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Quality Requirements for Reclaimed/Recycled Water

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Reclaimed/Recycled Water**

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ABSTRACT

Water used during current and previous space missions has been either carried or made aloft. Future human space endeavors will require some form of water reclamation and recycling. There is little experience in the U.S. space program with this technology. Water reclamation and recycling constitute engineering challenges of the broadest nature that will require an intensive research and development effort if this technology is to mature in time for practical use on the proposed U.S. Space Station. In order for this to happen, reclaimed/recycled water specifications will need to be devised to guide engineering development. Present NASA Potable Water Specifications are not applicable to reclaimed or recycled water. Adequate specifications for ensuring the quality of the reclaimed or recycled potable water do not exist either within or outside of NASA. NASA experience with potable water systems is reviewed, limitations of present water specifications are examined, world experience with potable water reclamation/recycling systems and system analogs is reviewed, and an approach to developing pertinent biomedical water specifications for spacecraft is presented. Space Station water specifications should be designed to ensure the health of all likely spacecraft inhabitants including man, animals, and plants, both separately and collectively.

INTRODUCTION

Presently, water necessary to support human life in space is either carried or generated aloft by fuel cells. This reflects the short duration of the missions (Mercury/Vostok, Gemini/Voskhod, Apollo/Soyuz), lack of need to conserve mass during orbital insertion (Skylab), and existence of a dependable reprovisioning system (Soyuz/Salyut/Progress). In each case, however, human space activities have been constrained primarily by the limitations of the human life support system (LSS) employed. The proposed U.S. Space Station, scheduled for implementation in the 1990's, is being designed to support a permanent manned presence in space (ref. 1). Present plans require that the Space Station be capable of supporting commercial/industrial applications, be assembled from a minimum number of modules within the size and weight limitations imposed by the U.S. Space Transportation System (STS) (Shuttle), and be as independent of ground support as possible (refs. 1 and 2). Therefore, limitations imposed by present LSS technology will likely prove unacceptable.

Of LSS constituents, water occupies first place by weight (ref. 3). Indeed, the human body's daily weight requirement for water exceeds that of oxygen and food substances combined (ref. 4). The minimum amount of potable water (PW) necessary to support human life in space is about 2.5 liters per sedentary crewmember per day (ref. 3). See table 1. U.S. and U.S.S.R. experiments indicate that as much as 6 liters per crewmember per day may be necessary to support vigorous activity in space. The minimum amount of water necessary to support a manned space mission is roughly proportional to the duration of the mission; all of this water must be consumable, or potable. In addition, PW may be used for other purposes such as handwashing, cooling, oxygen generation, or even fuel (hydrogen) generation. If PW is used for multiple purposes, it can become the primary limiting consumable.

One method under consideration for providing PW for longer duration missions such as the Space Station is reclamation and recycling of previously used water (e.g., humidity condensate, wash water, food wastes, urine, or feces). This represents a major departure from the fill-and-draw type PW systems used on previous and present space flight.

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TABLE 1 - SOME LSS CONSTITUENTS REQUIRED TO SUPPORT A SINGLE PERSON IN SPACE

Constituent	Amount (kilograms per person)		
	per day	per year	per lifetime (70 yr)
Water			
-hygiene	19.1	6,972	488,040
-drinking*	2.5	913	63,910
Oxygen	0.9	320	23,000
Food (dry)	0.6	219	15,300

* includes food rehydration.

POTABLE WATER SYSTEMS USED IN SPACE

Summary

The United States and the U.S.S.R. have extensive space flight experience with fill-and-draw PW systems. The United States, in addition, has experience with in-flight generation of PW. There is little space flight experience with the design and development of a reclaimed PW system for the proposed U.S. Space Station.

NASA Potable Water Systems

A fill-and-draw type PW system has been utilized by U.S. spacecraft for all water needs. In general, a spacecraft's PW system is disinfected in advance of a launch by flushing with chlorinated or iodinated water, an ethanol water mixture, or some combination thereof before filling or refilling. Spacecraft water is public drinking water which has been filtered, polished, tested, and certified potable using prevailing NASA PW Specification criteria (app. A). Water thus treated is then supplied to the spacecraft and periodically monitored for chemical/microbiological purity. Prior to launch, a bactericide is introduced, final samples are tested, and the PW system is certified for launch. Once aloft, water is used and spent water is returned to Earth or vented to space. Beginning

with Gemini 2, routine postflight testing was instituted; on later flights, in-flight testing and periodic disinfection were introduced.

During Project Mercury, the PW system was a 2.7-liter, passively pressurized, plastic pouch which supplied drinking water through a flexible tube inserted, when desired, into the astronaut's pressure helmet via a one-way flap valve (refs. 5 and 6).

Gemini spacecraft utilized a single, integrated PW system distributed between the spacecraft's reentry and adapter modules. A single, 7-liter holding tank in the reentry module delivered ground-supplied PW (GSW) to the crew. A second PW tank in the adapter module replenished the holding tank as necessary. A third water tank, also located in the adapter module, was designed to receive water produced from fuel cells. The original plan was to use fuel cell water to replenish consumed water, however, fuel cell water (FCW) did not meet NASA PW Specifications. As a result only GSW was used for consumption. Upon reentry, the adapter module was jettisoned. PW also provided spacecraft and space suit cooling. The system was pressurized by nitrogen gas/fuel cell water (refs. 5 and 6).

Much like Gemini, Apollo spacecraft utilized a single, integrated PW system distributed between command and service modules (fig. 1). A single, 16-liter holding tank, located in the command module, provided water to the crew via drinking water and food rehydration injection ports. Water could be heated and cooled. Unlike Gemini, Apollo FCW was capable of meeting NASA PW Specifications and was used to continuously replenish PW stores. Fuel cell water beyond PW usage requirements was directed toward a second 16-liter (waste water) holding tank, which also received humidity condensate from the spacecraft and space suits. Either or both tanks could supply water for spacecraft or space suit cooling, or be vented overboard via common distribution lines (refs. 9 and 10).

The Apollo Lunar Module (LM) had a separate PW supply. PW loaded in the LM prior to launch was stored in two 19-liter holding tanks located in the upper, ascent module and one 151-liter tank in the lower, descent module. The LM provided PW for drinking, for food reconstitution, and for spacecraft and space suit cooling. The system was pressurized by nitrogen gas and was independent of the waste water system. It was the first system to use iodine rather than chlorine for disinfection (refs. 3, 5, 9, and 10).

Skylab represented the first moderate-duration, multicrewed U.S. spacecraft. The Skylab orbital workshop (OWS) had three independent water subsystems. Water for drinking and food reconstitution (wardroom water) was supplied from one of six 278-liter tanks. Three additional tanks supplied personal hygiene/waste management water and another provided air lock servicing/contingency water. A 12.7-liter, PW tank provided for emergencies. All tanks were launched fully charged with GSW; water was not generated in flight. During each of the three manned Skylab missions (Skylab 2, 3 and 4), the crew reconnected and filled the wardroom water distribution system, checked disinfectant residuals, added iodine disinfectant as necessary, and drew samples for certification and further testing prior to use. Upon mission completion, the crew disconnected, vented, and sealed the wardroom water distribution system for subsequent use. The water subsystems were pressurized by nitrogen gas (refs. 5, 7, and 8).

