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SPACE STATION WATER QUALITY

CONFERENCE REPORT

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Special thanks to Richard J. Bull, Ph.D., College of Pharmacy, Washington State University, Pullman, WA 99164-6510. Dr. Bull served as co-chairman for the workshop, collected the various inputs of the panel members, and integrated the inputs into this report.

Charles E. Willis, Ph.D.
Editor

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SECTION 1

INTRODUCTION

The manned Space Station will exist as an isolated system for periods of up to 90 days. During this period, safe drinking water and breathable air must be provided for an eight-member crew. Because of the large mass involved, it is not practical to consider supplying the Space Station with water from Earth. Therefore, it is necessary to depend upon recycled water to meet both the human and nonhuman water needs on the station. Sources of water that will be recycled include hygiene water, urine, and cabin humidity condensate. A certain amount of fresh water can be produced by CO_2 reduction processes. Additional fresh water will be introduced into the total pool by way of food, because of the free water contained in food and the water liberated by metabolic oxidation of the food.

1.1 OBJECTIVES OF THE WATER QUALITY REQUIREMENTS WORKSHOP

An interdisciplinary panel of scientists and engineers with extensive experience in the various aspects of wastewater reuse was assembled for a two-day workshop at Johnson Space Center in Houston, July 1-2, 1986. The panel included individuals with expertise in toxicology, chemistry, microbiology, and sanitary engineering. The objectives of the workshop follow:

1. Solicit outside expert advice on specific medical requirements for potable water, reclaimed for direct reuse from wastewater and recycled.
2. Educate major national water quality experts about the special problems of spaceflight, the rationale for previous and planned spacecraft water standards, and planned direct reuse of water for the Space Station to include potable water system design.
3. Establish relationships with environmental engineering, toxicology, and other appropriate academic departments, who will be potential sources of research collaborators and technical support.
4. Establish liaison with potential contractors involved in water quality research and development.
5. Compile a written document to be used as a point of departure for future studies in water quality.
6. Define research requirements associated with closed-loop recycling of potable water to determine

    a. water quality constituent requirements (limits),

    b. monitoring requirements and constituent analysis,

c. disinfection requirements and interactions, and

d. verification requirements (validation/certification that reclaimed water produced by the recycle system is potable).

1.2 OVERVIEW OF THE CONFERENCE

A review of the status of Space Station water reclamation systems was provided by NASA and contractual personnel associated with particular processes. Unit processes that are being considered for use on the Space Station were described for the benefit of the panel. Some of these processes had already been subjected to preliminary evaluations. Although each process has a potential place within treatment trains proposed for each source of water for recycling, there has been no systematic testing of alternative treatment trains. The data on preliminary unit process evaluations were included in a briefing document prepared by NASA, which will be referred to in this report.

A description of some of the physiological effects of spaceflight was also provided. Certain parameters indicate that astronauts are subjected to some level of stress that continues beyond the early phases of the Space Adaptation Syndrome (SAS), which occurs within the first 48 hours of flight. Thus, synergism between exposures to potentially toxic chemicals in the atmosphere and the water system of the Space Station, and altered physiological states experienced inflight should receive considerable attention in immediate and long-term health effects studies.

A particular concern is the inability to project the types of experiments and manufacturing activities that might be conducted on the Space Station. The panel strongly suggested that no material should be introduced into the Space Station without establishing the following information: (1) the toxicological properties of the material, (2) the behavior of the material in the water and air revitalization systems, and (3) any emergency procedures related to the material that can and should be followed to prevent jeopardizing the health of the crew. A review process should be established to ensure the availability of this information before new chemicals are introduced into the Space Station. The panel felt that if the water treatment system has undergone appropriate development and testing, exposures to either chemical or microbial agents in the cabin air will be of the most concern. This would certainly be the case in the event of an emergency, but is likely to be the general case as well.

The water treatment and distribution systems on the Space Station must be viewed as *sources* of potentially hazardous chemicals as well as mechanisms for limiting exposure to unwanted contaminants. Consequently, the assessment of relative health hazards that might be associated with the water system on the Space Station is a complex issue. Because of the peculiar needs of the Space Station, some of the unit processes and associated chemicals proposed for use represent significant departures from usual water treatment methodology. It was noted that the treatment train(s) most likely to be useful in the Space Station have yet to be identified. As a result, the data supporting definition and characterization of the product stream are derived from only preliminary analyses of representative unit processes. Different combinations of unit processes will considerably alter the product water. For these reasons and others cited below, *it is exceedingly important that the most likely treatment trains be decided upon as quickly as possible*. This will facilitate characterization of the output of each of these treatment trains from the waters for which they are intended in ground-based testing. Data from these tests will serve to define those chemicals for which health-related standards must be developed and those operational parameters that are necessary to confirm that the treatment train is operating correctly in space.

Therefore, the first recommendation of the panel is to characterize the interactions between different unit processes and the effects they have on the output of the most likely treatment trains. Without this information, it is impossible to develop appropriate health-related criteria for the systems. This recommendation will be expanded upon in subsequent sections of this report to define the information required to develop the most desirable system. This system should include the use of redundant and backup treatment systems (e.g., use of multiple disinfectants), and its reliability should be established by extensive testing.

This report will tend to focus on those areas in which research and development efforts are needed, although the panel strongly believes that an effective water treatment system *can* be developed for the Space Station. This invariably creates a negative impression that is in this case not warranted. A substantial amount of good and critical development work was evident in the presentations made at the workshop. Without these pioneering efforts, it would be impossible to determine the direction for further development. The underlying conclusion of this report is that it is now time to begin to integrate the multidisciplinary efforts that will be needed to arrive at a final water treatment system.

SECTION 2

CONFERENCE AGENDA

SPACE STATION WATER QUALITY CONFERENCE
HILTON-NASSAU BAY

Sponsored By:
NASA/JOHNSON SPACE CENTER
HOUSTON, TX
JULY 1-2, 1986

Time	Remarks	Speaker
June 30		
7:00 p.m.	Reception, Parlor Room, Hilton Nassau Bay	
July 1		
8:30 a.m.	Hilton Ballroom: Introduction	N.M. Cintron
	Welcome	J.P. Kerwin S.L. Pool
9:00	Space Station Overview	J. Queller
9:30	ECLSS Baseline Design	R. Humphries
10:00	Water Reclamation and Management Baseline Design	B. Bagdigian
10:30	Physiological Effects of Space Flight	P.C. Johnson
11:00	Wastewater Contaminant Database	C. Verostko
11:30	Lunch at Hilton	
12:30 p.m.	Panel Responsibilities	R. Bull
12:45	Microbial Contamination	Panel
1:30	Microbial Criteria	Panel
2:15	Break	
2:30	Chemical Contamination	Panel
3:30	Chemical Criteria	Panel
4:30	Summation	R. Bull
5:00	Adjourn	
6:30	Social Hour at Hilton	
7:30	Banquet	
8:30	After Dinner Speaker	M. Cleave
July 2		
8:30 a.m	Opening Remarks	R. Bull
9:00	Engineering Considerations	Panel
10:30	Break	
10:45	Manned Chamber Test	Panel
11:30	Lunch at Hilton	
12:30 p.m.	Monitoring of Water Quality	Panel
2:00	Unresolved Issues	Panel
4:00	Summation	Panel
4:30	Adjourn	R. Bull

SECTION 3

SPACE STATION WATER QUALITY CONFERENCE PANEL MEMBERS

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SECTION 4

ISSUES AND RECOMMENDATIONS

4.1 HEALTH EFFECTS OF CONCERN

4.1.1 Microbiological Diseases

A wide variety of frank and opportunistic pathogens and nonpathogens may be present in the Space Station environment and wastewater because recycling couples the air and water systems. These microorganisms may be introduced into the environment during Space Station materials fabrication, construction and installation, pre-deployment testing and storage, and by Space Station habitation. Space Station personnel will harbor and carry aloft a wide variety of microbes as normal flora (including nonpathogens and opportunistic pathogens), as well as latent subclinical infections by frank pathogens. Quarantine measures and preflight clinical testing will identify and make possible the elimination of some microbes harbored by Space Station personnel; however, most microbes will not be readily eliminated by these measures.

Some of the more important viruses that are likely to be present are those that cause latent or chronic infections in humans, such as some enteric and respiratory viruses (e.g., adenoviruses), herpes viruses (herpes simplex, varicella-zoster, Epstein-Barr virus, and cytomegalovirus), hepatitis B virus and non-A, non-B hepatitis virus, papillomaviruses (human wart viruses), polyomaviruses (BK and JC viruses), and other microorganisms. Many of these viruses that cause latent or mild chronic infections can be reactivated or amplified to symptomatic infections by immunosuppression. Immunosuppression may be a problem in the Space Station due to prolonged radiation exposure or zero gravity.

In terms of the Space Station water supply system, the most important of these viruses are non-enveloped (adenoviruses, papillomaviruses, and polyomaviruses), because they are more resistant to adverse environmental conditions than the enveloped viruses.

The microbiological literature, including that concerning infectious disease, should be reviewed to construct a list of organisms that could be present (it is beyond the scope of this document to provide a complete list).

