

Chapter 4

Microbiological Contamination

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Micro-organisms are ubiquitous in spacecraft environments, as they are on Earth. Microbes are amazingly adaptive to a wide range of environmental extremes in temperature, pressure, and desiccation. The vast majority of microbial species are harmless to humans, and many have proven remarkably beneficial. Their capability to degrade complex organic materials into simple substances is essential in maintaining the natural balance on Earth. This property may make them useful in the bioremediation of waste materials (e.g., human wastes) on planetary outposts. As space exploration continues, microbes will be increasingly involved in food production and air and water purification. Unfortunately, however, microbial biodeterioration also may degrade materials responsible for maintaining environmental safety, such as airtight seals.

Relatively few microbial species cause infectious diseases in humans. However, the crowded, closed environment of the spacecraft may predispose crewmembers to the problems associated with the "tight building syndrome" on Earth.¹ An example is allergic reactions induced by fungal propagules and mycelium, which produce discomfort and decrease productivity.

Microbes will colonize an ecological niche that contains sufficient moisture and nutrients. Even though space vehicles, space stations, and planetary bases are closed environmental systems, microbial development and its associated problems will be dynamic. The initial resident microbial population will change over time as crews are exchanged and experiments involving plants, micro-organisms, and animals are conducted. As the environments evolve, each crewmember will be at risk for infections caused by the changing microbe populations.²⁻⁴ Many opportunistic infections observed in spacecraft environments have been caused by crewmembers' normal flora. Experiences from the U.S.S.R. (currently Russian) and American space programs have demonstrated clearly that morbidity resulting from opportunistic infections can reduce crew health and productivity.⁵ Greater knowledge of the effects of microgravity on microbial function is critical to understanding the potential for opportunistic infections and potential biodeterioration of materials.

Unquestionably, air, water, and interior surfaces in spacecraft will become contaminated. Environmental monitoring systems, acceptability limits, and appropriate countermeasures to protect the health of the crews, as well as the integrity of their space habitats, must be formulated and tested.^{5,6} Monitoring systems must incorporate flexibility in their designs to take advantage of technological advances over time. Microbial standards will change as new information on health effects becomes available. Finally, the microbial populations themselves will change through human habitation, periodic crew exchange, docking of resupply vehicles, biological experiments, and the presence of experimental plants and animals. Many micro-organisms will find niches in the interior of the space habitat regardless of preventive measures, because no environmental control system will be able to remove all micro-organisms. Furthermore, it is expected that environmental selection for changes in microbial metabolic activities will affect microbial virulence and sensitivity to disinfectants and antibiotics.

This chapter presents the sources of microbial contaminants and the principal means of infectious disease transmission in the closed environment of a spacecraft. Onboard capabilities for monitoring micro-organisms in the environment and decontamination procedures are also described. Tentative plans for the microbiology subsystem of the U.S. Space Station are discussed. Finally, some thoughts are presented on future directions for the field of microbiology in space exploration.

I. Infectious Diseases in Spacecraft

Infectious diseases remain an important concern associated with space flight.⁵⁻⁸ The morbidity and potential mortality associated with infectious diseases in space are exacerbated by the limited diagnostic capabilities and few countermeasures available to crewmembers during flight. In addition, the relatively small closed environment, crowded conditions, and lack of appropriate isolation facilities in the space habitat greatly increase the potential for transmission of disease-causing microbes among crewmembers.

Infections result from agents that are both endogenous and exogenous to the host. Endogenous infections result from changes in the relationship between the host and its commensal

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sal microflora. This relationship represents a delicate balance, and factors upsetting this balance may predispose individuals to infection from their own flora. The commensal flora normally protect the host from microbial pathogens through several mechanisms, including competition for nutrients, production of bactericides, and stimulation of the immune system in preparation for invading pathogens.⁹ Illnesses caused by the indigenous microbiota follow changes in either the host's resistance, the host's flora, or both. Exogenous infections, on the other hand, occur following the transmission of an infectious agent from an exogenous source to a susceptible host. Infectious agents are transmitted primarily via four routes: contact, common vehicle, air, and vector. Understanding the routes of transmission allows interruption of the chain of events that leads to infection and may provide a form of "countermeasure" in the closed spacecraft environment.

Contact between an infectious source and a host can be direct or indirect. Direct contact implies physical contact between the host and the source. Indirect contact refers to the passive transfer of micro-organisms from the source to the host, usually by means of an inanimate object. In common vehicle transmission, an infectious agent is transmitted to multiple hosts via a single inanimate vehicle, such as food, water, or airborne particles. Infectious agents can be aerosolized (see "Modes of Transmission") and reach potential hosts via airborne transmission. Potential pathogens may also be transferred via a vector (e.g., an insect); this route, although deserving of consideration in the preflight period, is unlikely to play a role in disease transmission during space flight.

Clearly, the host-microbe relationship will determine the probability of the onset of infectious diseases in spacecraft or in planetary habitats. The effects of the stresses associated with space habitation (reduced gravity, radiation, physiological changes, isolation, and others) on the host-microbe relationship are unknown. Although much work remains to be done in the study of this area, evidence suggests that the human immune response is attenuated somewhat during space flight.¹⁰⁻¹³ Blunting of the delayed-type hypersensitivity response after as few as 3 to 5 days in flight was reported by Taylor and Janney.¹⁴ Changes in the immune response have been observed in the cell-mediated component of the immune system; however, significant changes in the humoral immune response have yet to be demonstrated. The microbial agent is the other important aspect of the host-microbe relationship. The effects of space flight on microbial structure and function leading to changes in pathogenicity have not been demonstrated conclusively.^{6,15,16} Some bacteria, such as *Escherichia coli* and *Staphylococcus aureus*, have exhibited decreased susceptibility to selected antibiotics in space flight. Moatti et al.¹⁷ demonstrated similar findings during the German Spacelab D-1 mission. These *in vitro* findings, if consistent *in vivo*, may affect in-flight antibiotic dosages for infections. Probable changes in drug pharmacodynamics resulting from in-flight fluid shifts and other physiological changes

will exacerbate the problems associated with determining antibiotic dosages.

The environment also plays an important role in the chain of infection by affecting the infectious agent, the route of transmission, and the host. Environmental factors of interest in the space-flight environment include temperature, moisture, radiation, air pressure, ventilation, and the presence of chemicals and toxins. Environmental factors may promote or limit the infection process from or prevent it from progressing to clinically apparent disease.

To understand the role of the many stresses associated with space flight on the increased risk of infectious disease, we must first understand the changes in the host-microbe relationship. Specifically, space-flight-induced clinically relevant effects on the human immune response and the pathogenic potential of micro-organisms must be determined and evaluated.

That infectious diseases can have serious effects on crew health and performance during space missions has been recognized from the inception of the U.S. space program. The highest incidence of infectious diseases before and during flight was reported in the early Apollo missions, before the crews were routinely isolated from potential sources of infection before missions. During this period, 57 percent of the Apollo crewmembers reported illnesses during the 21-day period before. These illnesses included upper respiratory infections, gastroenteritis, urinary tract infections, and various skin infections.¹⁸ The Apollo 9 mission was delayed because an astronaut had an upper respiratory illness.¹⁸ After Apollo 13, the Flight Crew Health Stabilization Program was formulated and implemented, dramatically reducing the occurrence of infectious diseases. Infectious diseases reported during Skylab missions were restricted primarily to gingivitis and skin infections such as dermatitis, sty formation, and boils.¹⁹ Few infectious diseases have been reported during the Space Shuttle Program, attesting to the effectiveness of the present Health Stabilization Program for the relatively brief missions. However, the launch of U.S. Space Shuttle mission STS-36 was delayed because of a crewmember's upper respiratory infection.

