CHAPTER 4

POTABLE WATER SUPPLY

by

Richard L. Sauer
David J. Calley

Lyndon B. Johnson Space Center

Introduction

The potable water system was an essential element in the Apollo life support system. It provided water, on demand, for drinking, personal hygiene, dehydrated food reconstitution, and for cabin cooling. Unlike earlier spacecraft which relied upon stored water as the only potable water source, the Apollo system provided for resupply of onboard stores by utilization of byproduct water from fuel cell operation.

Underlying the development of the Apollo spacecraft water system, and that used on all prior spacecraft, are unique circumstances related to operation in the space environment, in general, and in spacecraft, in particular. The absence of gravity requires that the entire water system be sealed and that positive expulsion be provided through such techniques as movable diaphragms or bellows installed in water storage containers. Spacecraft operation demands highly reliable performance and minimum weight. System reliability is insured through careful materials selection and the use of redundant or multiple components. Volume constraints within the spacecraft itself and the closed atmospheric environment severely limit the choice of materials to be used. In addition toxicological and flammability parameters require consideration.

The interdependency of spacecraft systems imposes other constraints upon the potable water system. For example, protecting the integrity of the spacecraft's cooling system demands severe limitation of the types and amounts of additives which may be used in the water system to control microbial growth, prevent corrosion, or protect the taste of the water provided.

The bacteriological quality criteria used by NASA for potable water systems required the absence of viable organisms (sterility). The criteria did not specify indicator organisms but rather included specific analyses for the absence of *E. coli*, total count, yeast and mold, and anaerobic organisms. The design characteristics of the water system, possessing several potential sources of contamination, offered little restraint in preventing microbial entry and proliferation in the water. Information concerning the interrelationship between microorganisms and man in the spacecraft environment was limited. In addition, a remote but real chance existed that fecal contamination of drinking water could occur. For these reasons, the NASA standard requires that water in all spacecraft systems be maintained free of viable organisms.

The standard for water potability formulated by NASA was based on the United States Public Health Service Drinking Water Standards, 1962. Standards for the chemical composition of spacecraft drinking water were similar to Public Health Service standards; microbiological standards were, however, more stringent. In addition, several potential contaminants unique to spacecraft water were included.

The Apollo potable water system accomplished the objectives for which it was designed, and its overall performance was good. While design and operational difficulties existed, these were all successfully resolved. This chapter traces the history and evolution of the Apollo potable water system and describes its operation and performance.

Evolution of the Apollo Potable Water System

Project Mercury Potable Water System

For the first United States manned spacecraft program, Project Mercury, potable water was supplied by a simple "fill and draw" system. All metabolic water to be used was loaded onboard before launch. The system consisted of a flexible water pouch containing approximately 2.7 kg (6 lb) of water. The water was transferred to the crewman by means of a flexible hose that terminated in a drinking tube. Water was expelled from the tube by pressure on the pouch.

Gemini Program Potable Water System

The Gemini spacecraft was the first to use fuel cells to provide electrical power. These devices combined gaseous oxygen and hydrogen through an electrode to produce an electrical current, with water as a byproduct. While considerable effort was expended during the Gemini Program to process this fuel cell-produced water by means of filtration, carbon sorption, and ion exchange resins, none of these methods proved sufficiently effective to make the water potable. Consequently, Gemini crewmembers like their predecessors relied upon a fill and draw system for drinking water.

In addition to providing water for drinking purposes, the Gemini system (figure 1) supplied water to the secondary spacecraft cooling system. In the event of a partial failure of the space radiators (the primary spacecraft cooling mechanism), or during periods of high heat rejection, secondary or supplemental spacecraft cooling was provided by the spacecraft water boiler. This device evaporated water to the space vacuum and thereby rejected heat from the spacecraft. In a contingency situation, water was supplied to the boiler in the form of humidity or suit condensate, with supplemental water provided by the potable water system. This design required that the water system and humidity condensate system be interconnected. A potential cross-contamination problem was thereby introduced – a problem which was further complicated because the humidity condensate system was interconnected with the urine management system. To obviate the potential hazard, chlorine was added to the prelaunch-loaded water to prevent microbial contamination.

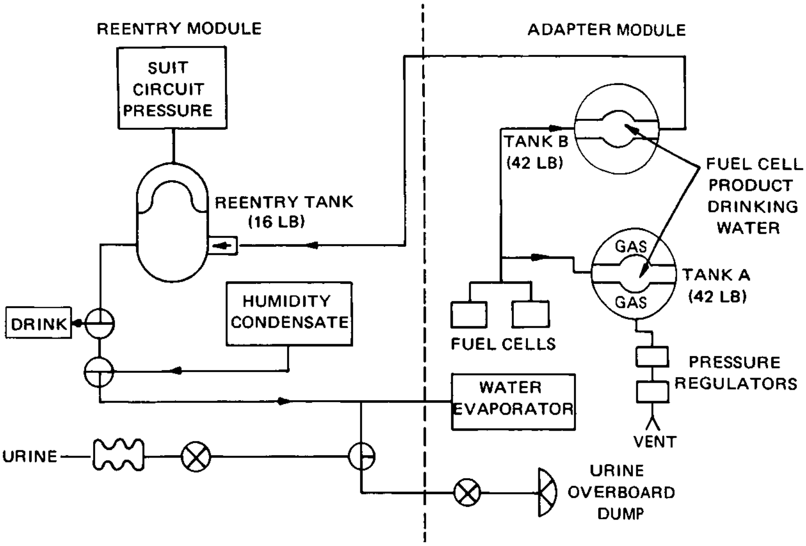

Figure 1. Gemini spacecraft water system.