4.1.2 Chemically Induced Diseases

The nature of adverse health effects arising from chemical exposures is quite diverse. The most important distinctions to be made are between those effects that are direct, immediate threats to life (acute toxicity or infectious disease), those effects that can indirectly threaten life (produce decrements in performance of activities essential to protecting human life and limb), and those effects that result in greater risks of developing chronic disease (e.g., increased risk of cardiovascular disease, cancer, or cumulative poisoning such as might be encountered with mercury or lead). Whatever the actual health goals are in establishing the standards, it is essential to understand the shorter-term effects of chemicals to deal realistically with emergency situations that may be encountered during the course of a mission. Concerns about chronic health effects usually dictate public policy for setting municipal water standards and should form the basis of guidelines for Space Station inhabitants. However, it should be recognized that the limited duration of exposure and the relatively uniform and small population exposed should narrow the uncertainty involved in risk estimation. For some substances (e.g., carcinogens), a considerably higher exposure level would be necessary during a 90-day mission to place astronauts at the same level of lifetime risk generally accepted for the general public. Purely from a mathematical point of view, shorter-term health effects will acquire greater visibility in the Space Station than on Earth because of the limited duration of the mission.

To gain appreciation of the minimum data base needed to deal effectively with the divergent effects of chemicals on man, it is highly recommended that NASA review the process used to develop Health Advisories by the Office of Drinking Water of the U.S. Environmental Protection Agency. These explicit documents specify the information upon which guidance values are based, including risk for varying periods of exposure, the safety or uncertainty factors that are involved in arriving at a recommended level, and the adequacy of the data base that is available. This detailed information can greatly speed decision-making under emergency situations. *The panel strongly recommends that NASA develop a similar process or work with EPA to use capabilities that are currently in place.* (EPA has alre~dy provided a group of 50 such advisories to NASA since the Conference, and more are under development.)

Effect of Altered Physiology in Space on Response to Chemicals and Microbes

During a mission, astronauts have elevated levels in ADH, aldosterone, cortisol, epinephrine, and norepinephrine in their urine, indicating some degree of stress. Their bodies experience a negative calcium balance and a tendency for a decrease in red cell mass. In addition, there is some evidence of altered immune function (primarily decreased T-helper cell function). From the briefing provided by Dr. Johnson, it appears that these changes persist beyond the acute nausea and vomiting that are associated with the initial Space Adaptation Syndrome (SAS). It is entirely possible that these altered states could make the astronauts more susceptible to the toxic effects of chemicals present in the atmosphere or drinking water of the Space Station. Changes in pressure associated with extravehicular activity (EVA) could predispose astronauts to middle ear infections. Synergy between chemical and microbiological exposures and higher doses of radiation experienced in space should be considered. Three examples of the potential for such interactions are described below. This discussion simply illustrates the types of concerns that should be pursued experimentally.

It was stated that cardiac arryhthmias are commonly associated with the intense physical exertion during EVA. Coupled with this was the observation that an "intense solvent odor" was associated with the space suits following an EVA. The source of this solvent odor was not established (could be baked out of the suit by the heating that occurs during EVA). With this background, NASA should be aware that halogenated hydrocarbons, and to some extent other solvents, have the capability of sensitizing the myocardium to arrhythmia. This type of interaction has been observed in man and experimental animals. In the latter case, the effect is most easily seen as a sensitization of the myocardium to catecholamine-induced arrythmias. It appears that astronauts have elevated catecholamine levels in their "basal" state, a condition likely to be exacerbated under the conditions associated with EVA. Consequently, a toxic effect that would not be seen in ordinary testing may well be produced in a stressed individual doing heavy exercise. Therefore, solvents used for cleaning on the Space Station should be carefully screened.

The decreased red cell count that accompanies spaceflight may also set up circumstances that would complicate an individual's response to hemolytic agents. At least two hemolytic agents were identified on the Space Station: iodine (I_2), for disinfecting drinking water, and chlorite, which is currently being used to disinfect the shower. The extent of the synergism with these agents would depend in part upon the mechanism by which the decreased red cell count was produced by spaceflight. If the decrease caused by spaceflight is merely an adaptation to a lower level of physical activity, the body may well retain the capability of responding fairly rapidly to oxidative and chemical stress. These types of questions could be easily investigated in experimental animals and confirmed in limited human studies.

Radiation at high doses is associated with an array of acute and chronic health effects. Assuming that the dose of radiation that each astronaut would receive over a 90-day mission would not approach the magnitude considered acutely dangerous, radiation effects that present a long-term hazard should be the primary concern. From a microbiological perspective, the chief concern would be the possibility of depressed immune function leading to more effective infection by a given exposure to a bacteria, parasite, or virus. Certain chemicals, however, share the biological activities of radiation. For example, some chemicals are capable of adversely affecting reproductive function, immune function, and increasing carcinogenic risk. Perhaps of most concern would be the possibility of synergistic activity such as that observed between initiators and promoters of cancer. Radiation is an effective initiator of cancer. Coupling a radiation dose not likely to produce cancer with effective doses of a chemical promoter could result in a substantially greater chance for developing cancer. Thyroid hyperplasia produced in susceptible individuals who consume iodine might be a "promoting" regimen for interaction with the cancer-initiating effects of radiation.

4.2 CONSIDERATIONS THAT IMPACT THE TREATMENT PROCESSES

The potential sources of water within the Space Station for human consumption and other uses include urine, cabin humidity condensate, CO_2 reduction (Sabatier water), and hygiene washwater. These sources may or may not be supplemented by fuel cell operation in the Space Station. This report assumes that only the first three sources above plus water introduced with food are the sources of water for reclamation. Table 4-1 outlines the treatment trains that constituted a baseline system for each of these wastewaters at the time of the Space Station Water Quality Conference.

TABLE 4-1. BASELINE TREATMENT SYSTEMS FOR SPACE STATION WATER REUSE

Source	Pretreatment	Treatment	Post-Treatment	Use
Urine	1. Oxone[a]	1. TIMES[b]	Multifiltration[c] & Iodine Disinfection	Hygiene & Possibly Potable
	Alternatives: 2. HDAB[d] 3. Iodophore 4. Metals	2. VCD[e] 3. Wick Evap[f]		
Humidity Condensate & CO_2-Red	Same as urine or none	None planned	Multifiltration & Iodine Disinfection	Potable
Hygiene Washwater	Same as urine or none	None planned, Alternative: Coagulation	Multifiltration & Iodine Disinfection	Hygiene

[a] A mixture of S_2O_8 and sulfuric acid, pH 2.5, DuPont and Co.
[b] Thermoelectric Integrated Membrane Evaporation System
[c] Mixed bed ion-exchange/granular-activated carbon
[d] Hexadecyltrimethylammonium bromide
[e] Vapor Compression Distillation
[f] Wick evaporation followed by recondensation

The performance of unit processes within these treatment trains has been evaluated to varying degrees, but testing thus far has not evaluated successive treatment processes or entire treatment trains. Consequently, interactions between the unit processes have received only cursory consideration. The panel repeatedly returned to this problem in its deliberations, because the nature of microbiological and chemical contaminants depends as much upon the treatment train as it does on the source waters. A ground-based study should be planned to test the reliability of the baseline systems. This recommendation is amplified by more specific comments throughout the body of this report.

4.2.1 Sources and Types of Microbial Contamination

Urine, Bathing, and Laundry Water

Some of the more prevalent bacterial and mycotic agents likely to be present in these waters have been identified in NASA studies, as indicated by Table 7 of the data base information. Urine produced in the bladder is normally aseptic, unless there is a urinary tract infection. However, voided urine usually contains a variety of microbes arising from mucosal and skin surfaces, including *Mycobacterium smegmatis*, diptheroids, nonhemolytic streptococci, *Staphylococcus epidermis*, lactobacilli, micrococci, ureaplasmas, and yeasts. Some of these microbes are opportunistic pathogens.

Bathing and laundry water is likely to contain a wide variety of microbes normally present on the skin, on mucosal surfaces, and in the upper respiratory and intestinal tracts. The list of these microbes is long and can be found elsewhere (e.g., Chapter 24, Joklik *et al.* 1984). Again, some of these microbes are opportunistic pathogens and, if they gain access to the appropriate host sites, frank pathogens.

Contamination of the Water System by Microorganisms Generally Found in the Environment

It is likely that a variety of environmental microorganisms will contaminate water systems in general. Therefore, the Space Station will probably have persistent problems with colonization by bacteria and perhaps other organisms. Water chemistry will determine the microbial populations that are present within the system. If bacteria behave in microgravity as they do on Earth, they will form biofilms and actively grow in and on all parts of the system. Some of the most likely contaminants of water systems on Earth have been described previously (Colwell *et al.* 1978; Committee on the Challenges to Modern Society [NATO]; Olson and Hanami 1980; Sobsey and Olson 1983). Some of these microbes are opportunistic pathogens.

Prediction of Most Likely Contaminants

A reasonable prediction can be made of the water contaminants that will be encountered in the Space Station based upon known contaminants of water systems on Earth. It is unlikely that Earthbound and Space Station water system contaminants will be identical because of the different history and treatment of the water. One potential difference from Earth that could influence microbial populations is the dissolved gas content of the spacecraft system. Under microgravity conditions, a typical air/water interface does not exist, hence, spacecraft fluid systems use sealed, positive expulsion storage and distribution systems. Space Station water will be much lower in dissolved gases, including oxygen. This may significantly influence the types of microbes that will persist in, grow in, or colonize the Space Station water system. It will also affect the performance of certain treatment processes. For example, granular activated carbon is likely to perform differently under anaerobic conditions than has been experienced with aerobic systems on Earth.

4.2.2 Microbial Contaminants and Water System Design

It is highly probable that water systems aboard the Space Station will become contaminated, regardless of the design option chosen. This will cause deterioration of the materials within the system, compromise the system's operation and pose potential health hazards to the crew. Because the crew cannot survive without water of acceptable quality, such conditions would jeopardize the success of the mission. For these reasons, each candidate unit process (especially those designed to remove or destroy microbes) should be carefully evaluated for its ability to remove or destroy specific, candidate microorganisms representative of those likely to be found in the Space Station environment. The microorganisms chosen for testing should include

1. one or more representative of each class of microorganism of concern, that is, viruses, bacteria, molds, yeasts, and protozoans;
2. organisms likely to be present in raw water sources to be treated;
3. organisms in the above groups that have a high survival potential or high resistance to removal or destruction; and
4. organisms that have a high potential to colonize the water treatment system.

