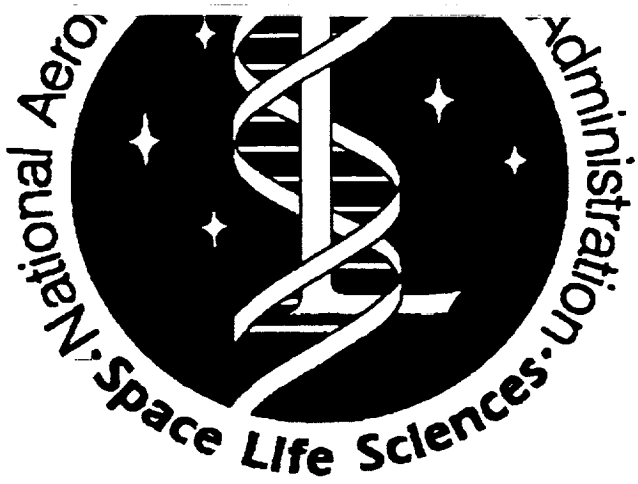
ENVIRONMENTAL HEALTH DISCIPLINE SCIENCE PLAN

1991



ENVIRONMENTAL HEALTH PROGRAM
LIFE SCIENCES DIVISION
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, D.C.

ENVIRONMENTAL HEALTH DISCIPLINE SCIENCE PLAN
TABLE OF CONTENTS

ENVIRONMENTAL HEALTH DISCIPLINE SCIENCE PLAN

1.0 INTRODUCTION

The Environmental Health Program of NASA's Life Sciences Division will assume greater significance as planning intensifies for Space Transportation System (STS) missions of longer duration, and for the construction and permanent habitation of Space Station Freedom (SSF). The health and well-being of crews in the spacecraft environment depend on proper atmospheric composition and pressure, and an environment free from accumulated air- and waterborne gaseous, particulate and microbial toxicants and contaminants. The Environmental Health Program monitors the spacecraft environment; conducts research to define microbiological and toxicological standards; and develops advanced environmental monitoring technology. The program develops standards for extravehicular activity (EVA) atmosphere (gas pressure and composition) and conducts barophysiological research to develop protocols.

The Environmental Health Program consists of three disciplines:
1) Barophysiology, 2) Toxicology, and 3) Microbiology. A brief history of each and its current status is reviewed in this Discipline Science Plan. In addition, the goals, objectives, and research and development (R&D) priorities related to answering the critical questions are provided for each of the disciplines.

1.1 PURPOSE

The purpose of this plan is to provide a conceptual strategy for NASA's Life Sciences Division research and development activities in environmental health. It covers the significant research areas critical to NASA's programmatic requirements for the Extended Duration Orbiter, Space Station Freedom, and exploration mission science activities. These science activities include ground-based and flight; basic, applied and operational; animal and human subjects; and research and development. This document summarizes the history and current status of the program elements, outlines available knowledge, establishes goals and objectives, identifies scientific priorities, and defines critical questions in the three disciplines: 1) Barophysiology, 2) Toxicology, and 3) Microbiology. This document contains a general plan that will be used by both NASA Headquarters Program Officers and the field centers to review and plan basic, applied, and operational research and development activities, both intramural and extramural, in this area. The document is divided into sections addressing these three disciplines.

1.2 DISCIPLINE GOALS

The goals of the Environmental Health Program are to:

- Utilize ground-based studies to understand the effects of the spacecraft and EVA environments on humans and other organisms
- Specify, measure, and control these environments

- Develop countermeasures where necessary to optimize crew health, safety, and productivity.

2.0 BAROPHYSIOLOGY

2.1 BRIEF DESCRIPTION OF THE DISCIPLINE

Barophysiology includes all biomedical considerations related to the atmospheric composition and pressure of the space habitat, the simulation of weightlessness by immersion, and the therapy for any adverse medical conditions that arise as a result of changes in atmospheric composition or pressure. These include hyperoxia, hypoxia, hypercapnia, heat balance, barotrauma, explosive decompression, decompression sickness, and the interacting influence of microgravity.

The sea-level environment provides a constant pressure and gas composition. In the outdoor atmosphere, gas composition is remarkably stable and local pressure changes only slightly as a function of weather. However, humans can tolerate and even adapt easily to pressures and gas compositions well outside the range of the sea-level baseline.

In the manned space program to date, several combinations of cabin pressure, gas composition, and suit pressure have been utilized without any reported deleterious response. Ground-based studies have shown, however, that the potential for decompression sickness is present in the current operational procedure. There are also contingency or emergency events that could result in air embolism, ebullism, and hypoxia. The planning and implementation of long-term missions involving long residence times in space and on planetary surfaces in a closed atmosphere require the investigation of chronic exposure to gas compositions other than the sea-level atmosphere. Such investigations are needed to maximize the efficiency and safety of normal operations and provide the base of information to deal with chronic contingency exposures to gas compositions and pressures.

2.2 BRIEF HISTORY OF THE DISCIPLINE AS PART OF SPACE LIFE SCIENCES

Barophysiology was a prime concern early in the space program. To allow engineering simplicity and to minimize weight, U.S. spacecraft through the Apollo Program utilized 100-percent 0_2 at a pressure of 5.0 psia. Chamber studies were conducted to assure the operational safety of this atmosphere for a period of twice the length of the anticipated operational exposure. The verification exposure at 5.0 psia lasted 30 days. Although some effects (some atelectasis and some effects on hematologic parameters) did begin to appear toward the end of the 30-day period, these were not considered operationally significant and did not constrain the use of that atmosphere for 15 days during the Apollo lunar exploration missions.

Pressure suits in these early programs were operated at pressures from 3.5 to 3.9 psia. The decompression from the 5.0 psia 100-percent 0_2 cabin after many days' exposure to this atmosphere involved no risk of decompression sickness. The

pressure reduction that did involve some risk of decompression sickness was the initial decompression from 14.7 psia to 5.0 psia at liftoff. To prevent decompression sickness the crew prebreathed 100-percent 0_2 for 3 hours prior to liftoff.

To avoid some of the effects of 100-percent 0_2 exposure that had been observed during the Apollo validation chamber tests, while still using the Apollo spacecraft as part of the Skylab flight system, the Skylab Program used a 70-percent 0_2, 30-percent N_2 atmosphere, which was near normoxic. In the Skylab Program the 7.6 mm CO_2 limit on previous programs was reduced to 5 mm to minimize the impact on the medical experiments being conducted during the missions.