Apollo Program Potable Water System

The problems encountered in the use of fuel cell-generated water during Gemini were resolved in sufficient time to make fuel cell water the principal source of potable water in Apollo Command Module spacecraft. The solution was effected by the choice of a sintered nickel electrode to replace the organic electrode used in the Gemini system. The sintered nickel electrode did not degrade as did the organic electrode, consequently, the Apollo fuel cell produced water of extremely high quality.

The water supply systems in the Command and Lunar Modules differed. In the Command Module, water was generated by fuel cell operation; in the Lunar Module, all water supplies were loaded in storage tanks before lift-off. Other differences between the two systems were dictated by the functions unique to each vehicle. In the Command Module system, provision was made for chilling and heating the water supply. No heating or cooling was be provided for Lunar Module water. The Lunar Module water supply was used as the primary means of vehicle cooling through a sublimation process. In the Command Module, the potable water system provided for supplementary cooling only via the spacecraft evaporators. (Primary sublimation cooling was accomplished through space radiators.)

Command and Service Module Potable Water System

A schematic diagram of the Command and Service Module (CSM) water management system is shown in figure 2. Water was generated by the fuel cells located in the Service Module. These fuel cells consisted of two chambers separated by porous nickel electrodes. The electrolyte was concentrated potassium hydroxide. One of the chambers was filled with oxygen (cathode), and the other with hydrogen (anode); pressure in both chambers was maintained at 4.1×10^5 N/m^2 (60 psi). Oxygen was diffused through the electrode into the hydrogen filled chamber, where the two gases reacted chemically to produce electrical power to meet the requirements of the Command/Service Module. The initial Apollo CM's were plagued with excess hydrogen in the water. As a consequence, a hydrogen separator was developed and used on Apollo 12 and subsequent missions. This device functioned as follows: hydrogen diffused from the water through the walls of palladium-silver tubes and then vented into space, and the degassed water was conveyed to the water valve (control) panel in the Command Module.

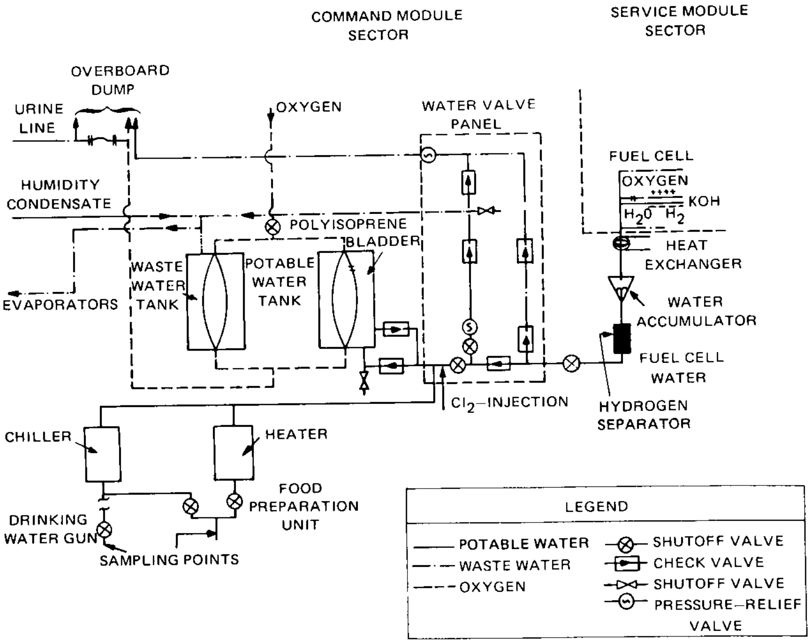

Figure 2. Command Module water system.

The fuel cells operated at a temperature of approximately 483°K (410°F) and at a pressure of 4.1 x 10^5 N/m^2 (60 psi), and produced water at a nominal rate of .54 kg/hr (1.2 lb/hr). The water production rate depended on the power drawn from the cells, and increased to as much as 1.0 kg/hr (2.2 lb/hr) for brief periods. Before fuel cell water was transferred to the Command Module, it was cooled to a temperature of 296°K (74°F), and then reduced to a system pressure of 1.7 x 10^5 N/m^2 (25 psi).

Fuel cell water was transferred to the water valve panel by means of an aluminum line. From this panel, water was routed either to the potable water tank or to the waste-water tank. From the potable water tank the water was routed to either the food preparation unit after passing through a heater, or to the drinking water gun after passing through a chiller. When the potable water tank was full, water was routed to the waste-water tank. The waste-water tank also received humidity condensate from the pressure suits and from the Command Module atmosphere. Excess water was dumped overboard.

The main controls on the water panel were two water-shutoff valves (one each for the potable water and waste-water systems), a shutoff valve that permitted access to the waste-water system, a chlorine-injection assembly, a control valve to the overboard dump, and two pressure-relief controls.

Possible microbiological contamination of the potable water resulting from the humidity-condensate input was prevented by maintaining a chlorine residual in the Command Module potable water. On Apollo flights 7 through 13, continuous minimum residual of 0.5 mg/liter was maintained by adding 22 cc of a sodium hypochorite stock solution (5000-mg/liter available chlorine) once every 24 hours. The chlorine solution was added manually at the port between the fuel cells and the potable water tank. A modified chlorine addition was used on Apollo 14 and the remaining flights. In these flights the water systems were injected with one 22 cc ampoule of sodium hypochlorite (1860 mg/l as available chlorine) and one 22 cc ampoule of mixed sodium dehydrogen phosphate (0.297 molar) and sodium nitrate (0.217 molar). The addition of sodium nitrate was found to have a conserving effect on the chloride, reducing its rate of decay in the system.

The food preparation unit consisted of a heater and two water-use ports for hot and chilled water. A pressure of 1.7 x 10^5 N/m^2 (25 psi) was maintained by applying oxygen to an expansion bladder in the potable water tank.

