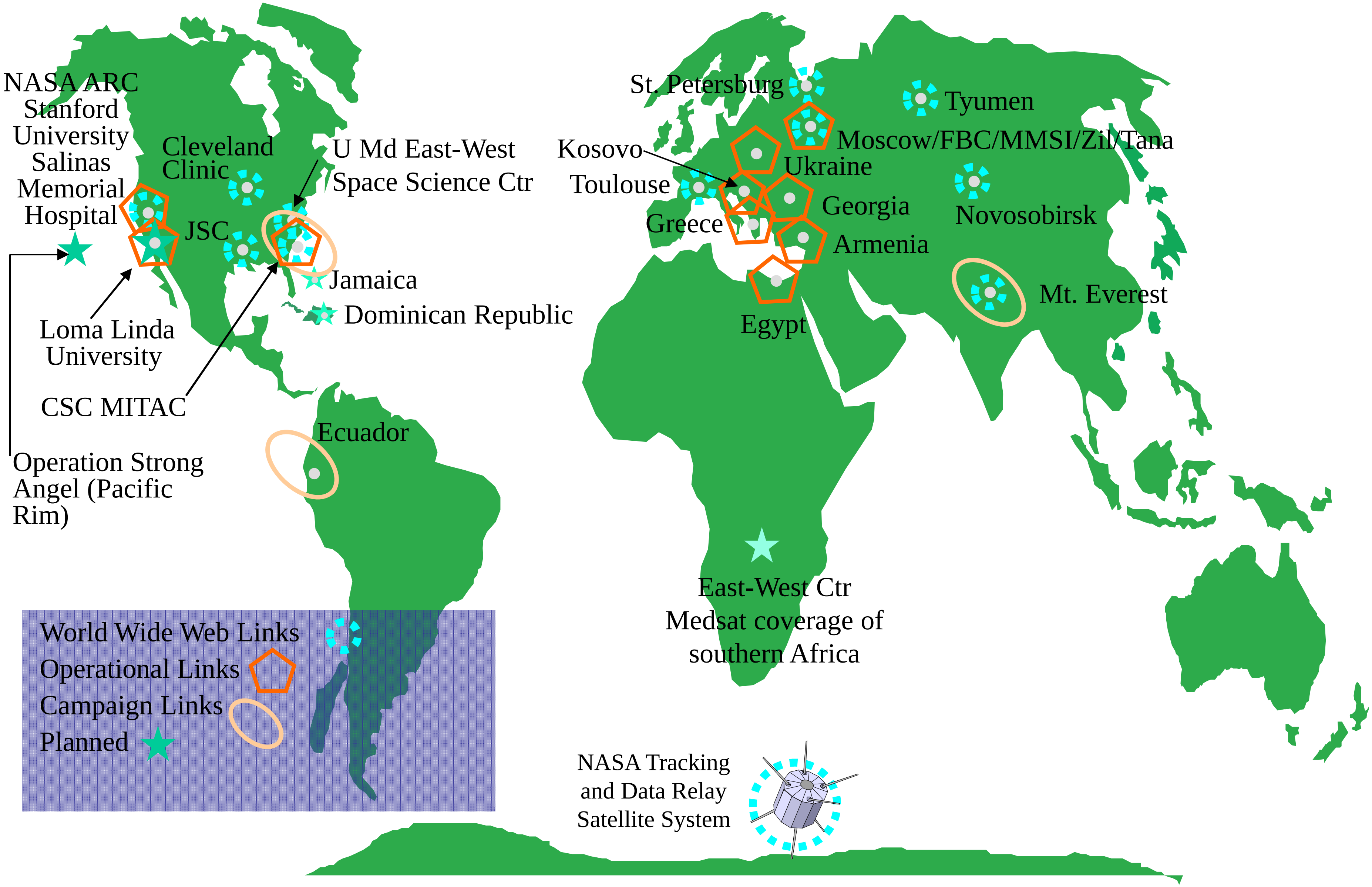

35 11

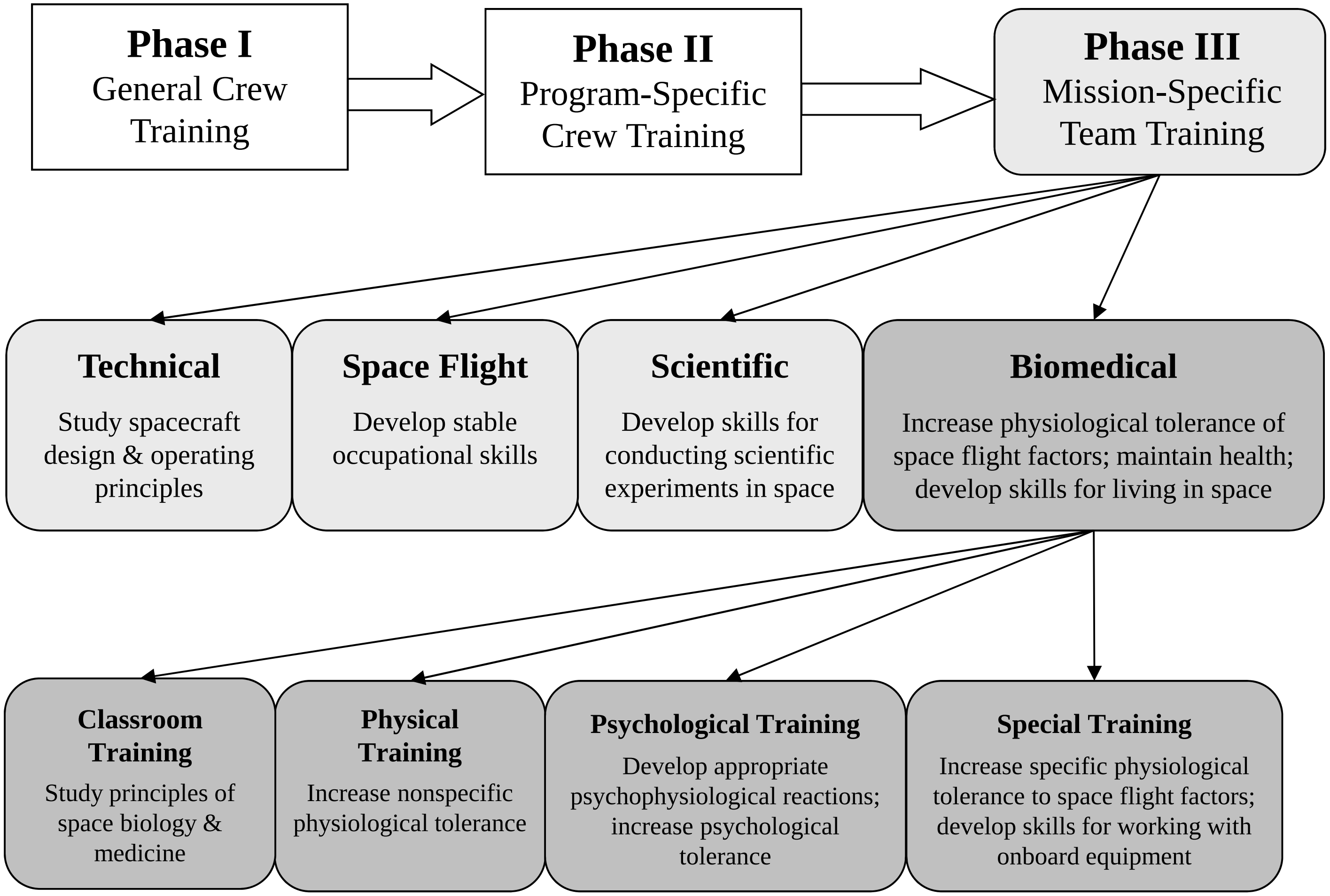


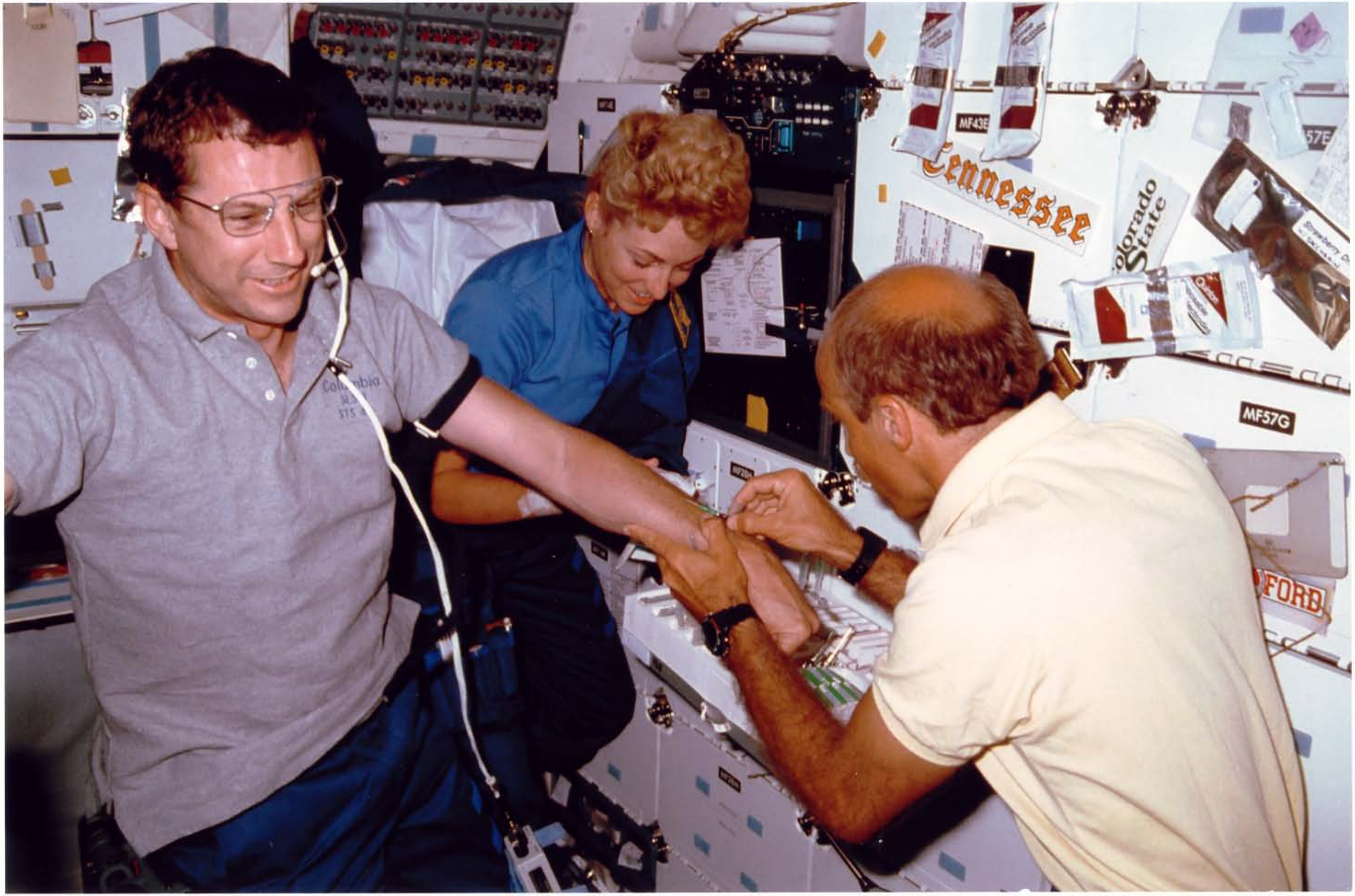

Heat shrinking tubing
Monomode optical fiber for beam transmission
Monomode optical fiber for receiving
Air gap
Outer housing
Lens housing
GRIN lens
Aqueous humor
Lens (cataract)
Retina
Vitreous
Fiber ferrule
Fiber housing
Miniaturized microscope
Outer nerve
Teflon tubing
Imaging system
Flexible tubing
Semiconductor laser
Avalanche photo diode (APD) detector
DLS data acquisition system


Diphtheria, 1993
Hantavirus, 1993
Anthrax, 1993
Dengue, 1994
Rift Valley fever, 1993
V. cholerae 0139, 1992
Dengue, 1993
Lassa fever, 1992
Plague, 1994
Yellow fever, 1993
Yellow fever/VEE, 1995
HIV-1 subtype O, 1994
Ebola, 1995
Dengue, 1992
Cholera, 1991
Bolivian hemorrhagic fever, 1994
Morbillivirus, 1994




NASA ARC
Stanford University
Salinas Memorial Hospital
Cleveland Clinic
U Md East-West Space Science Ctr
JSC
Jamaica
Dominican Republic
Loma Linda University
CSC MITAC
Operation Strong Angel (Pacific Rim)
Ecuador
St. Petersburg
Tyumen
Moscow/FBC/MMSI/Zil/Tana
Kosovo
Toulouse
Ukraine
Georgia
Greece
Armenia
Novosobirsk
Mt. Everest
Egypt
East-West Ctr Medsat coverage of southern Africa
World Wide Web Links
Operational Links
Campaign Links
Planned
NASA Tracking and Data Relay Satellite System


Phase I
General Crew Training
Phase II
Program-Specific Crew Training
Phase III
Mission-Specific Team Training
Technical
Study spacecraft design & operating principles
Space Flight
Develop stable occupational skills
Scientific
Develop skills for conducting scientific experiments in space
Biomedical
Increase physiological tolerance of space flight factors; maintain health; develop skills for living in space
Classroom Training
Study principles of space biology & medicine
Physical Training
Increase nonspecific physiological tolerance
Psychological Training
Develop appropriate psychophysiological reactions; increase psychological tolerance
Special Training
Increase specific physiological tolerance to space flight factors; develop skills for working with onboard equipment


Tennessee
Colorado State
MF43E
57E
MF57G
FORD
Columbia
SLS
STS


ACTIVITY MONITOR
U.S. Pat. No. 5,197,489
Precision Control Design
THE BAND
HEWLETT PACKARD 200LX
INPUT PWR
FUSE
ON
OFF
INLET