The Space Transportation System (STS) or Space Shuttle was designed with a 14.7 psia Earth-normal atmosphere to allow use of more off-the-shelf or near-off-the-shelf equipment that did not have to operate at a reduced pressure and to reduce the risk of fire. After the Apollo 1 launch pad fire that resulted in the death of three crewmen, Congress decreed that future spacecraft utilize an atmosphere that did not require an enriched oxygen concentration. The higher-pressure cabin, in combination with essentially the same pressure suit for extravehicular activity (EVA) that had been used in prior missions (4.3 psia), resulted in a higher and more persistent risk of altitude decompression sickness. Current research in altitude decompression sickness is directed at eliminating or at least significantly reducing the risk of its occurrence. The best estimate of the operational risk of significant decompression sickness occurring in an individual crewman during a single EVA is 5 percent.

2.3 CURRENT KNOWLEDGE BASE

The current knowledge base in Barophysiology derives from operational studies in environmental temperature directed at defining comfort and tolerance criteria for heating and cooling in buildings, vehicles, and other enclosed environments over the past century; and from investigations on the effect of pressure and gas composition on human physiology and performance at high pressure in divers, submariners, and caisson workers, and at low pressures in mountaineers, aviators, and spacefarers. The acute responses to high and low temperatures are well documented, and the mechanisms of thermoregulation elicited by such exposures are well known. Some data suggest that thermoregulation may be altered in microgravity aside from the physical effects of the spacecraft environment. Such alteration has not been demonstrated in flight and has not resulted in any obvious decrement in performance.

The response of the body to reduced pressure includes decompression sickness. Much data on decompression sickness derives from divers, caisson workers, and aviators. Specific complicating factors in the extravehicular environment are a significant length of exposure (6 hours) and continuous exercise during the exposure at a moderate level. A data base of over 1000 exposures of simulated EVA-type activities and incidents of decompression sickness has been compiled. An operational data base of EVA experience is also accumulating.

The responses of the body to unusual concentrations of gases in the atmosphere, including hyperoxia, hypoxia, hypercapnia, and various potential diluent gasses are concerns for space flight. The knowledge base covers the treatment of acute

exposures to various concentrations of O_2 and CO_2, but long-duration exposures tend to be limited to air mixtures in which only the pressure is altered. There is limited data on long-term exposure to alternative diluent gases and very little or no data on the impact of microgravity on tolerance to these potential atmospheres.

2.4 BAROPHYSIOLOGY DISCIPLINE GOALS, OBJECTIVES, AND CRITICAL QUESTIONS

2.4.1 Goals

The overall goals of the Barophysiology discipline are to:

- Understand the biochemical and biophysical effects of variations in component parts of the man-made atmosphere in the space environment
- Develop selection and maintenance criteria for safe and efficient gaseous environments in different situations and in different eras of the space program, and develop countermeasures to altitude decompression sickness.

2.4.2 Objectives

The objectives of the Barophysiology discipline are as follows:

- Determine the effect of physical activity during different mission phases on the susceptibility to altitude decompression sickness
- Determine the source tissue(s) of gas bubbles that: a) cause limb bends pain, b) are detectable as venous bubbles, and c) result in central nervous system (CNS) symptoms
- Determine the mechanism(s) of passage of venous bubbles into the arterial system
- Investigate factors affecting gas exchange and N_2 washout in critical tissues during O_2 prebreathe periods
- Investigate means of extending O_2 tolerance in order to expand operational use of O_2 as a treatment modality at increased partial pressure and investigate optimum therapy for decompression sickness and arterial gas emobolism
- Determine requirements for temperature, humidity, gas composition, and pressure for long-duration missions
- Investigate interaction between microgravity, as simulated by bedrest, immersion, and hypobaria, hypoxia, hyperoxia, and hypercapnia
- Investigate alternate natural and synthetic diluent gases

- Develop procedures for decompression (and flying) after training in underwater microgravity simulators.

2.4.3 Critical Questions (In priority order)

1. What, if any, are the interactions between the effects of microgravity on crewmembers and the effects of off-baseline levels of atmospheric parameters, including gas composition, pressure, and temperature?

2. What procedures and approaches are most appropriate to prevent decompression sickness or to minimize crew risk?

3. What are the optimal means for treatment of medical contingencies related to the atmosphere, including dysbarism, temperature, and adverse effects of the gaseous environment?

4. What are the acceptable and appropriate ranges of gas composition, pressure, temperature, and humidity for all current and future mission phases, durations, and circumstances?

5. What are the interactive effects of all potential atmospheric components and factors on physical and psychological well-being and crew performance?

6. What are the details of the etiology of decompression sickness and how do they relate to its incidence and the variability of its incidence?

7. What are the risk relationships among detectable venous gas emboli, very mild limb bends symptoms, limb bends symptoms that impair performance, and CNS and cardiovascular symptoms that are life-threatening under the specific conditions of EVA? What are the acceptable risks?

8. What are the adaptations and deteriorations associated with prolonged exposure to unusual atmospheric environments, including the impact of microgravity, and how can countermeasures be utilized against these deteriorations?

2.5 TECHNOLOGY

Technology requirements for conducting barophysiology research are discussed in the following subsections.

2.5.1 Environmental Simulator Chamber Facilities

In the area of Environmental Simulator Chamber Facilities the following hardware has been identified as required: A research altitude chamber at JSC dedicated to investigation of altitude decompression sickness, and a composite facility and

laboratory that can provide investigation and evaluation of long-term exposure to environments with controlled temperature, pressure, gas composition, including select diluent gas capability under hypobaric, normobaric, and hyperbaric conditions.

Research investigations in atmospheric pressure and barophysiology require careful control of the physical and atmospheric parameters to be studied. These parameters must be controlled for acute and chronic (multi-day) exposures in environmental simulator chambers suitable for animal and human subjects.

To evaluate the effect of atmospheric variables on thermal balance, chambers have been devised to allow control of humidity, gas velocity, and the temperature of the gas and the surrounding walls. These chambers may also incorporate the capability to simulate limited area high temperature or low temperature radiant sources or sinks.

Studies of the effects of atmospheric pressure on the body require hypobaric and hyperbaric chambers that allow the manipulation of pressure to high or low levels. Systems must be incorporated to allow respiration of O_2 or special gas mixtures as required. Chambers with a controlled gas composition are likely to operate as closed or partially closed systems and incorporate carbon dioxide scrubbers. Hypobaric research and use of hyperbaric chambers frequently involves some risk of decompression sickness. Therefore, specific treatment protocols and collateral medical treatment capabilities are required as well. Some existing individual chamber systems incorporate many of these capabilities. However, the full range of capability is more generally available only through the select use of different kinds of facilities available at several sites.

2.5.2 Instrumentation Systems

In the area of Instrumentation Systems equipment identified as requiring new development consists of: In-Suit Intravascular Bubble Detector; Physical Psychomotor and Cognitive Performance Systems. Instrumentation identified as needing improvement includes Perceptual Performance System Equipment; Respiratory Performance Systems; Extravascular Gas Detectors, and Thermal Balance Systems (temperature, metabolism).