Functional Components. The following key functional components were used in the Command Module water management system.

1. ***Potable Water Tank.*** The potable water tank served as a water storage container in case of fuel cell failure and as an equalization tank to provide water during peak demand conditions when the water demand rate exceeded the fuel cell production rate; for example, during meal preparation times. The cylindrical vessel held a maximum of 16 kg (36 lb) of water and was fabricated from 6061 aluminum alloy. An oxygen-filled polyisoprene bladder maintained a pressure of approximately 1.7 x 10^5 N/m^2 (25 psi) in the tank and throughout the system. Oxygen for pressurization was obtained from a common Service Module supply that also provided oxygen for metabolic consumption and for power generation. Because free hydrogen in the water diffused through the bladder material, a low-rate gas bleed-off was provided to prevent a buildup that could result in an explosive hydrogen/oxygen mixture in the oxygen plenum.

2. ***Waste-Water Tank.*** The waste-water tank held a maximum of 25 kg (56 lb) of water. It was similar in design and operation to the potable water tank.

3. ***Water Chiller and Water Heater.*** The chiller, which had a water storage capacity of 227 gm (0.5 lb), reduced the temperature of the water from 298° to 280°K (76° to 45°F) for the drinking water gun and the food preparation unit. The heat exchanger tubes and all other components in the chiller were made of stainless steel. Chilling was provided by the spacecraft water/glycol cooling system. Heating was accomplished through electrical resistance. The water heater had a storage capacity of 1.1 kg (2.5 lb), and a maximum of two hours was required to raise the water temperature from 289°K (60°F) to the operating temperature of 341°K (154°F).

4. *Food Preparation Unit.* The food preparation unit dispensed hot or cold water in 28-gm (1-ounce) aliquots into the dehydrated food and beverages. The unit consisted of two valves and one nozzle. The configuration of the nozzle was identical to the nozzle of the water gun and permitted water to be injected into the food and beverage packages to facilitate rehydration of the contents. The valves controlled either the hot or the cold water to be used for food reconstitution. The water gun was used primarily to supply cold drinking water to the crewmen, but could also be used for the reconstitution of food and beverages requiring cold water (see figure 2).

5. *Drinking Water Gun.* A drinking water gun was connected to the water system by a 178-cm (70-in.) long flexible hose fabricated from a fluorinated hydrocarbon elastomer, Viton®. It was calibrated to dispense 14 gm (0.5 ounce) of cold water upon each activation. A counter was provided to permit inventory of the amount of water dispensed. Water was ejected from the nozzle of the gun either directly into the crewman's mouth or into a food or beverage container.

6. *Transfer Lines.* All hard lines in the system were fabricated from 0.64-cm (0.25-in.) diameter aluminum tubing.

Lunar Module Water Management System

The Lunar Module power was supplied by batteries rather than fuel cells. Therefore, no onboard fuel cell water generation was possible. Potable water, loaded prior to launch, was stored in three tanks, a 151-kg (332 lb) tank in the descent stage and two 19-kg (42 lb) tanks in the ascent stage (figure 3). The descent stage tank supplied all water during lunar orbit descent and lunar surface exploration. The ascent stage tanks supplied water during the ascent, rendezvous, and linkup phases. For the Apollo 15, 16, and 17 missions, which involved extended lunar stays, an additional 151-kg tank was installed in the descent stage.

The Lunar Module water system was pressurized by gaseous nitrogen at 3.1×10^5 N/m^2 (45 psi). This pressure was transmitted to the water by silicone rubber (Silastic)® bladders in each of the water tanks.

Lunar Module cooling was provided by a water sublimator. This device, similar in operation to the boiler in the Command Module, sublimated ice to the space vacuum through a sintered nickel plate. As in the Command Module, the feedwater was provided by the spacecraft potable water system. The requirement to minimize solids was even more stringent for the Lunar Module sublimator operation. Consequently, distilled water was loaded into the tanks to reduce to a minimum the potential blockage of the small pores of the nickel plate in the evaporator unit.

The potential hazard of cross-connection between the humidity condensate and the potable water system demanded the use of a water disinfection system in the Lunar Module as well as the Command Module. Iodine was selected instead of chlorine because it was thought that chlorine would create operating problems with the sublimation units. Iodine was added (12 mg/liter) to the water prior to launch to ensure a minimum residual of 0.5 mg/liter throughout the manning of the Lunar Module.

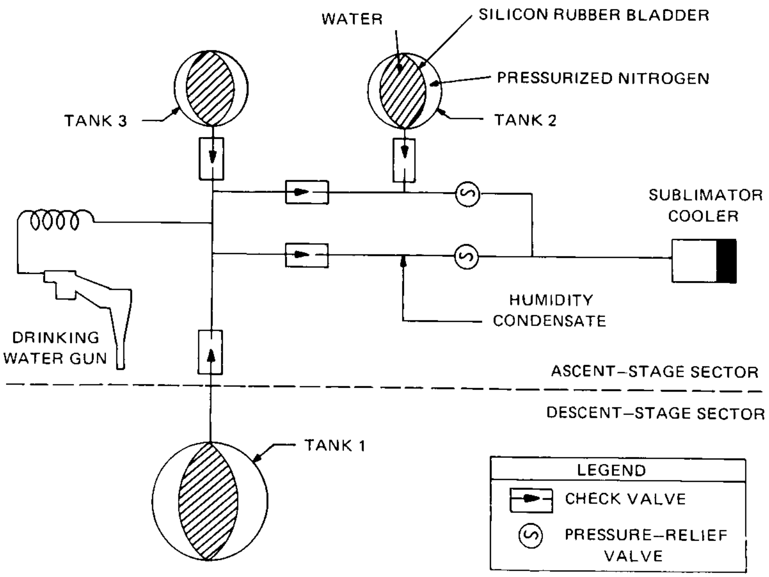

Figure 3. Lunar Module water system.