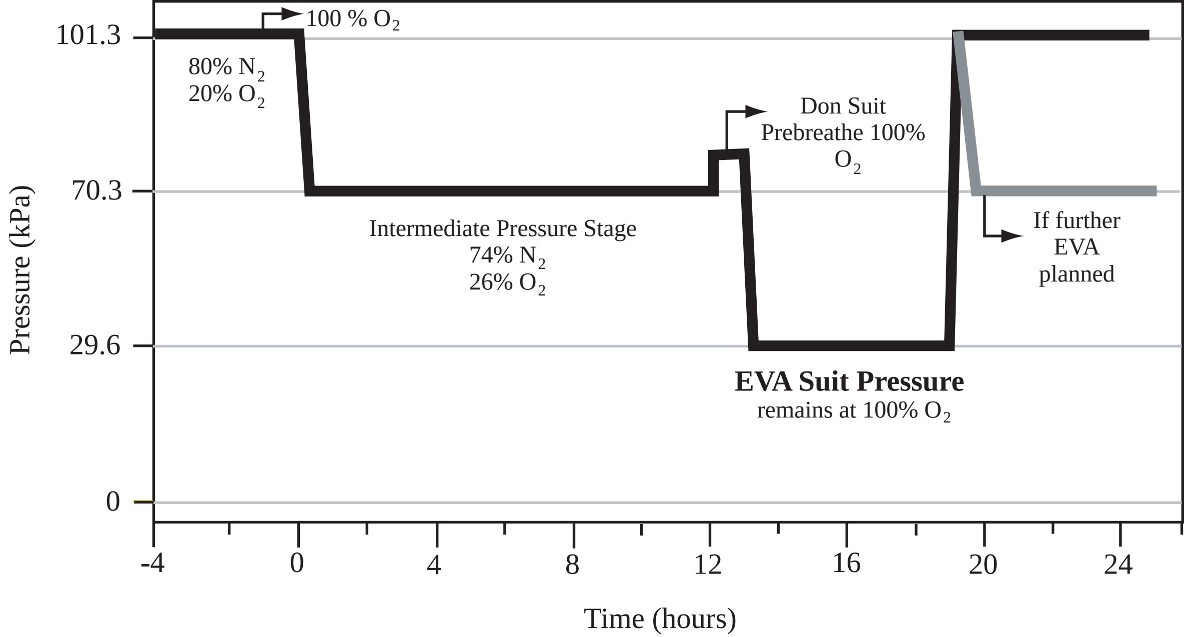

100 % O₂
80% N₂
20% O₂
Don Suit
Prebreathe 100%
O₂
Intermediate Pressure Stage
74% N₂
26% O₂
If further
EVA
planned
EVA Suit Pressure
remains at 100% O₂
Pressure (kPa)
101.3
70.3
29.6
0
-4
0
4
8
12
16
20
24
Time (hours)

Table 2 Summary of medical monitoring employed throughout the Russian and U.S. space programs [Ref.19]

Parameter	Vostok Program	Mercury Program	Gemini Program	Apollo Program	Apollo-Soyuz Test Project	Skylab Missions (every 3rd day)	Shuttle-Mir Program (monthly)	ISS (monthly)
Cardiovascular & Pulmonary	ECG Seismocardiography Respiratory rate Heart sounds Kinetocardiography Cutaneogalvanic response	Blood pressure Heart rate Respiratory rate ECG	Blood pressure Heart rate Respiratory rate ECG EVA monitoring	Continuous ECG Continuous respiratory rate	Continuous ECG Continuous respiratory rate	Vectorcardiography Lower body negative pressure Blood flow Venous compliance	Periodic	——
Musculoskeletal	——	——	——	——	——	Bone mineral measurement	——	Muscle strength
Anthropometric Measurements	——	——	——	——	——	Body mass measurement Leg volume Center of mass Stereophotogrammetry IR anatomical photography	Body mass	Body mass Other parameters as indicated
Metabolism	——	——	——	——	——	Mineral balance Metabolic activity Bioassay of body fluids Specimen mass measurement Urine volume and specific gravity	——	——
Hematology	——	——	——	——	——	Hematology and hemoglobin	Hematology and hemoglobin White blood cell count	Hematology and hemoglobin White blood cell count and morphology
Circadian Cycle & Sleep	Electrooculography	——	——	Sleep reporting	Sleep reporting	Sleep monitoring	Sleep monitoring	Wake/rest monitoring

Neurosensory	EEG Visuals (via telemetry) of optokinetic and vestibular changes	——	——	Reporting motion sickness	Reporting motion sickness	Human vestibular function Taste and aroma evaluation	——	——
Exercise	——	——	——	Minimal monitoring	Minimal monitoring	Time and motion study Aerobic and resistive exercise	Aerobic and resistive exercise	Aerobic and resistive exercise
Immunology/ Microbiology	——	——	——	——	——	Limited	Limited	As needed
Microbiology/ Toxicology	——	——	——	Periodic	Periodic	Atmospheric volatile concentration	Periodic	Periodic
Acoustic Levels	——	——	——	Yes	Yes	Yes	Yes	Yes
Radiation	Yes	Yes	Yes	Yes	Yes	Yes Light flash observations	Yes	Yes

Table 1 Graded scale for evaluating physiological response to stress

Physiological status		Level of applied stress	Regulatory system response scale (ПАРС)
1	Adaptation	Optimal	1
		Normative	2
2	Symptomatic	Moderate	3
		Pronounced	4
		Acute	5
3	Preclinical	Strain of regulatory function	6
		Early metabolic breakdown	7
4	Maladaptation	Exhaustion of regulatory function	8
		Acute exhaustion of regulatory function	9
		Failure of regulatory function	10

Table 3 In-flight medical monitoring during long-duration flights on the Mir station

Type	Instrument	Parameters	Data	Frequency
Medical monitoring during insertion and docking	Alpha-01	Cardiovascular function	Electrocardiography	Continuously from insertion through docking
		Respiratory function	Pneumography	Continuously from insertion through docking
Medical monitoring during EVA	Beta-08	Cardiovascular function	Electrocardiography	Continuously during EVA
		Respiratory function	Pneumography	Continuously during EVA
		Body temperature	Body temperature	Continuously during EVA
	Gamma-01, onboard cycle ergometer	Hand cycle ergometer	Arm muscle strength	10–15 days prior to EVA
In-flight medical monitoring	Gamma-01	Cardiovascular function	12-lead ECG	Every 30 days
	Gamma-01, Chibis pnuemo-vacuum suit	Cardiovascular response to LBNP	ECG, blood pressure, rheoencephalography	Every 60 days
	Gamma-01, onboard cycle ergometer	Cardiovascular system response to graded physical load	ECG, blood pressure, rheoencephalography	Every 45 days
	Body mass measurement device	Body mass	Body weight	Every 10 days
	Plethysmograph	Calf volume	Calf volume change	Every 10 days
	Reflotron	Blood chemistry	Hemoglobin, glucose, triglycerides, cholesterol, bilirubin, amylase, alanine, etc.	Every 90 days
	UBIM-9	Urine chemistry	pH, protein, glucose, red blood cells, leukocytes, etc.	Every 30 days
	Spacelab ECG	24-hour Holter monitoring	ECG using 2 leads over 24-hour period	Every 60 days
	Treadmill and cardiocassette for ECG recording	Effectiveness of physical training	ECG, workload	Every 60 days
	M-1100, Hematocrit	Hematocrit	Ratio of plasma to packed cells	Every 30 days
	FBM-01 filter pump	Environmental monitoring	Spacecraft microflora	Every 60 days
	Environmental sampler	Formation of microbial colonies	Bacterial and fungal flora of the habitat	Every 60 days
	Audiometer-2	Noise level parameters	Spacecraft acoustics	Every 60 days
	Aspirator AM-5	Spacecraft atmospheric contamination	Atmospheric toxicology	Every 60 days

Table 4 In-flight medical monitoring reports on the Mir station

Section/ Category	Type of information	Source/Originator	Information content
Routine	Daily medical reports	MCC medical group	24-hour summary of crew health and spacecraft environment
	Weekly medical reports	MCC medical group	Weekly summary of crew health and spacecraft environment
	Phased medical reports	MCC medical group	Monthly/quarterly summary of crew heath and spacecraft environment
	Experimental results	Mission Medical Control Center (TsUMOKO) medical group	Results from analysis and assessment of data from investigations performed for medical monitoring program
	Telemetry	MCC medical group	Raw data
Environment	Life support systems	Direct data downlink	Ambient temperature, atmospheric pressure, O_2 and CO_2 partial pressure, humidity
	Radiation exposure	Sources onboard (direct data downlink) and on ground	Amount of radiation—external and internal
Real-time information exchange	Radio communications data	Orbital station and MCC	Miscellaneous information
	Video information	Orbital station	Video images of crew, their activity, interior of station compartments, etc.
	Text	Orbital station	Teletype messages from onboard station, including crew inquiries and responses to questions from medical specialists
Scientific investigations and experiments[a]	Reports, conclusions, and recommendations based on results of scientific investigations	Mission Medical Control Center (TsUMOKO) medical group, specialists from R.F. State Research Center IBMP	Results of scientific investigations and experiments during the current flight that help to better assess crew health
Base of knowledge	Scientific reports based on results of medical investigations from previous space flights	Mission Medical Control Center (TsUMOKO), R.F. State Research Center IBMP	Results of scientific investigations and experiments performed during previous flights that help to predict probable in-flight changes in crew health
	Regulating documentation	MCC and Mission Medical Control Center (TsUMOKO)	Mission programs, medical monitoring procedures, operator instructions, norms and standards
	Space medicine reference and information system	Mission Medical Control Center (TsUMOKO)	Scientific publications and reference data

[a] On U.S. missions, medical data on individuals are covered by the medical privacy act and not considered part of medical monitoring. Per NASA governing policies, these medical data are only reported if there is a serious problem.

Table 5 Range of fluctuation in the atmospheric parameters in the Mir station

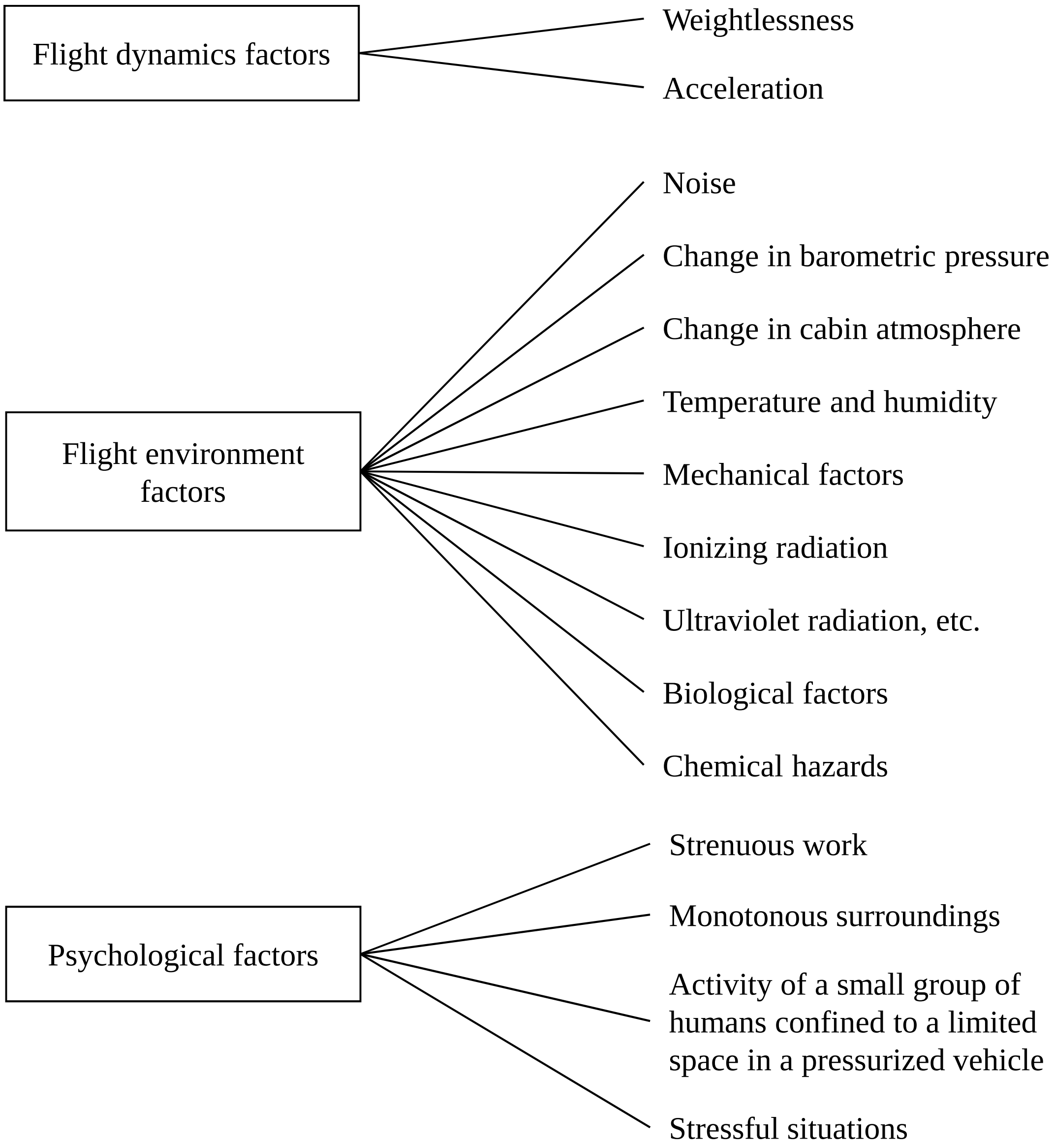
Atmospheric parameters	Recorded fluctuation[a]	Standards (GOST)
P_{total}, kPa	96.9-102.4	88-114.6
P O_2, kPa	21.0-23.6	18.7-26.7
P CO_2, kPa	546.5-719.8	Up to 800.0
Temperature in work module, °C	24.0-27.5	18-25
Temperature in transfer compartment, °C	17.6-19.8	18-25
Humidity, Pa	1345.3-1812.9	666.0-2666.0