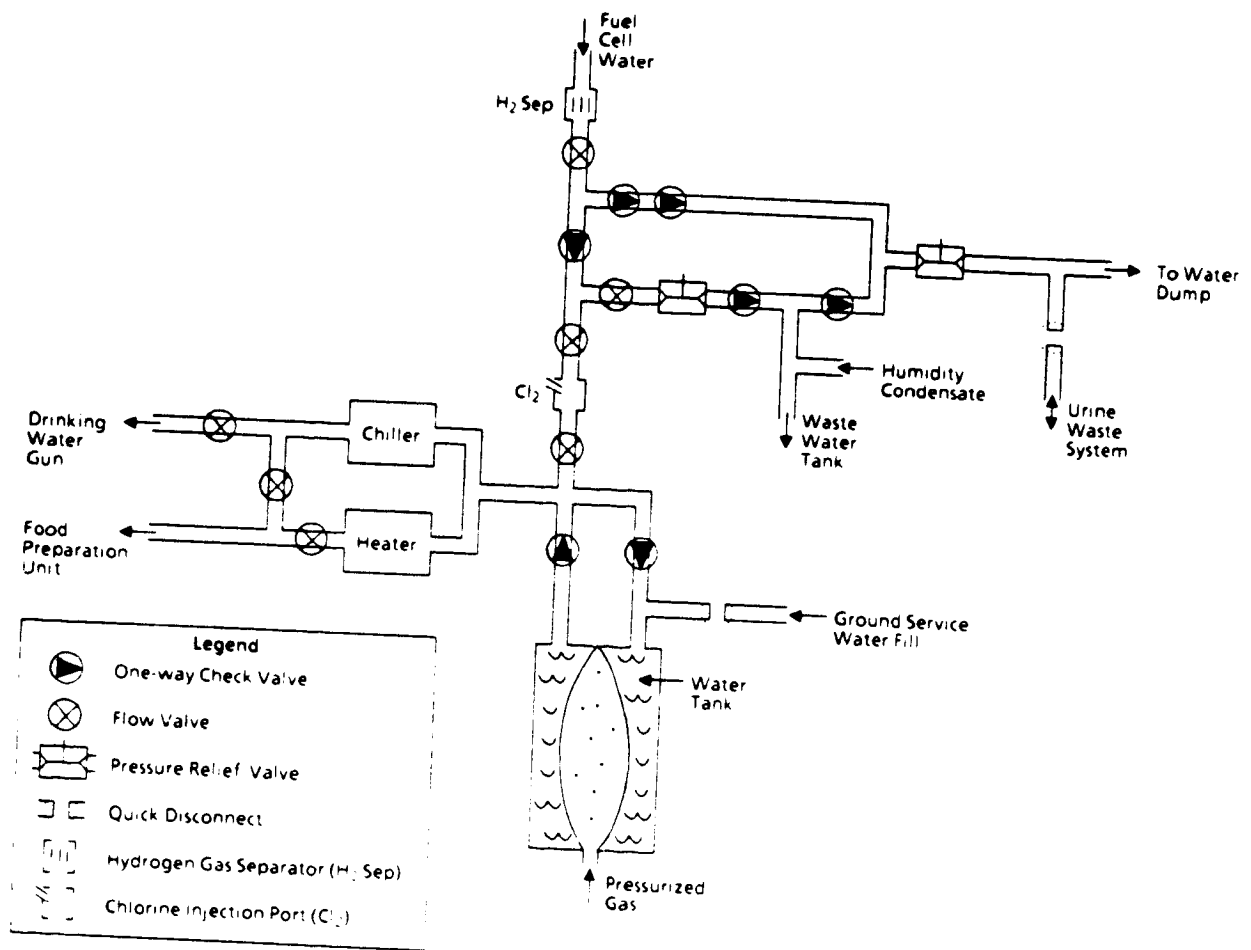


Figure 1.- Potable water system for Apollo command/service modules (ref. 9).

The Shuttle PW system (fig. 2) consists of four parallel water tanks replenished continuously with FCW. At launch, the primary tank is practically empty, while the second, third, and fourth tanks are fully charged with GSW. The primary tank is left empty to provide space for FCW produced during early phase. Degassed FCW is routed to the first tank passing through an iodine/anion-exchange bed [Microbial Check Valve (MCV)]. The first tank is the source of hot and cold PW for drinking and food reconstitution in flight. The second, third, and fourth tanks receive degassed water routed to bypass the MCV. Water from these tanks can be directed to the spacecraft cooling system (flash evaporators) on the space suit cooling system (via the service and cooling umbilical) and/or vented overboard as needed. Interconnections between the tanks allow reshunting of water to and from various tanks as needed. The Shuttle PW system is pressurized with gaseous nitrogen (refs. 11 and 12).

U.S.S.R. Potable Water Systems

U.S.S.R. Vostok, Voskhod, Soyuz, and Salyut spacecraft utilize fill-and-draw technology roughly analogous to Mercury, Gemini, Apollo, and Skylab (refs. 3 and 14). However, Salyut, which the U.S.S.R. describes as a space station, may augment stored wardroom water with reclaimed water from urine. What portion, if any, of the PW is actually regenerated is not explicit. However, Salyut's stores of PW are regularly provisioned with GSW from Progress cargo ships (ref. 15).

POTABLE WATER SPECIFICATIONS

Summary

The NASA PW Specifications are presently based on data compiled from terrestrial applications. These data have marginal applicability to the spacecraft environment and are not directly applicable to recycled water.

NASA Potable Water Specifications

The NASA PW Specifications were formalized during Apollo for the testing and certification of GSW and FCW (ref. 16). They were later used for testing and evaluation of pre-flight and postflight PW samples, and were revised in 1970 and again in 1971 primarily to incorporate a more testable definition of microbial sterility. They do not specifically address reclaimed or recycled water (refs. 17 and 18).

