

## Water Chemistry Monitoring

**Lizanna M. Pierre, John R. Schultz, Ph.D.**  
**Sandra E. Carr, Richard L. Sauer, P.E.**

### SUMMARY

The Lunar-Mars Life Support Test Project (LMLSTP), within the Advanced Life Support Program, is the first time NASA has attempted the direct recycle of water for human consumption since the late 1960's. The direct recycle of potable water from urine, wash water, and humidity condensate, as planned for International Space Station and future planetary missions, is not practiced on Earth. This is partially due to concern over the health impact of incomplete removal of potential contaminants in the recovered water. Since direct recycle is not an established practice, the United States Environmental Protection Agency has not developed water quality standards for recycled water. Thus, NASA has established its own stringent requirements for recycled water.

The Medical Operations Water and Food Analytical Laboratory (WAFAL) of the Medical Sciences Division of NASA Johnson Space Center (JSC) was responsible for ensuring that the quality of water generated during the LMLSTP chamber studies was medically acceptable for human consumption. As a result, water quality monitoring and technical support for the development of water recycling systems were provided from the inception of Phase I (1994) through the Phase III test (1997). A comprehensive water sampling and analysis protocol was accomplished to verify that the NASA requirements were met. Salient indicator quality parameters such as total organic carbon (TOC), pH, conductivity, total microbial content, color, iodine, turbidity, and trace metals were verified to ensure requirements were met before the water was consumed. Comprehensive organic analyses for volatile organic compounds, semivolatile organic compounds, alcohols, amines, carboxylates, formaldehyde, urea, glycols, anions, and cations were also performed. If the requirements were not met, the water was reprocessed until they were met. In addition to the water analyses, the test subjects were monitored to ensure that no health changes occurred. Analyses were also provided for nonpotable water sources, such as in-process samples, atmospheric moisture (humidity condensate), and plant condensate, to support engineering evaluations.

During Phase I, potable water was provided from the facility's public water supply system and was not recycled. For Phases II and IIa, potable water was generated from the recycle of wastewater using physicochemical methods, while Phase III water recycling systems were based on a combination of physicochemical and biological recovery systems. For each chamber study, trained crewmembers collected samples for chemical analysis using WAFAL-provided sampling equipment. After collection, samples were then transferred from the test facility to WAFAL for chemical analysis and to the microbiology laboratory for microbial analysis. Chemical results are reported in this chapter, while microbial results are reported in Chapter 4.3. With the exception of minor exceedances, the test provided water for consumption that met the established NASA potability requirements for recycled water. On numerous occasions, however, this required that the water be reprocessed in order to meet these requirements. Most of the reprocessing excursions were required due to high total organic carbon (TOC) and microbial content. On several occasions reprocessing was required due to high nickel and lead.

### **Introduction**

A major goal of the Advanced Life Support Program is to develop and validate technologies for regenerative life support systems for long-duration space missions (lunar, Mars, and orbital). One of the regenerative systems needed to achieve this goal is the water recovery system to produce potable water from various wastewaters. During the course of the chambers project, four separate and distinct tests with human test subjects were conducted, each progressively more complex in terms of the water recovery system.

Within the Medical Sciences Division, the Medical Operations' Water and Food Analytical Laboratory participated in the design, development, and testing of the water recovery systems for the LMLSTP. Specifically, WAFAL was responsible for: 1) providing assistance with the design of the water recovery systems, 2) providing analytical support for the testing of hardware components and the integrated systems, 3) developing water quality standards and monitoring requirements, and 4) supporting technology development through the analysis of humidity condensate and other liquids.

Water quality standards and monitoring requirements for the chamber studies were based on U.S. Environmental Protection Agency (EPA) standards and NASA Man-Systems Integration Standards (MSIS) (NASA-STD-3000), a set of standards specifically developed by NASA for recycled water (1). These standards were developed to document relevant human engineering requirements applicable to the space environment and are listed in Table 4.2-1. U.S. EPA standards are legally enforceable regulations levied by the U.S. government on water supplied by public water systems (2). In addition, the EPA provides health advisories and MCL goals which are non-enforceable guidelines for drinking water. Health advisories are estimates of acceptable drinking water levels for a chemical substance based on health

effects information; a health advisory is not a legally enforceable federal standard, but serves as technical guidance to assist federal, state, and local officials (2). NASA uses these advisories and MCL goals as required and to the extent possible to determine the acceptability of recycled water.

*Table 4.2-1 NASA Man System Integration Standards, Rev B, Volume III*

<b>Parameter</b>	<b>Units</b>	<b>Potable Maximum Contaminant Level</b>	<b>Hygiene Maximum Contaminant Level</b>	<b>U.S. EPA Maximum Contaminant Level</b>
<b>Physical Parameters</b>				
Total solids	mg/L	100	500	
Color True	Pt-Co	15	15	
Taste	TTN	3	–	
Odor	TON	3	–	
Particulates (maximum size)	micron	40	40	
pH		6.0-8.5	5.0-8.5	
Turbidity	NTU	1.0	1.0	
Iodine	mg/L	0.5-4.0	0.5-6.0	
Total I	mg/L	15	15	
<b>Trace Metals</b>				
Arsenic	µg/L	10	10	50
Barium	µg/L	1000	1000	2000
Cadmium	µg/L	5	5	5
Chromium	µg/L	50	50	100
Copper	µg/L	1000	1000	1300
Iron	µg/L	300	300	
Mercury	µg/L	2	2	2
Manganese	µg/L	50	50	
Nickel	µg/L	50	50	100 (HA)
Lead	µg/L	50	50	15
Selenium	µg/L	10	10	50
Silver	µg/L	50	50	100 (HA)
Zinc	µg/L	5000	5000	2000 (HA)

HA = Health Advisory

EPA Drinking Water Standards and Health Advisories, October 1996, EPA 822-B-96-002

*Table 4.2-1 continued NASA Man System Integration Standards, Rev B, Volume III*

<b>Parameter</b>	<b>Units</b>	<b>Potable Maximum Contaminant Level</b>	<b>Hygiene Maximum Contaminant Level</b>	<b>U.S. EPA Maximum Contaminant Level</b>
<b>Physical Parameter</b>				
<b>Anions</b>				
Chloride	mg/L	200	200	
Nitrate (NO <sub>3</sub> as Nitrogen)	mg/L	10	10	10
Sulfate	mg/L	250	250	500
Sulfide	mg/L	0.05	0.05	
<b>Cations</b>				
Ammonium (as N)	mg/L	0.5	0.5	30 (HA)
Magnesium	mg/L	50	50	
Calcium	mg/L	30	30	
Potassium	mg/L	340	340	
Total Acids	µg/L	500	500	
Cyanide	µg/L	200	200	200 (HA)
<b>Halogenated</b>				
Hydrocarbons	µg/L	10	10	
Total Phenols	µg/L	1	1	
Total Alcohols	µg/L	500	500	
<b>Total Organic Carbon (TOC)</b>				
Uncharacterized TOC	µg/L	100	1000	

HA = Health Advisory

EPA Drinking Water Standards and Health Advisories, October 1996, EPA 822-B-96-002

## Methods

For each chamber study, potable water samples were collected and analyzed during pretest, test, and post test operations. Samples were collected using WAFAL-provided sampling equipment consisting of benzalkonium chloride disinfectant wipes (PDI, Orangeburg, NY), cleaned Teflon® sample bottles, and labels. To collect a sample, the sample port was disinfected using a wipe. Next, approximately 250 ml of fluid was purged from the sample port and discarded. Then, 1000 ml of fluid was collected into a prelabeled sample bottle. The sample bottle

was transferred as soon as possible (usually within six hours) from the sample location to the laboratory for analysis. Upon receipt at the WAFAL, the sample was allocated and preserved according to the WAFAL Water Sample Receiving, Allocation, Preservation, and Storage Procedure (3).

Samples of recycled water collected from the potable water storage tanks during the chamber studies were analyzed for pH, turbidity, iodine, color, conductivity, anions, cations, trace metals, total organic carbon (TOC), volatile organics, semivolatile organics, alcohols, formaldehyde, amines, carboxylates, organic acids, diols (glycols), and urea. These samples were analyzed in an attempt to characterize at least 80% of the organic components of the recycled water. Other samples, such as the shower, galley, handwash sink, wastewater feed to the Water Recovery System (WRS), and effluent samples from many of the WRS subsystem components were also collected at various stages in the water treatment process. These samples were analyzed for a number of inorganic and organic parameters to verify system performance at various stages of water recovery and to collect data for future reference.

Analytical methods used for the analysis of water samples during the chamber studies were based on instrument manufacturer instructions, procedures outlined in Standard Methods for the Examination of Water and Wastewater (4), published methods from EPA, and other methods developed in the laboratory. Conductivity, pH, turbidity, and total organic carbon (TOC) were measured following standard methods and manufacturer instructions. Two instruments were used to measure TOC, a Sievers Model 800 TOC analyzer or an O.I. Analytical Model 1010 TOC analyzer.

Semivolatile organic compounds were assessed by the EPA 625 solvent/solvent extraction GC/MS method with a Hewlett Packard (HP) 5890 Series II GC coupled directly to a HP 5971 MSD. Three 15 ml methylene chloride extractions of a 500 ml sample were made at a pH of 11 or higher to obtain the base/neutral fraction. For the acid fraction, the pH of the sample was lowered to 2 or less and the sample was again extracted with methylene chloride. The extracts were dried with anhydrous sodium sulfate and concentrated to 0.5 ml with a Zymark TurboVap II automatic concentrator. An internal standard was added and the concentrated samples were analyzed. Extraction recoveries were assumed to be 100% and when a compound was extracted into both the base/neutral and acid fractions, each fraction was added together to get the total concentration for that compound.

Volatile organics analyses were determined by a headspace GC/MS method using a target list consisting of the EPA Method 624 compounds along with 24 additional compounds (4, 7). The system consisted of an HP 7694 headspace sampler attached to a HP 5890 Series II gas chromatograph coupled directly to an HP 5972 mass selective detector. The 5890 GC was equipped with an electronic pressure controlled inlet that was set to constant flow mode, with vacuum compensation on. Before analysis, each sample was equilibrated by agitating and heating the sample at 85°C for 15 minutes. Then a 3 ml volume of the headspace from each sample vial

was transferred to the instrument for analysis. Targeted compounds were confirmed and quantified using a five level calibration curve.

Iodine, iodide, triiodide, and hypoiodous acid were measured with a Shimadzu UV-265 UV-visible spectrophotometer, according to a method described by Schultz et al (5). In cases where contaminants in the sample interfered with the analysis, a leuco crystal violet method was used (4). Color was assessed using a Shimadzu spectrophotometer at an absorbance of 455 nm (6). Color levels in the samples were quantified using calibration curves generated with dilutions of a platinum-cobalt color standard.

Trace metals were determined by graphite furnace atomic absorption (GFAA) analysis with a Thermo Jarrell Ash Smith/Hiefje 400 atomic absorption spectrophotometer, according to standard methods (4). Formaldehyde was determined by direct aqueous phase *o*-2,3,4,5,6-pentafluoro-benzyl hydroxylamine (PFBHA) liquid-liquid extraction with a HP 5890 Series II GC coupled directly to an HP 5971 MSD, (8, 9). Five milliliters of sample were reacted with PFBHA, extracted with 0.5 ml of hexane, and chromatographed.