II. Sources of Micro-Organisms

Micro-organisms are plentiful in the spacecraft environment; moreover, they are capable of surviving in quite hostile conditions. During the Apollo 16 mission to the Moon, the survival rate of spores of *Bacillus subtilis* and *B. thuringiensis* placed outside the command module and exposed to solar ultraviolet radiation and the space vacuum was no different than that observed using ground-based controls.⁷ The ribonucleic acid (RNA) and deoxyribonucleic acid (DNA) viruses can survive conditions duplicating those in space.²⁰ Micro-organisms have survived in the artificial Mars apparatus used to reproduce various extreme environmental conditions.²¹ Soviet scientists have identified 94 species of micro-organism onboard their space stations (see Table 1).

Table 1 Micro-organisms isolated on Soviet spacecraft

Bacteria	No. of species	Fungi	No. of species
<i>Acinetobacter</i>	1	<i>Alternaria alternata</i>	
<i>Achromobacter</i>		<i>Aspergillus</i>	11 *
<i>Aeromonas</i>	1	<i>Candida albicans</i>	
<i>Alcaligenes</i>	1	<i>Cladosporium</i>	2
<i>Arizona</i>		<i>Fusarium</i>	2
<i>Bacillus</i>	9 *	<i>Mucor</i>	1
<i>Citrobacter</i>	1	<i>Oidiodendion cerealis</i>	
<i>Corynebacterium</i>	7 *	<i>Penicillium</i>	13 *
<i>Enterobacter</i>	4 *	<i>Rhizopus arrhizus</i>	
<i>Escherichia</i>	1 *	<i>Rhodotorula</i>	
<i>Flavobacterium</i>		<i>Stemphylium botryosum</i>	
<i>Klebsiella</i>	4 *		
<i>Micrococcus</i>			
<i>Moraxella</i>	2		
<i>Neisseria</i>	5		
<i>Proteus</i>	3		
<i>Pseudomonas</i>	5		
<i>Staphylococcus</i>	3 *		
<i>Streptococcus</i>	6		
<i>Streptomyces</i>			

* Always present.

The crew is the primary source of micro-organisms in the closed environment of space habitats. Microbes are shed continuously from the skin, the respiratory tract, the gastrointestinal tract, and the genito-urinary tract. For example, approximately 10^{10} skin particles are shed per person per day and each particle contains an average of 4 viable bacteria. Thus, 1 person can shed 40 billion bacteria from the skin alone in 1 day.²² The respiratory tract is another common source of micro-organisms. Sneezing, coughing, singing, and talking all produce aerosols, which provide an effective means of spreading micro-organisms in crowded, closed conditions.

Crews will harbor a broad spectrum of bacteria, fungi, and, to a lesser extent, viruses. Organisms such as *S. aureus*, *S. epidermis*, *Klebsiella*, *Bacteroides*, *Proteus*, *Pseudomonas*, *Flavobacterium*, *Serratia*, *Mima*, *Moraxella*, *Corynebacterium*, *Neisseria*, *Enterobacter*, *Haemophilus*, *Streptococcus*, *Micrococcus*, *Mycoplasma*, *Escherichia*, and *Candida* are expected.⁵ Of these microbes, the major bacteria dispersed and surviving in the spacecraft environment will probably be *Staphylococcus*, *Micrococcus*, *Streptococcus*, and a few others. During the Apollo 14 lunar exploration, and during Skylabs 2 and 4, the numbers of aerobic microbes, such as *S. aureus*, increased, although the numbers of anaerobic bacte-

ria decreased. In general, during the Apollo mission series, the absolute numbers of micro-organisms increased, while the diversity and number of anaerobes decreased. The number of fungal isolates decreased, as was the case during the Skylab missions. Different fungi were identified during different missions. The implementation of a preflight quarantine period was undoubtedly an important factor in the smaller numbers of both aerobic and anaerobic bacteria found during later missions.²³

Not surprisingly, micro-organisms were exchanged among the Apollo crewmembers. Bacterial exchange among crewmembers was demonstrated by bacteriophage typing of *S. aureus* isolated from nares. A high carrier rate for *Mycoplasma* was also documented.⁵ *Staphylococci* were also reportedly exchanged among crews on the Soviet space station Salyut 6.²⁴ Microbial exchange among crewmembers has many implications.⁷ The population dynamics of each individual's flora and the interactions between that flora and a host whose immune response may become compromised, establish one dimension for potential autoinfection. The transfer or exchange of the normal flora of one host to another host also has serious implications. Microbiological results from the Apollo, Skylab, and Apollo-Soyuz Test Project have been reported previously.^{19,25-27} During the Skylab missions, gross microbial contamination by normal flora microbes, intercrew transfer of known pathogens, minor in-flight infections, and microbial simplification of anaerobes were all documented.¹⁹

Although humans are the chief contributors to the microbial populations aboard spacecraft, other sources exist as well. During the assembly and testing associated with developing planetary quarantine requirements, it was reported that about 25 percent of the micro-organisms found with the Viking lander capsules, orbiters, and shrouds were soil bacteria. The remaining 75 percent were considered indigenous human flora.²⁸ Some of these microbes survived even the terminal heat treatment of the Viking spacecraft.²⁸ The location and type of environment in which spacecraft are assembled and tested has a profound effect on which micro-organisms will appear on the vehicles. The Explorer 33 spacecraft showed a microbial burden of 2.6×10^5 micro-organisms at launch.²⁹ Similarly, at the assembly and testing phases for Apollo 10 and 11, the command module was contaminated by 2.7×10^4 micro-organisms per square foot.²⁹ Approximately 95 percent of the micro-organisms recovered in both cases were indigenous human flora.³⁰ In addition, each time supplies and materials are brought to an existing spacecraft or planetary base, new organisms may be introduced. During the Skylab missions, small numbers of various fungi were detected, except in the third mission, in which the spacecraft was widely contaminated by species of *Aspergillus* and *Penicillium*. The sources of the fungi were traced to the liquid-cooling garment for the space suits.³¹

Other sources of micro-organisms in the space-flight environment are experimental animals and plants. Bacteria can be exchanged easily among experimental animals and their

Table 2 Some bacterial and viral zoonoses that can be transmitted to humans

Disease	Etiological agent	Host	Method of infection
Herpes B viral encephalitis	<i>Herpesvirus simiae</i>	Old World monkeys	Bites, contact with infected material
Leptospirosis	<i>Leptospira interrogans</i>	Mice, rats	Contact with contaminated food and water
Listeriosis	<i>Listeria monocytogenes</i>	Mice, rats	Unknown
Lymphocytic choriomeningitis	Arbovirus	Mice, rats, monkeys	Inhalation or ingestion of contaminated materials
Melioidosis	<i>Pseudomonas pseudomallei</i>	Mice, rats	Arthropod vectors, contaminated food and water
Pasteurellosis	<i>Pasteurella multocida</i>	Mice, rats	Animal bites
Rat bite fever	<i>Spirillum minus</i> , <i>Streptobacillus moniliformis</i>	Mice, rats	Bites
Salmonellosis	<i>Salmonella</i> sp.	Mice, rats	Direct contact, contaminated food

Adapted from Youmans, G. P. Zoonoses. In: Youmans, G. P.; Paterson, P. Y.; and Sommers, H. M., Eds. *The Biologic and Clinical Basis of Infectious Diseases*. Philadelphia, London, Toronto; W. B. Saunders, 1980. Reprinted with permission.

human caretakers, particularly in enclosed environments.³² Zoonoses, or infectious diseases transmitted from animals to humans, range from inconsequential to lethal. *Herpes virus simiae* is frequently carried by Old World monkeys, such as the rhesus monkey. *H. simiae* causes a relatively benign, self-limited infection of the oral mucosa in the rhesus monkey, not unlike a *Herpes simplex* Type I infection in humans. In humans, however, *H. simiae* can lead to fatal encephalitis.³³ Zoonotic agents can be transmitted by a variety of means, including direct contact with the animal or its excreta, contamination of foodstuffs, animal bites, and insect vectors (e.g., mosquitos). Infectious aerosols have been demonstrated to transmit disease among animals; thus, airborne transmission must be considered in human infections. Because many zoonoses are restricted to one or a few animal species, different species pose different infectious threats. Examples of some bacterial and viral zoonoses in species of interest to NASA are shown in Table 2. On Earth, various opportunistic pathogens often are first identified through instances of animal infections.