Microbiological testing of each unit process should be conducted by adding known amounts of specific test microbes to the test water. The test water should also contain the typical microbial community likely to be present in the water prior to treatment by the unit process being evaluated. Indigenous levels of some test microbes in the test water may suffice without further addition of these test microbes as long as their concentrations are documented before as well as after the unit processes.

A variety of alternative disinfection processes must be considered and carefully tested. There are at least three reasons why disinfection is needed in a water system. Application of a disinfectant close to the source of the water to be reclaimed decreases the likelihood that frank pathogens will enter and colonize the water system. Disinfectants control growth of both pathogenic and nonpathogenic organisms that might survive the initial application or enter and colonize the water system in subsequent stages, compromising the performance of the overall system. Finally, a barrier at the point of water use provided by a residual concentration of disinfectant in the finished water reservoir increases the reliability of the overall system. To meet all three objectives, a minimum of two disinfectant applications is usually required. The most desirable combination is a strong killing disinfectant applied early in the treatment train and the addition of a chemical that will provide a stable residual concentration to control outgrowth through the system and at the point of use.

Presently, Oxone or a quaternary ammonium compound (HDAB) for pretreatment and iodine as a post-treatment are being considered. Although these are acceptable disinfection processes, their performance characteristics and reliability must be established. In addition, alternative disinfection processes should be considered now, in case the baseline processes are found unsuitable. Any disinfectant that has some chance of being present in the final product water needs to be very carefully characterized toxicologically. For example, the panel is not aware whether HDAB has been evaluated for systemic toxicity or how it might compare to other equally effective quaternary ammonium compounds. Other disinfection processes worthy of consideration are ultraviolet light, halogenated resins, ozone, chlorine, and chlorine dioxide. If volatile agents are used, the possibility that they might enter the cabin atmosphere as an inadvertent emission or through accidental spillage must also be considered.

Based upon the above considerations, the Committee strongly recommends that the treatment and disinfection systems employ multiple barriers for reliability. Refrigeration of holding tanks is an additional way that microbial growth within the system could be controlled, because it is probable that significant levels of assimilable carbon will remain in the treated water. Reduced temperatures would thus extend the useful life of the product water.

Design of the Space Station water systems must also incorporate the following:

1. The system must be designed to allow cleaning in place using both physical and chemical means. This is particularly critical considering the lengthy design life (greater than 20 years) planned for the system.

2. Provisions must be made for replacement of components that would be subject to microbial plugging (e.g., various stages of the multifilter system), as well as scheduled or unscheduled replacement as a result of wear.

4.2.3 Sources and Types of Chemical Contamination

Urine, Bathing, and Laundry Water

Urine contains a wide variety of chemical constituents at varying concentrations depending upon the state of hydration of the individual, the presence or absence of disease states, and different physiological states. The bulk of these materials have a low order of biological activity (e.g., urea and NaCl) and should be easily removed by treatment systems that involve a phase change within the treatment system (for purposes of this document the collection of cabin humidity condensate is not considered a treatment process). It was the opinion of the panel that of more acute concern are compounds of high biological activity present at much lower concentrations. The most obvious examples of such chemicals are the trace levels of various hormones and their metabolites that are excreted in the urine. It is entirely possible that such chemicals are easily handled by the water treatment systems. However, if they were to accumulate in the Space Station water system, they might present serious threats to the crew's health. It is beyond the scope of this document to review in detail the biochemicals that might be of potential concern in urine. However, an appreciation for their diversity can be gained from Altman and Dittmer (1974).

The panel expressed similar concerns about drugs or metabolites of drugs that are utilized routinely by crewmembers on the Space Station. The eventual dose of such agents would depend upon the frequency of use, the total volume of the water system, its turnover rate, and the extent to which the material is removed from the system by treatment or wastage. Drugs would have to be taken at some minimum frequency before the exposure to crewmembers through the water system would approach a therapeutic dose. It may be assumed that most drugs would not present an unacceptable risk to health until they begin to approach therapeutic doses. Cardiac glycosides, hormones, and certain antibiotics are examples of drugs that would be exceptions to this statement. Drugs that would elicit high likelihood of hypersensitivity reactions would also fall under this category. The minimum frequency required to reach a therapeutic dose could be calculated assuming 100% retention in the water system.

As elaborated in the next section, chemicals (particularly organic chemicals) present in a wastewater stream have to be considered as substrates within the unit processes of the treatment system. Some processes actually change the chemical nature of the organics that are in the water (e.g., oxidation processes, disinfection). If the unit process depends strictly on physical separation of the chemical from the water (adsorption, phase change) the formation of by-products presents little difficulty, assuming efficient and consistent operation. If these processes do not efficiently remove organics or actually increase organic content of the water (e.g., the cabin condensate), they can provide substrates for reaction in subsequent processes. The production of by-products has toxicological implications that must be studied. By-products of disinfectants are the most familiar problem of this kind in drinking water systems. Another example found in the baseline treatment scheme (Table 4-1) for urine is the Oxone pretreatment process. The nature of by-products that arise in this process has received little attention and must be carefully studied. Bacterial colonization of a treatment system can also change the nature of the organic chemicals that are found in the finished water.

Synthetic Chemicals Present in Cabin Condensate

It was apparent in discussions at the Workshop that the cabin condensate of the Space Station had been considered a primary source of potable water. Representative analytical data on comparable source water and observations of the high levels of suspended particulate matter present in Shuttle atmospheres suggest that the quality of spacecraft condensate water may be less than anticipated. In addition, the panel noted that the cabin condensate is the source of water that is most subject to a variable input since it is the primary means by which chemicals present in the cabin atmosphere would be introduced into the water system. Chemicals from outgassing of the materials of construction within the Space Station, material produced by the abrasion of surfaces, and by-products of general human activity (exhaled air, epidermal cells, hair, dandruff, etc.) would provide a background of contamination in the cabin condensate. It is important to realize that the phase change "condensate" is not a means of cleaning this water, but rather a means of contamination. Materials that are used intermittently would superimpose a second, somewhat more variable contamination on this background. Least predictable would be contamination of the cabin atmosphere by biological experiments, spills of chemicals used in experimentation, and synthetic projects conducted in the Space Station. Without prior testing, it will be difficult to predict how effective the treatment train will respond to an unanticipated chemical input to this waste stream. From a toxicological point of view, the cabin condensate must be considered a vulnerable source of water.

Although there are difficulties associated with using the cabin condensate, filtration of the air before the condensate is formed or additional purification steps could make this an acceptable source of water. However, it will probably be the most difficult water to characterize.

Chemicals Leached from the Storage and Distribution Systems

Water will gradually leach material from almost any surface with which it comes into contact. Chemicals that may be introduced into the water system through contact with plastics include monomers, stabilizers, stabilizer reaction products, lubricants, plasticizers and other chemicals used in the manufacture of these materials. Some of these chemicals are quite toxic or carcinogenic if the dose is sufficiently high. If metallic (e.g., stainless steel, aluminum, solder) surfaces are present, various trace metals will appear in the water at a rate that is dependent upon the corrosivity of the water. Therefore, Pb-free solder should be used in Space Station plumbing. Such chemicals have been introduced into terrestrial water systems, sometimes at dangerous concentrations. Recycling Space Station water exacerbates the problem because the water may be in repeated or even continuous contact with a surface which may allow accumulation of chemicals within the system for a decade or more. Therefore, the materials used in construction of holding tanks, piping, and other surfaces that water will contact (e.g., condensers) should be carefully scrutinized for the type and extent of contamination they would introduce into the water over the life of the Space Station. If a product must be used that has the potential for introducing significant quantities of a toxic chemical into the water system, then it is essential to verify that the treatment train reliably removes the chemical to prevent its accumulation above hazardous levels.

Contribution of Treatment Processes

Treatment processes must be thoroughly examined to determine their impact on the final water quality in a recycling system. In particular, one must consider how unit processes interact with one another. When applied in municipal water supplies, chemicals used in treatment processes can be dissipated by a number of natural processes before the wastewater is reused as source water for another potable water treatment system. In the Space Station, by-products of such processes might remain and accumulate in the system. Consequently, it will be important to select pretreatments that produce chemical by-products that are amenable to removal by subsequent unit processes. For example, a pretreatment process (e.g., Oxone) may produce lower molecular weight polar organic compounds that might be effectively removed by a phase change process applied to one waste stream, but application of the same pretreatment process in another treatment train may reduce the overall effectiveness of organic removal if a subsequent unit process (e.g., activated carbon) adsorbs only neutral and nonpolar compounds.

The ultimate fate of chemicals used in water treatment processes must be considered. The use of HDAB as a pretreatment provides an example of a treatment chemical that might well be safe at normal levels of use. However, if HDAB were introduced into a waste stream that did not have a treatment process for effective removal of polar organics and its concentration was not monitored, resulting in more HDAB being added with each recovery cycle, it could accumulate to a dangerous concentration. In addition to the fate of the cation of this product, consideration must be given to ensuring that the bromide counterion does not accumulate to levels that might produce bromism in the crew.

Another potential problem was identified in terms of the operation of the Space Station shower. A bacteriostatic solution containing chlorine dioxide or chlorite was used during developmental testing (the actual form was difficult to determine). If this process leads to significant accumulations of chlorite in the potable water system, the crew will incur a risk for developing hemolytic anemia. Chlorine dioxide has also been found to interfere with normal thyroid function (Bercz *et al.* 1982; Orme *et al.* 1985). As mentioned earlier, this could be one toxicity problem to which individuals in space may be more sensitive because of the historical tendency of space crews to develop reduced hematocrits.