Cations, anions, diols, urea, amines, carboxylates, and alcohols were assessed using methods developed in-house. Inorganic anions and cations were assessed by ion chromatography using a Dionex 4000I ion chromatograph (IC). Direct aqueous injection GC/MS with a HP 5890 Series II GC coupled directly with an HP 5971 MSD was used to measure six C1-C4 alcohols. A 0.5 ml aliquot of sample and calibration curve standards were analyzed and quantified in the selected ion mode. A Waters quanta 4000 capillary electrophoresis unit (CE), was used to measure methyl, ethyl, and *n*-propyl amine and 5 C1-C4 carboxylic acids. Samples were injected onto a capillary and analyzed using 2.5 mM potassium hydrogen phthalate and 0.25 mM tetradecyl-trimethylammonium bromide electrolytes. Analytes were detected by indirect UV absorbance at 214 nm. Calibration and peak determination were performed by spiking with standard solutions of the targeted compounds.

## Findings

### *Phase I*

The main objective of this test was to verify the ability of a wheat crop to provide air revitalization to a crewmember for 15 days (10). Water recycling was limited to condensation of humidity from the air (human respired air, evaporation, plant transpiration). This recovered water, known as humidity condensate, was used to rehumidify the Variable Pressure Growth Chamber (VPGC) plant growth area and airlock, or to provide water for replenishing the plant nutrient solutions. No recovered water was used for human consumption during this test.

In preparation for Phase I, a system checkout pretest was conducted in April 1995 using a human metabolic simulator (HMS) in place of the human test subject. During this pretest, the HMS was sealed inside the airlock compartment of the VPGC while a crop of wheat was grown in the plant chamber. Two samples of

plant atmospheric moisture (condensate) were collected from the condensate collection tanks located on the outside of the VPGC, one from each side of the chamber (sides A and B).

For the actual Phase I test, a human test subject lived in the airlock compartment for 15 days while a crop of wheat grew in the plant chamber. Potable water was not recycled during Phase I. Drinking water for the crewmember consisted of water from the JSC public water supply that was deionized, filtered using a 0.2 µm microbial filter, and iodinated using a microbial check valve (MCV) to simulate spacecraft water supplies with iodine as the disinfectant (11). Two potable water samples were taken from the faucet at the sink in the airlock compartment of the VPGC: one before the start of the test and one at the end of the test. Four additional samples were collected in response to crewmember comments concerning a distinct iodine taste and odor. One of these samples was taken at the inlet of the MCV and another at the outlet of the MCV. Two more were taken at the outlet at the sink. A summary of the potable water analytical results obtained during Phase I is listed in Table 4.2-2.

*Table 4.2-2 Phase I Potable Water Results*

Parameter	Units	Minimum Concentration	Maximum Concentration	Average Concentration	n
<b>Physical Parameter</b>					
pH		4.38	4.80	4.59	2
Conductivity	µS/cm	3.52	11.57	7.54	2
Turbidity	NTU	0.003	0.057	0.03	2
Total Solids	mg/L	5.5	56	30.75	2
<b>Iodine</b>					
I <sub>2</sub>	mg/L	0.03	5.42	3.16	6
I <sub>3</sub> <sup>-</sup>	mg/L	0.00	0.05	0.03	6
I <sup>-</sup>	mg/L	0.00	2.96	1.11	6
HOI	mg/L	0.00	6.50	3.48	5
Total I	mg/L	3.30	13.00	8.62	5
<b>Trace Metals</b>					
Arsenic	µg/L	ND	3.8	2.8	6
Chromium	µg/L	ND	1.8	0.4	5
Copper	µg/L	ND	3.7	0.7	5
Iron	µg/L	ND	9.6	4.7	5
Manganese	µg/L	ND	1.6	0.5	5
Molybdenum	µg/L	ND	1.3	0.3	5

Table 4.2-2 continued Phase I Potable Water Results

Parameter	Units	Minimum Concentration	Maximum Concentration	Average Concentration	n
<b>Physical Parameter</b>					
Lead	µg/L	ND	0.6	0.1	5
Selenium	µg/L	ND	3.2	2.5	5
Zinc	µg/L	0.3	13.2	3.3	5
<b>Anions (IC)</b>					
Chloride	mg/L	ND	0.130	0.065	2
<b>Cations (IC)</b>					
Ammonium					
(as Nitrogen)	mg/L	ND	0.0008	0.0004	2
<b>Total Organic Carbon</b>					
Total Inorganic					
Carbon	mg/L	0.255	0.371	0.313	2
Purgeable Organic					
Carbon	mg/L	<0.028	0.005	0.025	2
Nonpurgeable					
Organic Carbon	mg/L	0.244	0.427	0.336	2
Total Organic Carbon	mg/L	0.244	0.432	0.338	2
<b>Volatile Organics</b>					
Acetone	µg/L	1.50	7.75	4.63	2
2-Butanone	µg/L	12.47	39.79	26.13	2
Iodomethane	µg/L	ND	1.31	0.66	2
Tetrahydrofuran	µg/L	19.52	24.07	21.80	2
<b>Extractable Organics</b>					
Benzothiazole	µg/L	ND	2.3	1.2	2
2-(2-Butoxyethoxy) ethanol acetate	µg/L	ND	2.0	1.0	2
Butylated hydro- xyanisole (BHA)	µg/L	ND	1.3	0.7	2
3-t-Butylphenol	µg/L	ND	1.6	0.8	2
4-Chloro-3,5 dimethylphenol	µg/L	ND	0.5	0.3	2
Cyclohexanone	µg/L	1.0	2.5	1.8	2
Decamethylcyclo- pentasiloxane	µg/L	ND	0.9	0.5	2
Di-n-butylamine	µg/L	ND	25.1	12.6	2
n,n-Dibutylformamide	µg/L	ND	0.90	0.45	2
2,6-Di-t-butyl-1, 4-benzoquinone	µg/L	ND	2.7	1.4	2

*Table 4.2-2 continued Phase I Potable Water Results*

Parameter	Units	Minimum Concentration	Maximum Concentration	Average Concentration	n
<b>Physical Parameter</b>					
3,5 Di-t-butyl-4-hydroxybenzaldehyde	µg/L	0.2	0.4	0.3	2
2,4-Di-t-butylphenol	µg/L	ND	0.1	0.1	2
Dibutyl phthalate	µg/L	ND	0.5	0.3	2
Diethyl phthalate	µg/L	ND	0.6	0.3	2
Diiodomethane	µg/L	ND	1.4	0.7	2
Dimethyl phthalate	µg/L	ND	0.2	0.1	2
Diocetyl phthalate	µg/L	ND	5.8	2.9	2
Dipropylene glycol methyl ether	µg/L	ND	76.3	38.2	2
2-Ethyl-1-hexanol	µg/L	ND	1.5	0.8	2
bis-2-ethylhexyl ester adipic acid	µg/L	ND	0.2	0.1	2
2-Hexanol	µg/L	ND	3.3	1.7	2
Iodoform	µg/L	ND	8.8	4.4	2
Methyl sulfone	µg/L	ND	4.6	2.3	2
4-t-Octylphenol	µg/L	ND	1.0	0.5	2
Octamethyl-cyclotetrasiloxane	µg/L	ND	0.1	0.1	2
Phenol	µg/L	ND	5.1	2.6	2
2-Phenylphenol	µg/L	ND	2.2	1.1	2
2-Phenyl-2-propanol	µg/L	ND	0.4	0.2	2
Toluene	µg/L	1.6	3.9	2.8	2
<b>Aldehydes</b>					
Formaldehyde	µg/L	9.5	12.6	11.1	2
<b>Carboxylates</b>					
Formate	µg/L	ND	560	280	2
Acetate	µg/L	ND	140	70	2
<b>Organic Carbon Recovery</b>	percent	13.03	132.76	72.90	2

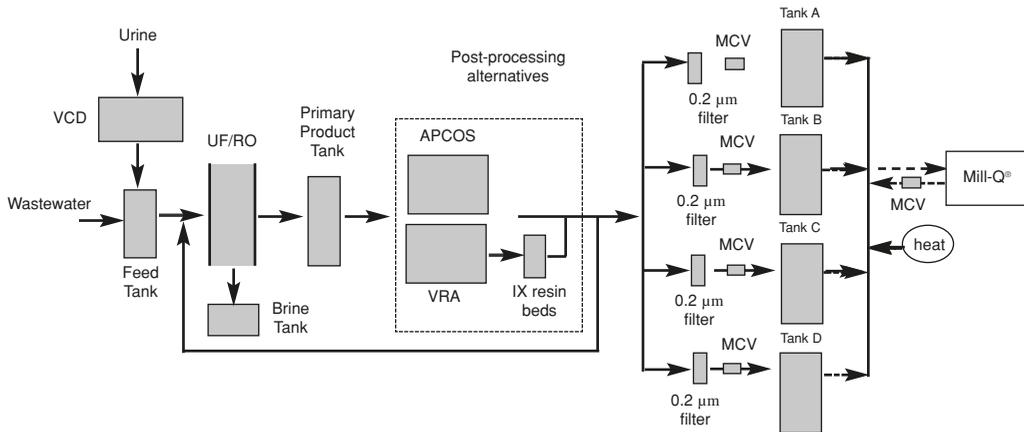
The potable water analysis results show that all chemical parameters met the U.S. EPA water quality specifications. Although the Phase I water source was the JSC public water supply, the results were also compared to the NASA Man-System Integration Standards for recycled water. The potable water samples did not meet MSIS specifications for pH, iodine, and total phenols. The pH of samples collected before and after the test were 4.80 and 4.38, respectively, as compared to the MSIS requirement range of 6.0 to 8.5. This low pH was due to the addition of

iodine to the potable water. Iodine added to water hydrolyzes to hypiodous acid and iodide, forming a slightly acidic solution. Iodine also imparts a yellowish-brown color to the water as well. Iodine results ranged from 0.33 to 5.42 mg/L. The MSIS specification for this parameter is 0.5 to 4.0 mg/L, which is considered the desirable range for taste considerations and microbial control. The sample collected at the end of the test had 10.4  $\mu\text{g/L}$  of total phenols, which exceeded the MSIS limit of 1  $\mu\text{g/L}$  for total phenols. This amount included 5.1  $\mu\text{g/L}$  phenol, 1.6  $\mu\text{g/L}$  3-t-butylphenol, 0.5  $\mu\text{g/L}$  4-chloro-3,5-dimethylphenol, 1.0  $\mu\text{g/L}$  4-t-octylphenol, and 2.2  $\mu\text{g/L}$  2-phenylphenol. None of these were a health concern at the levels detected. The source of these phenol compounds is unknown, and the MSIS phenol specification is presently under review.

To determine the amount of organic material that could be accounted for through the analysis of individual organic compounds present, the percent of organic carbon recovered was calculated. This was accomplished by adding the organic carbon content of each individual organic compound detected. This value was then divided by the measured TOC, thus giving the percent of organics recovered. Total organic carbon levels for the six samples analyzed ranged from 244 to 432  $\mu\text{g/L}$ , while the organic carbon recovery for the sample collected before the start and after the end of Phase I was 13% and 133%, respectively.