Rats and squirrel monkeys are at present the only mammals that have flown on manned U.S. spacecraft. An upcoming joint France-U.S. project will use rhesus monkeys. Safeguards taken to protect the space crewmembers from animal-borne infectious agents are described in further detail later in this chapter.

As for experimental plants, most plant diseases are caused by fungi, viruses, and insects; bacterial infections are rare. Plant viruses are highly host specific and the insects and bacteria pathogenic to plants are not major causes of disease in

humans. This is not the case, however, with fungi, which account for the majority of plant diseases. Fungi have been incriminated frequently in the etiology of superficial, subcutaneous, and mucocutaneous infections in humans.³⁴ Members of the genera *Alternaria* and *Fusarium* are the examples in this context. Cases of systemic or deep-seated infections in immune-compromised individuals have been attributed occasionally to these as well as other genera of plant pathogenic fungi.³⁴ Since long-duration space missions may compromise astronauts' immunity, the possibility of human infection from plant pathogenic fungi deserves to be taken seriously.

III. Modes of Transmission—Aerosols

Transmission of micro-organisms in space is most likely to take place via direct and indirect contact among crewmembers and common vehicles such as contaminated food, water, and air. Because particles of all sizes remain suspended in microgravity, microbial aerosolization presents a unique challenge to the health of the flight crews. Aerosols are liquid or solid particles suspended in air, which can then be inhaled. Bioaerosols are aerosols of micro-organisms or microbial products. Production of a microbial aerosol requires a reservoir, which can be a human, an animal, or an environmental niche; amplification, which occurs during favorable growth of the micro-organism in its host or environmental source; and dissemination or aerosolization through mechanisms such as coughing or sneezing. Several micro-organisms are capable of causing respiratory infections upon inha-

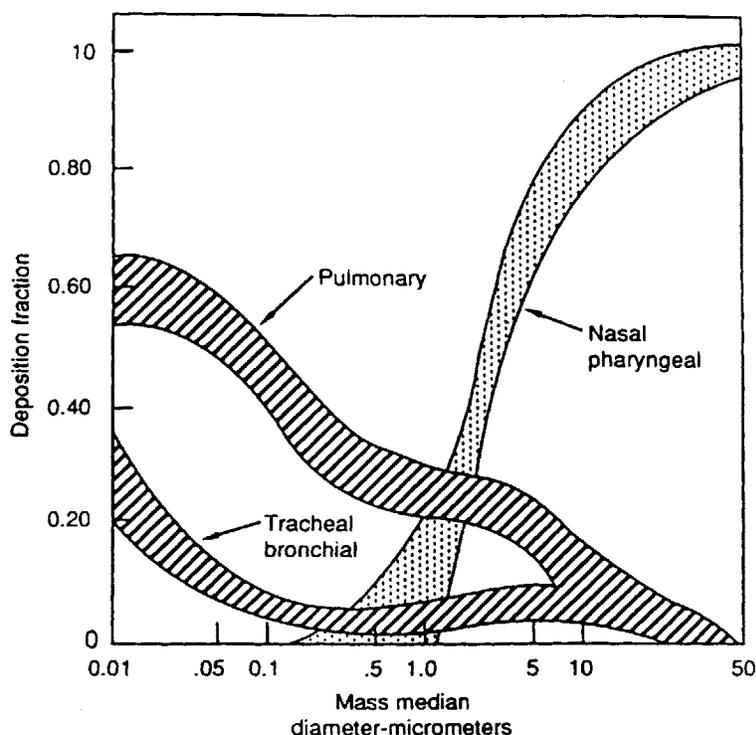


Fig. 1 Deposition of particles of different sizes in the human respiratory tract.

lation by a susceptible host. Both solid and aqueous airborne particulates can harbor microbes; therefore, both are important in the airborne transmission of disease.

The size and surface area of the particulates comprising aerosols are extremely important in determining their clinical effect. The diameter of individual aerosol particles can range from less than 0.1 μm to greater than 100 μm . As an example, a 2- μm droplet of water is large enough to contain a single cell of *Legionella pneumophila*;³⁵ larger particles may contain greater numbers of organisms. In general, aerosol particles up to 1 μm in size present the greatest hazard because of the likelihood of their being deposited in the lower respiratory tract³⁶ (see Fig. 1), where they may remain, become locally established, and eventually produce pathology.³⁷

In 1-g, particles larger than 1 μm cannot remain long in suspension; for example, a 40- μm particle settles to the floor in about 60 s. Therefore, fewer potentially infective airborne particles are available for dispersion, and those particles that are inhaled often cannot efficiently negotiate beyond the upper respiratory passageways. In microgravity, however, even large or dense particles, which can accommodate many micro-organisms, will remain suspended in the spacecraft atmosphere and may penetrate more deeply into the respiratory system. Dense particles, with their greater mass and inertia, can also cause physical damage as they impact the walls of the respiratory system, even in the upper portion of the respiratory tract.

Relative humidity can also affect the size and disposition of bioaerosols. As atmospheric humidity decreases, the size of aqueous particles decreases because of fluid evaporation.

On the other hand, air is humidified to approximately 95 percent relative humidity by the body upon inhalation.³⁷ If hygroscopic viral aerosols are inhaled, their size increases through hydration: a 1.5- μm viral-aerosol particle can increase to nearly 4 μm through the addition of moisture from the respiratory tract.³⁸ Droplet nuclei are classic infectious units; in tuberculosis, the droplet nuclei are less than 5 μm in size. If their matrix contains proteinaceous materials, these materials can help retain the water associated with the droplet nuclei, thereby increasing the possibility of microbial survival.

The relative humidity of the atmosphere can also affect bioaerosols in other ways. The stability of some viruses in aerosols is governed by the presence or absence of lipids in the virion, the air temperature, and the relative humidity of the atmosphere.³⁹ Some lipid-enveloped RNA viruses (e.g., influenza and measles) are relatively stable in dry atmospheres (<40 percent relative humidity), whereas lipid-free viruses (e.g., enterovirus and rhinovirus) prefer higher moisture content (>60 percent relative humidity). Deposition of viruses in the lower regions of the respiratory tract is not necessary to initiate disease. Unlike bacteria, respiratory viruses, such as influenza, often cause infections when deposited in the upper respiratory tract.

It is clear that some bacteria, such as *Pseudomonas aeruginosa* and *Serratia marcescens*, can be spread as components of aerosols. A related question of great import in microgravity is whether bacteria can reproduce in aerosols. Experiments using *S. marcescens* have demonstrated that bacteria can grow, be metabolically active, and divide in aqueous particles and that these processes are enhanced when the

particles are greater than 5 μm in size.³⁸ Anaerobic bacteria, however, may not behave like their aerobic counterparts in aerosols. Anaerobic bacteria tend to produce nonvolatile products, which may accumulate as potential toxins. Anaerobic bacteria also require slightly reduced molecules as an energy substrate for metabolism and subsequent growth.