In addition to environmental chambers, those laboratories involved in atmospheric environmental research require specific support equipment items. These include a broad range of gas analyzers, temperature monitoring systems both for the environment and the body, and physiological monitoring equipment to study the effect of alterations in the atmosphere on the cardiovascular, respiratory, endocrine, renal, neural and other systems. Equipment is required to measure pulmonary functions, including the rate of N_2 washout. Special detection and imaging equipment is required to detect gas phase and gas bubbles in tissue and in the circulatory system. Another area that must be pursued is the development of bubble monitor transducers that can be used inside a pressure suit during both operational training and actual and EVA. In addition, access to biochemical and hematology laboratories is required to analyze changes in blood and other body fluids. As a general principle, noninvasive monitoring devices are usually preferable.

2.5.3 Data Systems

In the area of Data Systems equipment requiring new development consists of: shared/common aerospace, atmospheric, undersea environmental data bank systems (respiratory, pulmonary, neurologic, sensory, endocrine, cardiovascular, hematologic, oxygen, hypoxic, carbon dioxide, decompression, and thermal).

The laboratories involved in barophysiology research will require individual data handling, analysis and storage systems for the extensive information generated during chamber studies. Functions should also include analytic, modeling and research planning applications. In addition, it is essential to develop composite databases derived from multiple laboratories, including aerospace, atmospheric and undersea research results. Basic research from university, industry, NASA, Air Force aviation laboratories, Navy diving laboratories, international facilities, and operational laboratories should be collected and made available to all participants.

2.5.4 Modeling

In the area of Modeling, new development is required in the following areas: environmental/physiologic interactions (descriptive, predictive, analytic, risk assessment); data acquisition systems (national, international, real-time data acquisition); and documentary/ technical communication systems.

To maximize the scientific yield from past and prospective studies it is essential to devise models of the effects of alterations in the atmosphere on animals and humans. These models should utilize the joint data systems and multiple data bases previously identified; both operational and basic descriptive models are needed. Operational models predict physiological response to a set of environmental conditions with the most simple structure consistent with the desired accuracy of prediction. Descriptive models are research tools used to aid investigation of etiology. They are developed iteratively with the results of empirical studies that include mathematical depiction of the physiological mechanisms of response to alterations in the atmosphere. All such modeling depends upon improvement and expansion of relevant data systems.

2.6 RESEARCH STRATEGY

The Barophysiology research area priorities for each of the NASA mission eras are presented in Table 1.

2.6.1 Space Shuttle Era

The Space Shuttle Era (1990-1994) includes biomedical Spacelab experiments and Extended Duration Orbiter operations. It also includes operational flights with manifested extravehicular activities (EVA).

The JSC Neutral Buoyancy Laboratory (NBL), to be fabricated for training purposes, should come into service in this era. It is a large-scale underwater microgravity simulation facility that will allow diving exposures outside of those normally utilized in military or commercial diving.

Ground-based research throughout this period should be directed at developing safe protocols for training and decompression in the NBL, at expanding the data base on chamber tests simulating EVA decompressions, and elaborating models based on this data base that will allow assessment of the incidence of altitude decompression sickness.

Flight research during this period should include measurement of metabolic rate during EVA and Detailed Supplementary Objectives (DSOs) should focus on the effects of microgravity on the incidence of decompression sickness.

2.6.2 Space Station Freedom Era

The Space Station Freedom (SSF) Era (1995-2000) will require extensive EVA during the construction and maintenance of the SSF. The EVA Physiology Facility (EPF) should address concerns associated with EVA. The Biomedical Monitoring and Countermeasures (BMAC) Program should address in-flight operational biomedical limits and potential limits, along with appropriate countermeasures. The Space Biology Initiative will provide facilities for additional basic research on humans and animals in flight.

Ground-based research in the SSF Era should include investigation of the chronic effects of decompression, generation of venous bubbles, and decompression sickness. The intense usage of the NBL will allow investigators to amass a unique, large, and controlled and delineated data base on decompression sickness in long-duration dives to moderate depth.

Flight research should examine the effects of the microgravity environment on heat exchange during exercise. Spacelab medical experiments on the effects of microgravity on the cardiopulmonary system may impact this task area.

2.6.3 The Exploration Era

The Exploration Era (2000-2030) may include human missions to the Moon and Mars, with attendant long-duration exposures to microgravity and partial gravity. This era should include a robust EVA program, and multi-environment programs involving diverse vehicles, habitats, and pressure suits. The potential for contingencies leading to protracted stays in minimally supportive environments must be considered.

Ground-based research in the Exploration Era should include studies on decompression sickness mechanisms leading to countermeasures that allow safe EVA, optimal suit pressures, and gas compositions. Ground-based investigations may partially address interactions of hyperoxia, hypercapnia, hypoxia, hypobaria, decompression sickness, and microgravity.

Flight research primarily in the STS Era should support the Exploration Era by addressing the effects of micro- and partial gravity on hypoxia, hyperoxia, hypercapnia, hypobaria, and decompression sickness, and the interaction of these factors and ambient pressure.

2.6.4 Interactions Between Laboratories, Agencies, and Countries

Exposures to physical and atmospheric environmental stresses have been investigated by multiple national laboratories in the United States, including those operated by university, industry, and government agencies. Specific efforts of leading university laboratories have resulted in close collaboration in environmental R&D collaboration among universities, Navy, NASA, National Oceanic and Atmospheric Administration (NOAA), Air Force, and the offshore petroleum and aerospace industries.

The program should consider establishing relationships with the U.S. Air Force Armstrong Laboratory, U.S. Naval Medical Research Institute, U.S. Naval Submarine Medical Research Laboratory, U.S. Naval Health Effects Centers, National Oceanic and Atmospheric Administration, Environmental Protection Agency, National Institutes of Health, U.S. Army Environmental Laboratory, etc., to exchange information. These organizations have already conducted considerable research in barophysiology; NASA can benefit from these sources of expertise and experience. Much of this research may be of direct relevance to barophysiology discipline. Furthermore, plans to have a U.S./U.S.S.R. cooperative effort in barophysiology should be pursued.

3.0 TOXICOLOGY

3.1 BRIEF DESCRIPTION OF THE DISCIPLINE

Toxicology involves understanding the mechanisms of chemical poisoning at the molecular level. The concept of poisoning has been increasingly refined to the point where it must be recognized that some measurable changes resulting from chemical exposure are adaptive rather than the result of poisoning. Toxicologists are asked to set a concentration (dosage) that will not cause poisoning (injury) to the population at risk. Typically, the only data available are from rodent exposures, and the toxicologist must extrapolate from results of these exposures to the human population at risk. This extrapolation involves considerable uncertainty, which explains why regulatory exposure levels may vary over several orders of magnitude.