Disinfectants

This class of chemicals is essentially a special case of #4. However, it is now widely recognized as a treatment process that produces a variety of potentially toxic by-products in municipal water supplies and deserves special attention. More recently, it has become apparent that some of these by-products are produced within the gastrointestinal tract if water containing residual disinfectant is ingested. As clearly indicated in previous sections, reliable disinfection processes are absolutely essential to the maintenance of a safe water supply on the Space Station. Adequate disinfection should never be compromised for trace chemical control. Nevertheless, it is important for NASA to be aware that toxicological hazards can arise with the use of particular disinfectants. Different disinfectant practices cannot be considered as being equivalent from a toxicological point of view (Bull and McCabe 1985).

Direct Toxicity. Disinfectants are usually reactive chemicals and, as such, are unlikely to accumulate within the water system. Nevertheless, it should be recognized that the use of different disinfectants carries different degrees of toxicological hazard in qualitative as well as quantitative terms. Use of disinfectants will be a particular problem if it becomes necessary to use a nonconventional disinfectant at high concentrations or repeatedly. Iodine or compounds that release iodine have been used in Shuttle missions, however, physiological effects of inflight iodine ingestion have not been studied. Iodine is not widely accepted as a routinely applied disinfectant in municipal water supplies because of the possibility of producing congenital goiter and for economic considerations. There are also subpopulations that become easily sensitized to iodine. Unfortunately, virtually all of the information concerning the use of iodine as a disinfectant depends upon studies of iodide or iodate. These are not the forms that are active as disinfectants or bacteriostats. No toxicological studies exist that evaluate hazards that might be associated with repeated exposure to the forms of iodine that are active as disinfectants. Another option might be to remove residual iodine at the point of use. However, the lack of appropriate data prevents recommendation of an acceptable level, and complete removal may result in microbial contamination of the system used for removal. For further details on the toxicology of iodine, the reader is referred to the literature review on iodine toxicology produced for NASA by Janik and Thorstenson (1986).

Indirect Toxicity. Iodine (I_2) introduced into water exists in the following forms:

$$\underset{\text{Biologically active (viruses)}}{HOI} + \underset{\text{Inactive}}{I^-} \longleftrightarrow \underset{\text{Active (cysts \& spores)}}{I_2} + OH^- \xleftrightarrow{+I^-} \underset{\text{Inactive}}{I_3^-}$$

Several of the above forms react with organic chemicals in the water to produce iodinated by-products. Both the effectiveness of iodine as a disinfectant and its ability to form organic by-products is dependent upon pH. Because iodine is infrequently used in municipal water supplies, the production of iodinated by-products in water has received very little study compared to chlorine. However, in domestic water supplies, chlorine can activate traces of iodide in the source water to form by-products such as iodoform (NAS 1980). Because of the many other advantages of using iodine within the Space Station environment, it is critical that further research is conducted in this area. With any disinfectant, its specific role (primary or residual) in the treatment train will affect the amount applied and the resultant concentration of residues and by-products.

In the course of the Conference, it was noted that iodinated water on Shuttle missions was not always palatable, perhaps reflecting some difficulties with the resin used in the water system. If drinking water is not palatable, it will discourage consumption, which, in turn, can adversely affect the health of the crew.

4.2.4 Chemical Contaminants and Water System Design

Within the Space Station environment, the air handling and water systems are not distinct. The most intimate link between the two systems is the recovery of cabin humidity condensate. Various uses of water within the cabin will result in volatilization into the cabin atmosphere. Therefore, any chemical with the appropriate physical/chemical properties that is introduced into the cabin atmosphere will end up in the water supply, and any chemical produced in or contaminating the water system will be found in the air. Detailed knowledge of the makeup of materials placed in the Space Station and the points of potential interaction between the air and water systems should allow determination of the likely concentrations in these two media by modeling of the overall system. It is recommended that NASA develop mathematical models that make use of the physical/chemical characteristics of unit processes included for treatment of these media in the Space Station. These models must be sensitive to the chemical and physical properties (e.g., water solubility, volatility) of individual contaminants and any possibility of aerosol formation that might occur during use of the water or servicing of the treatment system.

Design of the water treatment and distribution system for the Space Station must take into account that (1) unit processes within the system may be significant contributors to chemical hazards in the finished water, (2) the chemical processes that occur in unit processes will often influence the performance of a subsequent step, (3) waste water streams of predictable quality (e.g., urine) are more easily dealt with than those subject to variable or unknown inputs (e.g., cabin condensate), and (4) materials of construction in the water system that provide contact surfaces for water will contribute chemicals to the water system.

The chemical composition of influent vs. effluent of each unit process should be understood in some detail. Based on this knowledge, an integrated treatment system should be designed. Those chemicals that are not completely removed by the treatment system or are produced by a unit process within the system should be of highest priority for toxicological characterization. These chemicals should also be selected as monitoring parameters to characterize performance of the treatment system. Every effort should be made to characterize the products that result from processes that rely heavily on chemical reactions. It will probably not be possible to predict the occurrence of these chemicals by simply examining the composition of waste streams that serve as the water sources. The need to identify such compounds is twofold. First, they may produce unanticipated health effects. Secondly, they may not be effectively dealt with by the unit processes in the treatment system and therefore may accumulate in the treated water.

Critical examination of the source waters and the treatment processes applied to those waters intended for potable reuse is essential. The panel was uncomfortable with the focus on the cabin condensate as the primary source of drinking water and the degree of treatment to which it was to be subjected. Although they contain a relatively high concentration of chemicals, both urine and hygiene water are much more predictable waste streams. Properly treated, the cabin condensate may well result in perfectly adequate potable water; however, the reason it has received more attention as a potable source than the alternatives appears to be based upon social rather than scientific considerations.

The panel also strongly recommends that chemicals used experimentally or manufactured in the Space Station, which might be introduced into the water system, should be characterized for their behavior in the Space Station air and water treatment systems. Their toxicological properties should be identified before they are allowed on a mission. Assembly of such information beforehand is essential for developing emergency procedures to deal with spill situations that might be hazardous to the crewmembers' health. Taking into account the toxicological effects of these chemicals in advance could avoid aborting a mission or adversely affecting the lives of crewmember's for lack of appropriate information.

It would be very useful if the treatment system could be evaluated under microgravity conditions. While it is likely that the performance of treatment systems on the Space Station will be reasonably paralleled by similar systems on Earth, it is impossible to guarantee similarity in the absence of comparative data. Consequently, panel members believe it essential that the system be proven in microgravity before human lives depend upon it. The panel also recognizes the enormous costs that would be involved. However, it would greatly increase confidence in the life support systems, thereby justifying the expense. Perhaps this effort could be coupled with a Shuttle mission developed for other purposes.

Once a treatment system has been developed, it should be exhaustively tested for its reliability. The Denver Reuse Demonstration Plant was offered as one test site. Reliability testing should include at least two years of continuous operation of the system. If possible, this testing should also include pre-Space Station orbital flights to compare the system's performance on Earth with microgravity. The panel believes that the primary protection afforded to the crew will come from confidence that the system will take care of any problems for which it was designed. It is impractical to consider routine, comprehensive inflight monitoring of all potentially dangerous compounds that might appear in the water system. Therefore, the presence of any dangerous chemicals that would be routinely present in the Space Station in the treatment system must be identified and scheduled for monitoring well before launch. Other inflight monitoring must be directed toward measuring reliability of the treatment trains and selected to verify that the system is operating as it was designed. More sophisticated analyses of long-term trends should involve sampling with each crew change. These samples would be returned to Earth for analysis.

4.3 ESTABLISHING CRITERIA

For the purposes of this document, the panel views criteria as the experimental data that establish both the nature of the health effects of concern and the dose-response relationships between exposure to an agent and an adverse health effect. The purpose of developing criteria is to establish target levels of performance for a treatment system. The panel does not believe that the development of such criteria mandates continued monitoring of all agents for which criteria have been developed. Once it is established that a treatment process can produce water that meets these criteria, routine monitoring should be directed primarily at verifying system performance and reliability using appropriate surrogate parameters.

4.3.1 Microbiological Criteria

A standard of essential sterility has been established for the Space Station water system. It is very unlikely that the water system on the Space Station can be maintained sterile. Because it cannot be defended on the basis of what is known of the microbiology of water within virtually all treatment systems, the panel felt sterility to be inappropriate as a standard. Rather, it should be considered as a design goal. Water quality criteria should be developed from existing health effects information, and "set points" should be derived for appropriate measures that are more defensible as standards. Means of establishing microbiological criteria for each general class of microbial pollutant are considered below.

In defense of sterility as a criteria or standard, NASA personnel identified some operational difficulties that arise from a non-zero standard. In summary, decision makers apparently require (or desire) absolute decision criteria in terms of continuing a mission, taking emergency action, or attempting rescue. If a nonzero standard is used, a general microbiological screen must be supplemented with identification techniques to exclude the presence of pathogenic organisms before a health hazard can be ruled out. Otherwise, a clear-cut decision on consumption cannot be made. The panel recognized this difficulty, but felt that it was not justified in altering its position. It should be pointed out that integrated evaluation of appropriate surrogate and operational parameters should provide sufficient criteria for such decisions. For example, confirmation that disinfectant application and residuals have remained adequate in critical portions of the treatment system could allow dismissal of the results of a general microbiological assay. This decision would require a thorough understanding of the system that can only be obtained by thorough reliability testing and knowledge of how performance is reflected in surrogate parameter measurements.