Disease transmission by aerosols in microgravity will also be influenced by inertial impaction, Brownian motion, and air circulation patterns.⁴⁰ In the space-flight environment, particles are not deposited on surfaces by natural sedimentation; an enormous number of particles of differing sizes remain suspended in the air. These larger particles may carry larger numbers of micro-organisms, which, in turn, might survive longer with greater amounts of substrate. Because the deposition of aerosols in the respiratory tract is normally influenced by particle size and density as well as the involved site in the respiratory tract, the lack of sedimentation in microgravity may result in deposition at different sites and changes in retention relative to a gravity environment. Aerosols can also participate in other modes of infection, including contamination of eyes, skin, equipment, and internal surfaces of the space habitat. Direct contact among crewmembers who have touched contaminated surfaces or inhaled infectious droplets further increases the probability of transmitting infectious agents among the crew.

IV. Microbial Acceptability Limits and Monitoring Strategies

Given that achieving and maintaining spacecraft sterility is neither a realistic nor a desirable goal, appropriate microbial limits must be set to protect the health of space crews and the physical integrity of the environment. Although Soviet scientists did collect some information on micro-organisms present in the spacecraft environment (Table 1), most data in both U.S. and Soviet (currently Russian) space programs have been restricted to preflight-to-postflight comparative measurements. Few data are available concerning the interactions of micro-organisms with their substrates or their human hosts in the space environment, although Zaloguyev, Konstantinova, and others^{24,41-43} have observed that microfloral status tends to change in cyclical rather than linear fashion during flight, probably in response to selection pressures from the environment. The changes microbes undergo in response to environmental selection, in turn, affect their interactions with that environment. A further complication in predicting microbial acceptability limits from a health standpoint is the possibility that human immune function is altered in microgravity.¹⁰⁻¹⁴ Finally, implementing and verifying acceptability limits during flight will require the use of monitoring strategies appropriate to the space-flight environment. Onboard diagnostic and monitoring equipment—and its associated procedures—must conform to the physical and operational limitations imposed by space flight. These limitations include requirements for low power, weight, and volume; simplicity of operation; high reliability and low main-

tenance; limited crew time and expertise; and, of course, the ability to function in the absence of gravity.

Despite these difficulties, some microbial limits have been set as experience has been gained from space flight and from Earth-based studies of closed environments. The following paragraphs present a brief history of microbial surveillance efforts and acceptability limits for numbers and types of micro-organisms in the U.S. and Soviet space programs. Further details of the philosophy underlying the selection of microbial limits for the U.S. Space Station can be found in a recent NASA review.⁴⁴ Clinical monitoring strategies are discussed first, followed by plans for monitoring the microbial populations in the spacecraft environment.

A. Clinical Monitoring Strategies

The first U.S. space crew microbiology program was established during the Apollo Program in response to requirements developed with the Interagency Committee on Back Contamination. This committee included representatives from the National Academy of Sciences, the U.S. Public Health Service, the U.S. Department of Agriculture, and the U.S. Department of the Interior. The committee recommended characterizing each crewmember's microflora in detail, in part to identify contaminants of terrestrial origin that might appear in lunar soil samples and, also, to provide a tool for clinical screening. Thus, microbial pathogens could be detected before flight, aiding in the diagnosis and treatment of ill crewmembers; and changes in microfloral population dynamics resulting from space flight could be observed.²⁵ The reasoning behind this study is still valid today, although most assessments are made only before and after flight.

Under the Apollo Program, specimens were collected from each crewmember three times before launch (30 days, 14 days, and immediately before flight) and once immediately after flight. Urine and fecal samples were collected, as well as swab specimens from the nose, throat, and skin. In addition, the immune status of each crewmember was determined serologically for mumps, rubella, and rubeola. Antibody titers were also determined for Influenza A and B, echovirus, adenovirus, *Herpes simplex* 1, parainfluenza, cytomegalovirus, respiratory syncytial virus, and *Mycoplasma pneumoniae*. Microbiological surveillance during the Skylab Program was similar to that described for the Apollo Program. Additional sample collections were added at 45 days before flight and at approximately 2 and 10 days after flight.

As part of the Health Stabilization Program, U.S. Space Shuttle crewmembers are screened for the presence of bacteria, fungi, and parasites during examinations for Astronaut Corps selection, in the course of recertification examinations, and before and after missions. Standards and procedures for selection and recertification examinations are described elsewhere.⁴⁵ Mission-related clinical evaluations begin 3 months before flight, when the crew's immune status to selected viral agents is reviewed. Specimens are next collected for bacterial, fungal, parasitic, and viral culture 10 days before flight.



Fig. 2 Microbiological monitoring equipment used on Mir; includes thermostat, air sampler, test-tube rack for smears, and nutrient media.

Although viral results generally are not available until after the flight because of culture time requirements, these data are used for diagnostic and epidemiological purposes. Microbial sampling is repeated 1 to 2 days before launch and again after landing to evaluate any change in the microbial flora and to detect cross-contamination among crewmembers. Clinical monitoring in both the U.S. Space Shuttle Program and the Russian space program includes a period of isolating crewmembers before flights and limiting their contacts with other people, all of whom undergo medical examinations to identify potentially infectious agents.

As part of the "Plan for Sanitation, Hygiene, and Epidemic Prevention in Spacecraft," Russian cosmonauts also undergo microbiological and immunological testing with the goal of characterizing each individual's microflora and identifying occult infectious states. The latter are defined as the presence of pathogenic micro-organisms (e.g., Group A streptococci), or "dysbacteriosis" of the intestinal microflora. In cases where such deviations are identified, the cosmonaut undergoes a course of prophylaxis, including bifidobacterin or lactobacterin preparations, immunoprophylaxis, and other means of correcting the microflora. The effectiveness of these actions is verified through re-examination, and the results are used to determine whether that person is allowed to fly.^{3,46}

During Salyut and Mir missions, signs of increase in staphylococci and gram-negative bacteria were observed in cosmonaut nasal, oral, and throat cultures in association with crew exchange.^{24,42,47,48} As new crews were exposed, they became carriers of *S. aureus*; some developed clinical symptoms of disease, and some remained asymptomatic. Other microfloral changes noted during flight included colonization

of mucous membranes in the nose, mouth, throat, and occasionally the skin by species of *Proteus*, *Klebsiella*, *Enterobacter*, *Citrobacter*, and *E. coli*.

Lizko⁴³ compared characteristics of cosmonauts' intestinal microflora during preflight training to those after space flights varying in duration. Minor aberrations tended to be present before flight (e.g., decreased numbers of bifidobacteria and lactobacilli), although the statistical significance of these aberrations is unclear. The state of the intestinal microflora after flight tended to depend upon the degree of dysbiosis observed before flight. In general, lactobacilli and bifidobacteria levels were decreased, and levels of opportunistic enterobacteria such as proteidae, clostridia, and enterococci were found to have increased.

B. Environmental Monitoring Strategies

Space-flight crews must also be protected from exogenous agents of infection during their missions. Maintaining the microbial safety of the space environment, including its air, water, food, and internal surfaces, is just as critical to ensuring in-flight health, safety, and performance as is maintaining the clinical safety of the crew. Moreover, maintaining limits on environmental contamination is also useful in preventing the mechanical or material failures associated with biodeterioration. *Pseudomonas aeruginosa*, for example, is an opportunistic pathogen that can grow on the polymers used in hermetically sealed chambers^{49,50} and on 2-methylstyrene,⁵¹ pseudomonads were isolated from Soviet space stations (see Table 1).

Despite deliberate attempts to minimize microbial contamination of spacecraft components by assembling them in highly filtered "clean rooms," with airlock chambers used as sterile passageways to these rooms, and testing and disinfecting during the vehicle preparation process, micro-organisms were found to be present during both U.S. and Soviet space missions. Observations of Salyut 7 over several years revealed a periodic, cyclical pattern to fungal colonization of the station; the 13 micromycete species isolated during occupation by the first prime crew decreased to 4 with the second crew and increased again to 8 with the third. Because of concern over the structural stability of space station materials under conditions of fungal colonization, a bank of strains isolated from Salyut and Mir were established with regular checks of the air and structural materials onboard Mir using the equipment pictured in Fig. 2.