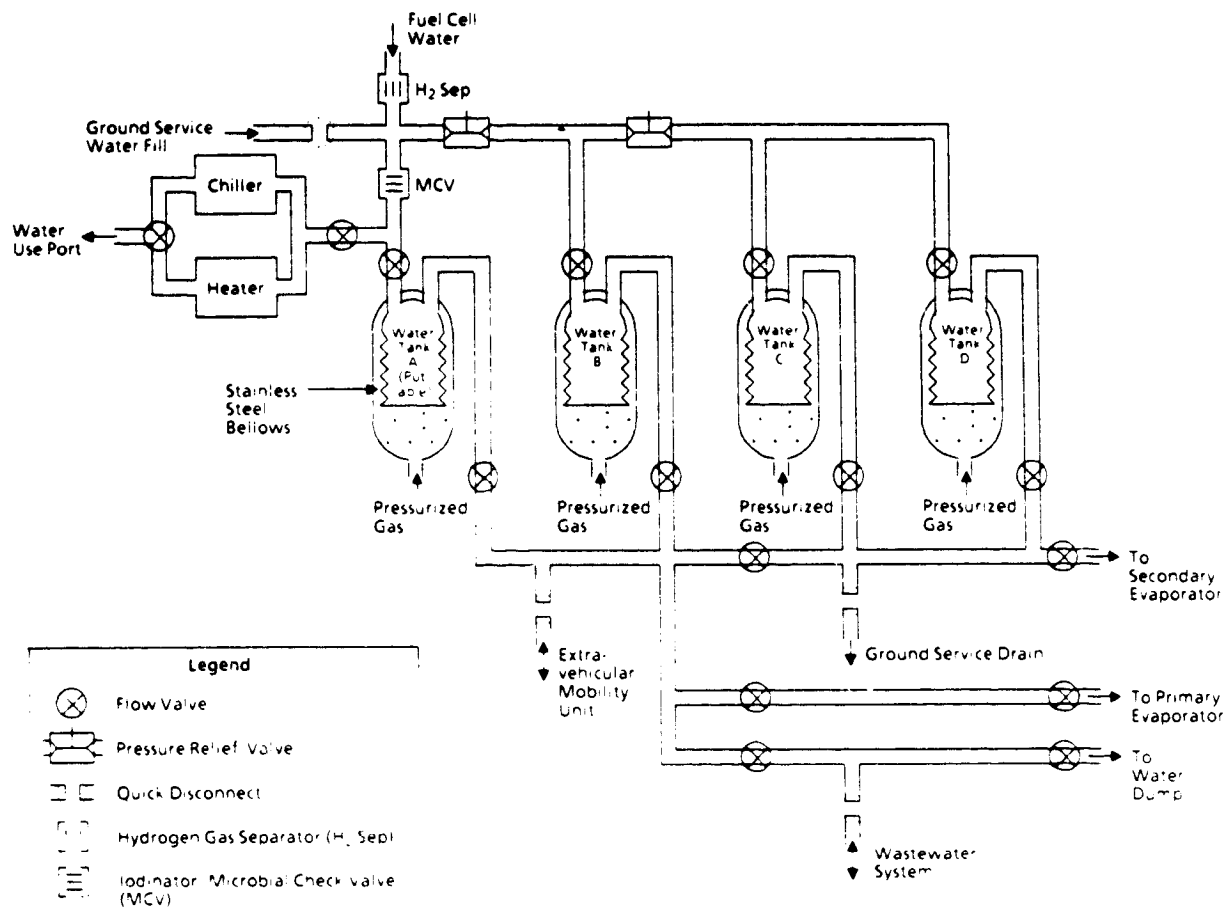


Figure 2.- Potable water system for Space Shuttle (ref. 12).

The U.S. Public Health Service (1962) primary and secondary drinking water standards (DWS) as amended, and the National Academy of Sciences (NAS) recommended water quality standards for manned space missions (SMR's) served as major source documents in development of these specifications (refs. 19, 20, 21, and 22). The present NASA PW specifications reflect assumptions inherent to these source documents, and correspond to present Environmental Protection Agency (EPA) DWS's, namely:

1. Humans are the only PW consumers
2. Spacecraft PW systems are similar to public PW systems
3. Crew exposure(s) from sources other than PW are known or insignificant.

DWS/SMR's address substances associated exclusively with human disease. Present plans call for support of multispecies life sciences experiments on the Space Station, including metabolic studies on animals and plants, and the cultivation of animals and plants for food. Plans also exist for flight testing advanced LSS's which incorporate plants into the controlled environmental life support system (CELSS). Substances which cause dysfunction and disease in humans do not necessarily cause such in animals or plants. Substances which might cause dysfunction and disease in animals or plants are not addressed. Unless each species of spacecraft inhabitants has its own isolated PW and waste-collection systems, NASA PW Specifications will have to support their individual and collective requirements.

DWS/SMR's define human exposure whenever possible in terms of maximum allowable concentrations (MAC's) (refs. 19 and 22) or maximum concentration limits (MCL's). MACs are based on an "average," terrestrial PW consumption of less than 2 liters per person per day. Consumption of more than this amount, especially during vigorous activity, or through the rehydration of food, would result in correspondingly higher exposures.

The MCL's do not apply well to situations in which cohabitant life-forms are involved in a food chain. For instance, if a plant preferentially bioaccumulates a particular substance, even though the substance might be present in PW in concentrations well below the MCL, an astronaut consuming the plant would experience an increased and otherwise difficult-to-explain exposure to the substance.

Clinical human dysfunction and disease is addressed by MCL's. However, subclinical or physiologically "correctable" metabolic dysfunction (stress) is not addressed. In addition, MCL's do not address minimum necessary concentrations (MNC's), or optimal concentrations (OTC) of nutrients essential to various life-forms. MNC's and OTC's are of critical importance in maximizing yield and quality whenever animals or plants are cultivated for consumption or commercial use.

Organoleptic data are based on rudimentary studies of substances which, when present in chlorinated terrestrial surface water, make water unpalatable. MCL's do not address substances which enhance the flavor of PW. The extent of the PW's positive character will, nonetheless, determine the form, method, and total quantity of PW and PW contaminants ingested.

The DWS/SMR's were directed at undesirable substances commonly present in terrestrial surface water (refs. 19 and 20). GSW, FCW and reclaimed spacecraft PW are considerably different in physical, chemical, microbiological, and radiological makeup than surface water. Some substances common in terrestrial surface waters will not be present at all in spacecraft PW. Negative results of tests for such substances may inappropriately imply overall PW purity. Spacecraft PW will potentially contain a variety of unique substances, determined to a large extent by (1) materials used in construction of the spacecraft and PW system, (2) route(s) and mode(s) of introduction into the PW system, and (3) interaction with environmental reservoirs (sinks). If the water is recycled, these substances (which may or may not have been present in GSW or FCW) will slowly change in concentration until a characteristic, but different chemicoecological equilibrium is attained.

Spacecraft PW systems are similar to terrestrial, public PW systems in that both involve water treatment, disinfection, storage, and distribution (refs. 19, 20, and 23). However, because of weight, size, interdependence and reliability restrictions, unique technologies are proposed for space applications. In addition, system byproduct, wear-and-tear, and component-failure contaminants will contribute significantly to water contamination.

The DWS/SMR's are based on the assumption that the non-PW sources of contaminants (e.g., food, air) are quantifiable or insignificant. For example, exposures from substances found in food were generated from U.S. Food and Drug Administration data on the composition and use of common, public consumables (ref. 20). Exposures from substances found in air were similarly derived from urban, ambient air pollution information prepared by the NAS for the U.S. EPA (ref. 23). These resource data do not incorporate terrestrial indoor and occupational exposure data. They are not at all applicable to spacecraft.