Viruses

Within the Space Station, predominant viruses may vary as the missions change. Even in cases in which assay techniques are developed and available, it would be difficult to select a small and reasonable number of viruses that should be routinely monitored. Virus concentrations in treated water are usually too low to be detected by direct assay. Therefore, enteric and respiratory viruses and other human viral pathogens in water are typically detected only after concentrating them from large-volume samples and subjecting the concentrated samples to bioassay in mammalian cell cultures. This is a technically complicated, labor-intensive, and time-consuming process that is impractical to consider on the Space Station. Again, the most efficient way to address this problem is to prove out the system's ability to inactivate or remove viruses in preflight testing.

New techniques for rapid virus detection by nucleic acid hybridization and enzyme immunoassay are being developed, but they are not yet routine, nor can they currently detect low levels of viral contamination. Furthermore, these assays do not distinguish between infectious and non-infectious viruses or viral components. From a public health and medical standpoint, it is the infectious viruses that are critical and must be detected.

Bacteria

Criteria for bacteria levels currently proposed for Space Station water are inappropriate and must be reconsidered. This subject is more thoroughly discussed in the final section of this report.

Protozoans, Yeasts, and Molds

The protozoans of concern in domestic water are the enteric pathogens *Giardia lamblia*, *Entamoeba histolytica*, and *Cryptosporidium*, which, in cyst forms, are very persistent in water. If the treatment system is operating properly, these organisms should not appear in the product water. Appropriate preflight quarantine and clinical screening should be conducted to eliminate certain enteric protozoans (e.g., *Giardia*) from the personnel before a Space Station mission. Consequently, monitoring for this group of organisms in space is probably unnecessary. This is fortunate because the available methodology for their detection is cumbersome and inefficient.

Yeasts and molds will undoubtedly be present in the Space Station environment, including the water system. It is difficult to establish specific water quality criteria for yeasts and molds. Previous efforts have proposed the use of the yeast, *Candida albicans*, as an indicator of water quality because it is associated with the human skin, intestinal tract, oral cavity, and genitals. It is quite resistant to chlorine disinfection. This organism is an opportunistic pathogen, capable of causing systemic infections in a variety of organs. To date, no specific standards have been established for acceptable levels of *C. albicans* or other yeasts or molds in municipal water. Until the Space Station water system is subjected to rigorous preliminary testing, the requirement to monitor for *C. albicans* or other yeasts or molds cannot be established. If preliminary testing of the treatment system demonstrates efficient and reliable removal or inactivation of *C. albicans* and other yeasts and molds, there should be no need to monitor for them inflight. Alternatively, if such organisms persist in the treated waters, establishment of acceptable water quality standards for them may be necessary. It should be noted that a membrane filter method for viable counts is available for enumeration of *C. albicans* in water (Buck and Bubucis 1978), if inflight monitoring is deemed necessary.

Disinfection as a Barrier

Evidence of adequate disinfectant residual associated with some minimum contact time has been used to ensure microbiological safety in some circumstances on Earth. While it is important to monitor disinfectant residual concentration, there are some potential pitfalls in using this as the only monitoring method for microbiological water quality.

Possibility of Development of Resistance. For cellular microbes, such as bacteria, yeasts, molds, and protozoans, the potential exists for development of resistance to a disinfectant. This potential should be fully evaluated as soon as possible for all disinfection processes being considered for the Space Station water treatment system.

Minimum Contact Time after Disinfection. Iodine has to be present at a sufficient concentration for a minimum of time to render the water microbiologically safe. If difficulties with iodine are encountered from a toxicological perspective, it would be appropriate with respect to microbiological concerns to reduce the level of iodine after disinfection at the point of use. The disinfectant residual should only be removed at the point of use to prevent colonization and biofilm formation in the water system. Furthermore, even at the point of use, iodine should only be removed to the degree that a small iodine residual (e.g., 0.2 mg/L) remains in the water to prevent contamination of the dispenser.

4.3.2 Chemical Criteria

Chemical criteria can be developed only with a detailed knowledge of the chemicals that are present in or produced on the Space Station. As with microbiological agents, it will be impractical and unnecessary to routinely monitor all the chemicals that might be present. Consequently, it is important to establish how well and consistently the treatment system is able to remove chemicals from water. Those chemicals that are effectively and reliably removed require little further attention. Chemicals that do not fall into this category should be focused upon for the development of monitoring criteria. This will mean that toxicological data must be developed if it does not already exist. Particular attention must be paid to chemicals produced in the course of water treatment or increased in the water storage and distribution system as a result of solvation of surfaces that contact the water. Consequently, the main steps involved in developing chemical criteria are as follows:

1. identify those chemicals that have been used in the construction of the Space Station and its components, those chemicals that are to be deliberately brought on board, and those chemicals that will be produced on board (intentionally or as by-products);

2. evaluate the likelihood that these chemicals would be introduced into one of the wastewater streams or be produced in the treatment train;

3. establish the treatment train and alternative treatment trains, and determine how effectively they will deal with the contaminants identified above;

4. collect the toxicological information from the literature (if available) or conduct appropriate toxicological studies for those chemicals that are poorly or inconsistently removed by treatment;

5. establish criteria based upon the dose-response information that is available;

6. determine which health effects are considered unacceptable for crewmembers and at which levels the associated risks become unacceptable. Water quality criteria should then be derived from these two considerations. It may be desirable to identify two or more levels of risk. Candidate levels of risk are those that are immediately threatening to life, those that would seriously interfere with astronaut performance and thus constitute indirect threats to life, those that may result in increased incidences of chronic disease, and those which cause any untoward effects from the use of the water or render living on the Space Station uncomfortable; and

7. compare the ability of alternative treatment trains to reliably meet the above criteria (#6).

At present, only limited information is available concerning the types of chemicals that might be expected routinely on the Space Station. Part of this data base can be assembled from the known composition of construction materials within the Space Station and inventory of chemicals that are to be introduced into the Space Station environment. However, it will be necessary to establish analytically the concentrations at which chemicals will occur in air and water and to identify those chemicals that may be produced on board as process derivatives in water treatment. Careful attention must be paid to developing an inventory of possible contaminants on the Space Station and for updating the inventory with respect to design changes. A procedure needs to be developed for the Space Station water system that is analogous to the procedure developed for monitoring atmospheric contaminants outlined in the report "Toxicology Requirements for Space Station," as a result of the December 3-4, 1985, conference sponsored by NASA. There is and should be overlap in the chemicals considered in this report and the previous report. Every effort should be made to provide an integrated assessment of hazards, considering the intimate links between the air handling and water treatment systems. However, it should be recognized that many compounds will occur in water and not in air, and reliance on analytical methods specific to volatile components of the atmosphere is inadequate to assess water quality.

As the analytical data base expands, it will become necessary to exercise judgment with respect to which chemicals will require toxicological characterization. Undoubtedly, a very large number of compounds will actually be identified in the water system. Among these will be a variety of compounds that are normal body constituents and substrates (e.g., fats, carbohydrates, amino acids). Even though a formal toxicological data base may not exist for such compounds, it would be a waste of scarce resources to try and develop one. The majority of compounds that are identified in the water system will be found at very low concentrations, particularly in the finished water. At some point, a minimum concentration of concern must be established for those compounds for which there is an inadequate toxicological data base. If these compounds are consistently present below some minimum concentration and are unlikely to accumulate in the system, they might be ignored unless there is some suspicion that a particular molecular structure may have very high biological activity (e.g., a structural congener of a hormone). The panel suggests that 1 µg/L might serve as a useful cutoff at this time. However, there is no reason why that figure could not be increased or decreased by a factor of 10 or more if there is an indication that the chemicals identified have structures that elicit more or less concern.

Processes involved in the treatment of water should not produce unacceptable risks. If chemicals are to be used in water treatment and they or their by-products appear in the finished water supply, it is imperative that they be thoroughly characterized. In this case, one cannot be satisfied with the fact that no appropriate toxicological information exists. Several of the processes suggested for the Space Station are not routinely used in municipal water treatment and have not been well characterized with respect to their effects on health, particularly in the long term. These include the use of Oxone and HDAB as pretreatments and the use of iodine as a disinfectant. Consequently, the question of whether they can be used safely in consecutive missions that last up to 90 days has not been established.

Administrative procedures should be developed to document and track data concerning full characterization of the toxicology of chemicals that will be taken up to the Space Station for experimental work or that are precursors or products from synthetic processes. The behavior of these chemicals in the air and water handling systems should also be known and emergency procedures developed in case these chemicals are involved in spills.

Once the configuration of water treatment and air handling systems of the Space Station is finalized, it should be possible to systematically model movement of chemicals with varying physical and chemical properties through the Space Station. Ground-based testing of the treatment systems should provide the data needed to determine how quickly the chemicals would be removed from the cabin air and what concentrations are likely to be achieved in the treated water. Combining this information with the criteria based on toxicological data, decisions could be arrived at quickly in the event of an emergency.

Adverse health effects take many forms. Circumstances that might exist at any given moment on a mission can and will affect how seriously a particular health effect must be regarded. As a general rule, the Space Station crew should not be expected to endure any greater risks from chemically induced disease than persons working and living on earth. That assumption should rule the derivation of standards (with due consideration of the less-than-lifetime exposures that are involved). However, if a choice arises between accepting a small increase in the long-term risk of developing cancer and death from dehydration, the logical choice is to accept the added risk of developing cancer. Such choices should become necessary only under emergency circumstances.