The following sections review microbiological findings; identify microbial limits established for air, internal surfaces, water, food, and experimental animals; and outline monitoring strategies planned for the U.S. Space Station.

C. Air

Acceptability limits have been set for the air quality in the U.S. Space Shuttle, but assessments of success in achieving these limits are generally restricted to measurements taken

Table 3 Bacteria and fungi isolated from orbiter air

Bacteria	Fungi
<i>Acinetobacter calcoaceticus</i> *	<i>Acremonium sp.</i>
<i>Corynebacterium sp.</i>	<i>Alternaria sp.*</i>
<i>Flavobacterium</i>	<i>Curvularia sp.</i>
<i>Staphylococcus sp.*</i>	<i>Nigrospora sp.</i>
<i>Staphylococcus aureus</i>	<i>Pithomyces sp.</i>
<i>Bacillus species*</i>	<i>Aspergillus fumigatus</i>
<i>Enterobacter agglomerans</i>	<i>Aspergillus sp.*</i>
<i>Micrococcus sp.*</i>	<i>Cladosporium sp.</i>
<i>Streptococcus sp.</i>	<i>Bipolaris sp.</i>
	<i>Penicillium sp.</i>
	<i>Rhodotorula sp.</i>

*Frequently isolates.

before and after flight. Air samples are collected from the Space Shuttle crew compartment approximately 25 days before launch to verify the effectiveness of cleanup procedures. Samples are collected again within 1 day of launch to obtain preflight baseline levels, and a third time at landing to assess microbial buildup during flight. The air in the crew quarters at Johnson Space Center and Kennedy Space Center is also monitored and the microbial content evaluated before these areas are occupied by the crewmembers. Typical organisms detected during Space Shuttle flights are shown in Table 3.

At present, air samples are collected in the U.S. space program using a centrifugal air sampler. The Russian program uses an air sampler consisting of a manual pump with a reflux valve and a set of removable cassettes containing a fibrous capron filter soaked with preservative. Air samples will be collected on the U.S. Space Station, using portable, battery-powered devices that collect airborne particles onto an agar medium attached to a plastic strip. After sample collection, the strip is incubated for an appropriate interval and microbial colonies are enumerated and their morphology recorded. If the test sample reveals potentially harmful airborne micro-organisms, isolation and identification procedures are then performed. Figure 3 depicts an air-sampling device that has been used successfully on U.S. Space Shuttle flights and will be modified for use aboard Space Station.

The density and type of fungal propagules present in the Space Station's internal atmosphere will also be monitored using another device that eliminates the need for culturing filamentous fungi, thus reducing the risk of fungal-propagule contamination. Air contaminants will be collected on a sterile 0.45- μm membrane filter during filtration of a known volume of air. The filter is then treated with reagents, stained, and examined under a microscope. The underlying principles, concepts, and functional approach of this portable device are described elsewhere.⁵²

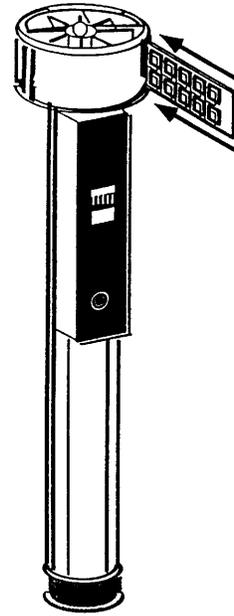


Fig. 3 A prototype air sampler being tested for in-flight use. A known volume of air is drawn into the device by rotating vanes (top), where it impacts an agar strip (arrows).

NASA has established an acceptability limit for airborne micro-organisms on Space Station of 1000 colony-forming units (CFUs) per cubic meter.⁵³ This level, which includes both bacteria and fungi, is typical in U.S. office buildings.¹ Like Mir, Space Station's air revitalization system includes strategically placed air filters and is designed to avoid stagnant areas and cross-contamination. Its air filters are expected to achieve the 1000-CFU limit by removing particulate matter larger than 0.3 μm . Standards for unacceptable organisms, that is, those that must not be present on Space Station, are under consideration,⁴⁴ with the classification system of the National Institutes of Health, Centers for Disease Control, being used as a model.

D. Internal Surfaces

Swab samples of Space Shuttle interior surfaces are collected with the preflight and postflight air samples. Approximately 20 sites throughout the Shuttle's flight deck, middeck, and Spacelab are swabbed with duplicate calcium alginate swabs, which are then stored in tubes containing phosphate buffers for later analysis. Surfaces showing visible contamination, or contamination exceeding 100 CFUs per 25 cm^2 are disinfected before launch. Disinfectants are provided onboard in the event of visible growth on surfaces. On Russian stations, cosmonauts use a device consisting of a cotton swab attached to a capillary tube containing a preservative, all of which are housed in a test tube with a screw cap. This device was used to collect samples from the crew's skin and mucous

membranes, as well as to take smears from the interior of the spacecraft. Cosmonaut samples are typically returned to Earth for analysis within 6 days of their collection.

The crew of Salyut 6 described a "white film" on parts of the interior, including the rubber straps of the exercise machine. This film was found to consist of micromycetes belonging to the genera *Aspergillus*, *Penicillium*, and *Fusarium*.²⁴ On Salyut 7, visible growth on the hull, joints, and cables in the work module was found to contain *Penicillium* (mostly *P. chrysogenum*), *Aspergillus*, *Cladosporium*, *Mucor*, and actinomycetes. In the Soyuz transport vehicle that was docked with Mir for 6 months, the viewing window was nearly obscured with fungi, as well as spore-forming bacteria, such as *Bacillus polymixa*. In some of these instances, the contaminated materials have shown physical changes and structural damage.^{49,50,54} Future plans to protect the spacecraft interior include selection of structural materials that are resistant to degradation, efforts to make surfaces water-repellant, and efforts to incorporate antiadhesive, antibacterial, and antifungal properties in construction materials wherever possible. Plans for the U.S. Space Station at present include collecting swab samples as needed. Routine sampling of internal surfaces is not anticipated, although a means of collecting and analyzing samples will be onboard in the event of visible growth.

E. Water

The Space Shuttle's onboard potable water supply is maintained and monitored at the launch site; microbial isolates are identified and characterized before and after flight; and samples are analyzed for chemical and microbial content, including the presence and numbers of anaerobic, aerobic, and coliform bacteria and yeasts and molds.

The U.S. Environmental Protection Agency has established a limit of 1 CFU of coliform bacteria per 100 mL for public potable water supplies.⁵⁵ The present microbial acceptability limit for the Space Shuttle potable water system is 1 CFU of any bacteria per 100 mL of water. This stringent microbial limit has also been set for the potable water system aboard Space Station. This low number was derived under the assumption that no onboard capability for identifying bacterial contaminants will exist; further details on current and planned water sampling and analysis procedures can be found elsewhere in this volume.

F. Food

Crewmembers can become ill from food contaminated with toxic chemicals or pathogenic micro-organisms. In addition, the management of leftover food and cleanliness of the dining areas are as important in controlling pathogens as is aseptic packaging of microbiologically safe foods. In the U.S. Space Shuttle Program, random food-lot samples are evaluated microbiologically before flight. Random samples of nonthermostabilized food to be consumed on U.S. spacecraft

may not exceed 10,000 aerobic bacteria per gram;⁵⁶ in addition, these foods must not contain pathogens such as *Clostridium botulinum*, *Salmonella* sp., *Shigella* sp., *S. aureus*, or *Bacillus cereus*. Frozen foods planned for use aboard Space Station will require similar testing. It should be noted, however, that aerosolized food particles can supply a rich source of nutrients for microbial growth. Controlling this nutrient source will depend upon housekeeping procedures and the efficiency of air filtering devices onboard space vehicles.