The NAS recently completed a monograph on water quality criteria for reused water (ref. 24). In it, they question several assumptions including:

1. Total organic carbon as an indicator of organic chemical toxicity
2. Coliforms as indicators of microbial contamination
3. Applicability of fill-and-draw criteria to reclaimed PW

U.S.S.R. Potable Water Specifications

The U.S.S.R. All-Union State (GOST) Standards have been reportedly applied to reclaimed/recycled PW without substantive change. They do not, however, address or apply to such. GOST Standards are similar to U.S. primary and secondary DWS's in that they incorporate the basic assumptions discussed above (ref. 25).

POTABLE WATER RECLAMATION/RECYCLING TECHNOLOGY

Summary

Water reclamation and recycle technology is uncommon, largely experimental, and poorly developed, especially for PW reclamation. PW reclamation and recycle preprototypes are under evaluation at NASA, and probably within the U.S.S.R.. U.S. efforts are mainly directed toward developing engineering test beds. Some analogs to PW reclamation systems exist within the public and private sectors which provide some additional information useful in determining reclaimed PW specifications.

Water Reclamation Terminology

Water may be used once and disposed of, reused without reprocessing, or reprocessed and reused (reclaimed). Reclaimed water may be applied to the same purpose for which it was previously expended (e.g., used wash water reclaimed for reuse as wash water), or to different purposes (e.g., used wash water to PW). Water reprocessed and then reintroduced into a system for the same purpose is termed recycled. To some extent, the concept of recycling depends on perspective. For example, urine which is reprocessed and reused as PW could be called recycled if one considers that urine is only an intermediate step in the PW cycle (PW/urine/PW). For this reason, it is probably better to specify the immediate influent and effluent of a particular water processing system, and then categorize it as a reclamation or recycling system in the broader context. In addition, recycled water systems may be configured to diminish or eliminate the need for outside resupply. A recycled water system which eliminates the need for outside resupply is called a closed-loop system. The U.S. and U.S.S.R. have yet to demonstrate space-flight-tested, reclaimed, recycled, or closed-loop PW systems.

NASA Technology

Several PW reclamation systems are being ground-tested by NASA for possible use on the Space Station. These include

1. Air evaporation system (AES)
2. Vapor compression distillation system (VCDS)
3. Thermal, integrated, membrane-evaporative system (TIMES)

The AES is the oldest, best described, and most thoroughly tested PW system. Used water is stabilized and fed into an array of wicks. Water vapor is taken up by air flowing over the saturated wicks and is condensed. The reclaimed water requires further filtration, polishing, and disinfection for reuse. The wicks require either regular servicing or replacement. Mixed urine/humidity condensate to PW recycling, and used washwater to wash-water recycling have been tested in partially closed 60- and 90-day manned ground tests using this technology (refs. 26 and 27).

An advanced VCDS preprototype (VCD2A) is also undergoing testing. Used water is stabilized and boiled under low pressure on the inside of a rotating drum. Water vapor is condensed under high pressure on the outside of the drum. The reclaimed water requires filtration, polishing and disinfection prior to reuse. The residual fluid (brine) is collected and reintroduced into the influent (concentrator loop) to increase system recovery efficiency. The drum and housing require regular servicing. Atmospheric condensate to PW reclamation and urine to PW recycling have been demonstrated. A spent washwater to PW reclamation demonstration system is also being tested (refs. 22 and 28).

The TIMES preprototype is undergoing similar development and testing. Spent water is stabilized, pasteurized in the hot side of a heat exchanger, and fed into bundles of hollow, tubular, membrane filters. Low pressure maintained outside the filters causes low-temperature vaporization and migration of the water vapor across the membranes. As water vapor is fed through, it condenses on a porous plate on the cold side of the heat exchanger. Reclaimed water must be filtered, polished, and disinfected for reuse. Residual fluid (brine) is collected and reintroduced using a concentrator loop. The membranes require regular servicing and replacement (refs. 29 and 30).

U.S.S.R. Technology

U.S.S.R. PW reclamation/recycling technology is not well described in the literature. A humidity condensate and/or urine to PW reclamation system was reportedly tested on Salyut #6. However, the system is said to have produced an insufficient amount of PW for life support purposes, and PW was regularly supplied to the spacecraft during this period (ref. 7). A 1-year, manned, closed-loop life support system for recycling humidity condensate/urine to PW was announced. Details, however, are incomplete (ref. 33).

In addition, freeze-drying, lyophilization, vacuum distillation, and catalytic processes have been reported by the U.S.S.R. for use in urine to PW reclamation and also in mixed humidity condensate/urine/spent washwater to PW recycling. In the lyophilization process, urine is subjected to low pressure in the presence of heat and sublimed water vapor is condensed, filtered and polished. Descriptions of the freeze-dry, vacuum distillation and catalytic processes were not available to the author at the time of this report (refs. 34 and 35).

The U.S.S.R. has reported space-flight testing of a humidity condensate/spent washwater to washwater recycling system on Salyut (ref. 32). In addition, various partially closed, unmanned, "higher life-form habitats" have been reportedly flown (ref. 36).

Experimentation with long-duration (as long as 1 year), manned, closed-loop hermetically sealed "habitats" (BIOS 1, 2, and 3) which incorporate higher plant life-forms, have been conducted (ref. 36).

Other Technologies

The U.S. EPA has expressed interest in developing and testing PW reclamation systems for public use. However, no reports were found in the literature (ref. 37).

The U.S. Department of Defense (DOD) has indicated interest in reclaimed PW systems for possible use at advanced, remote military sites (U.S. Army) and for desalinization (U.S. Navy) (ref. 37). However, no reports were found in the literature.

Various other PW reclamation/recycling analogs exist. The U.S. Center for Disease Control and various state public health departments have had extensive experience with recycled swimming pool and hydrotherapy water. Numerous reports in the medical literature have been directed at recycled humidifier water.

EXPERIENCE RELEVANT TO RECLAIMED/RECYCLED POTABLE WATER

Summary

World experience with PW reclamation is extremely limited. NASA expertise is thus far restricted to engineering bench tests of preprototype hardware. Organic chemical and bacteriological quality specifications and testing procedures are of greatest immediate interest.

NASA Flight Experience

During Gemini, it was found that bacteria could be cultured from GSW. Some persisted and even multiplied during short duration missions. The bacteria identified were generally non-coliforms, except during Gemini II, where it was concluded that coliforms had been introduced into PW via space suit condensate (ref. 38).