Inhalation toxicology depends on several other scientific disciplines. Analytical chemistry is an integral part of exposing test animals to controlled concentrations of gases or vapors. Analytical chemistry expertise must also be available to address questions of air monitoring in human habitats and workplaces. If the chemical in question is a liquid aerosol or particle, then aerosol physics must be used to characterize animal exposures and develop strategies for monitoring. The disciplines of pathology, biochemistry, physiology, and behavioral science must be applied to the characterization of the magnitude and nature of chemical injury following exposure of test animals. Likewise, human exposures in the workplace or environment may result in changes that are detected by analyses in one or more of these disciplines.

3.2 BRIEF HISTORY OF THE DISCIPLINE AS PART OF SPACE LIFE SCIENCES

Toxicological problems have been relatively minor since the Apollo Program due to the effective preventive strategies employed. The required offgas-test program for all nonmetallic materials flown in spacecraft has prevented the unexpected accumulation of potentially harmful gaseous products within the cabin. Each offgas test item is warmed at 120 degrees F for 72 hours and all gaseous products are quantified. If the concentration of a contaminant exceeds its spacecraft maximum allowable concentration (SMAC), the item will not be accepted for use during a mission. In addition, each new or refurbished orbiter is offgassed before it is considered ready for flight. During Shuttle missions, archival samples are taken with evacuated cylinders or a Solid Sorbent Air Sampler (SSAS) to provide a basis for identification and quantitation of contaminants. Samples taken during missions have shown consistently that concentrations are below applicable SMACs.

Despite the precautions described above, recent experience on the Shuttle has emphasized the need to deal with thermodegradation (nonflaming combustion) of synthetic materials that are near electrical wiring. The 13 recent incidents include a teleprinter cable short on STS-28, burning of circuits inside two data display units on STS-35, and thermodegradation of an electrical monitor on STS-42.

A major scientific effort of the JSC Toxicology Group is focused on setting and documenting recent experience on combustion SMACs for individual and groups of contaminants. Ordinary permissible exposure levels are not applicable to space flight because astronauts are exposed continuously to contaminants (rather than in 8-hour occupational increments). In addition, they may be more susceptible because of microgravity-induced physiological changes, and the toxicological endpoint acceptable for an astronaut may be less severe than an endpoint acceptable for an industrial worker. In addition, the SMACs tend to be conservative because the escape options and treatment options are much more limited for astronauts than for their Earth-based counterparts. At present, official 7d-SMACs are available for many compounds (JSC Document 20584); however, they are being extensively revised and documented and exposure times of 1 hour, 24 hours, 30 days, and 180 days are being added to the data base. The short-duration SMACs (1 and 24 hours) are set to permit a minor degree of irritation or reversible effects that do not impair crewmember performance during a contingency. The long-term SMACs are set to prevent adverse effects from long-term contaminant exposures during Shuttle missions (7 days), Extended Duration Orbiter flights (30 days), and Space Station Freedom operations (180 days).

All payloads flown on the Space Shuttle are subjected to a thorough safety review by the JSC Payload Safety Review Panel. A major aspect of that review is a toxicological hazard evaluation of any chemicals involved in the payloads. The degree of containment of payload experiments is often set based on toxicological concerns expressed by JSC toxicologists.

A toxicological risk assessment document has been prepared for all Space Shuttle missions since 51-L. The document discusses hazards that could result from release of chemicals into the cabin from Detailed Supplementary Objective (DSO)

experiments, payloads, utility operations, and fluid system leaks. Recently, a generic utility-chemical toxicology document was published for orbiter operations (JSC 24621) and the mission-specific documents will no longer discuss utility chemical hazards.

3.3 CURRENT KNOWLEDGE BASE

For space-flight applications, just as for ground-based applications, it is essential to know the susceptibility of the population that will be exposed to the contaminant in question. A data base of biochemical, physiological and immunological changes that occur as a result of prolonged stays in a microgravity environment is essential to estimating astronaut susceptibilities. In general, the changes appear to be neither of sufficient magnitude nor of the appropriate kind to significantly increase susceptibility; however, important exceptions have been found.

Not only is the process of setting SMACs complicated by uncertainties in the population susceptibility, the toxicological data base is often of insufficient scope and quality to derive SMAC values. The process of setting a SMAC begins with a thorough literature search and identification of key studies from which a SMAC for human exposure may be determined. The quality of those key studies is evaluated and they are used as the basis for SMAC calculations. Typically, one must extrapolate from the exposed species to humans, and also from short exposures to longer ones. Most inhalation studies involve intermittent exposures that simulate industrial workday exposures; however, astronauts will be subjected to continuous exposures, so a correction must be applied for this difference. Sometimes the endpoints evaluated in test animals are not appropriate to humans, so further judgement is required.

Setting safe exposure levels is meaningless without the ability to monitor potentially hazardous chemicals in a timely manner. Analyses of archival contaminant samples obtained with bottles or resin traps are completed after each mission. Such methods, however, do not provide timely results if a contingency occurs. Also, reactive compounds, such as ozone or nitrogen dioxide, disappear from the sample before analysis. Hence, real-time, on-orbit monitoring is necessary to protect crew health. Instrumentation is available to detect and quantitate almost any imaginable contaminant; however, adapting that technology for spacecraft is a challenge. The constraints of weight, power consumption, size, and cost must be considered along with other tradeoffs. For example, only a limited number of specific chemicals can be monitored in real time. In some cases this tradeoff cannot be made, and two instruments are required. Space Station Freedom will have several total hydrocarbon monitors operating as real-time, first-alert instruments. If an alarm occurs, then air samples will be obtained and subjected to a 1- to 2-hour analysis for specific hydrocarbons. Only when the compound causing the alarm is identified and quantitated can the SMAC value be applied to assess potential health hazards.

3.4 TOXICOLOGY DISCIPLINE GOALS, OBJECTIVES, AND CRITICAL QUESTIONS

3.4.1 Goals

The goals of the Toxicology discipline are to:

- Understand toxicity and risk assessments, physiochemical properties, exposure limits, and contingency procedures

- Develop procedures/methods to ensure that during missions crewmembers do not receive harmful exposures to any airborne chemical.

3.4.2 Objectives

The objectives of the Toxicology discipline are to:

- Set, document, and periodically review SMACs for spacecraft environments

- Ensure that contaminants offgassed from materials are below levels that could harm crewmembers

- Detect and monitor chemical contaminants that could result from credible contingency scenarios (e.g. combustion)

- Identify those technologies that offer thorough analyses (analytical instrumentation) without excess size, weight, energy, or crew time.

3.4.3 Critical Questions (In priority order)

1. What impact do space-flight-induced biological, physiological, and immunological changes have on the susceptibility of crewmembers to toxic materials, alone or in combination? The concern is for both in-flight performance and residual health. (See 1991 Regulatory Physiology Discipline Science Plan for further discussion of immunological issues.)