G. Animals

The two major means of protecting the crewmembers from zoonotic agents are careful microbiological screening of all animals to be used in the space environment and isolating the animals from the crewmembers through the use of specially designed containment facilities and judicious animal husbandry practices. Animals to be flown on U.S. missions must be certified before flight as free of specified pathogens (see Table 4).

Rats were first flown on a U.S. Space Shuttle during the STS-8 mission. In addition to meeting microbiological standards, the animals were contained within an animal enclosure module (AEM, Fig. 4), a self-contained cage designed to fit on the orbiter middeck so that neither servicing nor direct contact was required during flight. Food was provided to the animals as prepackaged nutrient bars and potatoes served as a water source. Air from the crew compartment was drawn by two fans into a plenum that directed it through a filter at the rear of the unit. The air was pulled across the cage and exited at the front of the AEM through electrostatic filter material and charcoal to the crew compartment. Animal waste was entrained by the air flow and moved from the front to the back of the AEM into an absorbent material serving as a prefilter to the electrostatic air filter. This unit successfully contained odors and micro-organisms, in addition to maintaining its rodent inhabitants.

A more elaborate animal containment system, the research animal holding facility (RAHF), was designed at the NASA Ames Research Center to accommodate both rats and squirrel monkeys (Fig. 5). The RAHF was first flown on STS-51B [the U.S. Spacelab Life Sciences (SLS) 3 mission] with 32 rats contained in one section and 2 squirrel monkeys in the other. Although the SLS-3 animals generated many important biochemical and physiological findings, the RAHF did not contain food particles and waste products as well as expected, and some contamination of the Spacelab and orbiter resulted. After SLS-3, several features of the RAHF were redesigned, notably the addition of an auxiliary fan that minimized the probability of the cage contents escaping, even when the RAHF was being serviced or animals were being removed from the facility. After rigorous ground-based testing, the improved RAHF was flown on the SLS-1 mission (STS-40). Both this RAHF and a general-purpose workstation (a modified Class II cabinet) successfully contained particulate matter. Although the animal containment facilities planned for

Table 4 Exclusion criteria for animals to be used during flight

Rats	
<u>Bacteria</u>	<u>Viruses</u>
<i>Streptobacillus moniliformis</i>	Lymphocytic choriomeningitis virus
<i>Spirillum minus</i>	Rat parvoviruses
<i>Streptococcus pneumoniae</i>	Rat coronavirus
<i>Streptococcus pyogenes</i>	Sialodacryadenitis virus
<i>Bacillus piliformis</i>	Sendai virus
<i>Corynebacterium kutscheri</i>	
<i>Salmonella</i> sp.	<u>Fungi</u>
<i>Pasteurella pneumotropica</i>	All dermatophytes
<i>Leptospira</i> sp.	
<i>Campylobacter</i> sp.	
Squirrel Monkeys	
<u>Bacteria</u>	<u>Fungi</u>
<i>Shigella</i> sp.	All dermatophytes
<i>Salmonella</i> sp.	
<i>Streptococcus pneumoniae</i>	<u>Endoparasites</u>
<i>Mycobacterium tuberculosis</i>	<i>Trichomonas</i>
<i>Pasteurella multocida</i>	Acanthocephalans
<i>Campylobacter</i> sp.	<i>Strongyloides</i>
<i>Leptospira</i> sp.	<i>Entamoeba histolytica</i>
<i>Streptococcus pyogenes</i>	Hemoprotozoa
<u>Viruses</u>	
Lymphocytic choriomeningitis virus	
<i>Herpes tamarinus</i>	
<i>Herpesvirus saimiri</i>	
Rhesus monkeys	
<u>Bacteria</u>	<u>Viruses</u>
<i>Mycobacterium tuberculosis</i>	<i>Herpesvirus simiae</i>
<i>Shigella</i> sp.	Yaba
<i>Salmonella</i> sp.	Yaba-like viruses
<i>Pasteurella multocida</i>	(OrTeCu, BEMP, Tanapox)
<i>Yersinia pseudotuberculosis</i>	Monkey pox
<i>Yersinia enterocolitica</i>	Measles (Rubeola)
<i>Streptococcus pyogenes</i>	Lymphocytic choriomeningitis virus
<i>Campylobacter</i> sp.	Rabies
<i>Leptospira</i> sp.	SAIDS (SRV-1, SRV-2)
HIV	
STLV III	
<u>Parasites</u>	<u>Fungi</u>
<i>Hymenolepis nana</i>	All dermatophytes
<i>Entamoeba histolytica</i>	
<i>Giardia intestinalis</i>	
<i>Giardia lamblia</i>	
<i>Balantidium coli</i>	
<i>Trichomonas hominis</i>	
<i>Ascaris</i> sp.	
<i>Strongyloides</i> sp.	
Acanthocephalans	

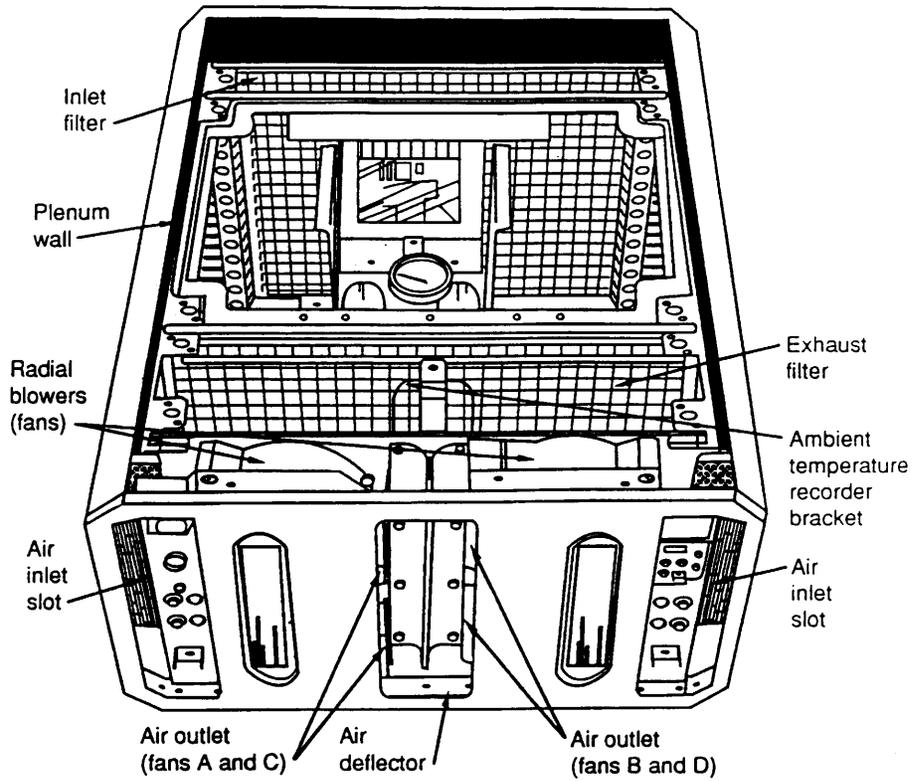


Fig. 4 The U.S. animal enclosure module.