Differing criteria for the same chemical (i.e., primary and secondary standards) apply only to emergency situations. No one should be expected to endure conditions in which water is unpalatable (perhaps leading to dehydration) even if the threat to life is not immediately apparent. The principal use of this gradation would be to help in decision-making processes that would select between a very hasty and perhaps risky rescue attempt on one hand (i.e., if life was in immediate danger) vs. a more deliberate rescue attempt where life may not be immediately threatened, but the chances for adverse health effects were increased to an unacceptable level.

Criteria based on health effects data should not be confused with criteria (often referred to as surrogate parameters) that are used to determine whether the treatment process is operating properly (e.g., palatability, conductivity, ultraviolet absorption, total organic carbon, or total iodine concentrations). Compromise of the former criteria carries an additional risk for an adverse health effect. However, it is impractical and unnecessary to monitor all possible contaminants of concern on a routine basis. In the latter case, the relationship to health is not as direct. Nevertheless, inability of the treatment system to meet these latter criteria does indicate that the system may no longer be producing a water that is safe for human use. Appropriate knowledge of the chemicals present on the Space Station, their toxicological properties, and how effectively these chemicals are handled in the treatment system provide a clear course for rapid and systematic investigation of whether the crew is at immediate, intermediate, or long-term risk. It is recommended that NASA develop a systematic data base that provides this information plus descriptions of appropriate analytical measures that can be employed to allow rapid pursuit of such problems if the treatment system fails to meet performance criteria. These data should be available for immediate communication should the need arise.

4.4 NEED FOR AN INTEGRATED CHARACTERIZATION OF WATER

The most desirable final testing of the water treatment systems including those applied to the humidity condensate would take place in an isolated chamber in which humans reside under microgravity conditions. This test would require a Space Shuttle mission to carry one module of the Space Station into orbit for testing and to return it to Earth for detailed analyses. Such a mission would be valuable even if it was of a relatively short duration (e.g., 10-15 days). This test should follow detailed testing of unit processes and alternative treatment trains, and thorough evaluation of their reliability on Earth. Therefore, this test would be primarily a confirmation of earthbound results under microgravity conditions.

It became clear in the panel's discussion with NASA personnel that earthbound testing is not always representative of conditions that are encountered in space. In terms of the water system, the main differences that can be anticipated involve material that would be introduced into the cabin condensate. At present, this is regarded as the preferred source of water for potable reuse. As has been stated previously in this report, cabin condensate is the most variable and least controlled waste stream on the Space Station. The major difference in input to this system in microgravity would be a greater amount of particulate matter than would be anticipated from testing on Earth. Collection of particulates (microbial as well as chemical agents) along with the humidity condensate compromises the phase change that has been assumed historically to constitute the primary treatment process in this stream. This treatment train lacks a subsequent phase change unit process and raises the possibility that nonvolatile chemicals may be solubilized in the condensate and carried through the treatment train.

If a flight test cannot be conducted, the first deployment and manning of a Space Station module should be regarded as an experiment with regard to the water treatment systems. Therefore, preparations should be made to collect and preserve appropriate samples for the detailed ground-based, post-mission analyses that will be necessary to confirm the effectiveness of the water treatment system in space. Depending upon the results of these analyses, modifications to the system already deployed in space may be required.

At a minimum, the air and water systems of the Space Station should be evaluated on Earth in a chamber containing the integrated environmental control life support system and inhabited by humans for as long as is practical. Ideally, it would be continued to a point at which the system is in steady state with regard to microbial ecology and concentrations of chemical contaminants in the treated water. This test is essential to document the types of contaminants that are of principal concern, to evaluate the efficiency of the overall treatment process, and to select and verify the adequacy of water quality criteria. Detailed testing protocols should be developed from the prior testing of unit processes that have been challenged with appropriate microbial and chemical contaminants. In general, these protocols should evaluate (1) the microbial ecology of the entire chamber with time until some form of a steady-state condition is approached, (2) total organic carbon (TOC) and assimilable organic carbon (AOC) throughout the system with time, (3) the appearance and removal of specific inorganic and organic chemicals selected to critically test the capability of the treatment system to control chemicals, (4) the disinfection processes for controlling microbial growth vs. their contribution to toxic by-products in the system, and (5) the efficacy of proposed microbiological monitoring methods.

A manned chamber test will also be useful in determining the palatability and aesthetic quality of the product water. As mentioned previously in the context of disinfectant residual, if the water is not palatable or aesthetically acceptable, it will discourage consumption, which could adversely affect the health of the crew.

4.5 MONITORING REQUIREMENTS FOR THE SPACE STATION WATER SYSTEM

It is imperative that any monitoring scheme developed for the Space Station be simple, automated, and involve as little of the crew's time as possible, but still be informative enough to provide specific direction for resolving any problems that are identified. The panel was skeptical of a routine inflight monitoring scheme that focused on detailed identification of a large number of chemical or microbial contaminants. They would rather see the operational monitoring strategy directed toward confirming that the treatment system is functioning properly through the analysis of selected surrogates. This, of course, places an emphasis on defining the system's capabilities and reliability in earthbound testing in relation to the surrogate parameters and more detailed analyses of the behavior of both chemical and microbial agents within the system. A number of parameters that are potentially useful for this purpose are mentioned below. However, in the case of both microbial and chemical monitoring, the specific parameters that are used inflight are best determined from the results of the prelaunch tests of unit processes and the treatment system.

4.5.1 Inflight Microbiological Monitoring

From the microbiological point of view, supplies and equipment carried inflight must include sterile media, sterile culture vessels, sterile transfer devices (e.g., pipets), and possibly incubators. There must also be facilities to contain and dispose of infectious waste and to decontaminate test materials that will be reused. Membrane filter methods may be easier to perform than other microbiological methods and may be easily adapted to microgravity conditions. If other techniques, such as microscope counts, or immunological or nucleic acid probes, are used to measure microbial concentrations, there will be a need for additional equipment and material, and the procedures will have to be developed further to increase their sensitivities. In the next few years, there will probably be considerable improvements in these latter methods, making them more sensitive and less cumbersome and time consuming. They are likely to be available commercially as miniature disposable kits.

Viruses and protozoans in water probably do not need to be monitored inflight. Until more microbiological studies are performed for each unit process and the treatment system, including integrated chamber testing, it is impossible to define monitoring requirements for bacteria, molds, and yeasts. Other surrogate parameters may prove more useful, but again, recommendations cannot be made without some preliminary testing. For example, routine measurement of disinfectant residual would be convenient to measure, but it is impossible to know if this is an acceptable substitute for microbiological testing without a chamber test with humans housed in the chamber. If disinfectant residual is adopted as the microbial surrogate test, confirmatory tests should be included in routine inflight monitoring that deal more directly with the microbiological quality of the water, perhaps at less frequent intervals.

4.5.2 Inflight Chemical Monitoring

The types of parameters developed for inflight monitoring of the chemical quality of water should also depend upon prelaunch test results. Candidate parameters that could be considered for prelaunch evaluation include TOC, pH, conductivity, by-product formation potential (analogous to the trihalomethane formation potential test used in municipal systems), or removal of selected chemicals that are routinely present in the wastewater streams and whose decreased removal with treatment would indicate exhaustion or malfunction of the system. The application of more comprehensive, sophisticated analytical capabilities for routine monitoring of chemical water quality will monopolize crew time and generate a data base that is difficult to deal with on a routine basis. Eventually, large data bases of limited utility are ignored.

While sophisticated capabilities for chemical analysis are not likely to be needed for routine monitoring, there will be a need for substantial general purpose analytical capabilities on the Space Station for other reasons. A specific problem would be the need to perform selected chemical analyses to determine if a spill of a dangerous chemical or a mixture of chemicals is being adequately handled by the air and water treatment systems. The analytical problem is simplified in this case since the potential contaminant is known in advance of the incident. Availability of appropriate analytical instrumentation could avoid aborting a mission simply because of a spill whose impact on health cannot be estimated. The nature of the instrumentation that should be available depends largely upon the nature and diversity of chemicals that are to be taken on Space Station. Because a broad range of chemicals are to be used over the life of the Space Station, mass spectroscopic capability will undoubtedly be necessary. This instrument needs to be coupled to at least two different types of separative instruments, a gas/liquid chromatograph and a high performance liquid chromatograph. Where relatively few chemicals are of interest, separative techniques such as gas/liquid chromatography and high performance liquid chromatography equipped with appropriate detection devices (which could include a mass spectrometer) might suffice. If problems with trace metals are anticipated, other appropriate analytical instrumentation will be necessary. Another possibility would be to develop an instrumentation package that would be carried up with each crew change with the analytical capabilities tailored to each mission.

In the event of a water treatment system failure that cannot be dealt with immediately, it could become necessary to perform analyses for a wide range of chemicals to determine whether the water can be consumed. In general, the panel felt this would be a highly improbable event if the system has been appropriately developed and tested on Earth. Therefore, plans directed at expeditious cleanup of the system or replacement of expendable components is a more rational response to such a circumstance.

4.5.3 Crew Health Monitoring and Water Quality

Routine physiological monitoring of the crew cannot substitute for monitoring of water. Monitoring of the crew will essentially identify a problem when it may be too late for remedial action if serious physiological effects are observed. This approach is disadvantageous because it does not unambiguously identify the source of the problem (i.e., water, air, food, change in radiation levels). On the other hand, the crew's senses might be an excellent way of determining if the water treatment system is malfunctioning. However, these should not be the sole criteria on which performance of the system is judged.

4.6 RECOMMENDATIONS

4.6.1 Microbiological Contaminants

Turbidity Levels of Potable and Hygiene Water

Current proposed water quality standards for the Space Station specify a turbidity of 11 NTU. This turbidity level is 11 times higher than the 1 NTU standard specified by the U.S. EPA. Considering the proposed treatment system(s) for Space Station potable and hygiene water, turbidities of 1 NTU should be readily achieved unless the system is malfunctioning or becomes colonized. Therefore, the standard of 11 NTU is not useful for microbial monitoring. The panel members were divided on the question of whether the turbidity standard served any useful purpose at all as a health-related parameter.