Results and Discussion

Overall, performance of the Command Module and Lunar Module water management systems was good. Problems did, however, arise. The low solids requirements constrained the use of materials for microbiological and corrosion control. Other areas of concern were taste and odor control, water potability, and materials selection. Overall system performance and resolution of problems that arose are described in the following sections.

Water System Materials Compatibility

Metallic Components. Corrosion of metallic components was found during development testing at the inlet tube to the heater, the tube in front of the drinking water gun hose connection, and the section of tubing between the chlorine injection port and the potable water tank. An investigation revealed that a pitting-type corrosion occurred throughout the system. Because of the corrosion, nickel, cadmium, and manganese were present in the water supply at levels in excess of allowable limits. Corrosion was attributable to the following factors.

1. The use of ultra-high purity water, which is corrosive by nature.

2. Incompatibility of the biocide with the system (that is, the capability of chloride ions to penetrate the passivating oxide layer formed on aluminum tubing).

3. Materials selected for system fabrication resulted in dissimilar metals being electrically interconnected. For example, the interconnection of aluminum and copper in

the water system, produced an electromotive force of approximately two volts. Internal tubing surface imperfections provided sites for active localized corrosion.

Tests indicated that the CM fuel cell water containing sodium hypochlorite (NaOCl) and sodium dihydrogen phosphate (NaH_2PO_4) at concentrations used in the spacecraft produced considerable corrosive action on aluminum. Nickel, cadmium, manganese, and, to a lesser extent, other metals were released into the Command Module water supply as a result of corrosive activity and the attendant deterioration of the nickel brazing and copper baffles in the water heater and the aluminum alloy tubing.

In addition to the problems that corrosion imposed on maintaining Command Module system integrity, corrosion also was a sink for the chlorine biocide, resulting in a rapid loss of residual biocide. To solve the incompatibility problem, sodium nitrate was added as a corrosion inhibitor.

The interaction of iodine with aluminum caused similar corrosion in the Lunar Module water system. The presence of metallic ions in samples taken from the ascent tank and the descent tank use port were evidence of this corrosion. However, because corrosion proved to be limited, inhibitors were not deemed necessary.

Synthetic Components. A problem of iodine depletion was observed in the Lunar Module. The primary cause of this depletion was the diffusion of iodine through the Silastic® membranous material used in the water tanks. This material acted as a semipermeable membrane. The rate of membrane permeation increased with increasing iodine concentration and the time of exposure of the bladder to iodinated water. To solve the permeability problem, iodinated water was not placed in the tanks during ground-based testing, and the tanks were not loaded until the latest possible time before lift-off.

Interaction between the biocide and the membranous material in the Lunar Module did not cause objectionable taste and odors as did interaction between the chlorine and the chlorine-polyisoprene bladder material in the Command Module water tank. In addition, the original neoprene hose connecting the drinking water gun to the water system in the Command Module interacted with water to produce significant taste and odors. An organic precipitate was found in the Command Module water system. The precipitate, a metal carbamate, was a curing agent was used in the polyisoprene tank bladders.

Gases. Offgassing of water at the use ports caused problems during flight because the quantity of gas in the water formed bubbles of sufficient size to inhibit direct use for drinking or food preparation. Techniques for gas/liquid separation in zero g (such as bagging and centrifugation) were not effective. Use of a hydrophobic/hydrophilic separator, which performed with reasonable success during the Apollo 11 mission, together with the palladium silver hydrogen separator that was used during the Apollo 12 and subsequent missions, relieved the problem somewhat; however, gases were still evolved.

The two major sources of gases dissolved in the Command Module water were hydrogen released from fuel cell water and oxygen diffused through the water tank bladders. Hydrogen gas was released from the fuel cell water as it passed through cascaded pressures from 4.1×10^5 N/m^2 (60 psi) to 3.4×10^4 N/m^2 (5 psi), the cabin atmosphere pressure. Oxygen, used as a pressure balance in the water tanks, diffused through the bladder membrane into the water supply. A third source of dissolved gases common to the Lunar Module and the Command Module was ground support equipment water that was not degassed before being loaded onboard the spacecraft.

Similar, but not nearly as pronounced, offgassing problems occurred at the use ports in the Lunar Module. The gases consisted either of nitrogen diffused into the water supply from the balancing plenum of the potable water tanks or air entrained in the water supply at the time of servicing (no inflight data were collected).

Chemical Quality of Water

Water used to fill ground support equipment before spacecraft loading was drawn from the resources of the city of Cocoa, Florida. The city water was filtered through particulate filters, charcoal filters, and two mixed-bed ion exchange units. This product water, which met the quality requirements shown in table 1, was then passed through 0.22μ bacterial filters and then into the ground support equipment units for the Command Module and the Lunar Module. The requirements for chemical quality for the ground support equipment water are listed in table 2.

Table 1

Water Quality Requirements for Facility Water Supply, Test Point 1*

Properties	Limits (max. allowable)
Electrical conductivity	.33 micromho/cm at 298°K (25°C)
pH	6-8 at 298°K (25°C)
Total residue	2 mg/liter
Sterility **	Reference only

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*Test Point 1 is at the facility water supply/spacecraft potable water the input interface.