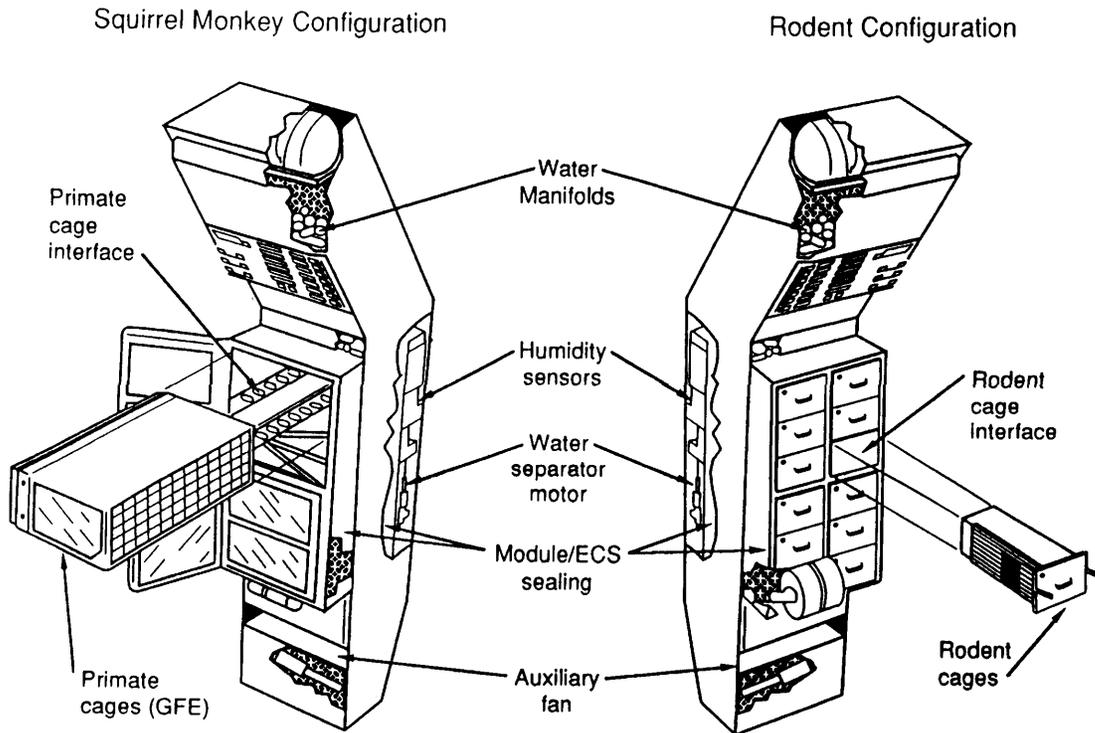


Fig. 5 The U.S. research animal holding facility.

Table 5 Techniques for near-real-time microbial monitoring

Direct detection of micro-organisms
Direct microscopy
Stains
Dyes
Fluorescent antibodies
Detection of microbial components and metabolites
Gas chromatography (GC)
GC/mass spectrometry
Pyrolysis
Raman spectrometry
Infrared/ultraviolet spectrometry
Photometry
Fluorometry
Polymerase chain reactions
Nucleic acid probes

Space Station have not been finalized, the level of bioisolation is expected to be similar to that exhibited by the RAHF.

H. Disinfection and Decontamination Procedures

Control of contamination during space flight has been of concern to NASA and the Soviet programs since the first manned missions. During the Gemini missions, crewmembers cleansed themselves with *Phisohex*, a topical disinfectant, before flight to reduce skin shedding in the spacecraft interior.⁵⁷ This practice was discontinued during the Apollo missions, and the spacecraft interior was decontaminated only if problems arose. The food preparation and waste collection areas, however, were cleaned routinely with a liquid disinfectant. Predictably, the Apollo environment was often contaminated with organisms such as *Staphylococcus aureus* and *Aspergillus fumigatus*.²⁵

Gross contamination of both spacecraft and crew was documented during Skylab 3.¹⁹ *Staphylococcus aureus* was isolated throughout the spacecraft and from all three crewmembers, and led to several skin infections. The possibility that *S. aureus* could have survived the interim between Skylab 3 and 4 prompted successful disinfection of the interior surfaces with the iodophor, BetadineTM, with the arrival of the Skylab 4 crew. Other incidences of contamination associated with Skylab included the inadvertent release of *Serratia marcescens* into the orbital workshop compartment, after which this micro-organism was isolated from the air and crewmembers. BetadineTM was used again for disinfection.

With the advent of the Space Shuttle Program, the reuse of space vehicles for multiple missions introduced another set of concerns. Not only was contamination possible during missions, but there was also potential for microbial carryover and contamination during refurbishment. In response to concerns about this issue, maintenance of clean rooms for vehicular assembly, regular use of iodine and other disinfectants,

and routine sampling have all been instituted to maintain a clean living and work environment. Despite these precautions, numerous potential pathogens have been isolated from flight hardware and the cabin atmosphere. The waste management area is disinfected during Shuttle flights with a mixture of denatured ethanol (10 percent), LysolTM liquid (5 percent), PalmoliveTM soap (1.5 percent), and distilled water (83 percent). Routine cleaning is performed with disposable wet wipes containing benzalkonium chloride.

Water systems, particularly those supplying potable water, present special disinfection problems. A further discussion of water systems of the U.S. space program is presented elsewhere in this volume. Iodine is used to disinfect water aboard the U.S. Space Shuttle; it has also been proposed as a water and surface disinfectant for Space Station. The disadvantages of iodine include its corrosiveness and its propensity to stain surfaces. The use of iodine in the Shuttle water system has already demonstrated the propagation of iodine-resistant bacteria;^{58,59} these resistant forms could eventually prove catastrophic to a space station's life support system. Moreover, the toxicological effects of iodine and its organic complexes are not understood completely.

Living in space, whether on spacecraft or on planetary bases, requires an environmental control system that provides safe air and water for crew consumption. Although sterility is not a realistic goal, microbial contamination must not be allowed to reach unsafe levels. Careful selection of structural materials to be used in spacecraft is a first step. Russian engineers have attempted to solve this problem by searching for ways to make surfaces water-repellant and seeking methods of incorporating antiadhesive and biocidal properties in construction materials. During flight, filtration of the air, purification of the water before reuse, good housekeeping practices, and environmental designs that do not allow accumulation of dirt or water will probably be effective in maintaining microbial contamination within safe limits. The possibility of occasional spills or leakage of biological materials (e.g., food, feces, urine, or vomitus), however, requires the capability for decontamination; i.e., the removal of pathogenic micro-organisms from the spacecraft.

The choice and application of a disinfectant or biocide depend on many factors, including the physical, chemical and biological characteristics of the environment to be treated. The ideal biocide would be simple to use, registered with an appropriate regulatory agency (such as the Environmental Protection Agency), and well documented as to its safety and efficacy. It should not cause deterioration of materials. It should be soluble, stable, and have "wetting action." It should not have significant human health effects (i.e., it should be nontoxic, nonallergenic, should not cause cancer or birth defects, and should not irritate skin or mucous membranes). In addition, it should not have a noxious odor; it should act rapidly at low concentrations in the presence of organic debris; and it should have residual biocidal activity. Unfortunately, no biocide exists that meets all these criteria.⁶⁰