### *Phase II*

The main objective of this test was to verify the performance of integrated physicochemical air revitalization, water recovery, and thermal control systems for a four-person crew for 30 days (12). Humidity condensate and wastewater from the shower, handwash, galley, laundry, and urinal were collected and recycled for potable use by the Phase II water recovery system (WRS). This water system consisted of a vapor compression and distillation subsystem (VCD), an ultrafiltration/reverse osmosis subsystem (UF/RO), and a post-treatment subsystem, as shown in Figure 4.2-1. The VCD is a rotating still that distills urine and produces a urine condensate that is mixed with washwater and humidity condensate for further processing. The UF/RO is a two-stage membrane filtration system designed to remove organic molecules and dissolved salts from the wastewater. The post-treatment subsystem provides final polishing of the recovered water. Processed water was stored in one of four potable water storage tanks that had a 0.2  $\mu\text{m}$  microbial filter and a MCV positioned at the inlet of each of the tanks for microbial control and for adding iodine to the product water. Each tank also had the capability of being heated to disinfect the tank, if required.



*Figure 4.2-1 Phase II Water Recovery System Schematic*

A series of system verification tests were conducted before the start of Phase II as outlined by Verostko et al. (13). A viral challenge test was also conducted to verify the capability of the water recovery system to remove viruses and provide potable water that met the NASA MSIS. No water produced from these tests was consumed. Once samples were collected, the product water was discarded. During the viral challenge test, several samples of processed water were collected for microbial analysis and one sample was collected for chemical analysis. Microbial and viral results of the challenge test are discussed in Bouma et al. (14). Results from chemical analyses indicated that all parameters met MSIS requirements except pH and color. The pH of the sample was 4.79 as compared to the MSIS required range of 6.0 to 8.5. Again, this low pH was due to the added iodine and did not represent a health hazard. The color of the sample was 37.6 platinum-cobalt (Pt-Co) units. Although this level was above the MSIS limit of 15 Pt-Co units, the color was due to the iodine and did not represent a health hazard. All parameters met U.S. EPA standards.

Three WRS donor mode tests and an integrated air revitalization system/water recovery system test were performed to validate the ability of the WRS to produce potable water from wastewater. During these tests, actual wastewater from human donors was processed. Although the final product water was not consumed by the donors, it was sampled and analyzed. The first donor mode test was initiated in March 1996 with a water recovery system consisting of a VCD, a UF/RO, and an Aqueous Phase Catalytic Oxidation Subsystem (APCOS) for post treatment. Chemical results of recovered water samples collected on days 3 and 6 of this test exceeded the MSIS limits for TOC, color, iodine, and turbidity. The measured TOC levels were 792 and 5170  $\mu\text{g/L}$ , color levels were 44.4 and 48.2 Pt-Co units, iodine levels were 4.07 and 4.38  $\text{mg/L}$ , and turbidity levels were 0.601 and 2.94 NTU,

respectively. To assist in troubleshooting, six additional APCOS recovered water samples were collected and analyzed for TOC. Levels ranged from 42 to 780  $\mu\text{g/L}$ . Next, the APCOS was isolated and flushed with deionized water several times and the fluid water sampled. These flush water samples had TOC levels from 137 to 8900  $\mu\text{g/L}$ . Based on this information, the test was halted and updates to the APCOS were performed to improve its capability to process the water. Another donor mode test (#2) was conducted in April 1996 and again, samples of processed water exceeded the MSIS limit for TOC. The high TOC levels were attributed to the breakdown of the carbon-based catalyst in the APCOS subsystem. As a result, the APCOS subsystem was abandoned as the post treatment subsystem in the Phase II WRS.

The APCOS was replaced with another catalytic oxidation system, called the Volatile Removal Assembly (VRA). A 2-phase gas separator and an ion-exchange resin bed were installed along with the VRA for a third donor mode test which was conducted in May 1996. During donor mode test #3, two recovered water samples were collected, and the TOC results for these samples were 268  $\mu\text{g/L}$  and 433  $\mu\text{g/L}$ . Results also showed that the samples exceeded MSIS specifications for pH and color, because of the iodine added to the water. These results indicated that the water recovery system consisting of a VCD, UF/RO, VRA, 2-phase gas separator, and an ion-exchange resin bed was capable of producing potable water that met the MSIS TOC standard. However, the reliability of the WRS with the VRA in place of the APCOS was unclear for a 30-day test duration because this new WRS configuration had not been extensively tested. Hence, a back up WRS post-processing subsystem consisting of a commercial Millipore Milli-Q<sup>®</sup> water purification system was provided for the Phase II test.

On June 12, 1996, the Phase II test began with three of four potable water storage tanks filled with about 211 kg (465 lbs) of water from the JSC public water supply that had been deionized, filtered with a 0.2  $\mu\text{m}$  microbial filter, and iodinated with a MCV. Samples were collected from the storage tanks once they were filled completely with recycled water. This normally occurred every two days. During the test, one of the four tanks would be "in use," one tank would be "on hold" awaiting completion of analytical tests, one tank would be a "spare," and one tank would be "filling" with processed water. The tanks were configured such that they were sequentially cycled from the fill, hold, spare, and use modes.

Processing of wastewater for reuse began on day 1. The crew initiated use of one of the water tanks containing deionized water, while wastewater from hygiene activities was collected in one of two wastewater tanks. Crewmembers continued to consume deionized water during this period. The first sample of recovered water collected on June 16, 1996 did not meet MSIS specifications for TOC and color. The TOC level was 2290  $\mu\text{g/L}$ , and the color measurement was 43.3 Pt-Co units. This sample contained 2160  $\mu\text{g/L}$  of acetic acid, 1670  $\mu\text{g/L}$  of propionic acid, 376  $\mu\text{g/L}$  of formaldehyde, 127  $\mu\text{g/L}$  of lactic acid, 5.4  $\mu\text{g/L}$  of acetone, and about 12  $\mu\text{g/L}$

of several semivolatile organic compounds. The organic carbon recovery for this sample was 86.1%. It appears the ion-exchange bed located after the VRA failed early on day 2 of the test (11). This water was not consumed but was reprocessed by the backup Milli-Q® postprocessing system. After reprocessing, the water met potability requirements and was eventually consumed.

During the 30-day test, nine potable water tank samples did not meet the potable water specifications for TOC and had to be reprocessed by the Milli-Q® system. The TOC of these samples ranged from 2010 to 2530 µg/L, with acetic and propionic acid levels ranging from 2160 to 3510 µg/L and 720 to 1670 µg/L, respectively. The organic carbon balances indicated 71.6 to 89.5% accountability for these samples. Potable water tanks reprocessed by the Milli-Q® system did meet MSIS TOC specifications, ranging from 105 to 243 µg/L, and were subsequently used for consumption. A summary of results from the potable water tanks consumed during Phase II, is presented in Table 4.2-3. The prevalent organics identified in these samples were acetic acid (60 to 165 µg/L) and acetone (9.6 to 32.0 µg/L). Bis-2-ethylhexyl phthalate was also found at levels ranging from 0.13 to 233.9 µg/L. However, this compound probably originated from laboratory contamination. The organic carbon balances indicated 11 to 51% accountability for the post-Milli-Q® samples.

Potable water tank samples collected also did not meet the MSIS limits for pH

*Table 4.2-3 Phase II Consumed Potable Water Tank Results*

Parameter	Units	Minimum Concentration	Maximum Concentration	Average Concentration	n
<b>Physical Parameter</b>					
Conductivity	µS/cm	1.96	6.19	3.66	7
pH	pH units	4.65	6.01	5.36	7
Turbidity	NTU	0.003	0.07	0.02	7
<b>Iodine (UV/VIS)</b>					
I <sub>2</sub>	mg/L	2.82	3.89	3.47	7
I <sup>-</sup>	mg/L	0.05	0.79	0.50	7
IOH	mg/L	0.05	0.18	0.09	7
Total Iodine	mg/L	3.54	4.46	4.05	7
<b>Color</b>	Pt/Co	31.10	42.2	37.83	7
<b>Cations (CE/IC)</b>					
Sodium	mg/L	0.11	0.995	0.27	7
Potassium	mg/L	0.14	0.244	0.08	7
Ammonium (NH <sub>4</sub> -N)	mg/L	0.26	0.505	0.11	7
Calcium	mg/L	ND	0.209	0.03	7

*Table 4.2-3 continued Phase II Consumed Potable Water Tank Results*

Parameter	Units	Minimum Concentration	Maximum Concentration	Average Concentration	n
<b>Physical Parameter</b>					
<b>Metals</b>					
Silver	µg/L	ND	0.6	0.09	7
Chromium	µg/L	0.4	2.4	0.61	7
Iron	µg/L	0.7	3.1	0.93	7
Manganese	µg/L	0.3	0.7	0.14	7
Nickel	µg/L	1.0	1.8	0.59	7
Zinc	µg/L	0.1	0.6	0.26	7
<b>Total Organic Carbon</b>					
TIC (Sievers 800)	mg/L	0.092	0.565	0.227	7
TOC (Sievers 800)	mg/L	0.105	0.243	0.166	7
<b>Volatile Organics</b>					
Acetone	µg/L	9.60	32.03	19.90	7
Naphthalene	µg/L	ND	2.98	0.43	7
Tetrahydrofuran	µg/L	ND	1.88	0.27	7
<b>Extractable Organics</b>					
Benzothiazole	µg/L	ND	0.1	0.01	7
Benzyl alcohol	µg/L	ND	0.3	0.04	7
n-Butylbenzene-sulfonamide	µg/L	ND	0.4	0.06	7
4,4'-Butylidenebis					
(6-tert-butyl-m-cresol)	µg/L	ND	1.3	0.54	7
Di-n-butyl phthalate	µg/L	ND	0.3	0.13	7
2,6-Di-t-butyl					
-4-methylphenol	µg/L	ND	2.6	1.44	7
Diethyl phthalate	µg/L	ND	0.1	0.01	7
Diiodomethane	µg/L	ND	0.5	0.19	7
2-Ethyl-1-hexanol	µg/L	ND	0.4	0.11	7
bis-2-Ethylhexyl adipate	µg/L	ND	1.4	0.33	7
bis-2-Ethylhexyl phthalate	µg/L	ND	28.1	4.06	7
1-Hexadecanol	µg/L	ND	1.5	0.21	7
Iodoform	µg/L	ND	1.9	0.53	7
Methyl sulfone	µg/L	ND	1.5	0.93	7
Pentacosane	µg/L	ND	0.3	0.04	7
1-Tetradecanol	µg/L	ND	0.9	0.23	7