**Sterility samples consisted of an anaerobic and an aerobic sample. Total volume for both samples was 500 ml.

Command Module System. The Command Module water system was subjected to a 24-hour disinfection soak with chlorinated water (10 to 20 mg/liter). The ground support equipment water was prepared with the chlorine solution plus sodium dihydrogen phosphate (100 to 200 mg/liter) for pH buffering, and sodium nitrate (52 to 62 mg/liter) as a corrosion inhibitor. This solution was loaded into the Command Module system. At the end of the 24-hour period, the Command Module system was emptied, flushed, and refilled with unchlorinated, high purity water from the ground support equipment. The quality requirements for this water are cited in table 3. The water remained in storage in the Command Module potable water tank for five to seven days. Between two to nine hours before lift-off, chlorine and buffer/inhibitor solutions were added to the storage

Table 2

Water Quality Requirements for Ground Support Equipment Water Supply, Test Point 2[a]

Properties	Limits (max. allowable)
Electrical conductivity	1.0 μmho/cm at 298°K (25°C)
pH	6-8 at 298°K (25°C)
Total residue	2 mg/l
Fixed residue	0.5 mg/l
Taste and odor	Threshold No. 3
Turbidity	11 units
Color, true	5 units
Particulate[b]	
Particle size range	No. of particles/500 ml fluid CSM/LM
0-10 μ	Unlimited[c]
10-25 μ	875
25-50 μ	100
50-100 μ	50
(over)100	2
Ionic species	
Cadmium	0.01 mg/l
Chromium (hexavalent)	0.05 mg/l
Copper	1.0 mg/l
Iron	0.3 mg/l
Lead	0.05 mg/l
Manganese	0.05 mg/l
Mercury	0.005 mg/l
Nickel	0.05 mg/l
Selenium	0.01 mg/l
Silver	0.05 mg/l
Zinc	5.0 mg/l
Chloride	–
Magnesium	–
Iodide	–
Aluminum	–
Calcium	–
Potassium	–
Silica	–
Total nitrogen	10.0 mg/l (CSM only)
Bactericide	0.5 mg/l
Sterility[d]	–

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[a] Test Point 2 is defined to be at the last possible, but practical, point prior to the potable water load line/spacecraft load point interface; this test point allowed water sampling without breaking or remaking of water servicing system connections. Water was required to meet the Test Point 2 maximum property limits at the beginning of water servicing prior to bactericide/additive addition if used, or prior to servicing the spacecraft if bactericide was not used.

[b] The particulate sample was taken immediately following final servicing of the spacecraft.

[c] Unlimited means that particles in this size range were not counted; however, any obscuring of the filter grid lines was cause for rejection.

[d] Sterility samples consisted of an anaerobic and an aerobic sample: total volume for both samples was 500 ml.

Table 3

Water Quality Requirements for Spacecraft Water Supply, Test Point 3[a]

Properties	Limits (max. allowable)
Electrical conductivity	Reference only
pH	6-8 at 298°K (25°C) for CSM 4-8 at 298°K (25°C) for LM
Total residue	14 mg/liter CM/LM
Taste and odor	Reference only
Turbidity	11 units
Color, true	Reference only
Particulate[b]	

Particulate Size Range	No. of Particles per 500 ml Fluid CSM	No. of Particles per 500 ml Fluid LM
0- 10 microns	Reference only	Unlimited[c]
10- 25 microns	Reference only	875
25- 50 microns	Reference only	200
50-100 microns	Reference only	100
100-250 microns	Reference only	10

Properties	Limits (max. allowable)
Ionic species	
Cadmium	0.01 mg/l
Chromium (hexavalent)	0.05 mg/l
Copper	1.0 mg/l
Iron	0.3 mg/l
Lead	0.05 mg/l
Manganese	0.05 mg/l
Mercury	0.005 mg/l
Nickel[d]	0.05 mg/l
Selenium	0.01 mg/l
Silver	0.05 mg/l
Zinc	5.0 mg/l
Chloride	—
Magnesium	—
Iodide	—
Aluminum	—
Potassium	—
Silica	—
Total nitrogen	10.0 mg/l (CSM only)
Bactericide	0.5 mg/l
Sterility[e]	Free of viable organisms

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[a] Test Point 3 is defined to be the onboard test/use ports in the LM and CSM.

[b] The particulate sample was taken immediately following final servicing of the spacecraft.

[c] Unlimited means that particles in this size range were not counted; however, any obscuring of the filter grid lines was cause for rejection.

[d] For the CSM and for missions when water was used from the CSM for no more than 14 days duration, the maximum allowable limit of the effective nickel concentration was 1.0 mg/liter.

[e] Sterility samples consisted of an anaerobic and an aerobic sample: total volume for both samples was 500 ml.

tank by means of injection ampoules (22 cc). Water was cycled from the use ports to distribute the injected solutions from the injection port (figure 2) into the storage tank. During flight, injections were repeated at approximately 24-hour intervals. The corrosion inhibitor described above was used only on the flights after Apollo 13.

Separate ampoules containing sodium hypochlorite (5000 mg/liter as chlorine) and sodium dihydrogen phosphate buffer (0.7 molar) were used for inflight injection of the Apollo 7 through 13 Command Module water systems. After the Apollo 13 mission, sodium nitrate was added to the buffer ampoules to provide water system corrosion inhibition. The water systems were injected with one ampoule of sodium hypochlorite (1860 mg/liter as chlorine) and one ampoule of mixed sodium dihydrogen phosphate (0.297 molar) and sodium nitrate (0.217 molar).

Three hours before lift-off, and at 24-hour intervals inflight, water was withdrawn through the drinking water gun or the food preparation unit to permit a flow of fuel cell water past the biocide injection point and into the potable water tank, after which the contents of the ampoules were injected. The injected solutions were flushed into the potable water storage tank by flowing fuel cell water past the chlorine injection port and into the tank (figure 2). Most of the biocide and buffer passed the service line branching point and was carried into the storage tank, but a small fraction remained in the injection tee or was diffused into the service line. After a ten-minute contact time, an ampoule of water was withdrawn through the injection point. As a result of withdrawal, any chlorine solution in the service line was pulled back into the main line, where the chlorine was transferred into the storage tank by the fuel cell water. Before the water was used, an additional 20-minute period was required to allow biocide, buffer, and inhibitor to disperse in the potable water tank. The treated water was withdrawn for consumption through the drinking water gun and the food preparation service outlets.