The Apollo command and service module experienced problems with in-flight chlorination, gas bubble formation and PW palatability. Of the inorganic chemicals specified in the NASA PW Specifications, nickel, cadmium, aluminum, and manganese were occasionally detected in excessive levels. Approximately 150 organic compounds were detected in inflight "grab" air samples from Apollo 7-17 spacecraft (corresponding inflight PW samples were not obtained). Pre- and postflight bacterial cultures of PW were frequently positive. *Flavobacterium* and *Pseudomonas*, both conditional human pathogens, were commonly present. No coliforms were cultured. The highest bacterial concentrations and greatest numbers of positive plate cultures were consistently obtained from the crew hot-water dispenser. Postflight PW bacterial species did not correlate well with those found on crew skin, mucous membranes, clothing or spacecraft environmental surfaces (refs. 39, 40, and 41).

The Apollo LM experienced gas bubble formation and increased nickel levels. No bacterial contamination problems were identified. It was

concluded that iodine disinfection was superior to inflight chlorination (refs. 39, 40, and 41).

On Skylab, over 300 low molecular weight organic compounds were detected in inflight air samples. Again, corresponding inflight PW sampling was not done. OWS PW data further supported the use of iodine as a disinfectant. As long as effective iodine residuals were maintained, bacterial contaminants remained within NASA PW specifications. An ion exchange system was successfully incorporated to control previous nickel, iron, and chromium problems (refs. 39, 40, 42, and 43).

Although not directly related to the Shuttle PW system, on Shuttle flight STS-8, an experiment suffered contamination by *Pseudomonas* and *Flavobacterium* in spite of extensive preflight sterilization precautions. Combined Shuttle flight data are presently being collected for analysis (refs. 44, 45, and 46).

U.S.S.R. Flight Experience

Details on Soviet spacecraft PW quality were not found in the literature. Unsubstantiated reports suggest that Salyut has experienced problems with fecal coliform contamination.

Other NASA Experience

NASA's experience with PW reclamation systems is limited to experimental, preprototype, ground-tested systems.

In the McDonnell Douglas 60-day, 3-man test of the AES, mixed humidity condensate/urine was reclaimed to PW and recycled. Bacterial contamination from a "gram negative rod of the *Achromobacter* group" was noted to occur starting at a filtration device and eventually contaminating the entire distribution system forcing a temporary system shutdown approximately mid-test (ref. 47). Similar problems were experienced during the 90-day, 4-man test of AES/VCD systems on about the 30th and 60th days. Offending microbial species were not identified. A gradual rise in PW conductivity, total organic carbon and ammonia were reported starting at about the 30th day and continuing until system shutdown (ref. 48).

Data from 1200 hours of noncontinuous operation of the VCD1 preprototype revealed similar problems, where mixed urine was reclaimed to PW but was not recycled. A variety of non-coliform bacteria were isolated; *Flavobacterium* and *Pseudomonas* species predominated. Fungal cultures revealed *Aspergillus*, *Cephalosporium*, and *Candida* species (refs. 49 and 50).

Ten and 30-day noncontinuous operation of the VCD2 preprototype system, where mixed urine was reclaimed to PW but not recycled, showed similar problems (ref. 50).

Over 100 low molecular weight organics (including halobenzenes and nitrobenzenes) were detected in TIMES and VCDs effluent reclaimed from batches of pooled human urine in various bench tests. About 25 percent

of these compounds have been found in Shuttle air samples; 30 percent were identified in atmospheric condensate samples from Shuttle flight STS-9. Urine physical and chemical composition was not reported (ref. 50).

Other U.S.S.R. Experience

Soviet experience with PW reclamation systems appears largely limited to similar experimental, preprototype, ground-tested systems. A 3-month rat test and a 30-day, 3-man test of a "catalytic method" were described. In each case, mixed humidity condensate/urine/washwater was reclaimed to PW and recycled. PW was reported to meet select physical/chemical GOST Standards and several NASA PW Specifications. "Clinical and physiologic" tests performed revealed "no pathological changes or manifestations of toxicoses." PW organoleptic properties were judged to be poor and salt was added "with the aim of giving it the customary taste properties" (ref. 51).

Other Experience

Most other PW reclamation experiences represented in the literature would more accurately be described as reclaiming various mixtures of fecal, urine, wash, and/or industrial waste water to effluent meeting EPA surface waste water standards. Such effluents are usually diluted, percolated through soil or ground-injected and then subjected to classical water treatment prior to reuse as PW. As such, most public "recycle" systems are more accurately characterized as pass-through systems with partial, indirect recycle. However, a number of anecdotal observations may be applicable to recycle systems in general.

The types of inorganic and organic contaminants present in undiluted effluent appear related to the types of contaminants present in influent, while their concentrations appear related more to the reclamation process employed. Corrosion produces and consumes contaminants, attracts charged bacteria, affords them a surface on which to adhere, and provides them protection from disinfectants. Filtration devices filter and concentrate microorganisms as well as chemical contaminants, remove disinfectants, and soon act more like a biological rather than a physical/chemical filtration device. There is evidence that chemical filters, such as activated carbon filters, may exert a distinctly bimodal activity pattern; chemical adsorbance changes rapidly to selective biological treatment. Bacteria embedded in corrosion flakes or slime (biofilms) may be undetectable on standard plate units, but may be infective after passing through an acid solution, such as gastric acid. Chemical contaminants are competitively adsorbed, concentrated and desorbed onto granular activated carbon (GAC) filters in pulses. Hence, grab samples of GAC-filtered water may be contaminant-free, while consumers may receive infrequent, concentrated pulses of poorly adsorbed contaminants. Little is known about the chemical interactions of organics captured on filters, contributions of fungi, viruses and phages, and medical effects of microorganism by-products. Quantitative characterization of effluent organics remains one of the biggest problems in determining the chemical and microbiological dynamics of recycle systems (refs. 52, 53, 54, and 55).

Organolepsis and the characterization of organoleptic properties of PW are both highly experimental. Organoleptic properties, however, will determine the particular ways that PW will be consumed (e.g., drinking water, juice, food) and ultimately affect total human exposures (refs. 56, 57, and 58).

Recent epidemiologic evidence suggests that public outbreaks of waterborne diseases are increasing in frequency. Standard tests for bacteria identify an etiologic organism in less than 5 percent of outbreaks. Up to 60 percent of outbreaks occur in the presence of repeatedly negative, standard bacterial tests. There is some evidence that encysted or spore-forming protozoa, bacteria and fungi may be favored in terrestrial partial reclamation/ recycle systems. Coliform tests are and will continue to be of use in detecting sewage contamination in the presence of inadequate disinfection. However, it is likely that, in the absence of a fecal contamination event, "environmental" bacteria such as *Pseudomonas*, *Flavobacteria*, *Legionella*, *Proteus* or *Serratia* will pose the greatest bacteriological challenge to PW recycle systems. Standard plate counts consistently underestimate these particular bacteria (refs. 59, 60, 61, and 62).

Pseudomonas is a ubiquitous and hardy organism which has been identified as a contaminant in "sterile" distilled water, chlorinated swimming pools and whirlpools, faucets, public PW stores, space experiments, and spacecraft PW supplies. Pseudomonads have been associated with a wide variety of human, animal and plant diseases, including a urinary tract infection in a U.S. astronaut (refs. 63, 64, and 65).