*Table 4.2-3 continued Consumed Potable Water Tank Results*

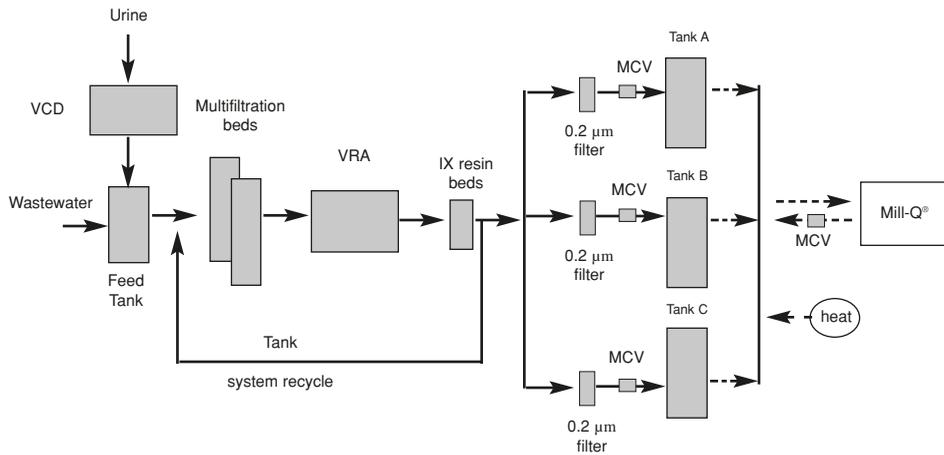
Parameter	Units	Minimum Concentration	Maximum Concentration	Average Concentration	n
<b>Physical Parameter</b>					
Toluene	µg/L	ND	1.7	0.56	7
Triethylamine	µg/L	ND	0.6	0.09	7
2,2,4-Trimethyl-1,3-pentanediol diisobutyrate	µg/L	ND	0.2	0.06	7
<b>Aldehydes (GC/MS)</b>					
Formaldehyde	µg/L	9.0	17.2	12.60	7
<b>Carboxylates (CE)</b>					
Acetate	mg/L	0.06	0.165	0.08	7
<b>Organic Carbon Recovery</b>	percent	11.07	50.88	32.77	7

and color. Color levels exceeded MSIS limits in both the pre- and post-Milli-Q<sup>®</sup> samples and ranged from 31.1 to 43.3 Pt-Co units. pH levels also exceeded MSIS limits and ranged from 4.20 to 7.2 in the pre-Milli-Q<sup>®</sup> samples and from 4.65 to 6.01 pH units in the post-Milli-Q<sup>®</sup> samples. As before, the pH and color exceedances were attributable to the iodine in the potable water. Comprehensive results for these samples and other samples collected during Phase II are discussed in Homan et al. (15) and Koenig et al. (16). Further discussion on the performance of the Phase II WRS can be found in Verostko et al. (13).

### *Phase IIa*

The Phase IIa test was conducted to demonstrate the specific life support systems developed for use on the International Space Station (ISS). This test incorporated integrated air revitalization, water recovery, and thermal control systems similar to those planned for ISS use in order to provide a liveable habitat for 60 days for four crewmembers. The water recovery system for Phase IIa included a VCD, a multi-filtration subsystem, and a volatile removal assembly with an ion-exchange resin bed as shown in Figure 4.2-2. The VCD is a rotating distillation unit that distills urine and produces the urine condensate which is mixed with washwater and humidity condensate for further processing. The multifiltration subsystem provided mixed-bed deionization and activated-carbon absorption. The VRA provides for the wet oxidation of organic (primarily nonpolar) that escaped the multifiltration unit. The VRA effluent was then treated by an anion-exchange resin to remove the oxidized organics (organic acids). Further details on these subsystems may be found at <http://advlifepupport.jsc.nasa.gov/>.

The VCD, VRA, and ion-exchange resin beds had previously been tested in



*Figure 4.2-2 Phase IIa Recovery System Schematic*

Phase II. As in Phase II, the Phase IIa system included a modified commercial Milli-Q® system to provide for reprocessing of the potable water if it did not meet potability requirements. The Phase IIa system was designed to accept wastewaters from the urinal, shower, handwash, and air revitalization system condensing heat exchangers (humidity condensate), as was the Phase II WRS. In addition, the Phase IIa WRS was required to process simulated wastewaters expected on the ISS, such as condensate from animal experiments, wastewater from the Crew Health Care System (CHeCS) water quality monitors used for offline water quality monitoring, and condensate from the off-gassing of equipment and new materials introduced into the ISS environment.

In order to test the ISS systems for Phase IIa, Phase II subsystems were configured as closely as possible to subsystems used in the Marshall Space Flight Center Stage 10 Water Recovery System tests (17). The Phase II UF/RO subsystem was replaced with a multifiltration subsystem. The laundry wastewater was removed as an input to the wastewater feed stream since a clothes washer is not planned for ISS.

The amount of water to be processed was reduced from 211 kg (465 lbs) to 52 kg (115 lbs) to reflect the water usage rates expected. For process control, an in-line process control water quality monitor (PCWQM) was added for continuous monitoring of the processed water's conductivity, TOC, and iodine ( $I_2$ ) levels. If any of the three parameters were out of specification, the product water was rejected and returned to the inlet of the system for reprocessing. After processing, the water was stored in one of three potable water storage tanks containing a 0.2  $\mu\text{m}$  microbial filter and a MCV at the inlet of each of the tanks.

As with previous tests, several pretest verification tests were performed prior to the 60-day test including a subsystem check, an integrated wet functional test, and a WRS Demonstration Test. During subsystem checks, each subsystem was operated individually using deionized water. Next, the subsystems were plumbed

together for the integrated wet functional test and deionized water was processed through the entire integrated system. Then, actual wastewater from human donors was processed by the integrated system during the WRS Demonstration Test. The processed water was not consumed by the donors, but instead was sampled and discarded. Six potable water samples were collected during the Phase IIa WRS Demonstration Test. Table 4.2-4 shows a summary of the results. Other samples of shower, wastewater feed, multifiltration effluent, and VRA effluent were also collected and analyzed for engineering evaluation.

The Phase IIa test began in January 1997 with water from the JSC public water supply that was deionized, filtered with a 0.2  $\mu\text{m}$  filter, iodinated using a MCV, and

*Table 4.2-4 Phase IIa WRS Demonstration Test Potable Water Results*

Parameter	Units	Minimum Concentration	Maximum Concentration	Average Concentration	n
<b>Physical Parameter</b>					
Conductivity	$\mu\text{S/cm}$	1.97	4.76	3.05	6
pH	pH units	4.65	5.76	5.11	6
Turbidity	NTU	0.03	0.11	0.06	4
<b>Iodine (UV/VIS)</b>					
I <sub>2</sub>	mg/L	2.21	3.22	2.83	6
I <sup>-</sup>	mg/L	0.24	0.73	0.50	5
IOH	mg/L	<0.05	0.17	0.03	5
<b>Color</b>	Pt/Co	31.40	34.80	33.58	4
<b>Anions</b>					
Chloride	mg/L	0.026	0.077	0.042	4
Phosphate	mg/L	<0.01	0.076	0.025	4
Sulfate	mg/L	<0.01	0.083	0.021	4
<b>Cations</b>					
Sodium	mg/L	0.002	0.017	0.008	4
Potassium	mg/L	0.005	0.014	0.008	4
Ammonium (NH <sub>4</sub> -N)	mg/L	<0.001	0.005	0.002	4
Calcium	mg/L	<0.005	0.008	0.002	4
<b>Metals</b>					
Aluminum	$\mu\text{g/L}$	1.90	34.00	11.15	4
Barium	$\mu\text{g/L}$	<1	1.20	0.30	4
Copper	$\mu\text{g/L}$	1.1	4.40	3.00	4
Iron	$\mu\text{g/L}$	<2	10.70	4.08	4
Manganese	$\mu\text{g/L}$	<1	2.10	1.35	4
Nickel	$\mu\text{g/L}$	1.60	5.10	3.88	4
Zinc	$\mu\text{g/L}$	<1	4.10	1.55	4

*Table 4.2-4 continued Phase IIa WRS Demonstration Test Potable Water Results*

<b>Parameter</b>	<b>Units</b>	<b>Minimum Concentration</b>	<b>Maximum Concentration</b>	<b>Average Concentration</b>	<b>n</b>
<b>Physical Parameter</b>					
<b>Total Organic Carbon</b>					
TIC (OI 1010)	mg/L	0.196	0.258	0.217	3
NPOC (OI 1010)	mg/L	0.187	0.621	0.353	3
TIC (Sievers 800)	mg/L	0.164	1.220	0.398	6
TOC (Sievers 800)	mg/L	0.139	0.555	0.273	6
<b>Volatile Organics</b>					
Toluene	µg/L	1.70	4.88	3.07	4
<b>Extractable Organics</b>					
Acetophenone	µg/L	ND	1.60	0.53	4
Anethole	µg/L	ND	1.00	0.25	4
Benzaldehyde	µg/L	ND	0.50	0.13	4
Benzyl alcohol	µg/L	ND	1.60	0.40	4
Decamethylcyclopentasiloxane	µg/L	ND	0.90	0.23	4
Di-n-butyl phthalate	µg/L	0.80	1.30	1.00	4
Diethyl phthalate	µg/L	ND	0.20	0.05	4
Diiodomethane	µg/L	ND	0.70	0.18	4
Dodecamethylcyclohexasiloxane	µg/L	ND	5.00	1.25	4
2-Ethyl-1-hexanol	µg/L	2.00	5.70	3.53	4
bis-2-Ethylhexyl phthalate	µg/L	ND	0.50	0.23	4
Iodoform	µg/L	ND	2.30	0.58	4
3'-Methylacetophenone	µg/L	ND	4.50	1.68	4
Methyl 4-hydroxybenzoate	µg/L	ND	1.50	0.38	4
1-Methyl-2-pyrrolidinone	µg/L	ND	1.30	0.33	4
Phenylethyl alcohol	µg/L	ND	1.80	0.63	4

*Table 4.2-4 continued Phase IIa WRS Demonstration Test Potable Water Results*

Parameter	Units	Minimum Concentration	Maximum Concentration	Average Concentration	n
<b>Physical Parameter</b>					
Alcohols (DAI/GC/MS)					
Methanol	µg/L	ND	274	68.50	4
2-Propanol	µg/L	ND	175	43.75	4
<b>Aldehydes (GC/MS)</b>					
Formaldehyde	µg/L	6.60	14.20	10.63	4
<b>Carboxylates (CE)</b>					
Oxalate	mg/L	<0.2	0.53	0.13	4
Organic Carbon Recovery	percent	7.24	78.19	38.12	4

filled in two of the three potable water storage tanks. The WRS processed wastewater nominally for the first 29 days. On day 29, problems with the VCD, the VRA, and the ion-exchange resin bed occurred. Several VCD components, the resin in the ion-exchange resin bed, and the phase separator in the VRA were replaced. It was noted that the ineffective phase separator of the VRA caused gas to accumulate in the ion-exchange resin bed, rendering the bed ineffective (18). A sample of processed water collected during this period had a TOC of 840 µg/L which exceeded the MSIS limit of 500 µg/L. This water was not consumed but instead was reprocessed through the backup Milli-Q® post processor so that the recovered water would meet potability standards.