On several occasions during the early Apollo flights, the crewmembers reported that the water had a strong chlorine taste. In most instances, the difficulty was traced to a procedural error that occurred during the injection of the chlorine and buffer. When clear and concise procedures were developed and used, the crewmembers had no objection to the taste of the water.

The chemical characteristics of the ground support equipment load water (test point 2) and the spacecraft water (test point 3) are shown in table 4. As the table indicates, the only potential contaminant consistently found was ionic nickel. The Apollo 12 ground support equipment load water sample was the only sample in which nickel appeared at a level above the specification limit. But, an excess of nickel was contained in five samples taken from the drinking water gun. The excess amounts were not considered medically significant for the short duration Apollo flights. Preflight samples from the hot water port were examined, and they, too, were contaminated with nickel. Based on these findings, a study was conducted to determine the inflight nickel content in the hot water port on the Apollo 14 flight. A good correlation existed between nickel concentrations found in flight and those found immediately after recovery (table 5). Postflight concentrations (6.0 mg/liter) exceeded preflight load water specifications in nine out of ten samples taken within 40 hours of recovery. All evidence suggested that the hot water heater was the source of the contaminant and that the concentration

Table 4

Preflight Chemical Analysis of Command Module Potable Water, Apollo 7 through 17

Parameter	Ground Support Equipment Test Point 2 Range	Spacecraft System Test Point 3 Hot Water Port Range	Spacecraft System Test Point 3 Drink Gun Range
pH (units)	4.76 – 7.65	5.50 – 7.79	4.82 – 7.60
Electrical conductivity (umho/cm)	0.31 – 2.30	0.28 – 7.90	.25 – 3.90
Total residue (mg/l)	0.72 – 2.70	0.62 – 17.50	.60 – 4.70
Taste and odor (threshold)	All <3	All <3	All <3
Turbidity (nephlos)	0.5 – <1	0.2 – 7.0	0.2 – 11.00
Color (true)	<1. – 1	<1 – 5.0	<1 – 5.0
Ionic species (mg/l)			
Aluminum	<0.1 – 0.28	<1 – 3.2	<0.01 – 1.8
Cadmium	All <0.01	<0.01 – 0.02	<0.01 – 0.13
Calcium	<0.01 – 0.34	<0.01 – 1.2	<0.01 – 1.08
Chromium (+6)	<0.01 – 0.05	<0.01 – 0.06	<0.01 – 0.06
Copper	<0.01 – 0.07	<0.01 – 0.06	<0.01 – 0.11
Iron	<0.01 – 0.05	<0.02 – 0.03	<0.01 – 0.06
Lead	<0.01 – <0.05	<0.01 – <0.05	<0.01 – <0.05
Magnesium	<0.01 – 0.5	<0.01 – 0.14	<0.01 – <0.5
Manganese	<0.01 – 0.05	<0.01 – 0.07	<0.01 – 0.07
Mercury	All <0.005	<0.005 – 0.006	<0.005 – 0.006
Nickel	<0.05 – 0.26	<0.01 – 1.30	<0.01 – 0.18
Potassium	<0.01 – 0.50	<0.01 – <0.50	<0.01 – <0.50
Selenium	<0.01 – 0.20	<0.01 – <0.20	<0.01 – <0.20
Silicon	All <0.5	All <0.5	All <0.5
Silver	<0.01 – <0.02	<0.01 – <0.02	<0.01 – <0.02
Sodium	<0.02 – 0.41	0.01 – 0.60	0.01 – 0.83
Zinc	<0.01 – 0.07	<0.01 – 0.10	<0.01 – 0.72
Total nitrogen	All <10	All <10	All <10

Table 5

Postflight Chemical Analysis of Command Module Potable Water, Apollo 7 Through 17

Parameter	Drink Gun Test Point 3 Range	Hot Water Port Test Point 3 Range
pH (units)	6.0 – 7.4	6.5 – 7.7
Electrical conductivity (umho/cm)	2.13 – 260.0	1.87 – 210.0
Total residue (mg/l)	11.56 – 214.4	7.72 – 178.8
Taste and odor (threshold)	<3 – 5	All < 3
Turbidity (nephlos)	0.3 – 2.0	0.4 – 18.0
Color (true)	<1 – 5	<1 – 5
Ionic species (mg/l)		
Aluminum	0.07 – 1.5	0.59 – 0.08
Cadmium	< .01 – < .05	<0.01 – <0.05
Calcium	.02 – 0.57	0.02 – 2.70
Chromium (+6)	<0.01 – <0.05	<0.01 – <0.07
Copper	<0.01 – 0.05	<0.01 – 0.08
Iron	<0.02 – 0.09	0.01 – 0.04
Lead	<0.01 – <0.05	<0.01 – <0.05
Magnesium	0.04 – 0.82	0.03 – 0.50
Manganese	<0.01 – 0.06	<0.01 – 0.07
Mercury	All <0.005	All <0.005
Nickel	0.02 – 1.12	0.34 – 6.0
Palladium	<0.01 – <0.05	<0.01 – <0.05
Potassium	<0.01 – 0.36	<0.01 – <0.5
Selenium	<0.01 – <0.08	<0.01 – <0.08
Silicon	All <0.5	<0.5 – 0.8
Silver	<0.01 – <0.02	<0.01 – <0.02
Sodium	10.2 – 59.9	6.4 – 50.0
Zinc	0.03 – 0.17	<0.01 – 0.08
Total nitrogen	<10 – 10	All <10

of nickel increased after the heater was activated inflight. A substantial quantity of nickel brazing material was used in the construction of the heater. In addition, small amounts of nickel appeared to be leaching because of corrosion from other components of the potable water system. A review of the medical literature indicated that ingestion of nickel in the amounts found for the relatively short duration Apollo missions would not create an acute or chronic toxicological problem, but that reconsideration would be required for missions of longer duration.