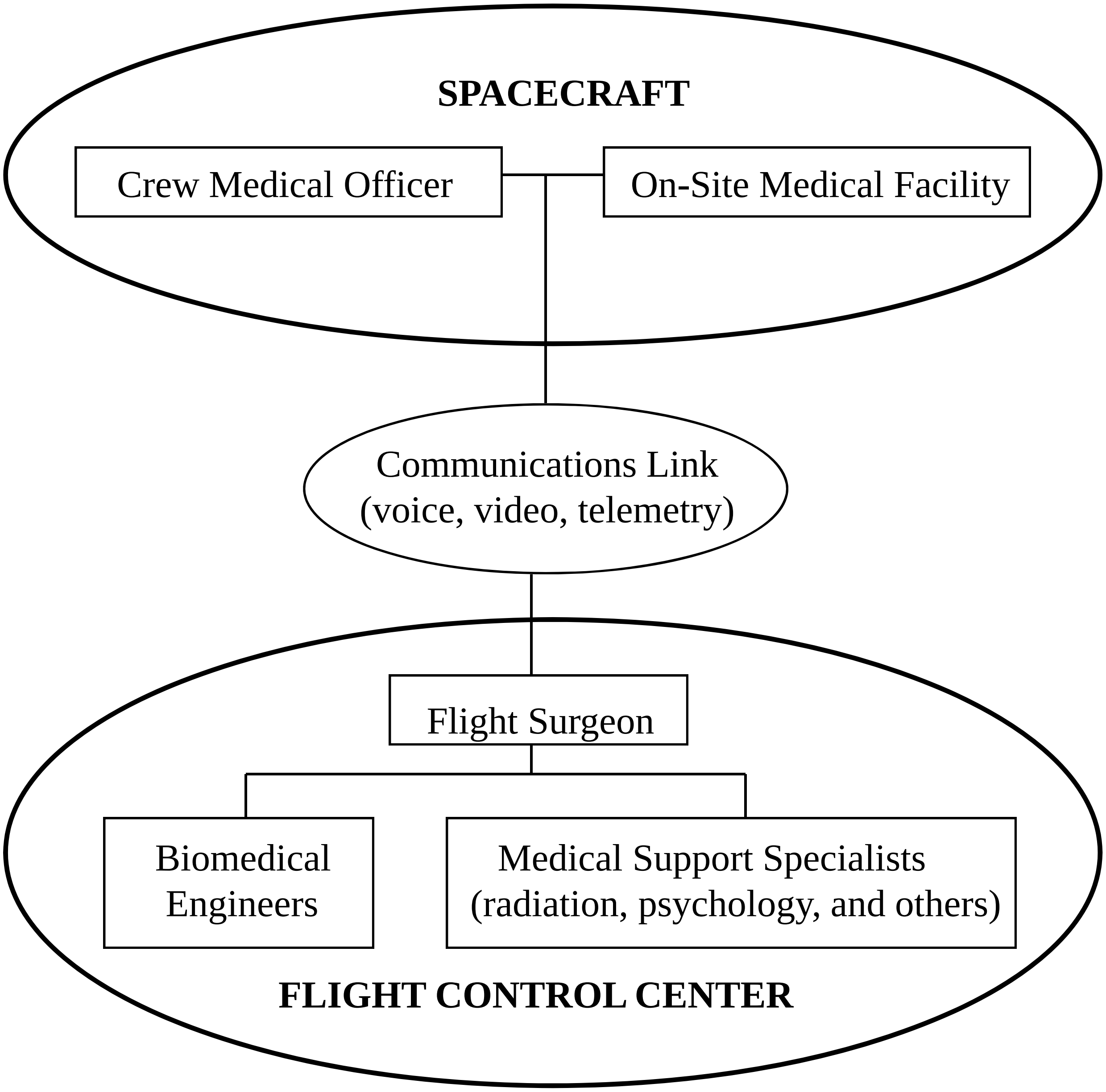
[a] During Mir 20-26 expeditions

Table 6 Radiation monitoring instruments used on the Space Shuttle

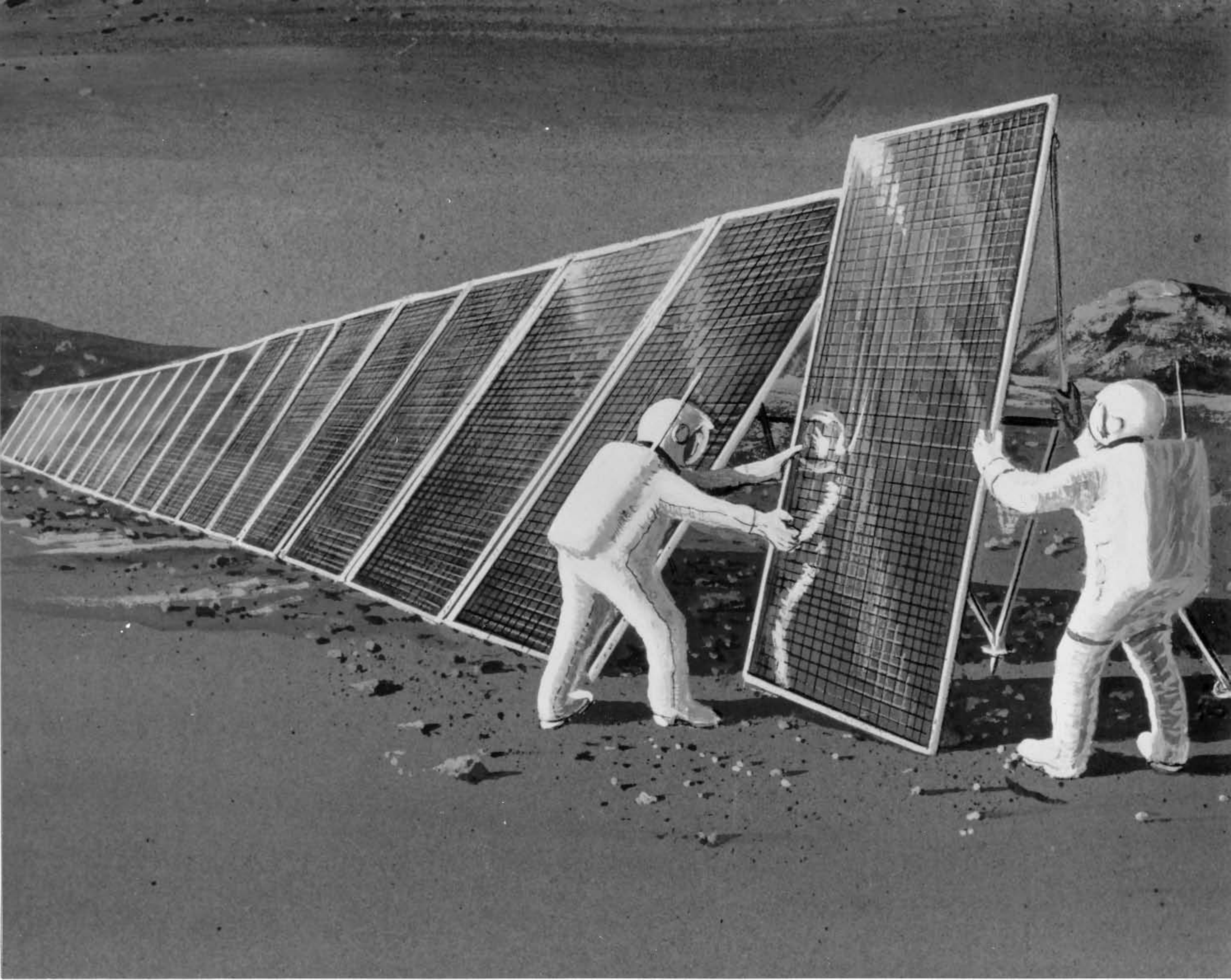
Type of dosimeter	Purpose	Location	Sensitivity[a]
Pocket dosimeter, low (active)	Contingency use only	Stowed in middeck	0-200 mrad
Pocket dosimeter, FEMA (active)	Contingency use only	Stowed in middeck	0-200 mrad
Pocket dosimeter, high (active)	Contingency use only	Stowed in middeck	0-100 rad
High-rate dosimeter (active)	Contingency use only	Stowed in middeck	0-600 rad
Crew thermoluminescent dosimeter (passive)	Measure absorbed dose	Upon crewmember at all times	0.5-10 rad

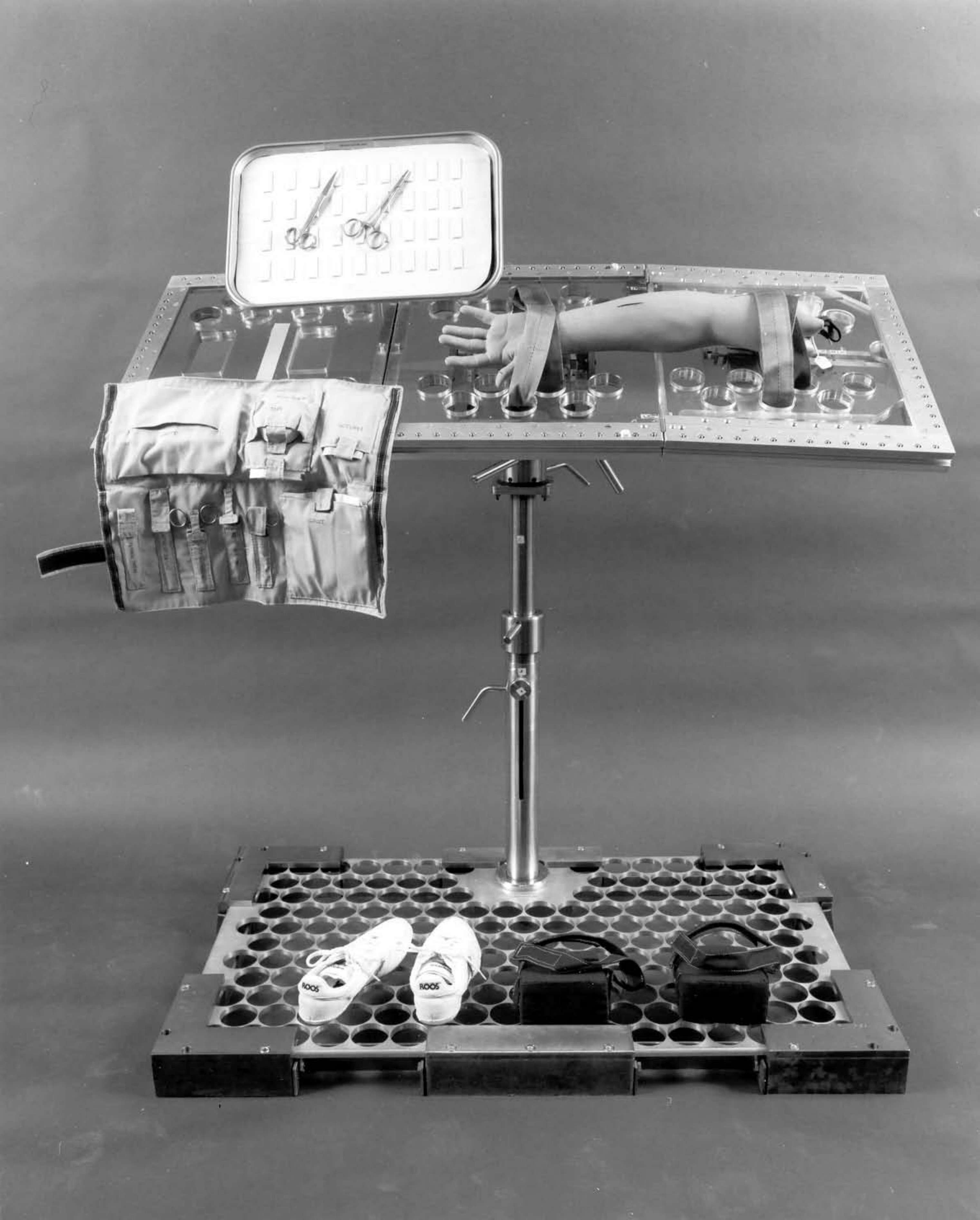
[a] The units of measurement, rads, are approximately equivalent to rems (roentgen equivalent in man), assuming a low-inclination orbit


Flight dynamics factors
Weightlessness
Acceleration
Flight environment factors
Noise
Change in barometric pressure
Change in cabin atmosphere
Temperature and humidity
Mechanical factors
Ionizing radiation
Ultraviolet radiation, etc.
Biological factors
Chemical hazards
Psychological factors
Strenuous work
Monotonous surroundings
Activity of a small group of humans confined to a limited space in a pressurized vehicle
Stressful situations