A total of 51 recovered water samples were collected during Phase IIa. A summary of results of the consumed recovered potable water tank samples is reported in Table 4.2-5. The potable water tank samples analyzed met MSIS limits except for TOC, pH, iodine, copper, and selenium. Typically, when the results exceeded specifications, the potable water tanks were reprocessed through the Milli-Q® system before human consumption. Potable water tanks were reprocessed through the Milli-Q® system 11 times for not meeting potable water chemical specifications. The tanks were also heat disinfected eight times for not meeting potable water microbial specifications. The TOC levels of the consumed recovered water ranged from 174 to 523 µg/L acetate (< 0.012 to 0.65 mg/L), lactate (< 0.012 to 1.10 mg/L), and oxalate (< 0.12 to 0.41 mg/L) were the organic acids detected. Acetone (not detected to 6.40 µg/L) and toluene (not detected to 9.53 µg/L) were the only volatile organic compounds identified. Methyl sulfone (not detected to 54.5 µg/L) was the only semivolatile organic found above 10 µg/L. Methanol (not detected to 233 µg/L) and 2-propanol (not detected to 154 µg/L) were the only alcohols detected. Only one of the 51 samples had detectable levels of urea (0.302 mg/L). Low concentrations of formaldehyde (< 2.0 to 13.8 µg/L) were also found. The

*Table 4.2-5 Phase IIa Consumed Potable Water Tank Results Summary*

<b>Parameter</b>	<b>Units</b>	<b>Minimum Concentration</b>	<b>Maximum Concentration</b>	<b>Average Concentration</b>	<b>n</b>
<b>Physical Parameter</b>					
Conductivity	µS/cm	1.40	12.20	3.20	51
pH	pH units	3.91	6.28	4.85	51
Turbidity	NTU	0.02	0.40	0.07	33
<b>Iodine (UV/VIS)</b>					
I <sub>2</sub>	mg/L	1.72	4.02	3.46	51
I <sub>3</sub> <sup>-</sup>	mg/L	<0.05	0.11	0.01	51
I <sup>-</sup>	mg/L	1.84	5.40	3.39	51
Total Iodine	mg/L	2.73	7.50	3.87	51
<b>Color</b>	Pt/Co	19.20	43.30	36.97	51
<b>Anions (IC)</b>					
Chloride	mg/L	<0.01	0.04	0.01	32
Nitrate (NO <sub>3</sub> -N)	mg/L	<0.01	0.25	0.02	32
Phosphate	mg/L	<0.01	0.17	0.01	32
Sulfate	mg/L	0.07	0.09	2.50	32
<b>Cations (CE/IC)</b>					
Sodium	mg/L	<0.001	0.007	0.001	32
Potassium	mg/L	<0.001	0.046	0.006	32
Ammonium (NH <sub>4</sub> -N)	mg/L	<0.001	0.009	0.001	32
Magnesium	mg/L	<0.001	0.001	0.001	32
Calcium	mg/L	<0.001	0.373	0.019	32
<b>Metals</b>					
Aluminum	µg/L	<1	6.8	2.16	32
Arsenic	µg/L	<1	1.2	0.04	32
Barium	µg/L	<1	1.9	0.13	32
Chromium	µg/L	1.2	9.7	0.74	32
Copper	µg/L	<1	1770	80.98	32
Iron	µg/L	<2	43.7	4.64	32
Manganese	µg/L	<1	24.7	2.10	32
Nickel	µg/L	<1	43.4	4.31	32
Selenium	µg/L	<1	12.20	0.60	32
Zinc	µg/L	<1	5.20	0.91	32
<b>Total Organic Carbon</b>					
TIC (Sievers 800)	mg/L	0.073	3.290	0.364	51
TOC (Sievers 800)	mg/L	0.174	0.523	0.286	51

*Table 4.2-5 continued Phase IIa Consumed Potable Water Tank Results Summary*

<b>Parameter</b>	<b>Units</b>	<b>Minimum Concentration</b>	<b>Maximum Concentration</b>	<b>Average Concentration</b>	<b>n</b>
<b>Physical Parameter</b>					
<b>Volatile Organics</b>					
Acetone	µg/L	ND	6.40	0.49	32
Toluene	µg/L	ND	9.53	3.21	32
<b>Extractable Organics</b>					
Acetophenone	µg/L	ND	0.3	0.01	32
Benzaldehyde	µg/L	ND	0.8	0.3	32
Benzothiazole	µg/L	ND	0.7	0.03	32
Benzyl alcohol	µg/L	ND	7.0	0.9	32
Benzylbutyl phthlate	µg/L	ND	3.6	0.1	32
2-Butoxyethanol	µg/L	ND	3.1	0.10	32
2-(2-Butoxyethoxy) ethanol	µg/L	ND	0.8	0.03	32
tris-2-Chloroethyl phosphate	µg/L	ND	0.9	0.03	32
Decamethylcyclopentasiloxane	µg/L	ND	0.2	0.02	32
1,4-Diacetylbenzene	µg/L	ND	0.3	0.01	32
Di-n-butyl phthlate	µg/L	ND	1.1	0.50	32
Diiodomethane	µg/L	ND	1.8	0.28	32
Diisopropyl adipate	µg/L	ND	0.9	0.30	32
N,N-Dimethylbenzylamine	µg/L	ND	0.6	0.02	32
Dodecamethylcyclohexasiloxane	µg/L	ND	1.2	.29	32
2-Ethylhexanoic acid	µg/L	ND	1.7	0.05	32
2-Ethyl-1-hexanol	µg/L	ND	2.7	0.88	32
bis-2-Ethylhexyl phthalate	µg/L	ND	1.7	0.14	32
1-Formylpiperidine	µg/L	ND	0.6	0.07	32
4-Hydroxy-4-methyl-2-pentanone	µg/L	ND	3.4	0.59	32
Iodoform	µg/L	ND	4.8	2.53	32
1-Methyl-2-pyrrolidinone	µg/L	ND	3.6	0.49	32
Methyl sulfone	µg/L	ND	54.5	19.36	32

*Table 4.2-5 continued Phase IIa Consumed Potable Water Tank Results Summary*

<b>Parameter</b>	<b>Units</b>	<b>Minimum Concentration</b>	<b>Maximum Concentration</b>	<b>Average Concentration</b>	<b>n</b>
<b>Physical Parameter</b>					
Monomethyl phthlate	µg/L	ND	4.8	0.15	32
Neomenthol	µg/L	ND	0.2	0.01	32
Octamethylcyclo- tetrasiloxane	µg/L	ND	0.6	0.03	32
Pentacosane	µg/L	ND	1.2	0.06	32
sec-Phenethyl alcohol	µg/L	ND	0.2	0.02	32
Phenol	µg/L	ND	1.00	0.08	32
2-Phenyl-2-propanol	µg/L	ND	0.5	0.02	32
Squalene	µg/L	ND	1.8	0.09	32
Tributyl phosphate	µg/L	ND	0.5	0.02	32
<b>Alcohols</b>					
<b>(DAI/GC/MS)</b>					
Methanol	µg/L	ND	233	25	32
2-Propanol	µg/L	ND	154	5	32
<b>Aldehydes (GC/MS)</b>					
Formaldehyde	µg/L	ND	13.8	4.70	32
<b>Carboxylates</b>					
<b>(CE/HPLC)</b>					
Oxalate	mg/L	<0.10	0.41	0.04	32
Acetate	mg/L	<0.12	0.65	0.05	32
Lactate	mg/L	<0.12	1.1	0.07	32
<b>Non-volatiles</b>					
<b>(HPLC)</b>					
Urea	mg/L	ND	302	9.44	32
Organic Carbon Recovery	percent	2.67	142.02	29.31	31

ND=None Detected

organic carbon recoveries of the potable water samples ranged from 2.67 to 142%.

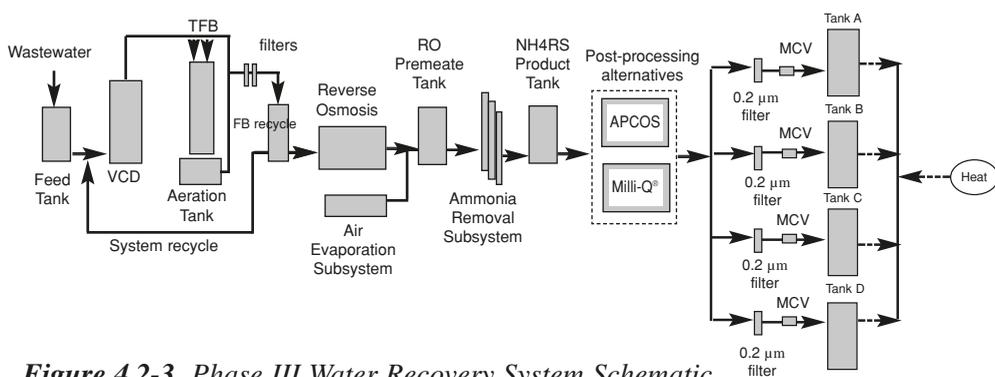
Two of the 51 recovered water samples analyzed did not meet MSIS pH requirements. These samples measured 3.91 and 3.75. All 51 samples exceeded color requirements. This is attributable to the iodine present in the potable water. One sample slightly exceeded the iodine requirement (4.02 vs 4.0 mg/L limit). One sample exceeded the 1000 µg/L copper limit at 1770 µg/L and another sample exceeded the 10 µg/L selenium specification at 12.2 µg/L.

Several other in-process samples of condensate, handwash, galley, shower,

wastewater feed, multifiltration bed effluent, VRA effluent, and ion-exchange bed effluent were also collected and analyzed for engineering evaluation.

### Phase III

Phase III was the first test to incorporate biologically-based wastewater processing. The overall objective of this test was to conduct a 90-day test of integrated physicochemical and biological life support systems for air revitalization, water recovery, thermal control, and solid waste management (19, 20). In terms of wastewater processing, biologically based systems were used to initially process the wastewaters and physicochemical systems were used for polishing and post-processing. The components of the Phase III WRS included an immobilized cell bioreactor (ICB), a trickling filter bioreactor (TFB), a reverse osmosis subsystem (RO), an air evaporation subsystem (AES), an ammonia removal subsystem (NH4RS), and the Milli-Q® polishing subsystem which was previously used in Phases II and IIa. In addition, an upgraded and refurbished APCOS was also available for use in this test. After processing, the recovered water was stored in one of four potable water tanks. A 0.2 µm microbial filter and a MCV were positioned at the inlet of each of the tanks for microbial control and for adding iodine to the product water. As in the previous tests, each tank and its contents had the capability of being heated to disinfect the tank if microbial water quality requirements were not met. A schematic of the Phase III WRS is depicted in Figure 4.2-3. The Phase III WRS was required to process laundry, shower, handwash, and oral hygiene wastewaters, along with urine, humidity condensate, and incinerator condensate from the processing of human solid wastes.



**Figure 4.2-3** Phase III Water Recovery System Schematic

In preparation for Phase III, a demonstration test was performed from March through June 1997. This test processed urine and hygiene water generated by human donors but the water was not consumed. The recovered water was analyzed during the final two weeks of the test to evaluate the system's capability to produce potable water. Ten samples were collected and analyzed. The analytical results from these samples can be found in Table 4.2-6. All 10 samples exceeded the MSIS

specification for color. Color levels ranged from 41-64 Pt/Co units, which resulted from the iodine in the water. Five samples collected in the first week of the two-week collection period exceeded the MSIS specification of 10 mg/L for nitrate and ranged from 18 to 20 mg/L. Nitrate levels from samples collected in the second week of the collection period ranged from 0.88 to 1.08 mg/L. All other parameters routinely met MSIS and U.S. EPA standards.