2. How can traditional limited-time exposure and human toxicological data be used to predict acceptable values for inhalation and ingestion exposures to single chemicals and/or to mixtures including biological toxins and particles under flight conditions?

3. What is the composition of the air, water, and spacecraft systems to which flight and ground-based crewmembers may be exposed?

4. What is the appropriate monitoring strategy and technology for toxicological assessments of crew health, safety, and performance?

5. What are the potential biomarkers for assessing either exposure or response to chemicals?

6. What are the effects of in-flight exposure to ultrafine and larger (respirable and nonrespirable) particles on crew health, safety, and performance?

7. What approaches may be used when data are insufficient to allow prediction of acceptable exposure levels?

3.5 TECHNOLOGY

Instrumentation is needed for monitoring air and water contaminants; volatile organic compound particulates (51) (including the ultrafine range); metals in air and water, inorganics in air (e.g. ozone, NOx) and water (dissolved organics); and for continuous detection and warning of combustion products (e.g. CO, HCN). Instrumentation is also required for clinical toxicology and routine hematology, chemistry and urine studies and specialized studies for toxicities. Technology must also be available for decontamination absorbents and adsorbents. Analytical instruments for monitoring contaminants should be developed with wider ranges of detection capability, improved response times, and reduced power demands.

3.6 RESEARCH STRATEGY

The Toxicology research area priorities for each of the NASA mission eras are presented in Table 1.

3.6.1 Basic Research

A fundamental concern is whether long-term space flight changes the susceptibility of crewmembers to toxic chemicals. To address this concern, one must know as much as possible about the physiological, biochemical, immunological, and performance changes that occur during spaceflight . The changes should be studied at the molecular level also to facilitate their comparison with known mechanisms of toxicity. Research in this area must include a comparison of animals tested in space experiments as well as animals used in ground-based microgravity models and controls.

Data from animal exposures will be extrapolated to set safe, long-term, continuous exposure levels for humans. Research is needed on selected compounds to understand the relationships between contaminant concentration and time of exposure, human versus test animal susceptibility, and intermittent and continuous exposures. The goal is to develop both model equations and biological markers so that uncertainty related to the process of setting SMACs (spacecraft maximum allowable concentrations) and SMCLs (spacecraft maximum contaminant levels) may be reduced.

Research is needed to better understand offgassing of materials and to develop model equations that predict contaminants produced by offgassing. Such equations are crucial for risk analysis for chemical hazards and design of air revitalization systems. Contaminant sources, such as microbial metabolites, as well as effects of chemicals and physical factors should be considered in developing models for long-term space flight.

A classic problem in toxicology is predicting the toxicological behavior of chemical mixtures, especially at low-level exposures. Studies are needed to verify current approaches used in evaluating toxicological effects of contaminant mixtures, and to identify improved methods for estimating the hazard from mixtures of potentially toxic contaminants. As part of this effort, the interaction of volatile particulates and biological contaminants must be considered.

3.6.2 Applied Research

Classic toxicological testing of potentially toxic chemicals must continue for ground-based as well as for space-flight applications. Such studies must be carefully controlled, with absolute attention to regulatory guidelines. The studies should address both short- and long-term exposures targeted to relevant endpoints.

An emerging area of concern is the effect of both ultrafine and very large particles on the respiratory tract. Ultrafine particles have been identified in thermodegradation events. The mechanisms of their toxicity need to be better understood.

Carefully controlled human exposure studies will be needed in selected cases to address the possibility of performance decrements. The recent Halon study is an example of the approach that could be used. Toxic endpoints applicable to mission-critical tasks must be used in such studies to ensure safe levels for crewmembers.

Models for extrapolation of animal data to human risk should be applied to airborne contaminants present in spacecraft cabins. This includes gaseous contaminants as well as particles, and models must consider microgravity. Validation under space conditions is needed for nonhuman primate and human respiratory system models.

Analytical studies should comprehensively characterize the chemical composition of air and water supplies, and closed systems that may add contaminants to the spacecraft environment.

3.6.3 NSCORT (NASA Specialized Center of Research and Training)

The Discipline Working Group (DWG) strongly supports the newly established NASA Specialized Center of Research and Training (NSCORT) in Environmental Health. This should provide NASA with a broad range of research in pulmonary toxicology, drug metabolism, immunotoxicology, microbiology, and molecular and cellular biology which should greatly enhance NASA's ability to evaluate and predict human health risks from potential or actual exposures in space vehicles and establish a scientific basis for safety standards. In addition, the center should provide a mechanism for training space life sciences professionals in environmental health.

4.0 MICROBIOLOGY

4.1 BRIEF DESCIPTION OF THE DISCIPLINE

Microbiology is the biology of organisms that are not directly visible to the unaided eye. These microorganisms include the viruses, bacteria, fungi. Microorganisms are integral constituents of the environment and play an irreplaceable role in the recycling of biomass in nature. The vast majority of microorganisms are not harmful to humans and are enormously beneficial in maintaining balance of nature in our environment and in the production of many consumer products. However, there are a relatively small number of microorganisms that may cause discomfort (e.g. allergies), disease, or even death. These microbial pathogens may prove to be especially problematic in spacecraft and space habitats, because the relatively crowded conditions and closed environment promote the spread of infectious agents. With adequate precautions most known pathogens may be excluded from the space habitats, but the normal human endogenous microflora may cause infections under certain conditions. Endogenous infections result from changes in the relationship between the host and the microbes residing in the host. This relationship represents a delicate balance, and factors upsetting this balance may predispose an individual to infection from his or her own microflora (or that of a fellow crewmember). Normally, through competition, a host's microflora provides important protection from colonization by pathogens. This balance may be upset by antibiotic treatment, stress, and other factors.

The effects of space flight on the human immune system are not well established; however, some data suggest that the immune response may be diminished, with a resulting increased risk of illness. Similarly, the effects of space flight upon the pathogenicity and virulence of microorganisms are largely unknown.

In addition to causing infections, microorganisms may prove troublesome as allergens. Fungal spores are second only to pollen as frequent airborne allergens. Microbes are also important in food spoilage and degradation of a wide variety of materials. An example of the importance of microbial degradation would be the deterioration of rubber seals involved in spacecraft integrity. Microbes are ubiquitous and amazingly adaptable to almost any ecological niche, including spacecraft and space habitats. They will be essential components of waste remediation and food production in future space habitats on lunar and Martian surfaces.

4.2 BRIEF HISTORY OF THE DISCIPLINE AS PART OF SPACE LIFE SCIENCES

Microbiology has been a primary concern since early in the space program. The Crew Microbiology discipline was initiated in response to requirements from the Interagency Committee on Back Contamination to address the potential for the return of microorganisms from the lunar surface to Earth. Since crewmen were the prime source for lunar soil contamination, an extensive catalog of crew microflora was prepared for each mission. This catalog was an essential tool in determining the origin of recovered contaminants.