Command Module Fuel Cell Water Quality. Chemically, the fuel cell byproduct water was of equal quality to distilled water, but the water was saturated with hydrogen gas. The total dissolved solids in this water averaged 0.73 mg/liter, with an average pH of 5.6. Analyses for total solids, turbidity, and particulates during chamber testing indicated that the water met specifications except for the presence of a metal carbamate, Bis-(pentamethylenedithiocarbamate) Ni (II). As noted previously, this precipitate appeared only after fuel cell water had collected in the water storage tank.

Lunar Module Water Quality. The Lunar Module water tanks were filled with ground support equipment load water containing 20 to 30 mg/liter iodine solution for disinfection. After three to four hours contact time, approximately one-fourth of the loaded water was drained out and uniodinated water added. This process resulted in a final load iodine concentration of 11 to 13 mg/liter. No provision was made for the inflight addition of iodine to the water storage tanks. In most cases, the degradation rate of iodine in the system was such that the initial load concentrations were adequate for biocidal action during the entire Lunar Module mission. The iodine concentrations were checked three times before lift-off, and depletion curves were plotted from the data. The depletion rate, projected for the duration of the flight, had to be low enough that an iodine concentration of at least 0.5 mg/liter was maintained during the period of Lunar Module manning When preflight data indicated a depletion rate that was too rapid to maintain an adequate iodine residual during the mission, a bacterial filter was installed in the line just ahead of the water use port.

The preflight chemical quality of the Lunar Module ground support equipment load water (test point 2) and of water from the spacecraft system (test point 3) is shown in table 6. As with the Command Module, comparison of these data with specification requirements listed in tables 2 and 3 shows that the upper range of certain parameters, slightly exceeded specification limits. These were turbidity test point 2 and nickel in test point 3 samples. These excursions were not considered to be medically significant. No data were collected to determine inflight Lunar Module potable water quality.

Microbiological Quality of Water

The NASA specifications for potable water require that water be "sterile"* throughout the course of a mission. The use of a biocide in the water system was necessary to meet this requirement. Command Module and Lunar Module data indicated adequate control of microbial growth existed when a proper biocide concentration was maintained. Preflight data gathered on the Command Module water demonstrated that system sterility could not be maintained without an adequate biocide residual.

During the preflight water storage period, several microorganisms were found in routine sampling of the water system. Because the growth phenomenon was consistent throughout the Apollo Program, chlorination of each CM water system (normally three hours before lift-off) was accomplished. Verification of the effectiveness of this procedure was obtained from Apollo 17 prelaunch water samples. For this mission, the water system was chlorinated nine hours before lift-off and microbiological samples were taken two hours before lift-off. These samples were negative for all forms of microbial growth.

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*Sterile is defined as the absence of viable organisms when employing specific analysis procedures, as in the filtration of three 150-ml samples through 0.45-micrometer filters, and then applying selective media for *E. coli,* total count or yeast mold to each of the filters. In addition, a qualitative anaerobic analysis was performed.

Table 6

Preflight Chemical Analysis of Lunar Module Potable Water, Apollo 9 through 17

Parameter	Ground Support Equipment Test Point 2 Range	Spacecraft System Test Point 3* Range
pH (units)	5.10 – 7.7	4.3 – 7.4
Electrical conductivity (umho/cm)	0.35 – 4.2	0.37 – 10.5
Total residue (mg/l)	0.2 – 2.7	0.49 – 8.3
Taste and odor (threshold)	All <3	All< 3
Turbidity (nephlos)	0.2 – <5	0.2 – 22.0
Color (true)	0.2 – 1.0	1.0 – >100
Ionic species (mg/l)		
Aluminum	0.04 – <0.5	0.4 – < 0.5
Cadmium	All <0.01	<0.01 – 0.039
Calcium	<0.01 – 0.03	<0.01 – 2.0
Chromium (+6)	<0.01 – <0.05	<0.01 – 0.08
Copper	<0.01 – <1.0	0.01 – 0.12
Iodide	<0.05 – <0.1	0.1 – 7.6
Iron	0.01 – <0.30	<0.01 – 0.04
Lead	<0.01 – <0.05	<0.01 – < 0.05
Magnesium	<0.01 – <0.5	<0.01 – < 0.5
Manganese	<0.01 – <0.05	<0.01 – < 0.06
Mercury	<0.005 – <0.013	All < 0.005
Nickel	<0.02 – 0.35	<0.01 – 0.25
Palladium	<0.01 – <0.02	<0.01 – < 0.05
Potassium	<0.04 – <0.10	<0.01 – 0.30
Selenium	<0.01 – <0.2	<0.01 – < 0.2
Silicon	All <0.5	All< 0.5
Silver	<0.01 – <0.05	<0.01 – < 0.02
Sodium	<0.01 – 0.21	<0.1 – 0.76
Zinc	<0.01 – 5.0	<0.01 – 0.12
Total nitrogen	All< 10	All<10

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*Test Point 3 was the use port inside LM cabin, with water drawn from the descent storage tank.

The types and numbers of microorganisms isolated from preflight and postflight samples are listed in tables 7 and 8. The most commonly found microorganisms were *Flavobacteria.* Seven species of this group were identified in preflight samples. At least one *Flavobacterium* species was found before each Apollo mission. Approximately 90 percent of the preflight samples taken during the storage period prior to chlorination contained viable microorganisms.