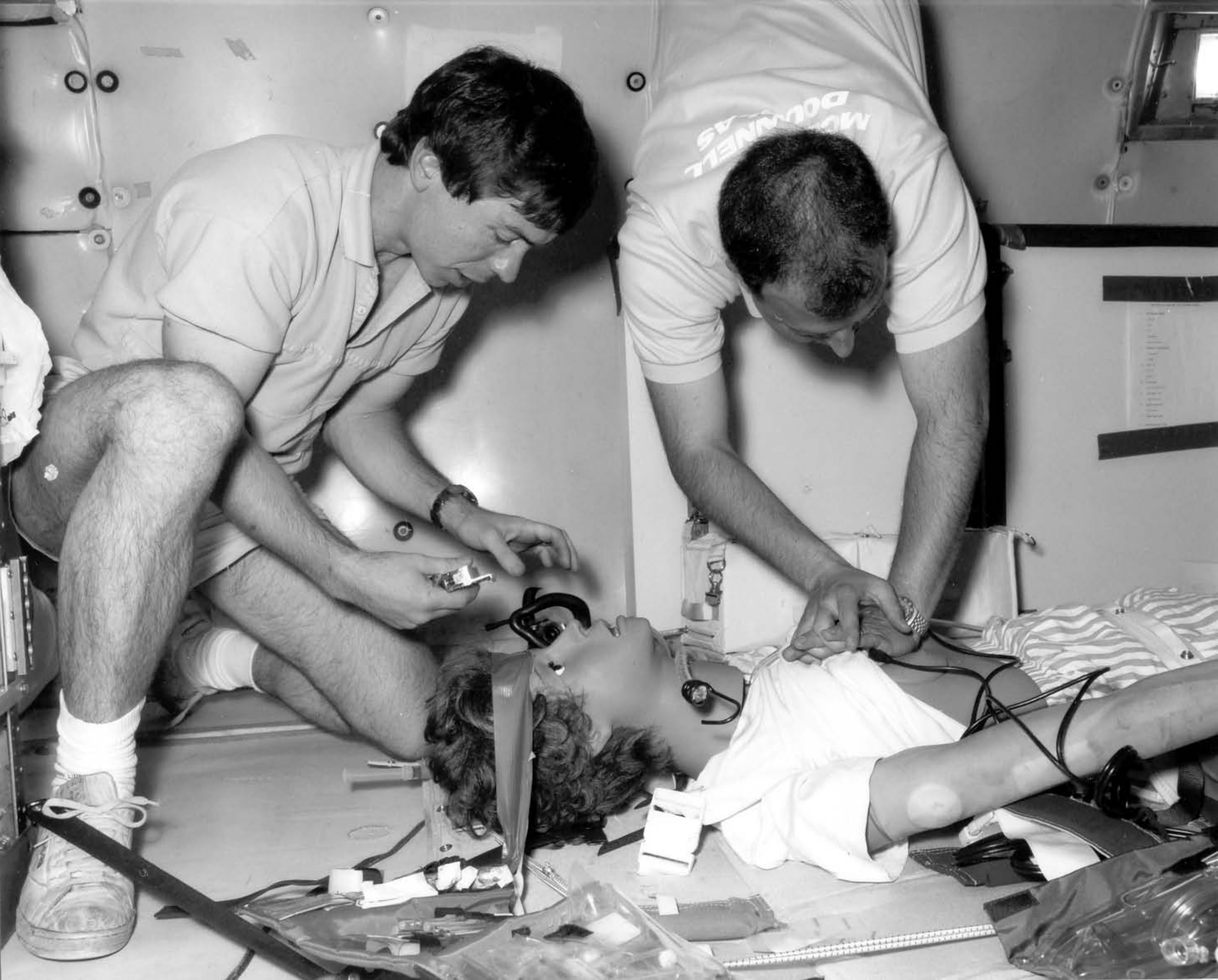

SPACECRAFT
Crew Medical Officer
On-Site Medical Facility
Communications Link
(voice, video, telemetry)
Flight Surgeon
Biomedical Engineers
Medical Support Specialists
(radiation, psychology, and others)
FLIGHT CONTROL CENTER

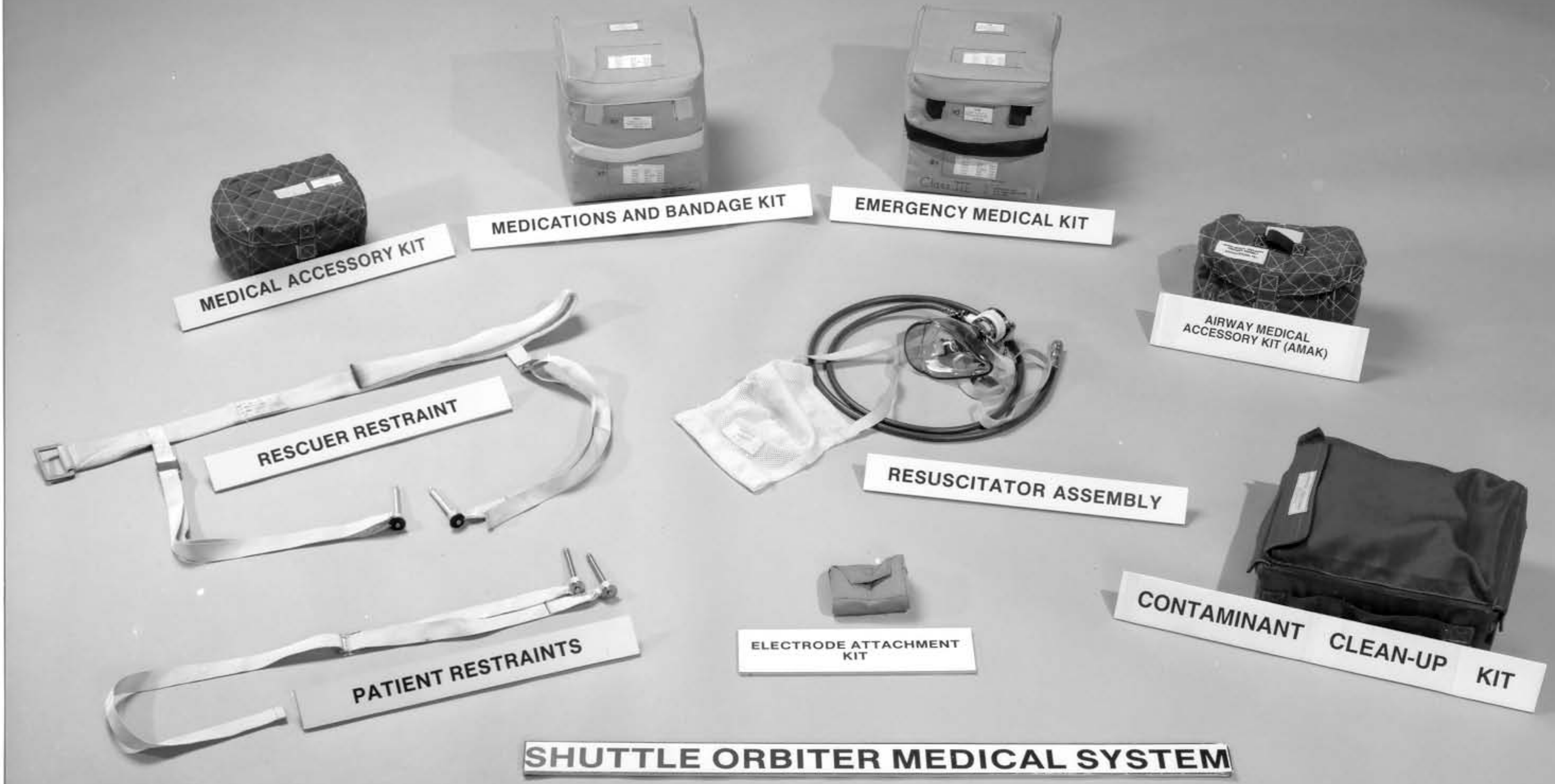

SHARP
NDUS CAMERA
INTENSITY
POWER
OTO/OPHTHALMOSCOPE
POWER
STETHOSCOPE INPUT
INTENSITY
POWER
LIGHT SOURCE
LOCK
HITE BALANCE
INPUT
ECG INPUT
REF
ECG MONITOR
POWER
MODE
FREEZE
SCALE
PULSE OXIMETER
ALARM SILENCE
INPUT