Analysis of crew specimens was performed to satisfy three objectives in addition to lunar contaminant evaluation. The primary objective was to detect potentially

pathogenic microorganisms so that associated medical problems could be identified early and preventive measures established. A second objective was to identify medically important microorganisms recovered from ill crewmen to aid in diagnosis and treatment. The third objective was to collect microbiological data that would aid in elucidating the response of the crew microbial autoflora to the space flight environment and in evaluating the resultant effect on the crewmember.

A dynamic microbiology program during the Apollo era played a key role in establishing the absence of microbes or primitive forms of life on the lunar surface. Also, these early efforts helped to dismiss the then widely held view that microbes normally present in the human body and surroundings might undergo radical changes following exposure to space.

Following the Apollo and Skylab Programs, the JSC Microbiology Laboratory has continued to function as a NASA-wide resource in microbiological planning, analyses, research, and assessment. It is actively involved in the current Space Shuttle and Space Station Freedom Programs as well as the future Space Exploration Initiative (lunar and Mars). The laboratory strives to minimize the detrimental effects of microorganisms on the health and productivity of flight crewmembers. Comprehensive capabilities in bacteriology, mycology, virology, and parasitology are maintained to provide prompt, professional responses to the medical operations phase of manned missions. The Microbiology Program is divided into two major divisions—mission operations and research. Mission operations includes environmental monitoring—appropriate analysis of the air, food, water, and surfaces to ensure a safe and habitable environment for the crew. The clinical portion of the laboratory is certified by the College of American Pathologists and provides microbiological evaluations of crewmembers during all phases of a mission. The laboratory also provides microbiological support to the Flight Medicine Clinic (astronauts and their families) and the JSC Occupational Health Clinic.

In addition to operational responsibilities, the Microbiology Laboratory has maintained research and development efforts in support of manned space flight. Studies on microbial levels and changing population dynamics have been conducted in the Apollo, Skylab, and Space Shuttle Programs. Few studies, however, have been conducted to determine the effect of space flight on microbial function (e.g. pathogenicity) or on the human immune response.

Advance program development for the Space Station Freedom (SSF) Health Maintenance Facility (HMF) and Environmental Health System (EHS) is currently in progress. Among the major functions of the Microbiology Laboratory are planning, designing, and identifying areas of microbiological concern; determining and establishing realistic and safe microbiology standards for environmental subsystems, e.g., water and air; developing monitoring plans; and designing and modifying microbiology equipments and work facilities for EHS and HMF subsystems.

4.3 CURRENT KNOWLEDGE BASE

Major issues in microbiology for current and future long-duration missions involve the establishment of requirements, acceptability standards, and technology development for health and environmental assessments.

Terrestrial acceptability limits for microorganisms in water have been established by the Environmental Protection Agency (EPA). However, no Federal limits have been established for air or surfaces, although such limits have been established for specialized environments, e.g. hospital operating rooms. These limits were somewhat arbitrary and not widely used. The current limit for spacecraft air is 1000 CFU/m^3. The Bioaerosol Committee of the American Conference of Governmental Industrial Hygienists has been asked to assist in reexamining the airborne levels of microorganisms in spacecraft air. Action is expected by 1992. Utilizing the expertise of the EPA, NASA is developing acceptability limits for waterborne microbes on spacecraft, and these limits should be in place by early 1992.

Requirements for microbial operations and support of the STS Program have been established and implemented. Requirements for diagnostic capabilities and environmental surveillance for SSF have been baselined and await implementation as the station becomes operational. Similar requirements for both diagnostic and environmental microbiology for the Space Exploration Initiative need to be developed by early 1993.

The Apollo missions demonstrated that microorganisms are exchanged among the crewmembers sharing the rather small closed environment. Studies by the Soviets, Germans, and others have demonstrated effects of space flight on microbial growth, antibiotic susceptibilities, genetic exchange, and other functional characteristics.

Relatively little is known about the effects of space flight on the structure/function of microorganisms. Microbes have been studied in space since 1967. However, the studies to date have not been conducted in response to an overall organized project plan designed to elucidate the effects of space flight on microbes. Instead, the many studies have been in response to the research interests of different investigators. A well organized plan directed toward the elucidation of specific critical questions must be developed and implemented.

4.4 MICROBIOLOGY DISCIPLINE GOALS, OBJECTIVES, AND CRITICAL QUESTIONS

4.4.1 Goals

The overall goals of the Microbiology discipline are to:

- Understand the deleterious actions of microorganisms
- Develop/maintain the health, safety and productivity of crewmembers involved in all manned space flight programs.

4.4.2 Objectives

The objectives of the Microbiology discipline are to:

- Implement research efforts to elucidate the effects of space flight upon microbial functions, population dynamics, and host-microbe interactions (e.g. pathogenicity)
- Investigate the effect of space flight stressors on the human immune system with emphasis on the risk of infectious diseases due to common commensal and environmental microorganisms
- Develop realistic and safe microbiological standards for spacecraft and space habitat environments (e.g. air, water, food, surfaces, experimental animals, payloads, etc.)
- Maintain a proficient, comprehensive, and state-of-the-art ground-based facility to provide microbiolgical expertise, analysis, and assessment for all NASA flight programs
- Provide support to the flight surgeons in the diagnosis and antimicrobial management of infectious diseases
- Develop methodology and procedures necessary for pre-, in- and postflight monitoring of the spacecraft and the crew, plants, and animals
- Maintain a program of careful monitoring of crewmembers, payload biological specimens, and the spacecraft environment (e.g. air, water, food, and surfaces) to minimize the harmful effects of microbes on mission safety and success.

4.4.3 Critical Questions (In priority order)

1. What are the acceptable numbers and kinds of microorganisms in air, water, food, on surfaces, the crew, and other biological hosts?
2. What is the effect of space flight on microorganisms?
3. What is the effect of long-duration space flights on the human immune system?
4. What onboard instrumentation is needed to assess microbiological problems in the environment and crew during long-duration missions?
5. What measures can be taken to control excessive numbers of microorganisms in space habitats and crew?

4.5 TECHNOLOGY

Second-generation instruments are needed for automated noninvasive monitoring of microorganisms on crewmembers' bodies and in the spacecraft environment. Technology is needed to determine antimicrobial susceptibility as well as immunological host responses. Prototype testing will proceed on Spacelabs, on SSF, and during the Exploration Era. Other needs include monitors for microorganisms in air and water, cleaning, disinfection, and waste management procedures within the cabins. Capabilities for identifying additional etiologic agents must be expanded. Methods need to be identified for specimen procurement and storage for later analysis. Instrumentation to monitor responses of microorganisms to space environment stress needs to be developed.

4.6 RESEARCH STRATEGY

The Microbiology research area priorities for each of the NASA mission eras are presented in Table 1.