Flavobacteria have been cultured from distilled water, distilled water lines, drinking fountains, faucets, and humidifier water. They are sensitive to heat. *Flavobacteria* have been implicated in hospital deaths (ref. 66).

During outbreaks of Legionaire's Disease, *Legionella* has been identified in cooling tower water, evaporative cooler water, evaporative condenser condensates, hot water tanks, and public PW supplies. *Legionella* has not been specifically looked for in spacecraft PW supplies or during PW reclamation system ground tests. It has, however, been demonstrated to grow in nutritionally deficient media in the presence of *Flavobacteria*, and may yet prove to be a commensal or secondary invader of clinical significance in spacecraft PW recycling systems (refs. 67 and 68).

Environmental bacteria have been shown to grow, multiply and spread in plastic, corrosion tubercles, corrosion pits, PW pipe coatings, GAC beds and ion exchange resins. GAC devices may act much like biological trickle filter beds in providing an ideal medium onto which such bacteria can attach and multiply. Adsorbed inorganic/organic chemicals provide nutrients. Slime coats and multiple layers of bacteria can provide protection from disinfectants. A contaminated GAC may serve as an area for virulence (V) and/or resistance (R), plasmid selection, and transmission. Seeding of a recycle system would theoretically proceed (and has anecdotally proceeded) from this site and can rapidly overgrow a system (refs. 69, 70, 71, and 72).

Environmental bacteria produce metabolic by-products, many of which are offensive, irritating, toxic or mutagenic to humans, animals or plants. It is theoretically possible that PW recycle systems could concentrate

endotoxins, exotoxins and pyrogens depending on the physical/chemical characteristics of the by-products and the particular treatment method employed (ref. 73).

It is assumed that viruses are generally spread from person-to-person. However, if small quantities of infective virus are ingested by small numbers of people on a daily basis, this would also result in an epidemiological pattern consistent with person-to-person spread. In fact, waterborne transmission has been demonstrated for hepatitis A, polio, and several viral gastroenteritides. No public or spacecraft PW standards exist for viruses. It is generally assumed that if bacteria are absent, so are pathological viruses. However, infective viruses have been recovered from public PW treatment plants in the presence of negative coliform and plate counts, and in groundwater which has received reclaimed effluent. Active poliovirus in public PW treatment plant effluent has been recorded to increase 24-fold following community-wide Sabin poliovirus immunization. Animal tumor and plant disease viruses have been isolated from public PW treatment plant effluents. Friend Disease virus, a reticulum cell leukemia virus similar in many respects to HTLV III (AIDS virus), has been transmitted to mice via treated PW. Some pathogenic viruses, like cytomegalovirus, are shed in large quantities in human urine. Bacteriophages and plasmids may serve as virulence or resistance factor transmitters. In addition, viruses are capable of concentrating and surviving on GAC beds, electropositive filters and ion exchange resins. Such devices may serve as sites for viral seeding within a recycle system (refs. 74 and 75).

The environmental conditions present in water recycle systems may similarly favor growth and multiplication of certain fungi. *Cephalosporium* fungi are ubiquitous, hardy, and are capable of producing potent toxins. *Aspergillus* can produce aflatoxin, an extremely potent human carcinogen. *Candida* produces metabolic by-products which have been shown to increase co-bacterial infection and enhance the medical effects of bacterial toxins. Fungal metabolic by-products, like bacterial by-products, could theoretically be concentrated within a recycle system (refs. 76 and 77).

The physical, chemical and medical properties of iodine disinfection productions are poorly understood. *Pseudomonas* has been cultured in iodine ampules. Little is known about the interaction of iodine with residual organics and resultant polyhalomethane production. Iodine exhibits potent physiological activity in man. The effects of iodine disinfection products on human, animal and plant metabolism are largely unknown (refs. 78, 79, and 80).

SUMMARY AND RECOMMENDATIONS

Summary

Present NASA PW Specifications developed for non-recycled water are inadequate for reclaimed/recycled (RR) PW systems. RR PW Specifications must be defined to appropriately direct Space Station LSS/CELSS development. The magnitude and complexity of this effort will probably require designation as a separate Research and Technology Operation Program.

Summary Recommendations

In order to currently support development of Space Station LSS/CELSS technologies, an intensive, joint, priority effort between the Johnson Space Center Life Sciences, the Johnson Space Center and Marshall Space Flight Center Engineering, and Ames Research Center Life Sciences will have to be undertaken to

1. Develop a detailed knowledge base on biomedical effects of iodinated, reclaimed/recycled water
2. Define Interim RR PW Specifications
3. Perform necessary basic science experiments
4. Perform appropriate tests of existing hardware systems
5. Standardize and certify RR PW testing methods and procedures
6. Develop appropriate methods and procedures for inflight monitoring

Knowledge Base

This memorandum is meant to serve as a starting point for developing an engineering/life sciences knowledge base on PW RR technology. It should be augmented with refereed papers on U.S. and foreign PW RR systems and system analogs. Requests for information should be made to the NAS, U.S. EPA, and DOD for similar information. Scientists currently involved in PW RR system research need to be identified. U.S. DOD classified literature needs to be searched for information on closed environments such as submarines, missile launch facilities, and hardened command facilities. National/international meetings on PW RR or RR technology need to be identified. Key research sites, groups, scientists or meetings need to be selected, visited and informed of NASA's interests. The world literature needs to be searched and summarized regarding (1) the biomedical effects of iodine disinfection products, and (2) optimal crew, test-animal and space station plant metabolic requirements, individually and collectively.

Interim Reclaimed/Recycled Potable Water Specifications

A set of interim medical RR PW Specifications must be developed for humans. In addition, comparable biomedical specifications must be developed for animals and plants likely to be present on the Space Station. Metabolic requirements for PW users need to be determined individually and collectively. Total contaminant exposures from all sources, including water, and food and air, need to be projected based on actual and projected mission exposures. Mission exposures must be calculated based on 24-hour exposure, should include contaminants likely to occur from spacecraft and PW system construction materials, and need to reflect NASA and Soviet PW RR system preprototype experience. NAS quality criteria for water reuse data needs to be incorporated where appropriate. Preferential qualitative and quantitative PW organoleptic specifications need to be specified. A set of Interim RR PW Specifications for Space Station inhabitants based on recal-

culated MCL's, (and where appropriate, MNC's and OTC's) which take into account NASA PW consumption and co-exposure data, need to then be formalized. Specifications need to be consistent with presently available influent, effluent and/or "at the tap" standard testing methodologies, with special emphasis on inorganic, organic, bacterial, viral, and fungal contaminants. Indicators for low molecular weight organics (which may be "carried over" with water during the reclamation), high molecular weight organics (e.g., steroids, antibiotics), inorganic/ organic substances which are selectively retained in the concentrator loop (e.g., may become present in effluent with wear-and-tear), key bacterial contaminants (including *Pseudomonas*, *Flavobacterium*, and *Legionella*), viruses, and fungi will need special consideration. The best bacterial and fungal indicators may be their unique metabolic by-products. The best viral indicators may be oral vaccine viruses introduced periodically into influent.