The Phase III test began on September 19, 1997. The WRS processed water nomi-

*Table 4.2-6 Phase III WRS Demonstration Test Results*

Parameter	Units	Minimum Concentration	Maximum Concentration	Average Concentration	n
<b>Physical Parameter</b>					
Conductivity	μS/cm	18.30	333.0	170.0	10
pH	pH units	5.93	6.11	6.03	10
Turbidity	NTU	0.00	0.03	0.01	10
<b>Iodine (UV/VIS)</b>					
I <sub>2</sub>	mg/L	3.8	5.63	4.69	10
I <sub>3</sub> <sup>-</sup>	mg/L	0.054	0.296	0.154	10
I <sup>-</sup>	mg/L	1.35	6.28	3.411	10
IOH	mg/L	<0.05	0.13	0.60	10
<b>Color</b>	Pt/Co	41.0	64.4	51.8	10
<b>Anions (IC)</b>					
Chloride	mg/L	1.83	31.70	15.92	10
Nitrite (NO <sub>2</sub> -N)	mg/L				
Nitrate (NO <sub>3</sub> -N)	mg/L	0.88	20.00	10.21	10
Sulfate	mg/L	0.50	8.92	4.37	10
<b>Cations (CE/IC)</b>					
Sodium	mg/L	1.23	53.42	26.63	10
Potassium	mg/L	0.091	1.86	0.905	10
Magnesium	mg/L	<0.002	0.017	0.008	10
Calcium	mg/L	1.48	25.21	12.389	10
<b>Metals</b>					
Aluminum	μg/L	1.1	9.0	2.4	10
Barium	μg/L	<1	20.8	6.28	10
Chromium	μg/L	<5	58.0	16.2	10
Copper	μg/L	<1	3.2	1.04	10
Iron	μg/L	7.9	144.0	71.36	10
Nickel	μg/L	<1	3.3	1.11	10
Selenium	μg/L	<1	1.5	0.26	10
Zinc	μg/L	<1	8.5	4.47	10

*Table 4.2-6 continued Phase III WRS Demonstration Test Results*

Parameter	Units	Minimum Concentration	Maximum Concentration	Average Concentration	n
<b>Physical Parameter</b>					
<b>Total Organic Carbon</b>					
TIC (OI 1010)	mg/L	1.230	0.462	0.988	6
NPOC (OI 1010)	mg/L	0.106	0.210	0.171	6
TIC (Sievers 800)	mg/L	0.457	1.930	1.096	10
TOC (Sievers 800)	mg/L	0.097	0.246	0.161	10
<b>Extractable Organics</b>					
Cyclododecane	µg/L	ND	15.4	3.9	10
Diiodomethane	µg/L	ND	4.9	1.8	10
Dodecanol	µg/L	ND	16.3	3.0	10
Iodoform	µg/L	ND	6.2	2.6	10
1-Octanol	µg/L	ND	53.8	29.9	10
2,2,4-Trimethyl-1,3-pentanediol diisobutyrate	µg/L	ND	21.6	2.16	10
<b>Aldehydes (GC/MS)</b>					
Formaldehyde	µg/L	<2	4.6	2.1	10
<b>Carboxylates (CE/HPLC)</b>					
Lactate	mg/L	<0.25	0.44	0.044	10
<b>Organic Carbon Recovery</b>	percent	2.02	46.5	41.5	9

nally throughout the test, except from days 47 to 56 when the APCOS was being tested. Water processed by the APCOS exceeded MSIS limits for lead and nickel and was only consumed after further processing by the Milli-Q®. During this period, crewmembers conserved water, until the Milli-Q® system could reprocess the APCOS effluent. Details concerning the performance of the APCOS subsystem can be found in the *Lunar-Mars Life Support Test Project: Phase III Final Report* (21).

A total of 52 recovered water samples and 15 in-process samples were collected for analysis during Phase III. The summary data for the consumed recovered potable water tank samples are listed in Table 4.2-7. Color and pH levels were consistently above MSIS specifications because of iodine addition to the recovered water. Recovered potable water samples consistently met U.S. EPA requirements. Two samples exceeded the NASA potable water requirement for TOC. One recovered water sample collected on October 16, 1997 had a TOC level of 615 µg/L, slightly above the 500 µg/L limit. The elevated TOC was attributed to the presence

of isopropanol that was used to disinfect the sample port for microbial sample collection. The probable cause of this was that the sample port, after being disinfected with isopropanol, was not sufficiently flushed prior to the collection of the chemical sample. The sample was recollected with an acceptable TOC level (0.055 mg/L). Another sample collected on November 11, 1997 also was above the limit, with a TOC level of 1.55 mg/L. This was also attributed to the presence of isopropanol. The tank was processed through the Milli-Q®, which lowered the TOC level (64 µg/L), but the total microbial count at 48 hours exceeded the 100 CFU/100 ml MSIS limits. After heat disinfection, the tank was certified on November 14, 1997 for crew consumption. The average TOC level of all the Phase III consumed recovered water samples was 146 µg/L and ranged from 55 to 291 µg/L.

**Table 4.2-7 Phase III Consumed Potable Water Tank Results Summary**

Iodine levels were elevated in three samples collected from tank A between

Parameter	Units	Minimum Concentration	Maximum Concentration	Average Concentration	n
<b>Physical Parameter</b>					
Conductivity	µS/cm	2.6	51.5	15.0	45
pH	pH units	4.42	6.37	5.80	46
Turbidity	NTU	<0.01	0.16	0.03	33
<b>Iodine (UV/VIS)</b>					
I2	mg/L	0.69	4.69	2.61	46
I3-	mg/L	0.008	0.127	0.047	46
I-	mg/L	0.26	7.87	2.40	46
IOH	mg/L	<0.05	0.17	0.04	46
Total Iodine	mg/L	3.56	8.63	5.11	46
<b>Iodine (LCV)</b>					
Total I	mg/L	0.250	6.920	3.245	6
I2	mg/L	0.109	0.163	0.275	6
I-	mg/L	0.445	0.543	1.956	6
<b>Color</b>	Pt/Co	7.3	51.0	28.0	46
<b>Anions (IC)</b>					
Chloride	mg/L	0.31	3.97	0.86	36
Nitrite (NO2-N)	mg/L	<0.01	0.50	0.11	36
Nitrate (NO3-N)	mg/L	0.40	3.60	0.57	36
Sulfate	mg/L	<0.01	0.10	0.03	36
<b>Cations (CE/IC)</b>					
Sodium	mg/L	0.69	7.270	1.076	36
Potassium	mg/L	<0.02	0.514	0.066	36
Calcium	mg/L	0.344	1.910	0.917	36

*Table 4.2-7 continued Phase III Consumed Potable Water Tank Results Summary*

Parameter	Units	Minimum Concentration	Maximum Concentration	Average Concentration	n
<b>Physical Parameter</b>					
<b>Metals</b>					
Aluminum	µg/L	<2	17.9	0.8	40
Chromium	µg/L	<5	36.6	0.915	40
Copper	µg/L	1.5	331	80.1	40
Iron	µg/L	<5	14.2	3.1	40
Manganese	µg/L	<1	3.3	0.6	40
Molybdenum	µg/L	<1	10.2	2.6	40
Nickel	µg/L	6.9	125.0	22.0	40
Lead	µg/L	2.3	38.2	11.1	40
Zinc	µg/L	3.7	123.0	12.3	40
<b>Total Organic Carbon</b>					
<b>Carbon</b>					
TIC (OI 1010)	mg/L	0.083	0.667	0.591	5
NPOC (OI 1010)	mg/L	0.127	0.300	0.221	5
TIC (Sievers 800)	mg/L	0.054	0.722	0.467	45
TOC (Sievers 800)	mg/L	0.055	0.291	0.146	45
<b>Extractable Organics</b>					
2-Ethyl-1-hexanol	µg/L	ND	8.9	0.3	40
4-Hydroxy-4-methyl-2-pentanone	µg/L	ND	47.4	4.4	40
Iodoform	µg/L	ND	5.6	0.1	40
2-Methyl-2,4-pentanediol	µg/L	ND	34.1	3.6	40
Methyl sulfone	µg/L	ND	25.4	2.2	40
<b>Aldehydes (GC/MS)</b>					
Formaldehyde	µg/L	<21	2.2	1.31	36
<b>Organic Carbon Recovery</b>	percent	0.00	97.9	8.83	36

October 20 and 22, 1997, before and after heat disinfection for two hours, and overnight (4.74, 4.57, and 4.69 mg/L, respectively). On day 35 of the Phase III test, the test physician determined that it was necessary to remove the iodine from water consumed by test subjects based on crewmember physiological data. See chapter 5.5 for further discussion. To remove the iodine, a system of ion-exchange resins and activated carbon, called the iodine removal subsystem, was incorporated in the galley on October 23, 1997. Samples from the galley showed that total iodine levels

(iodine and iodide) were reduced to  $<10 \mu\text{g/L}$ . Iodine was not removed from the potable water tanks. The crew consumed water only from the galley, while water from the potable water tanks containing two to four mg/L of iodine was used for hygiene purposes only.

Nickel and lead levels in a few cases exceeded the MSIS limits. Six samples exceeded the nickel standard of  $50 \mu\text{g/L}$ , ranging from  $50.4$  to  $125 \mu\text{g/L}$ , and three samples exceeded the lead standard of  $50 \mu\text{g/L}$ , ranging from  $66$  to  $184.4 \mu\text{g/L}$ . A sample collected from tank B on November 3, 1997 had an elevated nickel level ( $64.9 \mu\text{g/L}$ ), but the corresponding galley sink sample was within limits. Another sample collected on November 9, 1997 from tank C was not certified potable due to elevated levels of nickel ( $206.9 \mu\text{g/L}$ ), aluminum ( $19.8 \mu\text{g/L}$ ), lead ( $184.8 \mu\text{g/L}$ ), and nitrate ( $19.9 \text{mg/L}$ ) which all exceeded MSIS requirements. After reprocessing the water with the Milli-Q<sup>®</sup>, the parameters were within limits and the tank was certified on November 12, 1997. A tank B sample collected November 11, 1997 had elevated nickel ( $328 \mu\text{g/L}$ ), aluminum ( $15.2 \mu\text{g/L}$ ), and lead levels ( $106 \mu\text{g/L}$ ) but was also processed through the Milli-Q<sup>®</sup> which lowered the nickel, aluminum, and lead levels to within acceptable levels.

Elevated nickel ( $302 \mu\text{g/L}$ ) and lead ( $66.0 \mu\text{g/L}$ ) levels in a sample collected on November 13, 1997, along with a too-numerous-to-count microbial result prevented another tank from being certified potable. After being reprocessed by the Milli-Q<sup>®</sup>, heat disinfected, and recirculated through a MCV, another sample collected one day later still had an elevated total microbial count. The tank was heat disinfected and the water recirculated through a MCV again before this tank was finally certified potable on November 17, 1997 with a note to investigate why the iodine level was in the lower range of acceptability.

The nickel level ( $125 \mu\text{g/L}$ ) was elevated in the tank C sample collected on November 17, 1997, but the corresponding galley sink sample was within limits. Another sample collected on November 21, 1997 also had a slightly elevated nickel level ( $50.4 \mu\text{g/L}$ ) but was certified without reprocessing with the qualifier to analyze the nickel on the corresponding galley sink sample. This was done, and the nickel level was found to be within limits.