The goals, objectives, and critical questions identified for the Microbiology discipline can only be realized by the implementation of an effective research program. The following research topics should be included:

- Establishment of microbiological standards for air, water, food, surfaces, payload animals, and other components of internal spacecraft environments. Much of this effort can be accomplished by working groups or expert panels with some ground-based and in-flight studies to provide essential data.

- Determination of the effects of space flight on microorganisms. Stressors associated with long-duration missions in spacecraft and space habitats may lead to changes in microbial form and function. For example, changes in the pathogenicity/virulence of microorganisms may have a profound effect on crew health. In addition, studies on topics such as microbial population dynamics, plasmid exchange, and antibiotic resistance should be investigated.

- Determination of the effects of space flight on the human immune system. An effective and responsive immune system is absolutely essential for space exploration and habitation. Studies should be directed to ascertain the effects of infectious disease risks associated with space flight at the molecular, cellular and organism level.

- Development of a monitoring strategy for spacecraft and space habitats. Determine which components of the spacecraft internal environment require monitoring to assess environmental safety. Identify the samples/specimens (air, water, food, surfaces, etc.), sampling frequency, and data analysis necessary for environmental assessments.

- Determine the effects of microbial degradation of spacecraft materials on the habitability of internal environments. Effects of volatiles generated by microbial action on air quality should be assessed.

An ad hoc committee of microbiologists to serve as an advisory group to the JSC Microbiology Laboratory on research efforts should be considered. Every effort should be made to establish strong relationships with the U.S.S.R. space program to exchange information relating to space microbiology. In addition, much information cold be gained from discussions and perhaps collaborative studies with the Navy (submarine service), NOAA (undersea habitat), and NSF (Antartica).

The Discipline Working Group (DWG) strongly supports the newly established NASA Specialized Center of Research and Training (NSCORT) in Environmental Health. This should provide NASA with a broad range of research in pulmonary toxicology, drug metabolism, immunotoxicology, microbiology, and molecular and cellular biology, which should greatly enhance NASA's ability to evaluate and predict human health risks from potential or actual exposures in space vehicles and establish a scientific basis for safety standards. In addition, the center should provide a mechanism for training space life sciences professionals in environmental health.

TABLE 1
ENVIRONMENTAL HEALTH DISCIPLINE PRIORITY RANKINGS

BAROPHYSIOLOGY	STS ERA (1-16 DAYS) MISSION	SPACE STATION ERA (3-6 MONTHS) MISSION	EXPLORATION ERA (1-3 YEARS) MISSION
GAS COMPOSITION AND PRESSURE	18	16	9.5
INTERACTIONS W/MICROGRAVITY	18	16	20.5
PERFORMANCE EFFECTS	13	5.5	9.5
LONG TERM ADAPTATION	18	16	9.5
DCS ETIOLOGY	6.5	16	20.5
DECOMPRESSION SICKNESS PROCEDURE	1.5	16	23
ACCEPTABLE RISKS	1.5	5.5	9.5
THERAPY	6.5	5.5	9.5
TOXICOLOGY			
PHYSIOLOGICAL	6.5	5.5	9.5
BIOCHEMICAL CHANGES	13	5.5	9.5
EXPOSURE TO PARTICLES	13	16	20.5
AIR PURIFICATION	6.5	5.5	9.5
SMAC LIMITS	13	16	9.5
DECONTAMINATION SYSTEM	6.5	5.5	9.5
RISK ASSESSMENT	18	16	9.5
EFFECTS OF CONTAMINANTS	6.5	16	9.5
MONITORING TECHNOLOGY	6.5	5.5	9.5
MEDICAL ISSUES	6.5	5.5	9.5
MICROBIOLOGY			
CELLULAR/HUMORAL IMMUNE SYSTEM	22	22	9.5
MICROBIAL STANDARD	13	16	9.5
MICROGRAVITY INDUCED EFFECTS UPON CELLS	22	4	9.5
MICROBIAL IDENTIFICATION	22	16	20.5
MONITORING TECHNOLOGY	18	5.5	9.5

5.0 SELECTED REFERENCES

5.1 BAROPHYSIOLOGY

1. Exploring the Living Universe, a stategy for Space Life Sciences report of the NASA Life Sciences Strategic Planning Study Committee, June 1988, Washington, D.C.

2. A strategy for Space Biology and Medical Sciences for the 1980's and 1990's. National Academy Press Washington, D.C., 1987.

3. Nicogossian, A. E., Leach Huntoon, C., and Pool S. L. Space Physiology and Medicine. Second edition. Lea & Febiger, Philadelphia, 1989.

4. Lambertsen, C. J. Report of meeting of Environmental Science Review Committee, Johnson Space Center Decompression Procedures for Neutral Buoyance facility, August 29-30, 1989.

5. Lambertsen, C. J. Report of meeting of Environmental Sciences Review Committee. Appraisal of denitrogenation requirements for EVA. Johnson Space Center, April 1987.

6. Waligora, J. M., Horrigan D. J., Bungo M. W., Conkin J. Investigation of the combined effects of bedrest and mild hypoxia. Aviation, Space, and Environmental Medicine 53: 643-646, 1982.

7. Waligora, J. M., Horrigan D. J., Conkin J. The effect of extended O2 prebreathing on altitude decompression sickness and venous gas bubbles. Aviation, Space, and Environmental Medicine 58(9, Suppl.): A110-A112, 1987.

8. Horrigan, D. J., Waligora J. M., Stanford J., Edwards B. F. Overview of crewmember energy expenditure during Shuttle flight 61-B ease/access task performance. Space construction. Hampton VA: NASA, Langley Research Center, p. 235, 1986. (NASA-CP-2490) (GWU 10655)

9. Waligora J. M., Horrigan D. J., Nicogossian A. The physiology of spacecraft and space suit atmospher selection. Acta Astronautica 23: 171-177, 1991. (GWU 12389).

5.2 TOXICOLOGY

1. Gross, S. B. Issues of regulatory requirements for inhalation toxicology testing// Inhalation toxicology/ Ed. H. Salem. New York. Marcel Dekker. Inc. 1987. pp. 361-383.

2. Space Transportation Operations: Safety policy and requirements for payloads using the space transportation system (STS)//NASA NSTS 1700. 7B. 1989.

3. Flammability, odor, and offgassing requirements and test procedures for materials in environments that support combustion. NHB 8060.1B Johnson Space Center 1981.

4. Space Station Freedom hazardous contamination study// Operations Integration Office. NASA Johnson Space Center. Dec. 1990.

5. Airborne particle measurements in the Space Shuttle. DSO 471. Johnson Space Center. 1989.

6. Ezell E. C., Ezell, L. N. The partnership: A history of the Apollo-Soyuz Test Project// NASA SP-4209, The NASA history series. 1978.