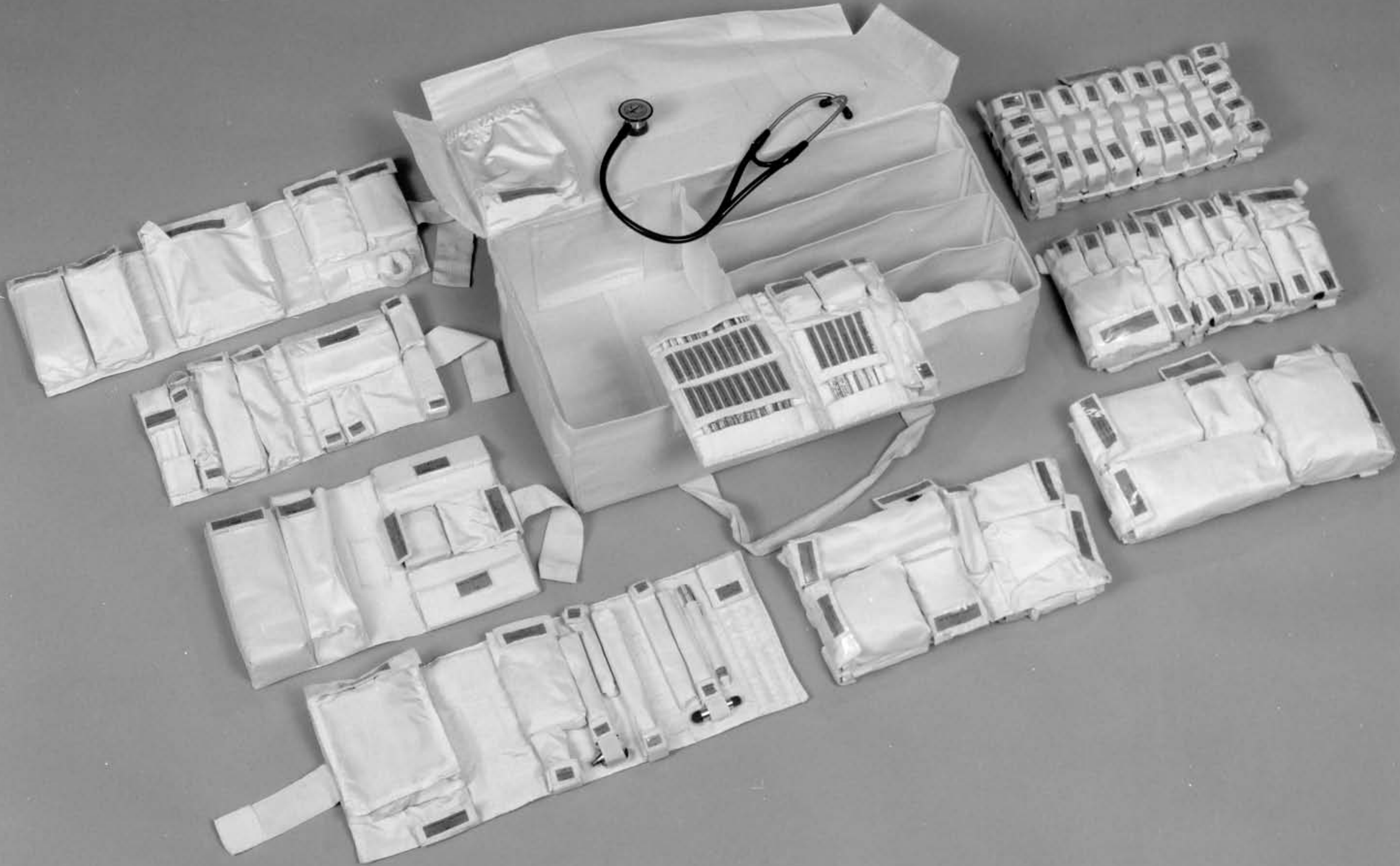

ROOS
ROOS

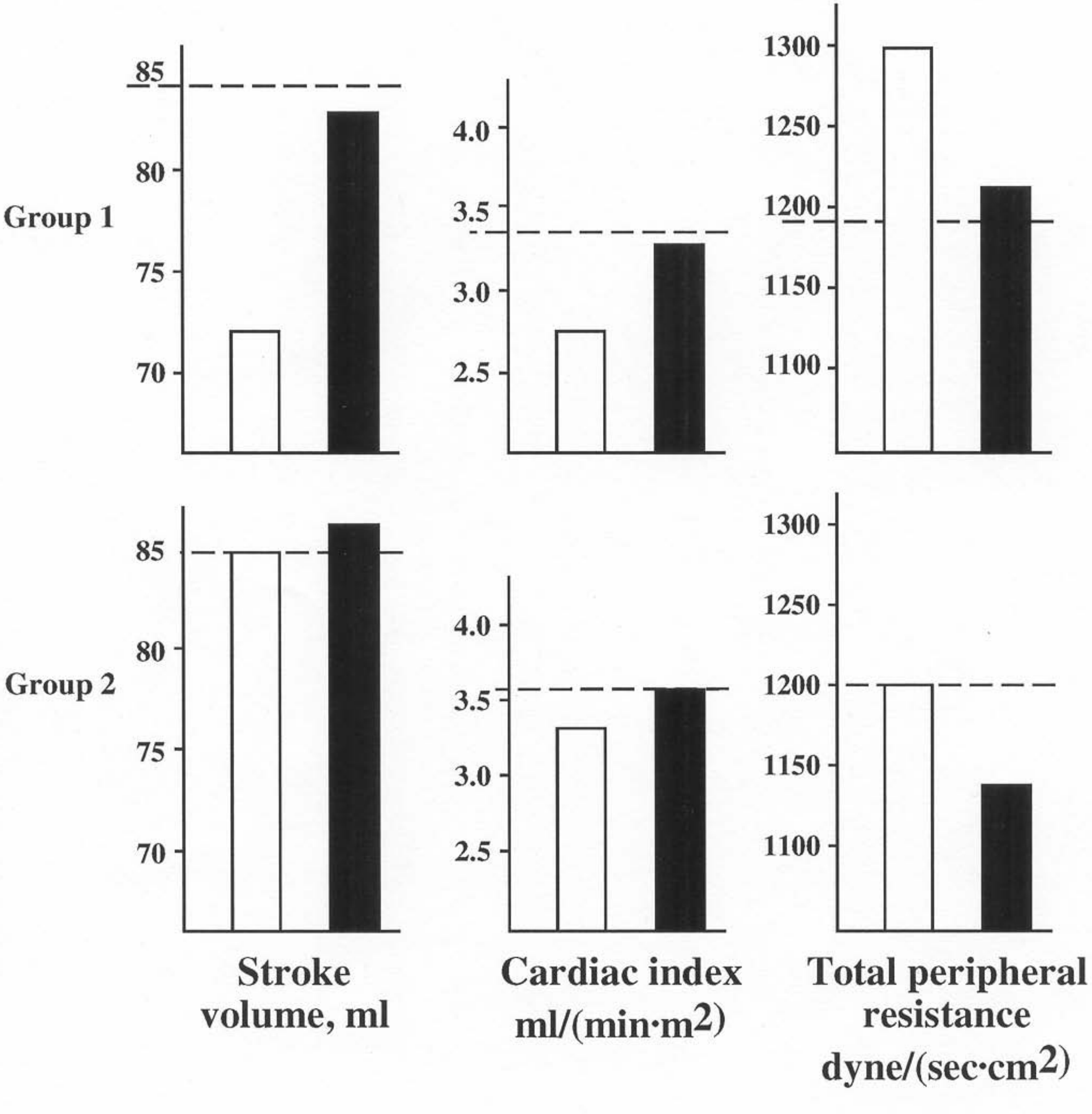
Columbia
SLS 1
STS 40

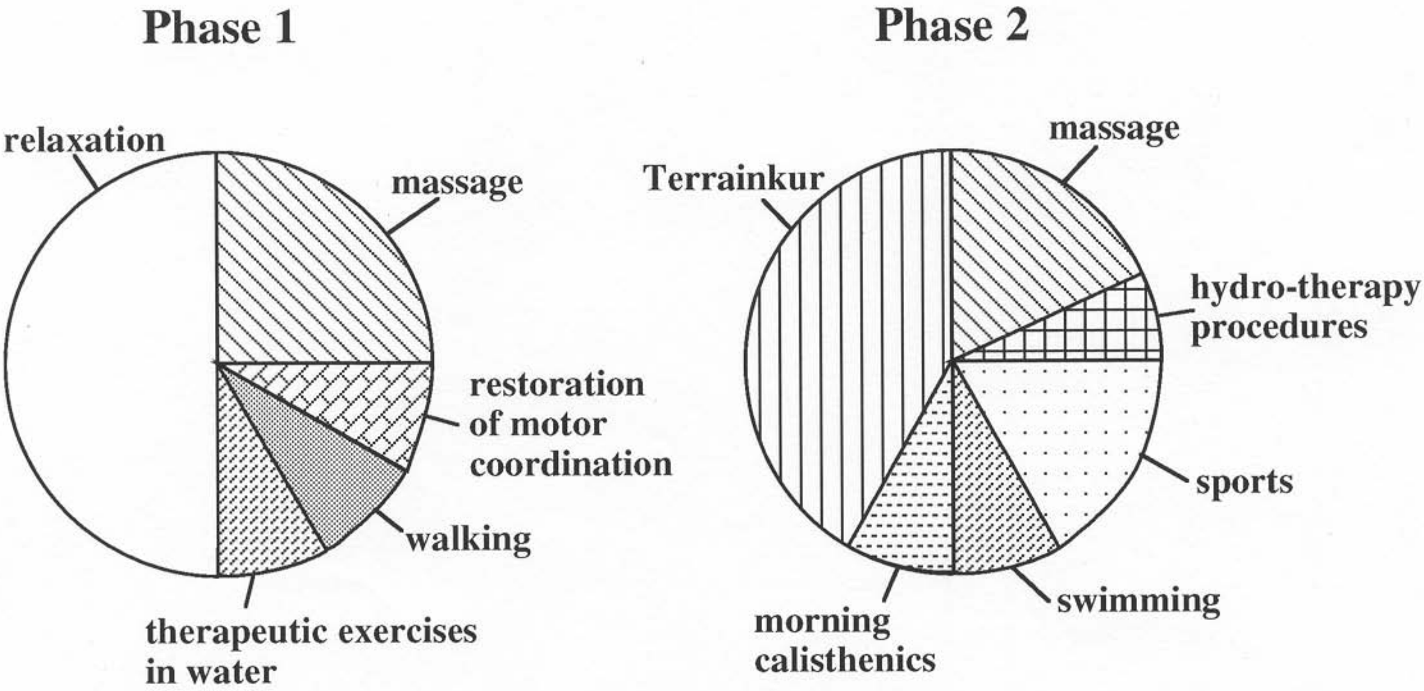

McDONNELL DOUGLAS


MEDICAL ACCESSORY KIT
MEDICATIONS AND BANDAGE KIT
EMERGENCY MEDICAL KIT
AIRWAY MEDICAL ACCESSORY KIT (AMAK)
RESCUER RESTRAINT
RESUSCITATOR ASSEMBLY
ELECTRODE ATTACHMENT KIT
CONTAMINANT CLEAN-UP KIT
PATIENT RESTRAINTS
SHUTTLE ORBITER MEDICAL SYSTEM


I
II
III
IV
V
VI
II

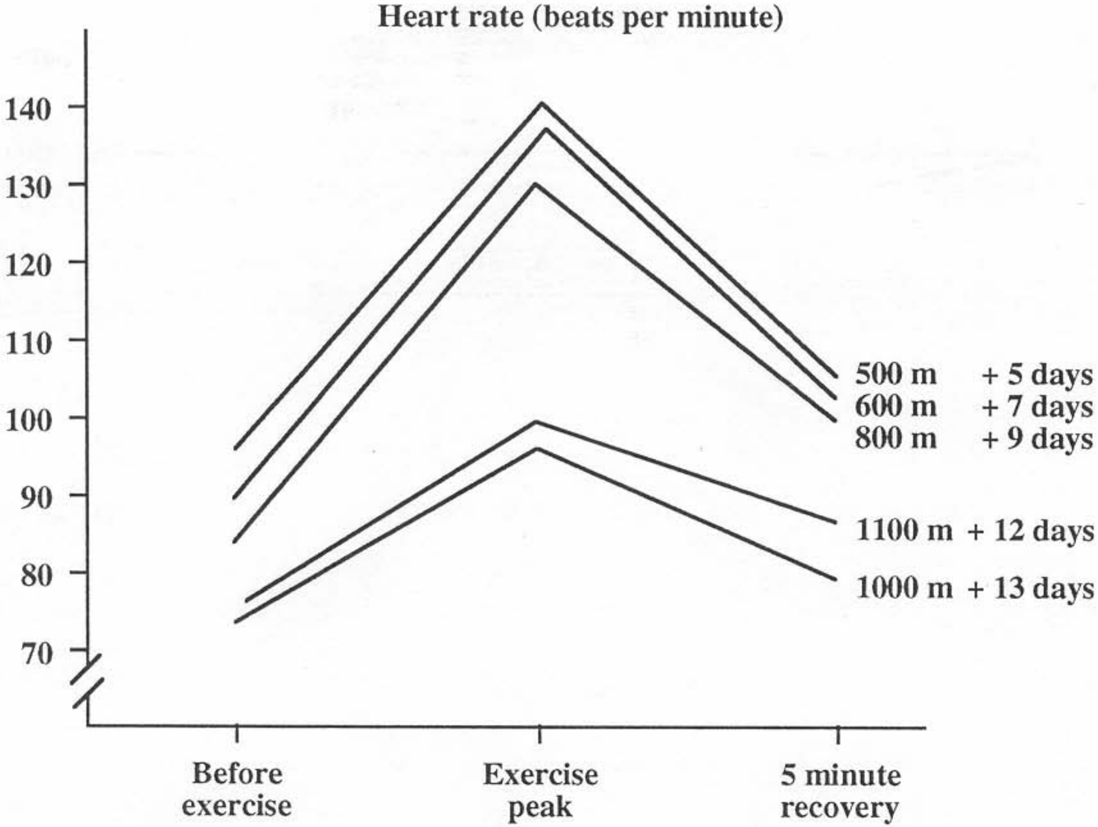


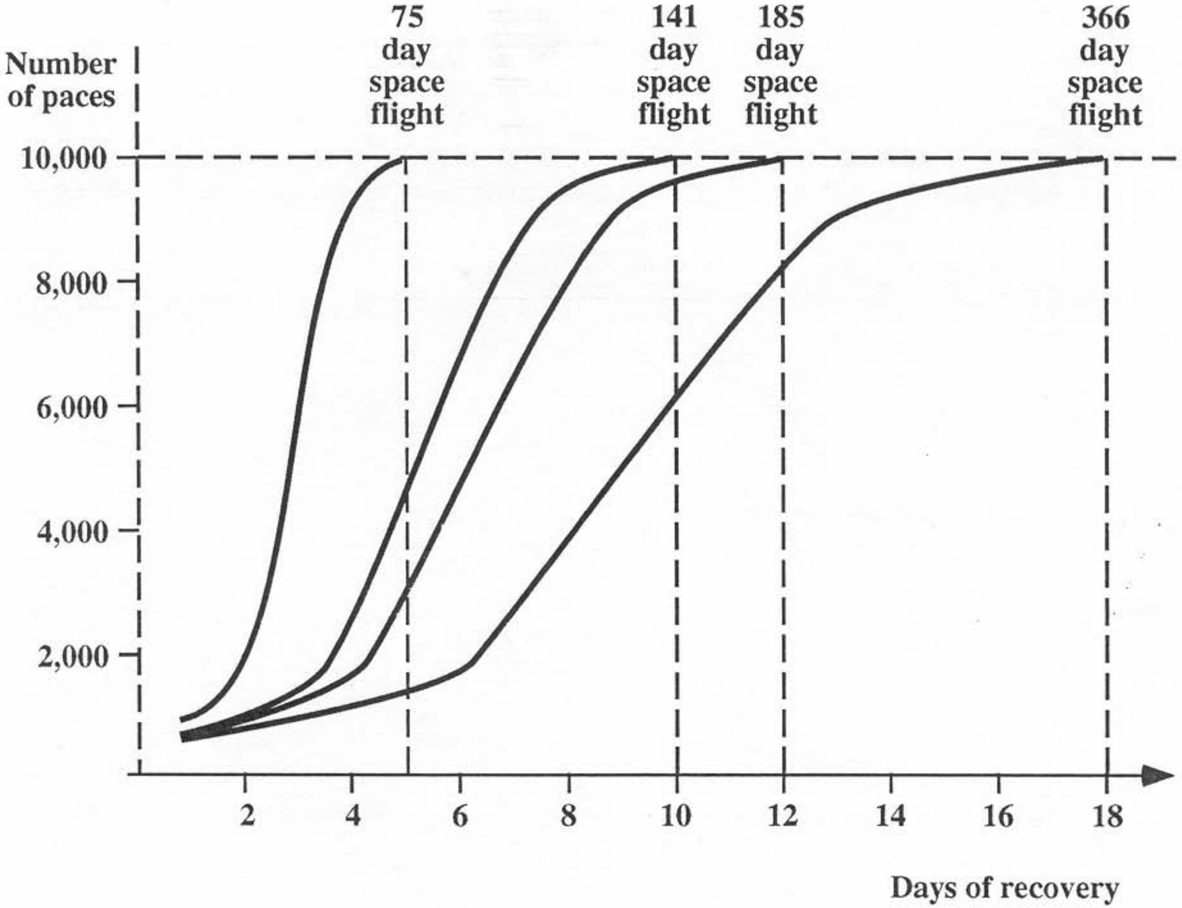

85
80
75
70
Group 1
4.0
3.5
3.0
2.5
1300
1250
1200
1150
1100
Group 2
85
80
75
70
4.0
3.5
3.0
2.5
1300
1250
1200
1150
1100
Stroke volume, ml
Cardiac index ml/(min·m2)
Total peripheral resistance dyne/(sec·cm2)



Phase 1

Phase 2


Heart rate (beats per minute)
140
130
120
110
100
90
80
70
500 m + 5 days
600 m + 7 days
800 m + 9 days
1100 m + 12 days
1000 m + 13 days
Before exercise
Exercise peak
5 minute recovery


Number of paces
10,000
8,000
6,000
4,000
2,000
75 day space flight
141 day space flight
185 day space flight
366 day space flight
2
4
6
8
10
12
14
16
18
Days of recovery

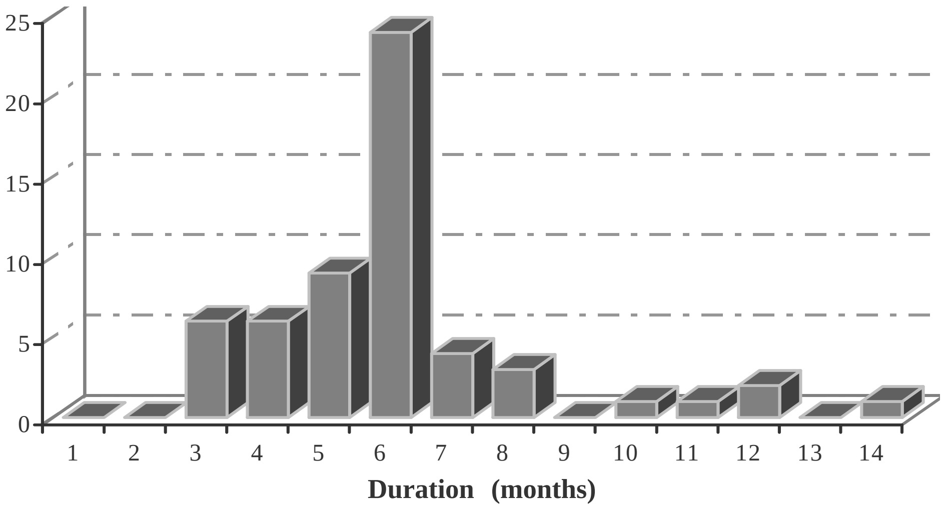
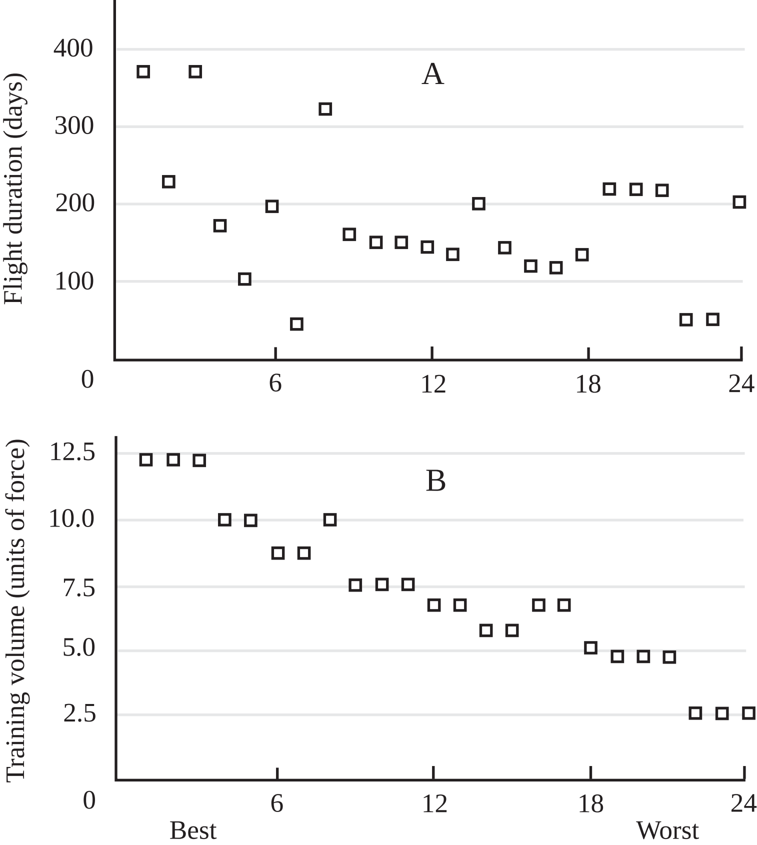
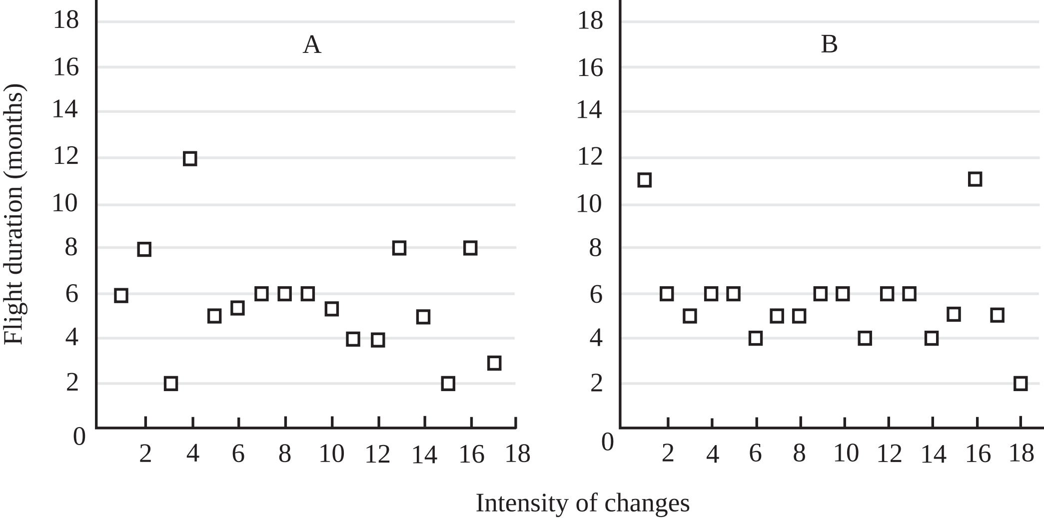
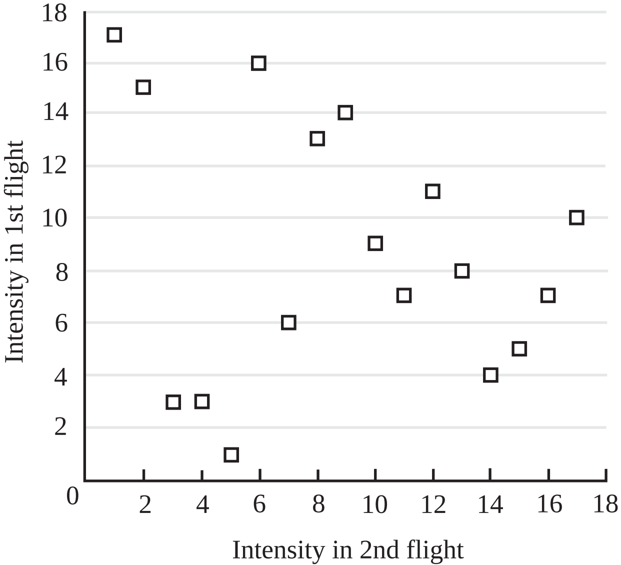