The closed nature of the spacecraft environment dictates

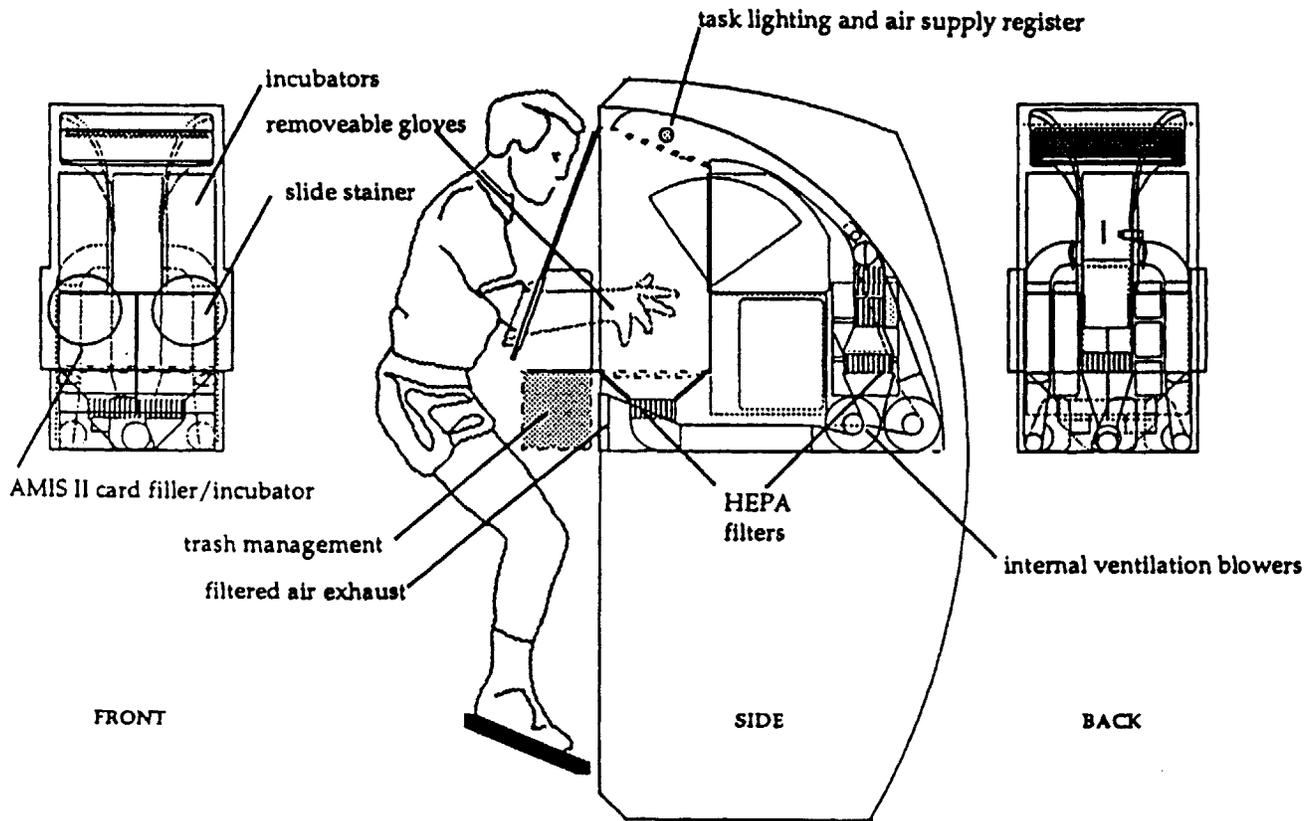


Fig. 6 An artist's conception of the bioisolation facility planned for Space Station.

that chemical germicides be used only in situations where physical methods (heat and ultraviolet light) are impractical and when microbiological hazards outweigh toxicological concerns. A nontoxic detergent, such as hydrogen peroxide, could be used for prophylactic treatment, routine disinfection, and microbial control. In addition, a more potent disinfectant should be available to counteract microbial spills from biological experiments, food, or biological wastes; glutaraldehyde is an example of such an agent. Biological control measures, such as the use of secondary microbial metabolites or antibiotics, may also hold promise for long-term space habitation.

VI. Microbiology Facilities for the U.S. Space Station

The Space Station microbiology subsystem is being designed to detect, collect, identify, and archive micro-organisms isolated from the crew and environment (air, water, and surfaces). In conjunction with the Health Maintenance Facility (HMF), the microbiology subsystem also identifies micro-organisms from clinical specimens and provides information on their antibiotic sensitivity.⁵² All sample processing, culturing, and maintenance will take place in bioisolation facilities to reduce the possibility of cross-contamination between crew and biological specimens.

A microbiology safety cabinet will serve as the principal bioisolation facility. The exposure of crewmembers to con-

taminants will be minimized by the inward flow of cabin air, high-efficiency filtration, vertical laminar air flow, and an access compartment fitted with ultraviolet lights for decontamination. This device will meet Class II requirements for biological containment cabinets, as defined by the National Sanitation Foundation.⁶¹ All microbiological equipment will be located close to the cabinet; some devices, such as the slide-staining apparatus, incubators, and the automated microbial system, will be operated within the bioisolation work space (Fig. 6).

Clinical and environmental isolates will be identified using an automated system being designed in collaboration with BioMérieux Vitek Systems, Inc. This device, which is being tested on the U.S. Space Shuttle, consists of a filler module and a reader/incubator module that are capable of identifying a wide array of bacteria and yeasts from environmental and clinical sources, as well as determining their susceptibility to antimicrobial agents. A detailed description of this device has been presented elsewhere.⁶²

A specialized slide staining apparatus has also been designed for use in microgravity.⁶³ This self-contained, compact manual unit requires no spacecraft power and uses a minimal amount of reagents and stains. This device may be used to test micro-organisms, as well as blood smears, sputum, and other clinical specimens.

A combined bright field-phase contrast-fluorescent microscope will be used to examine stained slides, microbial fil-

ters, wet mounts, and other specimens. Video and 35-mm images can be downlinked by telemetry to investigators at the NASA Johnson Space Center for consultation. Similar systems are already in use at other specialized facilities.^{64,65} Once the specimen has been prepared for microscopic examination by the crew, image telemetry and image analysis by the ground-based microbiology laboratory can expedite the analysis of a wide variety of samples and organisms. A system capable of archiving microbiological samples and specimens collected from the Space Station's air, water, food, surfaces, and clinical sources will be provided onboard. It is expected that some analyses will require the extensive analytical capabilities of sophisticated microbiological facilities on Earth.

VII. Conclusion

Meeting the challenges of future space exploration (including Space Station missions, a lunar base, and Mars exploration) will require increased knowledge of the interactions of micro-organisms with their human hosts. The effects of the space environment on microbial properties, such as virulence, antibiotic susceptibility, genetic stability, and population dynamics, are not well understood. Perhaps equally important is the need to determine the effect of space flight on the human immune system. Clinically significant decrements in the immune system during long stays in space could prove catastrophic to space crews and to the success of their missions.

In addition to being etiological agents of infectious diseases, micro-organisms are important sources of biodegradation. This property may prove detrimental to the integrity of the spacecraft or a Mars or lunar outpost. For example, microbial degradation of materials in airlock seals or extravehicular space suits may seriously compromise the safety of the pressurized closed environment.

Ensuring habitability of the space environment over long periods of time will require sophisticated monitoring equipment and technologies. Technologies must be developed to rapidly and reliably detect important contaminants such as *Legionella*. Rapid detection is essential to allow immediate containment and disinfection. In addition to environmental monitoring, diagnostic capabilities that detect and identify clinically important pathogens directly from clinical specimens are essential. All monitoring equipment and diagnostic technologies must meet the obvious requirements, such as minimal weight, volume, and power consumption; but equipment for long-duration missions must be vastly improved in the areas of reliability and maintainability. In addition, intense competition for crew time during flight dictates that equipment be automated whenever possible.

Although micro-organisms may pose obstacles to long stays in space because of their ability to cause illnesses and biodegrade foodstuffs and critical materials, the microbial world may prove invaluable in other ways. For example, the management of trash and biological waste products is an im-

mense logistical problem for long stays in space and one in which microbes may play a key role in bioremediation. Microbes may also play key roles in processes associated with regenerative life support systems, food production, water purification, and removal of airborne chemical contaminants. Given the ubiquity of micro-organisms, space exploration will ultimately benefit from an understanding of the host-microbe relationship in space, which allows us to exploit microbial functions to our advantage while minimizing their potential detriment to human health.

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