There are public health reasons why a turbidity standard of 1 NTU is desirable. First, high turbidity levels often interfere with disinfection processes, either by exerting a demand for the disinfectant or by shielding microorganisms. Second, turbid water often contains high levels of microorganisms. This can occur because microbes are associated with solids in the water or because microbial aggregates are the direct cause of the turbidity. In the Space Station water system there will be high potential for microbial colonization of surfaces (especially in activated carbon or ion-exchange columns) which may lead to the formation of biological films. High turbidity in the product water might indicate when this biomass begins to slough off.

Microbial Standards for Potable and Hygiene Water

Currently proposed Space Station standards specify 0 organisms/100 ml for the following microbes: anaerobic, aerobic, gram negative, gram positive, *E. coli* and enteric bacteria, yeasts and molds, and viruses. Routine monitoring for these microbial agents in Space Station water to meet currently proposed standards will be impractical and, from a public health standpoint, are either inappropriate or of only limited informational value.

The panel members believe that these standards must be reconsidered in the context of total sources of microbial exposure of personnel on Space Station. Microbial exposure will occur by means of a variety of potential routes in this closed environment, including direct and indirect person-to-person contact, fomites, airborne routes (aerosols and droplets) and possibly food as well as water. A goal of the overall effort to control microbial exposures should encompass all sources. Microbial standards for water should be established such that the water route represents only a minor source of exposure. Therefore, it is recommended that the proposed standards be dropped as requirements that need to be verified by routine monitoring.

NASA personnel pointed out that these numbers were not based on a maximum allowable microbial load to which the crewmembers can be exposed for a 90-day period. This requirement was set to prevent blooming of microflora in the water system and to alert the operators of the system in time to take positive preventive action. A second consideration was that the establishment of a zero level would remove the need to verify the absence of frank pathogens or opportunistic organisms. Considering that the ability to clearly define which organisms are actually pathogens on the Space Station (or even on Earth), it was felt that the design of the system should be such that it will eliminate all organisms. The microbiologists on the panel questioned whether a standard of zero is necessary to accomplish the first purpose, and pointed out that it may be necessary to increase the number of disinfectant points and carry a higher residual level of disinfectant throughout the system to accomplish the second. In either case, the issue of the microbiological standard should be considered unresolved at this time, but should be defined using the results of preflight testing of the system.

The ability to produce Space Station water of acceptable microbial quality should be verified initially by extensive performance evaluations of the candidate water treatment systems prior to Space Station launch. This should be done with indigenous microorganisms in the water sources and with source waters spiked (seeded) with known quantities of specific organisms.

Once the performance of the systems is established, some type of inflight monitoring of general classes of bacteria, and possibly other agents, can be developed to verify water quality, to demonstrate that the water treatment system is functioning properly, and to show that extensive microbial colonization of the water system has not occurred. Monitoring methods may rely on indicator systems based on simple cultivation and enumeration of microorganisms, systems currently under development based upon staining and microscopic methods, or immunological or nucleic acid probes.

Microbial Testing and Performance Evaluation of Prototype Water Treatment Systems

The need for thorough microbiological testing and evaluation of prototype treatment systems is repeatedly emphasized in this report. To the extent possible, such testing should be conducted under conditions that simulate the actual operation of the system on Space Station. Items to be evaluated are listed below.

(a) The biocide sensitivity and control of organisms colonizing the system.

(b) Thorough elucidation of the microbial ecology of all portions of the system, including biofilms on component surfaces.

(c) Determination of AOC in water as well as TOC measurements, providing information on microbial growth potential of the system water at each stage of treatment.

(d) A complete inventory of microorganisms in the water treatment system over time. Duration of testing should be long enough to achieve a microbial steady state and to determine if "blooms" of certain microbes occur.

(e) Parallel testing of all candidate alternatives for the treatment systems and their unit processes.

(f) System evaluation using raw source waters containing their array of indigenous microbes, as well as challenge tests with added test microbes representing those likely to appear in raw source waters under various worst-case conditions.

(g) Evaluation of the aerobic and anaerobic bacteria present and how their numbers relate to the oxygen content of the water at various points within the treatment system.

(h) Concurrent measurement of the physical and chemical quality of the water directed toward finding surrogate water quality parameters that correlate with and predict microbial quality within a environment that simulates the water system and its inputs on the Space Station. From this work, parameters should be derived that are most suitable for water quality monitoring on the Space Station.

Disinfection Process

Current options for disinfection of Space Station water calls for the use of iodine. In addition, both Oxone (potassium peroxymonosulfonate with acid) and a quaternary ammonium compound are being considered individually for pretreatment of raw wastewater. A major purpose of these pretreatments is to control excessive microbial growths.

HDAB and iodine attack the surface of the microorganisms as a primary target. They are relatively slow acting and provide residual disinfectants that will persist unless removed by a downstream treatment process.

It is recommended that at least two different disinfection processes be used in the treatment system. One, to be applied relatively early in the treatment train (e.g., immediately following phase change), which would have the genetic material of the microorganism as a target, is fast acting, and is perhaps a strong oxidizing agent (e.g., ultraviolt light, ozone, ultraviolet/H_2O_2, ionizing radiation). Another disinfectant process should be provided at the end of the treatment train (but before storage), which provides a persistent disinfectant residual (e.g., iodine, chlorine, or possibly a quaternary ammonium compound). The latter disinfectant will protect the product water during storage, but may have to be removed or reduced in concentration at the point of use if there is a potential for human toxicity, or if palatability (taste, odor, and appearance) would otherwise discourage consumption of water.

Control of Microbial Colonization of the Water System. Microbial colonization is a major problem with water treatment systems. Indeed, some treatment processes actually promote or encourage microbial colonization, such as activated carbon columns, ion exchange resins, and filter matrices. Furthermore, virtually all system surfaces in contact with the water may become colonized. Microbial colonization can cause a number of serious problems, including sloughing of high levels of microbes into the water, deterioration of water system surfaces (e.g., encrustation), and frictional resistance to flow followed by eventual clogging. Colonization also reduces the efficiency of some treatment processes, including disinfection.

At least some of the microorganisms that can colonize and proliferate in water treatment systems may be frank pathogens, such as *Escherichia, Flavobacterium, Klebsiella, Mycobacterium, Nocardia, Pseudomonas, Serratia,* and *Staphylococcus*. Therefore, efforts should be made to minimize the potential for and the extent of microbial colonization of the system. This may be accomplished by appropriate selection and microbiological evaluation of the treatment train, including application of disinfectants prior to treatment processes in which extensive microbial colonization is likely to occur.

Treatment System Design for Cleaning-in-Place and Component Replacement. The Space Station water system should incorporate designs and materials compatible with routine, convenient, and effective cleaning-in-place (CIP) procedures. In addition, design and materials of the water system should be such that component replacement is possible, if no other means of eliminating microbial colonization are effective. In particular, replacement regimes should be developed for activated carbon and ion-exchange filters.

4.6.2 Chemical Contaminants

The Safety of Prolonged Exposures to Iodine (I_2) and Other Treatments Has Not Been Established

In proposing the use of iodine as a disinfectant for prolonged periods of time, NASA is departing from usual municipal practice. Iodine has been principally in isolated situations or for short periods of time. Although iodine has been and probably is still used in a number of small systems at low concentrations, little toxicological research has been devoted to it relative to other, more commonly used disinfectants. The use of iodine has been justified in the past primarily on the basis of studies on iodide and iodate. These data are clearly not appropriate to the use of iodine species that are active as disinfectants. In addition, one must be concerned about iodine by-products that are be produced in the water in which iodine is applied, as well as the manner in which residual active iodine species react with organic material in the gastrointestinal tract. Serious problems are attributed to similar mechanisms in instances where other halogens have been used as disinfectants.

The panel noted that the proposed chemical treatments have yet to undergo strict review regarding the toxicity of repeated exposures to the treatment chemical (e.g., iodine), or by-products that result from the chemical treatment process (e.g., Oxone). It is possible that these agents or their by-products are substantially or completely removed by subsequent treatment processes. However, it was clear to the panel that this has not yet been established.

The panel strongly recommends that NASA determine whether the toxicology of active iodine species parallels that of iodide at the concentrations that are encountered in drinking water, and whether evidence exists that additional toxicities might arise from reactions of iodine compounds with organic constituents in water or in the gastrointestinal tract. Second, the impact of elevated iodine intakes on thyroid function should be determined, with emphasis on how normal physiological function and development might be affected. Third, the panel suggests that NASA determine whether the hyperplastic response of the thyroid gland following ingestion of levels of iodine increases the likelihood of thyroid cancer. Finally, NASA should investigate the possibility that intake of iodine could result in toxicity secondary to oxidant stress.

Chemical Contaminants of the Water, Their Behavior in the Treatment System, and Their Concentrations in the Final Product Water Must Be Defined

Chemical contaminants anticipated in the Space Station water system fall into two general classes, organic and inorganic. The behavior of these chemicals in the water system, their transition into the vapor phase, and their recovery via the cabin condensate must be thoroughly understood. This kind of information can only be developed into meaningful standards or monitoring parameters in the context of the treatment train that is finally selected for the Space Station. However, a good method of identifying chemicals that are likely to be of concern is to thoroughly test the candidate unit processes and materials that will be in contact with water.