## Discussion

### *Physical Parameters*

Conductivity, turbidity, color, iodine, and pH were routinely analyzed in samples collected from the potable water storage tanks during Phases I, II, IIa, and III. Of these, pH and color frequently exceeded the NASA MSIS limit because of the addition of iodine to the potable water. Phase I samples had a pH range from 4.38 to 4.80, Phase II samples ranged from 4.65 to 6.01, Phase IIa samples ranged from 4.65 to 5.76, and Phase III samples ranged from 4.42 to 6.37 pH units. Color levels measured were 31.1 to 42.2 Pt-Co units in Phase II, 31.4 to 34.8 Pt-Co units in Phase IIa, and 7.3 to 51 Pt-Co units in Phase III. This parameter was not analyzed

in Phase I. Iodine levels measured in Phase I ranged from 0.03 to 5.42 mg/L, from 2.82 to 3.99 mg/L in Phase II, from 2.21 to 3.22 mg/L in Phase IIa, and from 0.69 to 4.69 mg/L in Phase III in the tank samples. Conductivity levels seen in the potable water samples were 3.52 to 11.57  $\mu\text{S}/\text{cm}$  in Phase I, 1.96 to 6.19  $\mu\text{S}/\text{cm}$  in Phase II, 1.97 to 4.76  $\mu\text{S}/\text{cm}$  in Phase IIa, and  $<2.6$  to 51.5  $\mu\text{S}/\text{cm}$  in Phase III. Turbidity levels were typically low and ranged from  $<0.01$  to 0.40 for all samples tested from Phases I through III.

### *Inorganic Parameters*

The inorganic parameters detected in the potable water samples were low and usually significantly less than the MSIS and EPA standards. No traces of fluoride, bromide, or magnesium were found in any of the potable water samples analyzed. However, other anions and cations such as sodium, potassium, calcium, chloride, nitrate, nitrite, phosphate, and sulfate were detected in some of the samples. During Phase I, chloride was detected in one sample at 0.13 mg/L. In Phase II, sodium (0.11 to 0.995 mg/L), potassium (0.14 to 0.244 mg/L), ammonium (0.26 to 0.50 mg/L as nitrogen), and calcium (not detected to 0.21 mg/L) were measured in the samples analyzed. For Phase IIa, chloride levels ranged from 0.03 to 0.42 mg/L, nitrate levels were  $<0.01$  to 0.25 mg/L as nitrogen, phosphate levels ranged from  $<0.01$  to 0.17 mg/L, and sulfate levels were 0.07 to 0.09 mg/L. Sodium, potassium, calcium, and ammonium levels were all less than 0.1 mg/L, while calcium levels reached a maximum of 0.373 mg/L. Higher levels of ionic compounds were detected in the Phase III samples, probably due to the biologically based water processing systems that were used in this test. Chloride (0.31 to 34.0 mg/L), nitrite (not detected to 0.50 mg/L), nitrate (0.40 to 3.60 mg/L), sulfate (not detected to 0.10 mg/L), sodium (0.69 to 7.27 mg/L), potassium (not detected to 0.514 mg/L), and calcium (0.344 to 1.91 mg/L) were detected in Phase III potable water samples.

Trace metals detected in potable water samples, but typically below potability requirements, included arsenic, barium, chromium, copper, iron, manganese, molybdenum, nickel, lead, selenium, and zinc. No mercury or cadmium was detected. Arsenic levels varied from nondetectable in all Phase II and Phase III samples to a maximum of 3.8  $\mu\text{g}/\text{L}$  in a sample from Phase I. Barium and manganese levels did not exceed 4  $\mu\text{g}/\text{L}$  in any of the samples analyzed. Chromium levels ranged from not detected to 1.8  $\mu\text{g}/\text{L}$  in Phase I, from 0.4 to 2.4  $\mu\text{g}/\text{L}$  in Phase II, from 1.2 to 9.7  $\mu\text{g}/\text{L}$  in Phase IIa, and from nondetectable to 36.6  $\mu\text{g}/\text{L}$  in Phase III samples. Copper was detected at levels exceeding the MSIS. One tank sample collected during Phase IIa had a copper level of 1770  $\mu\text{g}/\text{L}$  that exceeded both the 1000  $\mu\text{g}/\text{L}$  MSIS specification and the EPA action level of 1300  $\mu\text{g}/\text{L}$ . EPA has found copper to potentially cause stomach and intestinal distress, liver and kidney damage, and anemia when people are exposed to it at levels above the action level for relatively short periods of time. The source of high copper in the Phase IIa sample was never isolated. Levels of copper in Phase I samples were nondetectable

to 3.7  $\mu\text{g/L}$  and Phase III samples contained from 1.5 to 331  $\mu\text{g/L}$  of copper. All samples from Phase II had nondetectable levels of copper. Iron was detected in many of the potable water samples. Iron was found in Phase I samples (not detected to 9.6  $\mu\text{g/L}$ ), in Phase II samples (0.7 to 3.1  $\mu\text{g/L}$ ), in Phase IIa samples (<2.0 to 43.7  $\mu\text{g/L}$ ), and in Phase III samples (not detected to 14.2  $\mu\text{g/L}$ ). Nickel was detected in 4 of 6 samples analyzed during Phase I at 1.0 to 2.6  $\mu\text{g/L}$ , in 5 of 7 post-Milli-Q<sup>®</sup> samples during Phase II at 1.0 to 1.8  $\mu\text{g/L}$ , in post-Milli-Q<sup>®</sup> samples during Phase IIa at 1.2 to 42.4  $\mu\text{g/L}$ , and in tank samples during Phase III at 6.9 to 12.5  $\mu\text{g/L}$ . Nickel levels in 3 samples from Phase III exceeded the NASA MSIS specification of 50  $\mu\text{g/L}$  with one sample also exceeding the EPA Health Advisory of 100  $\mu\text{g/L}$ . The high nickel levels observed in Phase III may have resulted from the APCOS water processing subsystem as discussed in the LMLSTP Phase III final report (12). This is also the case for lead. While lead levels in all Phase II tank samples were nondetectable, lead was found in Phase I samples from not detected to 3.2  $\mu\text{g/L}$ , in the Phase IIa galley sink samples from <1 to 54.3  $\mu\text{g/L}$ , and in Phase III from 2.3 to 38.2  $\mu\text{g/L}$ . The NASA MSIS specification for lead is 10  $\mu\text{g/L}$  and the EPA action level is 15  $\text{mg/L}$ . Selenium was detected in Phase I (not detected to 3.2  $\mu\text{g/L}$ ) and Phase IIa (<1 to 12.2  $\mu\text{g/L}$ ) only; none was detected in Phases II and III. Zinc levels in the potable water samples measured from 0.3 to 13.2  $\mu\text{g/L}$  in Phase I, from 0.1 to 0.6  $\mu\text{g/L}$  in Phase II, from <1 to 5.2  $\mu\text{g/L}$  in Phase IIa, and from 3.7 to 123  $\mu\text{g/L}$  in Phase III. These zinc levels were very low compared to the MSIS limit of 5000  $\mu\text{g/L}$ .

### *Organic Parameters*

In general, the water recovery systems efficiently removed organic matter in the processed waters, so that few detectable organic compounds remained in the potable water consumed by test subjects. In summary, of the approximately 265 organic contaminants tested, about 35 compounds were detected in the Phase I samples, 25 compounds were detected in Phase II, 44 compounds were detected in Phase IIa, and 12 compounds were detected in Phase III. None of the compounds detected exceeded U.S. EPA maximum contaminant levels or health advisories that have been established. It must be noted, however, that EPA requirements are developed for normal terrestrial water supply systems and are not intended for water directly reused from spacecraft waste streams. As a result many of the compounds found in the recovered potable water do not have established limits.

TOC levels in the consumed recovered water samples averaged 338  $\mu\text{g/L}$  during Phase I, 166  $\mu\text{g/L}$  for post-Milli-Q<sup>®</sup> samples during Phase II, 286  $\mu\text{g/L}$  during Phase IIa, and 180  $\mu\text{g/L}$  during Phase III. Total carbon accountability is given in Table 4.2-8. The average TOC accountability ranged from 9 to 73%. Low accountabilities were normally observed in samples with low TOC as the analytical methods employed were unable to detect or identify the specific organic compounds at the low TOC values encountered. Higher levels of accountability were found for those sam-

ples with corresponding higher levels of TOC.

Low molecular weight compounds were detected in the potable water samples

**Table 4.2-8** TOC Accountability of Potable Water Samples

Samples	TOC (µg/L)	Average TOC (µg/L)	Accountability Range (%)	Accountability Average (%)
Phase I JSC facility water	244-432	338	3-133	73
Phase II Pre-MilliQ recovered water	90-2530	1740	8-90	72
Phase II Post-MilliQ recovered water	105-243	166	11-51	33
Phase IIa consumed recovered water	174-523	286	3-142	29
Phase III consumed recovered water	55-291	146	0-98	9

consistently throughout the chamber studies. Acetone was detected in Phase I (1.5 to 7.8 µg/L), Phase II (9.6 to 32.0 µg/L), Phase IIa (not detected to 6.40 µg/L), and Phase III (not detected to 29.27) samples. Toluene was also detected at 1.6 to 3.9 µg/L during Phase I, 0.9 to 1.7 µg/L during Phase II, and not detected to 9.53 µg/L during Phase IIa. Formaldehyde levels during Phase I measured 9.5 to 12.6 µg/L, during Phase II these levels were 9.0 to 17.2 µg/L, during Phase IIa levels they ranged from not detectable to 13.8 µg/L, and during Phase III the levels were <2 to 12.2 µg/L. Acetate was found at levels ranging from nondetectable to 140 µg/L in Phase I, from 0.06 to 0.165 mg/L in Phase II and from <0.12 to 0.65 mg/L in Phase IIa. Other low molecular weight compounds detected less frequently included 2-butanone (12.5 to 39.8 µg/L) in Phase I samples, formate (not detected to 560 µg/L) in Phase I samples, 2-propanol (not detected to 154 µg/L) in Phase IIa samples, and methanol (101 to 233 µg/L) in Phase IIa samples.

Other organic compounds detected above 5 µg/L during the tests included dibutylamine (not detected to 25 µg/L in Phase I); dipropylene glycol methyl ether (not detected to 76.3 µg/L in Phase I); bis 2-ethylhexyl phthalate (0.3 to 28.1 µg/L in Phase II); benzyl alcohol (not detected to 7 µg/L in Phase IIa); 2-ethyl-1-hexanol not detected to 8.9 µg/L in Phase III); methyl sulfone (not detected to 54.5 µg/L in Phase IIa and not detected to 25.4 µg/L in Phase III); oxalate (<0.10 to 0.41 mg/L in Phase IIa); lactate (<0.12 to 1.10 mg/L in Phase IIa); urea (0.302 mg/L in Phase IIa); methylmethacrylate (not detected to 6.74 µg/L in Phase III); 4-hydroxy-4-methyl-2-pentanone (not detected to 47.4 µg/L in Phase III); and 2-methyl-2,4-pentanediol (not detected to 34.1 µg/L in Phase III).