Basic Science Experiments

Several areas are of fundamental importance to the development and eventual certification of PW RR Specifications and need to be examined:

1. Properties of liquids moving in pipes in microgravity (MG)
 - (a) corrosion buildup
 - (b) particulate deposition
2. Properties of MG colloidal suspensions
 - (a) gas bubbles in water
 - (b) liquid droplets in water
 - (c) solid particles and aggregates in water
 - (d) mixed colloid interactions
3. Properties of substances adsorbed onto surfaces
 - (a) piping and joints
 - (b) filters and filter beds
 - (1) pulsing phenomenon
 - (2) MG bacterial/viral activities
 - (3) plasmid interchange
 - (c) biofilms
4. Properties of surfactants in MG

5. The medical and biological effects of consuming iodine and iodine disinfection products need to be experimentally evaluated and validated.

6. Organoleptic parameters critical to consumption need to be elucidated for humans, animals and plants.

7. Specific research experiments need to be devised and executed to elucidate the effect, if any, these particular physical properties might have on RR PW systems.

Testing Existing Hardware

Interim PW RR Specifications need to be tested against existing system prototype hardware. Techniques for sampling, testing, quality assurance, and evaluation of PW RR Specifications and hardware operation need to be critically defined, pretested, documented, and vigorously rehearsed. Present hardware will need to be adapted for sampling. Whenever possible, non-invasive sampling methodology should be incorporated. Real-time mechanisms for sensing, sampling and examination of components without interruption of operation or introductions of contamination need to be evaluated and incorporated into systems engineering.

Initially, unmanned PW reclamation tests need to be done on paired influent/effluent samples taken at fixed intervals during continuous system operation. Samples should be taken until influent and effluent physical, chemical and microbiological equilibriums are established. Similar testing will need to begin as soon as possible throughout the life expectancy of the system. Hardware and Interim PW RR Specifications will probably need to be revised periodically throughout this phase to reflect experience with actual PW RR hardware.

Unmanned PW reclamation tests need to be performed challenging differing influent/effluent reclamation prototype system hardware with specific substances of biomedical concern. Sterile ultradistilled water (or other appropriate negative controls) needs to be used for comparison purposes. Challenge substances should include at least the following:

1. Iodinated water
2. Concentrator loop water
3. Particulate colloidal solutions
4. Solvents which will probably be used on the Space Station
5. Volatilized organics which tend to condense like water
6. Human steroids (e.g., premarin)
7. Antibiotics commonly excreted in urine (e.g., ampicillin)
8. Atmosphere humidity condensate

9. Space suit coolant concentrate
10. Space suit humidity condensate
11. Washwater
12. Spacecraft wastewater
13. *Lactobacillus* or *E. coli* bacteria
14. *Pseudomonas* bacteria
15. Sabin oral poliovirus (vaccine)
16. *Aspergillus* fungi
17. Endotoxin/exotoxin analogs

During this period, plants which may be introduced into the Space Station as experiments or for food production should be evaluated and tested to determine if bioaccumulation of substances of concern is likely.

Testing and Monitoring

As open-loop testing nears completion, testing methodologies need to be revised for microcomputerized, online, real-time monitoring. Prototype systems may need to be reengineered to accommodate such.

Unmanned, closed-loop, integrated LSS/CELSS system recycle tests using animals, bioaccumulator plants, and plants which may eventually be cultivated for human consumption tracer tests, will need to be conducted. Atmospheric contamination tracer tests will need to be considered if humidity condensate to PW reclamation is anticipated. Testing should be done *in situ* and should allow parallel evaluation of monitoring techniques. These tests will need to be run continuously until system equilibrium is reached. Test animals, test plants, cultivated plants, and effluent equilibrium concentrates need to be subjected to standardized, toxicological testing. Determination of common and biologically significant substances and the establishment of their dose-response curves will need to be accomplished to substantiate MCL's and interim PW RR Specifications. It is likely that PW RR Specifications will undergo major revision at this stage. Hardware, monitoring and testing may need corresponding revision. A reasonable list of organic substances of concern for spacecraft PW RR should result. Final PW RR Specifications will need to be promulgated. Specific plant bioaccumulators may be selected to act as total accumulated exposure indicators for key substances in man.

Manned, Closed Testing of Integrated LSS/CELSS Systems

Continuous, closed-loop, integrated LSS/CELSS system recycle tests using human test subjects and bioaccumulator test plants will need to be conducted to system equilibrium, and should be extended to include at least

the duration of likely operation aboard the Space Station. Selected biomedical tests including enzyme-activity assays for key organ systems (e.g., fat, muscle, bone, liver, hair, nail and other analyses) need to be correlated with bioaccumulator plant results for later inflight use.

Flight-Testing of Prototype and Operational LSS/CELSS Systems

Water recycle technology represents a new technology largely without precedent. Prototype and/or operational LSS/CELSS systems should be flight-tested in parallel with existing life support systems prior to certification. Where this is not possible, such systems should be regarded as experimental until sufficient inflight experience is obtained. It is likely that the Space Station LSS will represent a first milestone in advanced LSS design and will utilize mainly physical/chemical processes. It would seem wise to engineer the operational LSS system to accommodate rapid advancement towards a combined physical/chemical/biological CELSS necessary for long-duration missions (e.g., Moon base, Mars). For instance, provision should be made for inflight modification of the Space Station LSS to test physical, chemical and biological subsystems in parallel without requiring major engineering redesign.

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APPENDIX A

NASA POTABLE WATER SPECIFICATION (MSC-SPEC-SD-W-0020 MAY 16, 1970)

4.1 WATER PROPERTIES

The potable water shall meet the following specific requirements:

<u>Properties</u>	Limits:	
	<u>Maximum Allowable Concentrations</u>	<u>Test Paragraph</u>
Ph	6.0-8.0 at 25° C (77° F)	4.3.1.1
Total Solids	TBD but <500 mg/liter	4.3.1.2
Total Organics	TBD	4.3.1.3
Taste and Odor	None at Threshold (Odor No. of 3)	4.3.1.4
Turbidity	11 units	4.3.1.5
Color, True	15 units	4.3.1.6
Particulate	TBD	4.3.1.7

Ionic Species

Cadmium	0.01 mg/liter
Chromium (Hexavalent)	0.05 mg/liter
Copper	1.0 mg/liter
Iron	0.3 mg/liter
Lead	0.05 mg/liter
Manganese	0.05 mg/liter
Mercury	0.005 mg/liter
Nickel	0.05 mg/liter
Silver	0.05 mg/liter
Zinc	5.0 mg/liter
Selenium	0.01 mg/liter

Microbial Control

Positive microbial control is required throughout the potable water system. The agent or mechanism of this control shall be determined by system requirements and shall require the approval of the MSC Medical Research and Operations Directorate.