Analytical methods exist for most inorganic chemicals that would be of health concern. Adequate data exist in the literature to establish criteria and standards for most inorganic compounds. However, NASA should be sensitive to the use of new alloys or organometallic chemicals, that might be included in the manufacture of items that contact potable water in the Space Station. Such chemicals may be poorly characterized toxicologically. It is very likely that many of the organic chemicals present in the system will have an inadequate data base to derive criteria or standards. Some of these chemicals may be eliminated as being normal food components, etc. Nevertheless, there will undoubtedly be some compounds requiring toxicological evaluation before the chemical safety of the product water can be evaluated.

Since many of the components in the water will be present at very low concentrations, several practical decisions will have to be made as to how far this problem will be pursued. The consensus of the panel was that if 500 µg/L is the maximum allowable TOC, then up to 100 µg/L of the organic chemicals present in the final potable water after several recyclings could remain uncharacterized. If this goal cannot be achieved, it may be necessary to resort to testing concentrated samples of complex mixtures of organic chemicals to establish the adequacy of the treatment train in dealing with routine contamination (Bull 1986).

Methodology and Data Requirements for Development of Standards Should Be Made Explicit

There are severe drawbacks to simply establishing standards for a chemical without specific reference to the health effect of concern or the mathematical derivation of the level. It is entirely rational to have one standard protecting the crewmembers against any conceivable health risk, and another ensuring protection only against immediate threats to life which might be applied in an emergency situation. A balanced approach to this problem was developed for the Health Advisory Program of the Office of Drinking Water of the U.S. EPA. Essentially, a standard is developed for exposure to chemicals for varying periods of time, such as 1-day, 10-day, 90-day, and lifetime exposures. Safety factors that are applied in developing these numbers are made explicit. Any risks that the chemical presents as a chemical carcinogen is expressed in terms of a predicted lifetime risk of cancer per unit of exposure (usually in the form of a μg/kg/day dose). Given a life-threatening situation on the Space Station, this information could be used to make informed judgments. Under nominal conditions, lifetime numbers, or a low level of carcinogenic risk, would be used as the "standard." The panel strongly advises that NASA review the Office of Drinking Water approach for deriving Health Advisories and implement a similar explicit approach that stores the basic data in a form useful for making emergency decisions during a mission. This approach dictates that NASA adopt some specific policies concerning the type and degree of hazard that is considered acceptable under normal conditions (i.e., non-emergency) on a mission.

Hazard Assessments for Individual Chemicals Must Integrate Air and Water Exposures

Even a cursory review of the life support systems on the Space Station indicates that many of the contaminants of air will eventually be found in water and vice versa. The use of the cabin condensate as a source of water provides for direct introduction of airborne chemicals into the water. In all likelihood, there will be similar opportunities for volatile chemicals produced in the course of drinking water treatment to end up in the air. The panel suggests that many of these problems can be dealt with thorough modeling of the air handling and water treatment systems, and knowledge of the chemical, physical, and biological characteristics of the treatment processes.

Chemicals Identified in Product Water Must be Characterized Toxicologically

The minimum level of data that should be developed (if it does not already exist) for chemicals that are present in the water at appreciable concentrations (i.e., > 1 ug/L or likely to increase above this level as a result of recycling) includes the following information: acute toxicity, subchronic toxicity (90-day exposures), and preliminary screening for carcinogenesis and reproductive toxicity. Appropriate detailed methodologies have been developed elsewhere for these tests, and will be dealt with in this report in only general terms. Subchronic studies should involve two species with exposures of at least 90 days. Animals should be observed for general well-being, and clinical chemistries and histopathological examination of major organ systems should be performed. Carcinogenic screening should include a clastogenesis assay as well as a point mutation assay. If these results are positive, a request should be made for the chemical to be tested in lifetime bioassays in both rats and mice by the National Toxicology Program. Reproductive studies should include both males and females because of the increased use of female astronauts. However, judgment should be exercised to decide whether teratology experiments need to be included based upon the likelihood of conception in the Space Station. Undoubtedly, reproductive effects will have to be considered in missions that might involve colonization of other planets.

A decision will have to be made with respect to the study of chemicals that are present in low concentrations for which adequate toxicological data do not exist. The panel suggested that compounds that are normal body constituents or substrates (an exception would be highly bioactive compounds such as hormones) should automatically be excluded from further characterization. In the opinion of panel members, other compounds that are present at concentrations below 1 ug/L can also be safely ignored. Admittedly, there are a few compounds that would present significant hazards at this level; however, they are exceptions rather than the rule, and it is very unlikely that they will be present in the Space Station environment.

Chemicals Involved in Experiments or Synthesized on the Space Station Should Be Toxicologically Characterized and Appropriately Contained

The panel recognized that chemicals that are brought on with each mission potentially represent a major variable in the performance of the water treatment system on the Space Station. An accidental spill of large quantities of such chemicals could represent a significant challenge to the water treatment system. However, exposure by inhalation of vapors, aerosols, or particulates will probably be of primary concern. The panel recommends that chemicals to be introduced or synthesized in the Space Station should be fully characterized with respect to their toxicology and their behavior in the air handling and water treatment systems. Appropriate analytical methods that can be applied onboard the Space Station with available equipment must also be determined. This information needs to be immediately available in case of an accident to determine whether there are immediate threats to the health of the crew, and to determine when the crisis is over.

Research and Derivation of Standards Should Consider Physiological State of Man and Other Effects Associated with Spaceflight

In an earlier section of this report, examples were provided of interactions that could result between the effects of microbial and chemical contaminants with other conditions experienced by the crew onboard the Space Station. These examples were not comprehensive because the panel members are not expert on the types of hazards that might be encountered in space or the detailed ramifications of Space Adaptation Syndrome. Nevertheless, NASA should be aware of this problem in reviewing literature or performing studies to develop criteria. Chemicals that may be more toxic under stressful conditions or in altered physiological states should be identified and investigated. Where appropriately verified, this information should be explicitly integrated into any health-related criteria that are developed for anticipated contaminants.

SECTION 5

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APPENDIX

SUMMARY OF RECOMMENDATIONS

NASA Water Quality Conference

July 1 & 2, 1986

System Development

1. The most promising treatment trains should be selected as soon as possible so that the output can be characterized. Development of standards without consideration of the system is not cost-effective.

2. The chemical compounds likely to be produced by unit processes should be identified, and the concentrations that they achieve in the final product water should be determined.

3. The unit processes should be evaluated for their ability to remove or destroy specific chemicals and microogranisms that are representative of those likely to be found in the Space Station environment.

4. Design of the water treatment system needs to accommodate (a) cleaning-in-place and disinfection, (b) replacement of expendable components, and (c) careful consideration of the composition of components (e.g., Pb-free solder).

5. An integrated water and humidity control system test should be conducted for an extended period in a manned chamber. This testing should be confirmed with a microgravity demonstration before the system is first used in Space Station.

6. Mathematical models based upon the chemical/physical properties of the treatment processes should be developed to predict the behavior of new substances within the Space Station environment.

Microbiological Considerations

1. NASA should develop a list of organisms that could be present in the spacecraft.

2. NASA should conduct ground-based microbiological testing of the treatment system by adding known amounts of specific test organisms to the test water so that treatment efficiencies can be determined.

3. At least two disinfection procedures should be used that employ different antimicrobial strategies. A strong killing disinfectant should be employed early in the system (e.g., immediately following the phase change), whereas an agent that provides a stable

residual should be applied just prior to storage. A device could be placed at the point of use to reduce the consumption of iodine, if iodine is used for the latter disinfectant, but a minimum concentration (not less than 0.2 mg/L) should remain in the product water to be consumed.

4. The potential for some microorganisms to develop resistance to the disinfectants employed should be thoroughly evaluated.

5. The system should be designed and operated to minimize the potential for and extent of microbial colonization of the water treatment system.

6. If turbidity is to be used as a surrogate measurement of system performance, a limit of 1 NTU is more appropriate than the proposed limit of 11 NTU.

7. NASA should develop attainable microbiological standards that are consistent with the total microbial exposure of Space Station personnel.

Chemical/Toxicological Considerations

1. NASA should review the process used by the U.S. Environmental Protection Agency to develop Health Advisories and develop a similar process for using new and existing data to arrive at safe levels of potentially toxic agents. Hazard assessments for individual chemicals must integrate air and water exposures.

2. NASA should develop a rapidly accessible data base that can provide appropriate toxicological information, behavior of chemicals in the treatment system, and analytical measures that can be consulted in the event of an emergency. This system should include a hierarchical consideration of health risks that would be encountered at different exposure levels to facilitate decision-making.

3. NASA should determine whether the toxicology of iodine depends upon its chemical species. Data available in the literature largely describe less reactive forms and are not necessarily applicable to the forms used for disinfection.

4. Any substitutes for iodine used as a residual disinfectant in stored water should be thoroughly evaluated toxicologically.

5. The ability of all disinfectants to produce by-products that appear in the final product water must be evaluated. If significant by-product formation occurs, these chemicals will require toxicological characterization.

6. Organic chemicals identified in the product water must be characterized toxicologically unless they are nutrients or occur in very small concentrations (e.g., <1 µg/L).

7. Research on health effects and the derivation of standards should consider the altered physiological state that is associated with spaceflight.

8. Chemicals involved in experiments and those that are synthesized on the Space Station must be characterized toxicologically and contained appropriately. The behavior of these chemicals in the air and water revitalization systems should be known and emergency procedures developed that will prevent jeopardizing the health of the crew in the event of a spill.

Monitoring Considerations

1. The routine inflight monitoring strategy should be aimed primarily at confirming water treatment system performance. Some provision should be made for follow-up investigations with multipurpose analytical equipment required by other activities on the Space Station.

2. The inflight monitoring scheme should be developed from the results of pre-flight testing of the water treatment system.