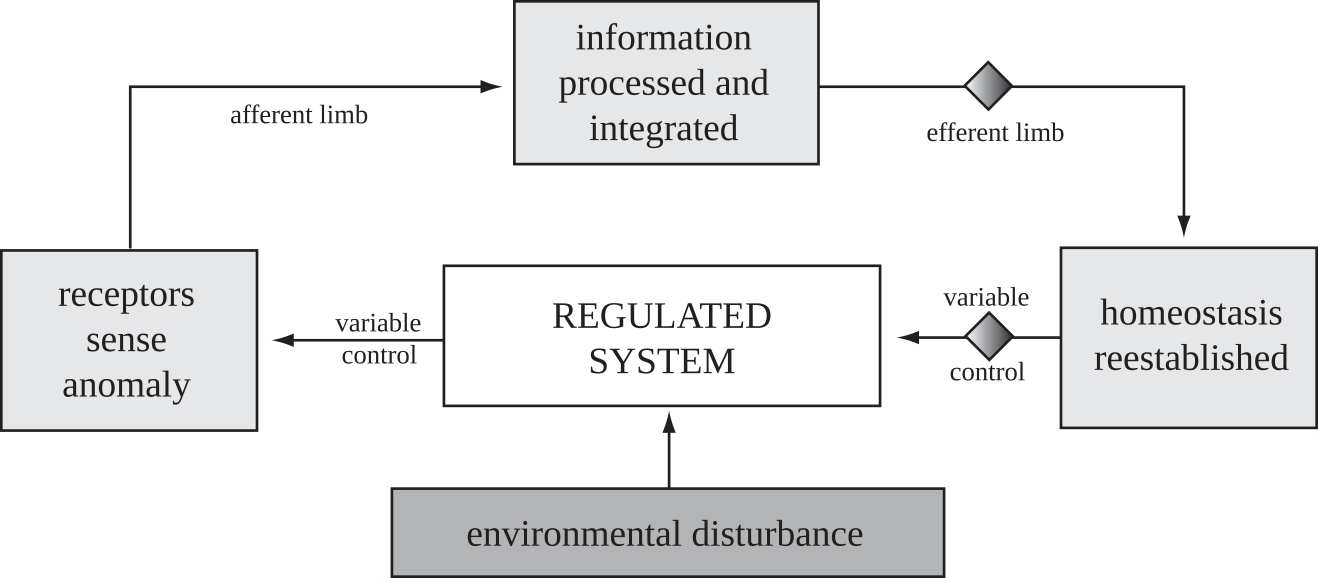
Fig. 1 Distribution of long-duration flights aboard Russian space stations.

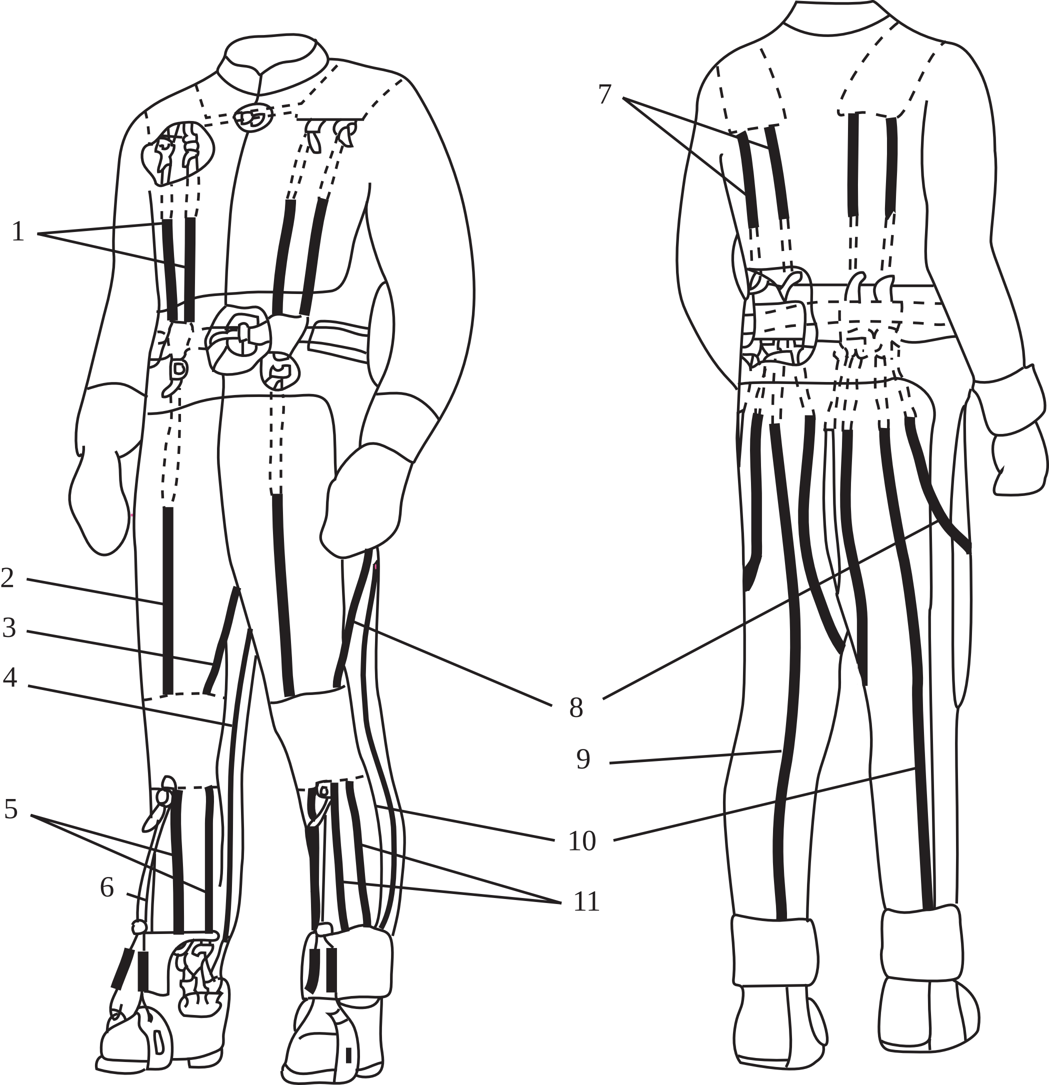

A
Flight duration (days)
400
300
200
100
0
6
12
18
24
B
Training volume (units of force)
12.5
10.0
7.5
5.0
2.5
0
6
12
18
24
Best
Worst

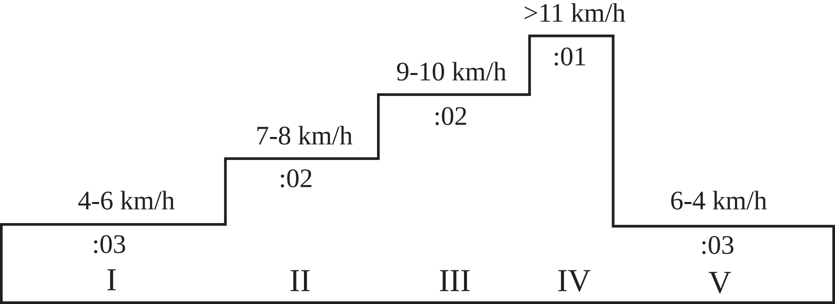

A
B
Flight duration (months)
0
2
4
6
8
10
12
14
16
18
Intensity of changes

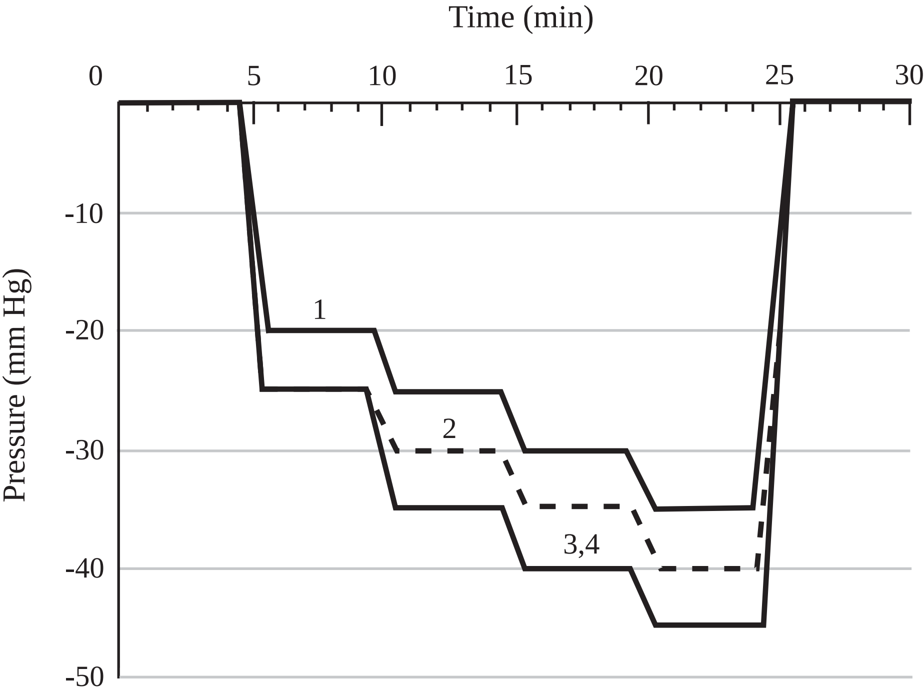


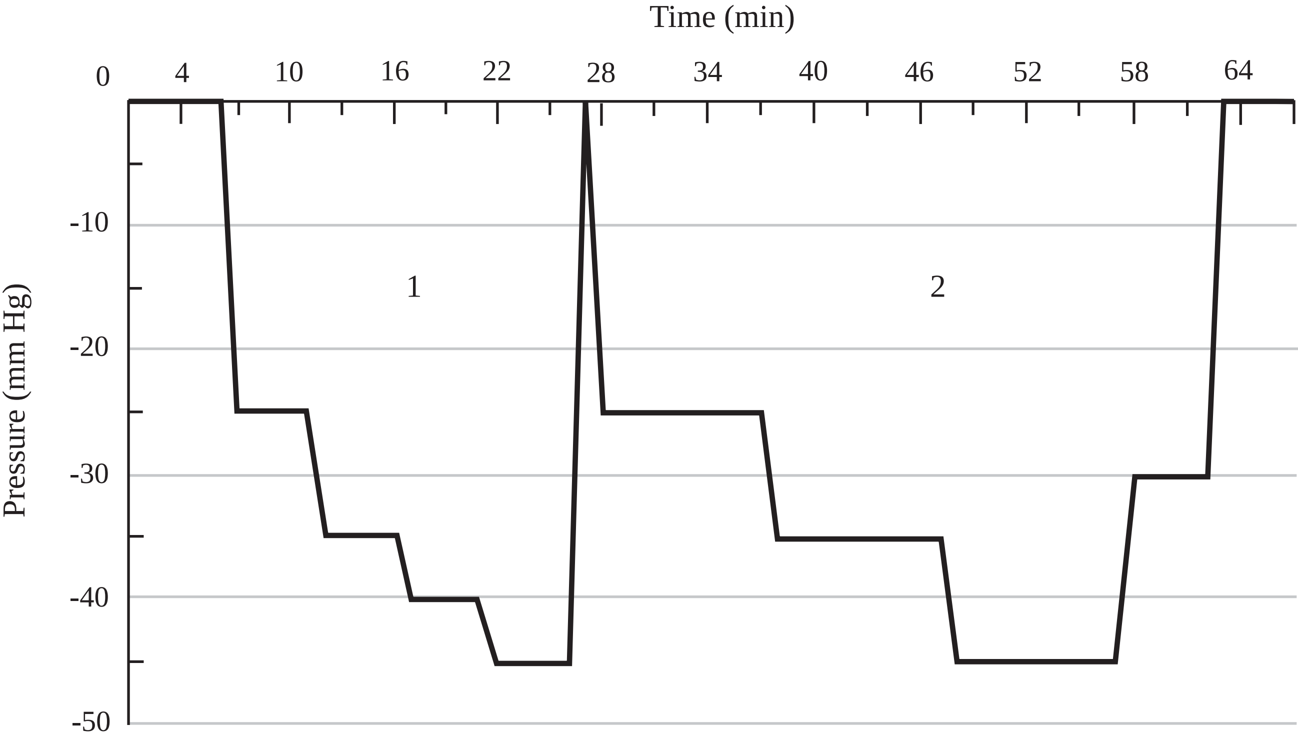
1st Flight			2nd Flight		
Intensity	Duration (months)	Training vol. (% baseline)	Intensity	Duration (months)	Training vol. (% baseline)
1	11	< 100	17	3	< 50
2	6	95	15	2	50
6	4	< 95	16	8	< 50
9	5	90	14	5	60
14	6	80	4	12	100
15	11	65	5	5	100
16	5	65	9	6	100
17	2	< 50	11	5	80