Phenolic compounds were detected in Phases I, II, IIa, and III at levels exceeding

the NASA MSIS of 1  $\mu\text{g/L}$  for total phenols. Compounds detected during Phase I include 3-t-butylphenol (not detected to 1.6  $\mu\text{g/L}$ ); 4-chloro-3,5 dimethylphenol (not detected to 0.5  $\mu\text{g/L}$ ); 2,4-di-t-butylphenol (not detected to 0.1  $\mu\text{g/L}$ ); 4-t-octylphenol (not detected to 1.0  $\mu\text{g/L}$ ); phenol (not detected to 5.1  $\mu\text{g/L}$ ); and 2-phenylphenol (not detected to 2.2  $\mu\text{g/L}$ ). Iodine disinfection byproducts such as iodomethane (not detected to 1.3  $\mu\text{g/L}$ ); diiodomethane (not detected to 1.4  $\mu\text{g/L}$ ); and iodoform (not detected to 8.8  $\mu\text{g/L}$ ) were also detected. Only one phenol compound, 2,6-di-t-butyl-4-methylphenol (2.5 to 2.6  $\mu\text{g/L}$ ), was detected in Phase II samples, while iodinated compounds such as diiodomethane (0.4 to 0.5  $\mu\text{g/L}$ ) and iodoform (1.8 to 1.9  $\mu\text{g/L}$ ) were also found. During Phase IIa, phenol ranged from not detected to 1.0  $\mu\text{g/L}$  and iodoform ranged from not detected to 4.8  $\mu\text{g/L}$ . No phenolic compounds were found in Phase III samples, and iodoform was the only iodinated compound detected at levels up to 5.6  $\mu\text{g/L}$ .

## SIGNIFICANCE

The development of water recycling systems is of paramount importance for the success of long-duration missions. In turn, the monitoring of water quality provides concrete evidence of the capability of the water recycling systems to provide clean potable water and is required to verify that the water is potable and acceptable for human consumption. WAFAL analyzed about 160 water samples throughout the course of the Lunar-Mars Life Support Test Project. This project was the first time since the late 1960's that water recycling with human consumption was performed and the first time systems developed for the ISS were tested in this manner. Results from the analysis of samples show that the water recycling systems developed during Phases II, IIa, and III were capable of producing potable water which met NASA and U.S. EPA requirements after the water was treated using a commercial system. All recovered water samples analyzed met U.S. EPA standards. Generally, the majority of samples also met NASA potability standards.

On several occasions the organic and inorganic content of the water exceeded the NASA specifications and required the water to be reprocessed prior to consumption. Parameters of most importance where requirements were not met included total organic carbon, total bacteria, copper, lead, and nickel. During Phase II, the water was reprocessed seven times because total organic carbon requirements were not met. During Phase IIa, problems with the water recovery system required the recycled water to be reprocessed eleven times for TOC excursions and ten times for excessive microbial levels. While Phase III did not require reprocessing because a commercial Milli-Q<sup>®</sup> was used as a post processor, high microbial levels did require the potable water tanks to be heat sterilized three times. Thus, systems for polishing and disinfecting the potable water tanks appear necessary.

That exceedances were detected that required the water be reprocessed for potability clearly demonstrates the need for onboard water analytical capabilities. Similarly, on several occasions microbial contamination in the potable water was

detected and required heat disinfection to assure microbial safety. This demonstrates the need for onboard microbial analysis capability and the ability to recover microbiological control.

Color and pH measurements consistently did not meet NASA standards because of the addition of iodine as a disinfectant in the potable water. With the help of these data, the MSIS specifications should be re-evaluated to determine more appropriate limits for pH and color in iodinated water. Another specification that should be evaluated is the MSIS total phenols specification. This level should be increased to agree with the EPA health advisory for phenol, which is 4 mg/L. Other standards outlined in the MSIS appear to be adequate. However, future work should concentrate on the development of short-term and long-term exposure requirements for the most critical water quality parameters.

The sampling and monitoring plan performed during these studies proved to be adequate. However, analytical methods for identifying organic constituents in recovered water at low levels should be improved. More work should be done to increase the organic carbon recovery of the potable water samples by either developing more sensitive methods of analysis and/or by testing a wider array of organic compounds, especially those of a biological nature such as proteins and biomolecules.

## References

1. NASA, Man-Systems Integration Standards, NASA-STD-3000, Volume III, Revision B, August 1994.
2. United States Environmental Protection Agency, Office of Water, Drinking Water Regulations and Health Advisories, EPA 822-B-96-002, October 1996. Online at <http://www.epa.gov/ost/drinking/standards/>.
3. Wyle Life Sciences, Systems, and Services, Water and Food Analysis Section. Instructions for Water Sample Receiving, Allocation, Preservation, and Storage. WI-WAF-001.6, Rev. 1. April 1998.
4. American Public Health Association, Standard Methods for the Examination of Water and Wastewater, 18th edition, 1992.
5. Schultz, J.R., Flanagan, D.T., Bruce R.J., Mudgett, P.D., Carr, S.E., Rutz, R.A., Huls, M.H., Sauer, R.L., and Pierson, D.L., Biofilm Formation and Control in a Simulated Spacecraft Water System: Three Year Results, SAE Technical Paper 921310, 22nd International Conference on Environmental Systems, Seattle, Washington, July 1992.
6. Hach, 1992. Method 8225-Color: Apparent and True, Hach Water Analysis Handbook, 2nd Ed., Hach Company, pp 265-267.
7. Stafford, S.S., Kolloff, R.H., Thorp, J.R., Hollis, J.S., Doherty, L.C., and Williams, A.S. May 1994. Analysis of Volatiles Using Purge and Trap with GC-MS – Methods and Instrument Configurations, Hewlett-Packard

- Applications Note 228-278, Hewlett Packard Corporation, pp 1-6.
8. Yamada, H., and Somiya, I., 1989. The determination of carbonyl compounds in ozonated water by the PFBOA method. *Ozone Science and Engineering*, Vol. 11 pp 127-141.
  9. Glaze, W. Koga, M., and Cancilla, D., 1989. Ozonation byproducts. Improvement of an aqueous-phase derivitization method for the detection of formaldehyde and other carbonyl compounds formed by the ozonation of drinking water. *Environmental Science and Technology*, Vol. 23, No. 7, pp 838-847.
  10. Edeen, M.A. and Barta, D., 1996. Early Human Testing Initiative Phase I Final Report, JSC-33636, NASA-Johnson Space Center, Houston, TX.
  11. Columbo, G.V., Putnam, D.F., and Sauer, R.L., July 1978. Microbial Check Valve for Shuttle, ASME Technical Paper 78-ENAS-27, Intersociety Conference on Environmental Systems, San Diego, CA.
  12. Henninger, D.L., Brasseaux, S., Cornwell, J., Dall-Bauman, L., Laws, B., Ming, D., Verostko, C., Bourland, C., O'Rear, P., and Hulburt, K., 1997. Lunar-Mars Life Support Test Project Phase II Final Report, JSC-38800, NASA-Johnson Space Center, Houston, TX.
  13. Verostko, C., Pickering, K., Smith, F., Packham, N., Lewis, J., Stonesifer, G., Staat, D., and Rosenbaum, M., July 1997. Performance of the Water Recovery System During Phase II of the Lunar-Mars Life Support Test Project, SAE Technical Paper 972417, 27th International Conference on Environmental Systems, Lake Tahoe, NV.
  14. Bouma, J.E., Koenig, D.W., Bell-Robinson D.M., and Pierson, D.L., July 1997. iral Challenge of an Advanced Life Support Water Treatment System, SAE Technical Paper 972413, 27th International Conference on Environmental Systems, Lake Tahoe, NV.
  15. Homan, M.E., Schultz, J.R., and Sauer, R.L., July 1997. Water Analysis Results from Phase II of the NASA Early Human Testing Initiative 30-Day Closed Chamber Test. SAE Technical Paper 972555, 27th International Conference on Environmental Systems, Lake Tahoe, NV.
  16. Koenig, D. W., Bell-Robinson, D.M., and Pierson, D.L., July 1997. Microbial Colonization of Closed Life Support Chambers, SAE Technical Paper 972414, 27th International Conference on Environmental Systems, Lake Tahoe, NV.
  17. Carter, D.L., Phase III Integrated Water Recovery Testing at MSFC: International Space Station Recipient Mode Test Results and Lessons Learned, SAE Technical Paper 972375, 27th International Conference on Environmental Systems, Lake Tahoe, NV, July 1997.
  18. Advanced Life Support Program, Results of the JSC 60-Day International Space Station (ISS) Phase IIA Life Support Test Quick Look Report, NASA/JSC, June 1997.
  19. Pickering, K.P., and Edeen, M.A., July 1998. Lunar-Mars Life Support Test

Project Phase III Water Recovery System Operation and Results. SAE Technical Paper 981707, 28th International Conference on Environmental Systems, Danvers, MA.

20. Edeen, M.A., and Pickering, K.P., July 1998. Biological and Physical-Chemical Life Support Systems Integration – Results of the Lunar Mars Life Support Phase III Test. SAE Technical Paper 981708, 28th International Conference on Environmental Systems, Danvers, MA.
21. Edeen, M.A., Lunar-Mars Life Support Test Project: Phase III Final Report, JSC-39144, NASA/JSC February 2000.

## ACRONYMS & ABBREVIATIONS

AES	Air Evaporation Subsystem
APCOS	Aqueous Phase Catalytic Oxidation System
ARS	Air Revitalization System
C	Conductivity
CHX	Condensing Heat Exchanger
CHeCS	Crew Health Care System
EPA	Environmental Protection Agency
F	Filter
GC/MS	Gas Chromatography/Mass Spectrometry
HA	Health Advisory
HMS	Human Metabolic Simulator
I2	Iodine
ICB	Immobilized Cell Bioreactor
ILSSTF	Integrated Life Support Systems Test Facility
ISS	International Space Station
IX	Ion Exchange
JSC	Johnson Space Center
MCL	Maximum Contaminant Level
MCV	Microbial Check Valve
MI	Matrix Interference
MSIS	Manned System Integration Standards
NA	Not Analyzed
ND	Not Detected
NH4RS	Ammonia Removal System
RO	Reverse Osmosis
STP	Standard Temperature and Pressure
TFB	Trickling Filter Bioreactor
TOC	Total Organic Carbon
UF/RO	Ultra Filtration/Reverse Osmosis
VCD	Vapor Compression & Distillation
VPGC	Variable Pressure Growth Chamber

VRA	Volatile Removal Assembly
WQM	Water Quality Monitor
WRS	Water Recovery System

### **Units of Measure**

Pt-Co	Platinum-Cobalt units
µg/L	Micrograms per Liter
µS/cm	Microsiemens per Centimeter
mg/L	Milligrams per Liter
NTU	Nephelometric Turbidity Units
TON	Threshold Odor Number
TTN	Threshold Taste Number

### **Acknowledgements**

We appreciate the contributions and support from members of the Advanced Life Support community, crewmembers of LMLSTP Phases I, II, IIa, and III, and especially members of the Medical Sciences Division, Water and Food Analytical Laboratory for their dedication to this project.