Sterility

Free of viable organisms 4.3.2
(as defined in paragraph 3.0)

Note: Specific system designs may necessitate the inclusion of other water property requirements in the above listing.

4.2 SAMPLING

4.2.1 Containers For Samples

The water samples for analysis shall be collected in containers approved by the MSC Medical Research and Operations Directorate. The collection containers shall be chemically inert and nonbreakable and shall be prepared according to instructions supplied by MSC.

4.2.2 Sampling Technique

Standard aseptic technique will be used in collecting water samples for analysis.

4.3 ANALYSES

Analysis of the water shall conform to established laboratory methods and shall be performed by a laboratory approved by the Medical Research and Operations Directorate.

4.3.1 Chemical And Physical Analyses

4.3.1.1 pH

The pH shall be determined per ASTM D 1293, taking special precautions to exclude the atmosphere during test. On line on-site analysis shall be performed where possible.

4.3.1.2 Total Solids

Total solids shall be determined by a gravimetric technique. The maximum allowable concentration will be established by system operational requirements yet must not exceed 500 mg/l.

4.3.1.3 Total Organics (COD, BOD, TOC)

Total organics shall be determined by standard laboratory technique. The maximum allowable concentration will be established by specific system requirements, yet shall not exceed 100 mg/l.

4.3.1.4 Taste And Odor

Taste and odor shall be determined per the method described on page 304 of Standard Methods for the Examination of Water and Wastewater (12th Edition).

4.3.1.5 Turbidity

Turbidity shall be determined using the nephelometric turbidity procedure described in ASTM D 1889.

4.3.1.6 Color

Color shall be determined using the method described in paragraph 1.4 on page 127 of Standard Methods for the Examination of Water and Wastewater.

4.3.1.7 Particulates

The particulate levels shall be determined by standard particle count methods. The maximum allowable concentration will be established by individual system operational requirements.

4.3.2 Sterility/Microbiological Analyses

If samples for microbiological analyses are not processed within 30 minutes following collection, the samples must be refrigerated at 4° - 6°C. If the waste contains chlorine or iodine, a sufficient amount of 0.1% solution of sterile sodium thiosulfate is added to the sample container to result in a concentration of 100 mg/liter of the sodium thiosulfate.

General: Aseptic technique within a Class 100 clean bench or equivalent will be employed throughout the analyses. Any organisms cultured at KSC in the following analyses will be shipped to MSC in biological shipping containers for identification.

4.3.2.1 Aerobic Analysis

The three 150 ml aliquots for the following microbiological analyses shall be obtained from a 500 ml minimum volume microbiological sample. Each aliquot shall be passed through a 35 mm 0.45 micron membrane filter, Millipore HAWG (for yeast and molds) or equivalent.

4.3.2.1.1 Total bacterial count.- Total bacterial count shall be performed according to procedures described in Standard Methods for the Examination of Water and Wastewater, N.Y., 12th Edition, 1965, and/or by the following membrane filter method: Filter, aseptically 150 ml of the water sample through a membrane filter monitor. Remove excess water from the membrane filter monitor using a syringe and extracting the water from the discharge end of the monitor. Disconnect the syringe and add 0.8 ml of M-TGE Broth (Difco or equivalent) into the discharge end of the monitor. Replace monitor plugs, invert, and incubate at 35° ± 0.5°C. (Membrane filters should always be incubated in 100% humidity). Count total number of bacteria on pad at 24 and 48 hours. Report out as the number of colonies per 150 ml of water. Serial dilutions of a minimum of 1:100 and 1:10,000 will be conducted in addition to the zero dilution above. If growth is observed, the sealed monitor will be shipped to MSC.

4.3.2.1.2 Coliform counts.- Coliform counts shall be performed according to procedures outlined in Standard Methods for the Examination of Water and Wastewater, N.Y., 12th Edition, 1965, and/or by the following membrane filter method: Filter, aseptically, 150 ml from the sample container through the membrane filter monitor. Remove excess water from the membrane filter monitor using a syringe and extracting the water from the discharge end of the monitor. Disconnect the syringe and add 0.8 ml of M-F Endo Broth into the discharge end of the monitor. Replace monitor plugs, invert, and incubate at $35^{\circ} \pm 0.5^{\circ}\text{C}$. Count total number of coliform colonies at 18 to 24 hours and report out as the number of colonies per 150 ml of water. If growth is observed, the sealed monitor will be shipped to MSC.

4.3.2.1.3 Yeast and mold.- Filter, aseptically, 150 ml from the sample container through the membrane filter monitor with black filter (Millipore MHBC or equivalent). Remove excess water from the membrane filter monitor using a syringe and extracting the water from the discharge end of the monitor. Disconnect the syringe and add 0.8 ml of M-Green Yeast and Mold (Difco or equivalent) into the discharge end of the monitor. Replace monitor plugs, invert, and incubate at $30^{\circ} \pm 1^{\circ}\text{C}$ for 48 hours. Count and report number of yeasts and molds per 150 ml of water sample. Cultures will be transferred to Sabouraud agar slants prior to shipment to MSC.

4.3.2.2 Anaerobic Analysis

An anaerobic analysis will be conducted by transferring, aseptically, 1 ml of water into a tube of fluid thioglycollate medium which has been freshly prepared. Do not mix. Incubate at $35^{\circ} \pm 0.5^{\circ}\text{C}$ for 48 hours. Examine for growth. Report growth as positive or negative growth. If any growth is observed, a portion of the growth will be transferred with a sterile loop to a tube of transport medium (Stuart or equivalent) and incubated for at least 12 hours prior to shipping to MSC.

4.4 If the ground test or flight mission purpose does not involve verification of acceptance for human consumption or will be used for human consumption, the water need not meet the requirements of paragraph 4.1.

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16. Abstract Water used during current and previous space missions has been either carried or made aloft. Future human space endeavors will require some form of water reclamation and recycling. There is little experience in the U.S. space program with this technology. Water reclamation and recycling constitute engineering challenges of the broadest nature that will require an intensive research and development effort if this technology is to mature in time for practical use on the proposed U.S. Space Station. In order for this to happen, reclaimed/recycled water specifications will need to be devised to guide engineering development. Present NASA Potable Water Specifications are not applicable to reclaimed or recycled water. Adequate specifications for ensuring the quality of the reclaimed or recycled potable water do not exist either within or outside of NASA. NASA experience with potable water systems is reviewed, limitations of present water specifications are examined, world experience with potable water reclamation/recycling systems and system analogs is reviewed, and an approach to developing pertinent biomedical water specifications for spacecraft is presented. Space Station water specifications should be designed to ensure the health of all likely spacecraft inhabitants including man, animals, and plants, both separately and collectively.					
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