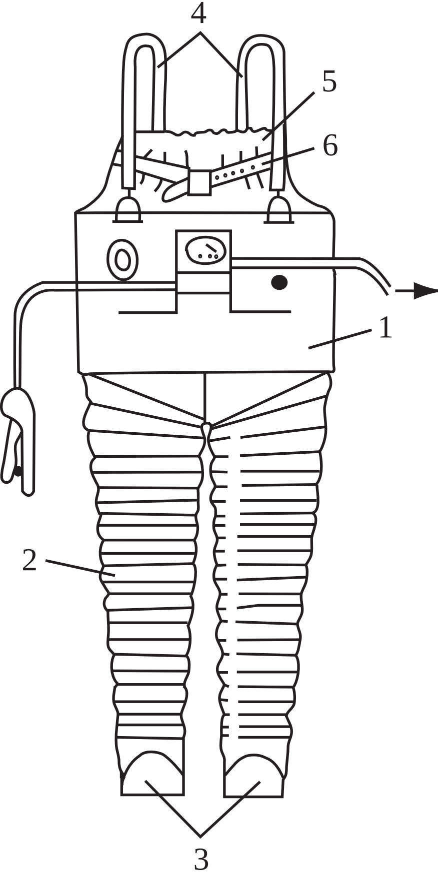

information processed and integrated
afferent limb
efferent limb
receptors sense anomaly
variable control
REGULATED SYSTEM
variable control
homeostasis reestablished
environmental disturbance


1
2
3
4
5
6
7
8
9
10
11


>11 km/h
:01
9-10 km/h
:02
7-8 km/h
:02
4-6 km/h
:03
6-4 km/h
:03
I
II
III
IV
V


Time (min)
0
5
10
15
20
25
30
Pressure (mm Hg)
-10
-20
-30
-40
-50
1
2
3,4


Time (min)
0
4
10
16
22
28
34
40
46
52
58
64
Pressure (mm Hg)
-10
-20
-30
-40
-50
1
2


4
5
6
1
2
3

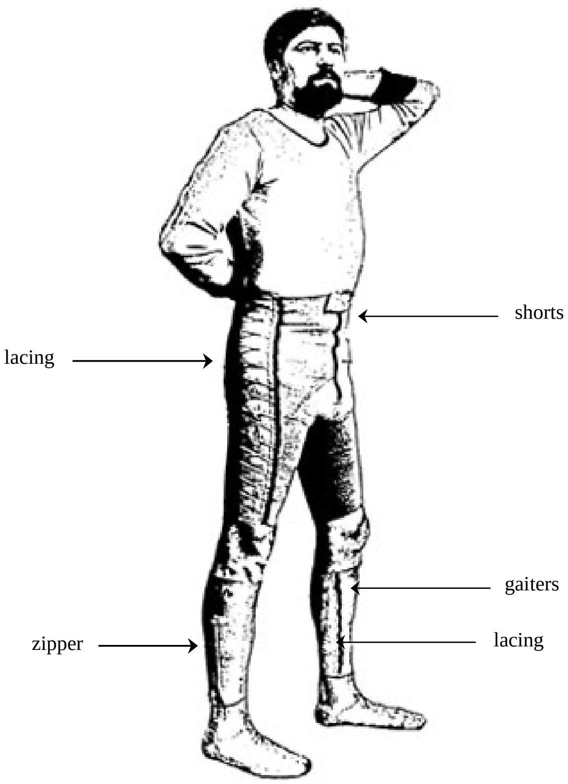


Fig. 8 The Centaur, or antigravity suit, worn by cosmonauts.

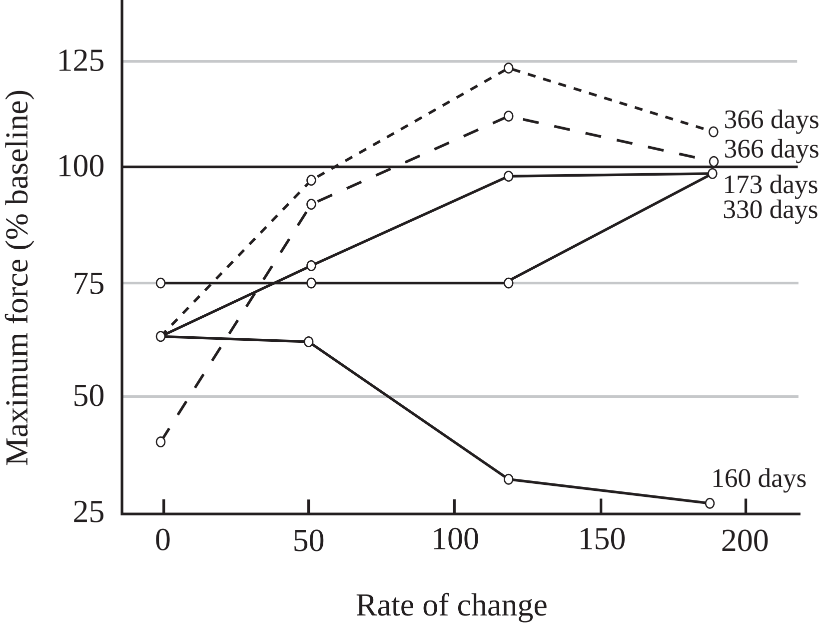

125
100
75
50
25
Maximum force (% baseline)
0
50
100
150
200
Rate of change
366 days
366 days
173 days
330 days
160 days

Table 1 Operational fluid loading protocol, based upon preflight body weight, used by all astronauts

Astronaut preflight weight, lbs	Volume of water, mL[a]	Salt tablets, g
≤120	24	6
121 ≤ 155	32	8
156 ≤ 190	40	10
≤ 191	48	12

[a] Equivalent volumes of isotonic substitutes are acceptable (e.g., “AstroAde” or diluted chicken consommé)

Table 2 Integrated cardiovascular data from landing-day comparing responses of presyncopal to nonpresyncopal subjects. Norepinephrine and calculated peripheral vascular resistance are statistically significantly different between the groups [Ref. 20]

Parameter	Presyncopal (n = 8)		Nonpresyncopal (n = 21)	
	Supine	Standing	Supine	Standing
Plasma norepinephrine, pg/mL	330 ± 67	420 ± 46[a]	278 ± 18	618 ± 88[a]
Peripheral vascular resistance, mm Hg/L/min	16.0 ± 1.3	22.9 ± 2.5[a]	21.1 ± 1.6	33.8 ± 2.7[a]
Diastolic pressure, mm Hg	74 ± 4	61 ± 4[b]	76 ± 2	81 ± 2[b]
Systolic pressure, mm Hg	110 ± 4[a]	80 ± 3[b]	120 ± 2[a]	109 ± 3[b]
Heart rate, bpm	72 ± 5[a]	114 ± 8[b]	62 ± 2[a]	91 ± 4[b]
Stroke volume, mL	78 ± 4	28 ± 2	77 ± 5	32 ± 9
Cardiac output, L/min	5.5 ± 0.3	3.3 ± 0.3	4.7 ± 0.3	2.9 ± 0.2
Mean flow velocity, cm/s	52.4 ± 4.7	40.0 ± 2.9	47.6 ± 2.3	39.7 ± 1.6
Cerebral vascular resistance, mm Hg/cm/s	1.7 ± 0.3	1.1 ± 0.1[b]	2.0 ± 0.1	1.6 ± 0.1[b]
Plasma epinephrine, pg/mL	42 ± 5	66 ± 12	23 ± 2	48 ± 6
Plasma renin activity, ng/mL/hr	2.7 ± 1.2	3.4 ± 1.5	2.2 ± 0.3	3.7 ± 0.6
Plasma volume, L	2.7 ± 0.2	——	3.2 ± 0.2	——

[a]$P < 0.05$ between groups, [b]$P < 0.01$ between groups

Table 3 Summary of orthostatic intolerance countermeasures employed, researched, and under consideration for American astronauts [Ref. 1]

Fully tested and in use	Previously tested	Under consideration
Ingest isotonic saline load 2 hrs before entry (eight 1g NaCl tablets and 960ml fluid) Inflate antigravity suit to approximately 1 psi during re-entry and landing Use the liquid cooling garment under the LES to provide conductive cooling Minimize orthostatic impact during re-entry with reconfigured middeck seats	Apply lower body negative pressure (LBNP) for 4 hours at 30 mm Hg decompression, combined with standard fluid load 24 hours before landing Inflate single-bladder re-entry anti-g suit to 1 psi during entry Perform graded exercise up to maximal effort (maximum oxygen uptake) within 24 hrs of re-entry	Establish standard dietary intake to minimize fluid-electrolyte variability Inflate LBNP during periodic exercise protocols Prescribe pharmacological countermeasures, such as adrenergic agonists and antagonists Simulate 1 g or greater with small-arm centrifuge Apply negative pressure to carotid baroreceptors

Table 4 Overview of American countermeasures employed, tested, and under consideration for neurosensory disturbances [Ref. 1]

Fully tested and in use	Under consideration
Crew training and briefing on strategies to avoid SMS, to include limiting head movements, use of LCG cooling and low ambient temperatures, and limiting food intake Crew training and briefings to identify observed problems during entry, landing, and post landing phases Timeline adjustment to minimize crew workload during critical SMS periods Promethazine injection to reduce SMS impact during first days of mission; proven effective despite questionable effects (drowsiness) on performance In-flight exercise to improve locomotion postflight (may induce SMS symptoms) Pilot landing simulation to practice landing task with onboard laptop	Preflight adaptation training (PAT) employs education and simulations of sensory conflict (TTD and DOME) to prepare crew for novel space flight experience and to dual adapt the vestibular system Unusual attitude experience to develop appropriate strategies and expectations when exposed to microgravity (environments include WETF, SCUBA, and PAT DOME training and parabolic flights in the KC-135) Vestibular suppressant medications (receptor-specific antagonists) to limit nausea and vomiting during entry and landing Standardized head motion protocol (pitch, roll, and yaw planes) performed during entry and after landing facilitates vestibular readaptation

Table 5 Summary of countermeasures introduced during the Soviet Salyut program

Countermeasure	Description and approach	Salyut station	Date
Integrated trainer	Treadmill stand for physical training Used to maintain muscle structure, simulate locomotion and movement on Earth	1	1971
Antigravity suit	Vertical elastic bands are integrated into full-body suit that stimulates antigravity muscles Counteracts circulatory adaptations to microgravity	1	1971
Pharmacological intervention	Sekofen administered	1	1971
Thermal loads harness and expanders[33,34]	Elasticized elements worn during exercise Enhance the benefits of treadmill and ergometer protocols by simulating axial muscle loads	1	1971
Lower body negative pressure	Veter-type device designed to produce negative vacuum pressure gradients on the lower torso	2-4	1973-7
Water-salt additives	Prevent dehydration and orthostatic intolerance upon landing	4	1974
Ergometer	Addition to integrated trainer complex Provides diversity of exercise Simulates locomotion and motor coordination	4	1974
Psychological support[44]	Revision of work and rest schedules Recognition of long-duration space flight as emotionally challenging and highly confined	6	1977

Table 6 Alteration in the activities of various body systems in long-duration space flights [Ref. 8,9,16]

System	Description
Sensory	Decreased proprioceptive input Altered activation thresholds of vestibular receptors (particularly otolith receptors)—decreased static excitability and increased dynamic excitability Disrupted interaction between sensory system elements
Locomotor	Atonia of the antigravity musculature Decreased mass and strength of antigravity muscles, resulting in subatrophy and atrophy Hypogravitational ataxia, the dysfunction of locomotor control systems
Skeletal	Decreased bone mineral density in the spine and weight-bearing bones of the skeleton Negative calcium balance
Cardiovascular	Decreased orthostatic and physical load tolerances Indications of venous congestion in internal organs Increased incidence of cardiac arrhythmia during load-bearing activities
Endocrine	Decreased levels of adrenocorticotrophic hormones Increased levels of plasma hydrocortisone Decreased levels of plasma and urine antidiuretic hormone Activation of the renin-angiotensin-aldosterone system
Fluid balance	Hypohydration Decreased plasma and intracellular fluid volume Negative electrolyte balance
Metabolism	Negative nitrogen balance Decreased levels of plasma amino acids Decreased rates of glucose utilization during sugar loading
Blood	Functional erythrocytopenia Decreased T-cell activity Altered erythrocyte metabolism and morphology