7. Shuttle operational data book (SODB), JSC-08934, Revision E., Vol. 1: Shuttle systems performance and constraints data. NASA JSC. Jan. 1988. pp. 4.6.1.10 to 4.6.1.17.

8. Rippstein, W. J. Shuttle toxicology// NASA technical memorandum 58245. STS-2 Medical report. 1982.

9. Coleman, M. E. STS-6 Summary Report for DTO 0602, Spacecraft Cabin Atmospheric Analysis// JSC memorandum SD4/82-215. 1982.

10. Coleman, M. E. Thermodegradation Products of an STS-28 Power Cable// JSC memorandum SD4/89-275. 1989.

11. James, J. T. Toxicological Analysis of STS-35 Atmosphere// JSC memorandum SD4/91-027. 1991.

12. Reviews of combustion - and pyrolysis - product toxicology of ten plastics// Board on Environmental Studies and Toxicology, Commission on Life Sciences, National Research Council. Washington, D. C., National Academy Press. 1987.

13. Space Station Freedom science facility assessment// Dec. 5, 1990. NASA-JSC Lunar & Planetary Institute. Houston, TX.

14. Halon 1301 human inhalation study. JSC 23845. NASA-JSC. Aug.1989.

15. Emergency and continuous exposure limits for selected airborne contaminants. Vol. 3 Bromotrifluoromethane// Board on Toxicology and Environmental Health Hazards, Commission on Life Sciences, National Research Council, Washington, D. C., National Academy Press. 1984.

16. Spacecraft maximum allowable concentrations for airborne contaminants. JSC 20584. NASA-JSC. May 1990.

17. Wydeven, T., Golub, M. A. Generation rates and chemical compositions of waste streams in a typical crewed space habitat. NASA TM-102799. 1990.

18. Airborne particulate matter in spacecraft. NASA Conference Publication 2499. NASA-JSC. 1988.

19. Detailed Test Objectives (DTO) 0616 (JSC 17462). NASA JSC. 1982.

20. Change Configuration Board Directive, Spacelab 4495. NASA MSFC. 1985.

21. Detailed Test Objective (DTO) 0623 (JSC 17625, Rev. F). NASA JSC. 1984.

22. Coleman, M. E. Postflight report for STS-26 atmospheric analysis//NASA JSC memorandum SD4/88-387. 1988.

23. Coleman, M. E. Postflight report for STS-27 atmospheric analysis// NASA JSC memorandum SD4/88-042. 1988.

24. Coleman, M. F. Postflight report for STS-28 atmospheric analysis// NASA JSC memorandum SD4/89-316. 1989.

25. James, J. T. Toxicological analysis of STS-33 atmosphere//NASA JSC memorandum SD4/89-432. 1989.

26. Ray, C. C., Stanley, J. B. Spacelab baselines ECS contaminant removal program//NASA TM 78135. 1977. NASA MSFC. pp. 28-29.

27. CO_2 adsorber element// Intermediate and depot maintenance requirements. Specification Nol 61V006.000.

28. Environmental Systems Console handbook// JSC-19935. Rev. A. Oct. 1985. NASA JSC. pp. 6.1-26 to 6.1-37.

29. NASA JSC Systems Division. Mission Operations Directorate. In-flight maintenance tool catalog. 1990 pp. 6-10.

30. Air contaminants - permissible exposure limits. Title 29 Code of Federal Regulations, Part 1910.1000. 1989.

31. National Research Council, Committee on Toxicology. Emergency and continuous exposure limits for selected airborne contaminants// National Academy of Sciences. Washington, D. C. 1984. Volume 1 to 1988, Vol. 8.

32. National Research Council, Committee on Toxicology. Atmospheric contamination in spacecraft// National Academy of Sciences. Washington, D. C. 1968.

33. National Research Council, Committee on Toxicology. Atmospheric contaminants in spacecraft// National Academy of Sciences. Washington, D. C. 1972.

34. National Research Council. Committee on Toxicology. Guidelines for developing spacecraft maximum allowable concentrations (SMACs) for Space Station contaminants// National Academy Press. Washington, D. C. 1991.

35. Guidance on radiation received in space activities. National Council on Radiation Protection and Measurements. Report No. 98. 1989.

36. Garcia, H. Hydrazine SMAC document. Johnson Space Center. 1991.

37. Wong, K. L. Methylene Chloride SMAC document. Johnson Space Center. 1991.

38. Wong, K. L. Formaldehyde SMAC document. Johnson Space Center. 1991.

5.3 MICROBIOLOGY

1. Taylor, G. R., Kroop, K.D., Henney, M. R., Ekblad, S.S. Baky, A. A., Groves, T. O., Molina, T.C. , Decelle, J.G., Carmichael, C.F., Gehring, N.J., Young, E. L., Shannon, I. L., Frome, W. J. and Funderburk, NR. Apollo-Soyuz Test Project Summary Science Report, NASA SP-412. Microbial Exchange (AR-002), Chapter 15, 237.

2. Taylor, G. R., Graves, R. C., Brockett, R.M., Ferguson, J.K. and Mieszkuc, B.J. Biomedical Results from Skylab, Skylab Environmental and Crew Microbiology Studies, Chapter 8, 53.

3. Pierson, D. L., McGinnis, M.R., Mishra, S.K. and Wogan, C. F. NASA Conference Publication 3108. Microbiology on Space Station Freedom, 1989.

4. Medical Sciences Division Space and Life Sciences Directorate, Shuttle Transportation Microbial Contamination Control Plan, JSC 16888.

5. Medical Sciences Division, Space and Life Sciences Directorate, Space Station Infectious Disease Risks, JSC 32104.

6. Pierson, D. L. and Cintron, N.M. Microbiology Support Plan for Space Station Freedom, JSC 32105, 1986.

7. Russian Chapter. Foundations of Space Biology and Medicine. Volume 2, 1992. In preparation.

8. Konstantinova, I.V., Antropova, YeN., Rykova, M.P., Guseva, O.A., Lesnyak, A. T., Vorotnikova, I.E. and Vasilyeva, E.F. Cell mediated and humoral immunity in cosmonauts exposed to space flight factors. Vestnik Akad. Med Nauk. CCCP 8:51-58.

9. Taylor, G. R., Neale, L.S. and Dardano, J. R. Immunological analyses of U.S. Space Shuttle Crewmembers. Avait Space Environ Med. 57:213-217, 1986.

10. Meehan, R., Neale, L., Kraus, E., Stuart, C., Smith, M. Cintron, N. and Sams, C. Phenotypic analyses of mononuclear leucocytes after space flight. FASEB J. 4.7: A1807, 1990.

5.4 SPACE FLIGHT

1. NASA Conference Publication, Microbiology on Space Station Freedom "Foundations of Space Biology and Medicine" (not yet available)