Table 7 Countermeasures used in long-duration space flight

Throughout flight	In final stage of flight
Physical training on the treadmill with a restraint system that creates loads on the body's longitudinal axis and a cycle ergometer used to maintain the structure and properties of the muscular system, the structure and strength qualities of the skeletal system, and conditioning of the body's most critical physiological systems as well as to maintain motor coordination and a high level of functionality Wearing the Penguin suit for 8–10 hours daily, which creates a load on the body's longitudinal axis Multichannel electrostimulation A well-balanced work and rest schedule, which provides a countermeasure to sleep disruptions and asthenization Psychological support to counteract the psychogenic effects of negative factors: social-psychological, occupational, and environmental Planned pharmacological countermeasures, including a routine course of cardiotropic and psychotropic agents and drugs to normalize the microbiocenosis of the gastrointestinal tract	Exposure to LBNP, which reproduces the effect of hydrostatic blood pressure in microgravity conditions Devices which aid in the retention of fluids and electrolytes in the body (LBNP and water-salt supplements) Devices which prevent the pooling of blood in the lower extremities (elastic and antigravity suits) and thereby help to increase tolerance to g-loads and orthostatic stability

Table 8 General characteristics of the physical training structure within a 3+1 microcycle [Ref. 8,34]

Cycle day	Primary objective	Load volume	Intensity	Energy expended, kcal
1	Speed, strength, and orthostatic stability	low	submaximal and maximal	380–420 (1591–1758 kJ)
2	Strength, endurance, and orthostatic stability	moderate	moderate	450–500 (1884–2093 kJ)
3	Overall endurance, orthostatic stability, and overall motor coordination	high	low	550–600 (2303–2512 kJ)
4	Active rest	low	*ad libitum*	150 (628 kJ)

Table 9 Characteristics of physical exercise as measured by treadmill for three Mir-2 crewmembers during long-duration space flight

	Cosmonaut 1 (per flight month)										
Parameter	1	2	3	4	5	6	7	8	9	10	11
Locomotion time, min	26.3	22.5	26.2	26.8	26.8	—	33.2	26.6	28.3	31	32.4
Volume, m	3031	2889	3366	3272	3398	—	4174	3411	3540	3577	4316
% of maximum	84	81	94	91	94	—	116	95	100	100	120
Walking, m	1291	979	1032	1296	1054	—	1194	1048	1054	1137	960
Running, m	1740	1910	2334	1976	2344	—	2980	2363	2486	2440	3356
Intensity, m/min	115	128	128	122	127	—	126	128	125	115	133
% of maximum	93	103	103	98	102	—	101	103	100	93	107
	Cosmonaut 2 (per flight month)						Cosmonaut 3 (per flight month)				
	1	2	3	4	5	6	1	2	3	4	5
Locomotion time, min	24.1	25.2	21.8	28.2	27.8	22.7	27.7	25	31.3	25.7	34.6
Volume, m	2834	3568	3053	3413	3439	2516	2799	3242	3810	3022	3865
% of maximum	81	100	85	103	95	78	80	90	107	84	107
Walking, m	1204	894	690	1139	1128	1039	1313	1037	1362	1234	1681
Running, m	1630	2674	2363	2574	2311	1477	1486	2205	2448	1788	2184
Intensity, m/min	117	141	140	132	124	111	101	129	121	118	112
% of maximum	94	114	113	106	100	90	82	105	98	95	90

Table 10 Comparison of locomotor function of crewmembers after first and second flights of different duration

Condition of crewmember (compared to 1st flight)	N of cosmonauts	Flight duration		
		Longer 1st flight	Equal	Longer 2nd flight
Condition was worse after 2nd flight	6	3 (12 vs. 6 mo[a]) (4 vs. 2 mo[a])	1 (~6 mo)	2 (5 vs. 11 mo) (7 vs. 14 mo)
Approximately the same level	6	1 (8 vs. 4 mo)	3 (5–6 mo)	2 (2 vs. 5 mo) (5.5 vs. 6.5 mo)
Condition was better after 2nd flight	5	1 (8 vs. 4 mo[a])	1 (~5 mo[a])	3 (2 vs. 6 mo[a]) (3 vs. 11mo[a]) (4 vs. 6 mo)
Total N of cosmonauts	17	5	5	7

[a] The difference in intensity of alterations observed after the 1st flight and those observed after the 2nd flight is statistically significant

Table 11 Comparison of American and Russian countermeasures currently in use

Countermeasure	U.S.	Russian
Preflight		
Sleep head down		r
Yoga		e
Biofeedback		e
Hostile/confined environments		r
Cross-cultural training	r[a]	
Bright light	r[a]	
Health stabilization period	r (7–10 d)	r (3 weeks)
Early in flight		
Bracelet		r
Pharmacological agents	r	r
Head stabilizer		e
"Cuban boot"		e
Electromyostimulation	e	e
LBNP	e	r
Limited activities/exercise		e
Periodic		
Penguin suit		r
Exercise	r	r
Electromyostimulation		e
Pharmacological agents	r	r
Psychological support	r	r
End of mission		
High-intensity exercises		
Salt/fluid load	r	r
LBNP	e	r
Recumbent seat	r	r
Karkas/g-suit	r[b]	r

r = performed routinely
e = performed experimentally

[a] as needed

[b] mandatory

Table 1 Medical and special studies conducted during ambulatory (outpatient) examinations of cosmonauts

Examination	Parameter/Purpose
In-depth study of medical history	To rule out paroxysmal disorders of consciousness, and episodes of angina pectoris, renal colic, intestinal colic, etc.
Therapeutic examination	Physical examination of the heart, lungs, internal organs; test with 20 squats during which the pulse rate and blood pressure are recorded
Neurological examination	——
Surgical examination	Weight; height (sitting and standing); examination of the lymph nodes, thyroid, musculoskeletal system; examination of the genitals; rectal examination; examination of pulse in the foot arteries; for women, a gynecological examination
Otolaryngological examination	External examination and endoscopy of the ear, nose, and throat; hearing test for whispering; and 2-minute test for cumulation of Coriolis accelerations
Ophthalmological examination	Examination of the eyes, test of color vision, visual acuity, night vision, and refraction
Special examinations	12-lead ECG, chest fluorography, and X-ray of the nasal sinuses in two views
Laboratory tests	Complete blood count, urinalysis
Dental examination	Exam of the oral cavity

Table 2 Interim physical examinations of cosmonauts during phased medical examinations

Type of load (tests and training sessions)	*Scope of physical examinations*	
	Before the exercise	After the exercise
Centrifuge	Urinalysis ECG at rest Examination by internist	Urinalysis Examination by internist
Heat chamber	Examination by internist	Urinalysis Examination by chief flight surgeon
Pressure chamber	Examination by internist and otolaryngologist	Examination by otolaryngologist
Pressure chamber with special gear	Examination by otolaryngologist and chief flight surgeon	Examination by chief flight surgeon
Physical exercise on cycle ergometer	Examination by chief flight surgeon	Examination by chief flight surgeon

Table 3 In-depth physical examinations

Laboratory tests	Functional tests	Examining clinician
Complete blood count Urinalysis Fecal analysis Blood test on Reflotron-1; once every 6 mo.	ECG at rest Ultrasound of the internal organs and the urogenital system; once every 6 mo.	Internist Surgeon Neurologist Otolaryngologist Ophthalmologist Dentist

Table 4 Annual examinations of cosmonauts

Examination	Parameter
Examination by clinical specialists	——
Laboratory data	Complete blood count
	Biochemical blood analysis
	Urinalysis (prostatic antigen)
	Fecal analysis
Electrophysiological examinations	12-lead ECG
	Graded physical exercise test on cycle ergometer
X-rays and special tests	Chest X-ray (once every 3 yrs.)
	Orthopantomography (once every 3 yrs.)
	MRI of spine (once every 5 yrs.)
	Radioisotopic renography (once every 3 yrs.)
	Fibrogastroduodenoscopy (once every 2 yrs.)
	Ultrasound of internal organs and urogenital system
	Rectosigmoidocolonoscopy (once every 5 yrs.)
Functional tests	Examination after exposure to pressure chamber (altitude 5000 m)
	Examination after exposure to centrifuge (G-loads of 3 to 5)
	Examination of vestibular function

Table 5 Scope and frequency of cosmonaut examinations

Examination	Frequency	Comments
Chest X-ray	Once every 3 yrs.	——
CT of nasal sinuses	Once every 2 yrs.	Clinical physiological exam before cosmonaut is designated as a crewmember
CT of skull	During selection	Thereafter, as needed
MRI of spine	Once every 5 yrs.	——
Orthopantomography	Once every 3 yrs.	——
Excretory urography	During selection	Thereafter, as needed
Radioisotopic renography	Once every 3 yrs.	——
Fibrogastroduodenoscopy	Once every 3 yrs.	——
Ultrasound	Annually	——
Passive orthostatic test	During selection	Clinical physiological exam before
flight		
Audiometry	During selection	Clinical physiological exam before
flight		
Doppler vasography	During selection	During passive orthostatic test
Electroencephalography	Once every 3 yrs.	——
Densitometry	——	Clinical physiological exam before
flight		

Table 6 Example of preflight and postflight medical evaluation for short-duration flight (Space Shuttle Program, launch-10 days)

Examinations/Studies	Included items
Full physical examination by the crew surgeon	Excluding rectal, genitourinary, breast and pelvic exam and Pap smear unless clinically indicated or unless annual exam requirements are to be met
Otolaryngology exam	Audiogram
Ophthalmology exam	Visual acuity, color vision, depth perception, phorias, tonometry, perimetry, fundoscopic examination
Cardiovascular/Cardiopulmonary studies	Stand test, standard graded bicycle ergometer protocol
Clinical laboratory assessment	CBC/diff, reticulocytes, ESR, UA, chemistry profile, serum osmolality, lipid profile, HDL, lipoprotein profile, CK isoenzymes, SPE panel, protein panel, thyroid panel, calcium (ionized) profile, hepatitis panel (A, B, C), HIV, PSA (males), amylase (fractioned)
Microbiological assessment	Throat, nasal, urine, fecal bacterial and fungal cultures, throat viral cultures

Table 7 Illnesses in the U.S. space program before and after the Health Stabilization Program [Ref. 29]

Mission	Illness	# of crew affected	Mission phase
Apollo-7	Upper respiratory infection	3	During flight
Apollo-8	Viral gastroenteritis	3	Before and during flight
Apollo-9	Upper respiratory infection	3	Before flight
Apollo-10	Upper respiratory infection	2	Before flight
Apollo-11	——	——	——
Apollo-12	Skin infection	2	During flight
Apollo-13	Rubella exposure	1	Before flight
[Health Stabilization Program implemented]			
Apollo-14	——	——	——
Apollo-15	——	——	——
Apollo-16	——	——	——
Apollo-17	Skin infection	1	Before flight
Skylab-2	——	——	——
Skylab-3	Skin infection	2	During flight
Skylab-4	Skin infection	2	During flight

Table 8 Number of people approved under the STS-1 Health Stabilization Program as primary crew contacts [Ref. 30]

	Location[a]					
	JSC	KSC	DFRC	ARC	HQ	Subtotal
NASA	216	35	7	1	5	264
Contractor	643	42	12	0	0	697
Others	10	1	0	0	0	11
Subtotal	869	78	19	1	5	972

[a] JSC, Johnson Space Center (Houston, TX); KSC, Kennedy Space Center (Cape Canaveral, FL); DRFC, Dryden Flight Research Center (Edwards AFB, California); ARC; Ames Research Center (Edwards AFB, CA); HQ, Headquarters (Washington, D.C.)

Table 9 Illnesses in the STS-1 primary contact population [Ref. 30]

Illness	JSC	*Location* KSC	DFRC	Percent of total[a]
Upper respiratory infections	24	3	3	81
Bronchitis	1	0	0	3
Pneumonia	0	0	0	0
Upper enteric illness	3	0	0	8
Lower enteric illness	2	0	0	5
Fever present	4	0	0	11
Headache present	1	0	0	3
Skin infection present	0	0	0	0
Other infectious illness	1	1	0	5

[a] Total percentages > 100% because some illnesses were included more than one symptom complex

Figure Captions

Fig. 1 Distribution of long-duration flights aboard Russian space stations.

Fig. 2 Schematic of the regulatory mechanisms that maintain system functionality in case of an environmental disturbance. Countermeasures are often directed to the latter stages of regulation, as indicated by the shaded diamonds. [Ref. 3]

Fig. 3 Major loading components of the Penguin suit—the tension straps: chest (1); front leg (2, 6); slanted outer/inner back leg (3, 8); straight outer back leg (4, 9, 10); front slanted leg (5, 11); back (7).

Fig. 4 The treadmill test with gradually increasing locomotor loads: I – walking at an increasing rate (4–6 km/h) for 3 minutes; II – running at a slow rate (7–8 km/h) for 2 minutes; III – running at an average rate (9–10 km/h) for 2 minutes; IV – running at a maximum rate (greater than 11 km/h) for 1 minute; V – walking at a gradually decreasing rate (6–4 km/h) for 3 minutes.

Fig. 5 Modes for preliminary LBNP (ОДНТ) training exposures performed 18 days (1st session), 14 days (2nd session), 10 days (3rd session), and 6 days (4th session) before landing.

Fig. 6 Modes for primary LBNP (ОДНТ) training exposures performed 2 days and 1 day before landing and include two cycles each (1, 2).

Fig. 7 The Chibis countermeasure vacuum suit, comprising the metal waist segment (1), corrugated pant legs (2), metal boots (3), shoulder straps (4), rubber sealing belt (5), and adjustment strap (6).

Fig. 8 The Centaur, or antigravity suit, worn by cosmonauts.

Fig. 9 Change in the shin extensor maximum strength for 5 cosmonauts after extended-duration flights.

Fig. 10 Intensity of changes in the locomotor systems of crewmembers after extended flights in relation to the flight duration (A) and the volume of physical training (B).

Fig. 11 Intensity of changes in the locomotor systems of crewmembers after extended first (A) and second (B) space flights.

Fig. 12 Relationship of the depth of changes in the locomotor system in the first (ordinate) and second (abscissa) space flights.