The single common-use water dispenser provided for the three Apollo crewmembers inflight offered no protection against microbial transfer from crewman to crewman. The Command Module water dispenser was attached to a 178-cm (70-in) flexible hose. The water in the hose had little or no residual biocide after remaining unused for extended periods: consequently, bacterial growth could occur during these periods.

Table 7

Microorganisms Isolated from Preflight and Postflight Apollo Command Module Potable Water Samples

Microorganism	Number of Microbes in Preflight Unchlorinated Water	Number of Microbes in Postflight Water
Aeromonas hydrophila	17	
Cephalosporium acremonium		15
Corynebacterium sp.	7	
Flavobacterium harrisonii	17	
Flavobacterium sp.	7, 15,16,17	14, 15
Flavobacterium sp II	11, 12, 17	12
Flavobacterium sp. III a	1, 8, 9, 10, 12, 14	11
Flavobacterium sp. III b	9, 10, 12, 14	10, 12
Flavobacterium sp. III c	7	
Flavobacterium sp. IV c	7, 12	
Flavobacterium sp. IV e		14
Gram negative rod	16, 17	
Herellea sp.	7	
Micrococcus sp.	7, 17	
NCDC Group III b	17	
NCDC Group IV c	16	16
NCDC Group IV d	16	16
NCDC Group IV e	16	16
Pseudomonas aeruginosa	16	
Pseudomonas maltophila	14	
Pseudomonas stutzerii	17	
Rhizopus sp.	7	
Sarcina sp.	7	
Staphylococcus, betahemolytic (Not Group A)	7	
Staphylococcus epidermidis	9, 12	
Streptococcus equinus	14	
Unidentified	11, 12	7,13
Yeast/moid growth	7, 13	

It had been noted that maintenance of system sterility could not be achieved in the absence of residual biocide. Connections, valves, metering dispensers, and O-rings in water systems could harbor bacteria, rapidly recontaminating the water. Back-contamination at use ports also occurred. Bacterial growth in the water storage tanks was unexpectedly rapid. During Command Module chamber tests when no biocide was used, bacterial levels of 6×10^6 organisms/100 ml of water were found during the time when the water was stored in the spacecraft. The source of the nutrients to support this growth is unknown; however, the nutrients may be received from the tank bladder material, the fluorocarbon hose, or other carbonaceous compounds.

Postflight potable water samples were taken from all missions except Apollo 13. The genus *Flavobacterium* was again the most commonly occurring microorganism (tables 7

Table 8

Microbial Concentrations Found in Preflight Command Module Unchlorinated Potable Water Samples

Apollo Mission	Range of Concentrations*	Ratio of Samples with Positive Growth to Total Number of Water Samples
7	Negative to TNTC**	7:11
8	$3 \times 10^2 - 1.1 \times 10^6$	5:6
9	Negative to 5.25×10^4	7:8
10	$86 - 1.2 \times 10^5$	6:6
11	$10 - 2.1 \times 10^5$	5:5
12	$1.1 \times 10^3 - 1.05 \times 10^5$	4:4
13	$6.0 \times 10^2 - 9 \times 10^6$	6:6
14	$4.5 \times 10^3 - 1.215 \times 10^6$	4:4
15	Negative – 1.13×10^7	3:4
16	$4.2 \times 10^5 - 1.9 \times 10^7$	4:4
17	$3 - 9.0 \times 10^5$	4:4

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*Concentration = Total microbes /150 ml of water

**TNTC = Too Numerous to Count

and 9). It was found in samples from five of the eleven Apollo missions. In addition, the National Communicable Disease Center group IVc, IVd, and IVe microorganisms isolated from Apollo 16 samples are very closely related to the *Flavobacteria* and some classifications include them with *Flavobacteria.*

The potable water samples from three missions (Apollo 8, 9, and 17) contained no microorganisms. All other mission samples contained concentrations ranging from three organisms per 150 ml of water to those too numerous to count (table 9). Based on preflight experience and public health data, microorganisms will not propagate in the presence of chlorine or iodine biocide in concentrations of approximately 0.1 mg/liter or higher. It must be assumed that residual chlorine was very low or absent in postflight water samples containing viable organisms. The inflight schedule called for chlorine addition to the water at approximately 24-hour intervals. The final inflight chlorinations were accomplished between 13 and 21 hours before splashdown. Samples for microbiological analysis were taken between 7.5 and 40 hours after splashdown. This schedule allowed the passage of approximately 25 to 55 hours, during which any residual chlorine could become depleted from the system before samples could be taken. It is known from qualification testing data that, in most cases, chlorine concentrations within the water system are greatly reduced or disappear within 24 hours.

As soon as possible after the recovery operation, the residual chlorine concentration in the hot water port and drinking water gun distribution systems was determined. These values are cited in table 10. As shown, chlorine residuals were present in the water in

Table 9

Microbial Quality of Postflight Command Module Potable Water Samples Collected 14 to 40 Hours After Splashdown

Apollo Mission	Microorganism	Ratio of Samples With Positive Growth to Total Number of Samples Taken	Concentration of Microbial Numbers Found (Irrespective of Species)
7	Unidentified	1:2	TNTC**
8	Negative	0:2	
9	Negative	0:2	
10	*Flavobacterium* sp. IIIb	1:2	20
11	*Flavobacterium* sp. IIIa	1:2	3
12	*Flavobacterium* sp. IIb *Flavobacterium* sp. IIIb	2:2	TNTC
13	No determinations		
14	*Flavobacterium* sp. *Flavobacterium* sp. IVe	2:2	1.5×10^5
15	*Cephalosporium acremonium*	2:2	No determination
16	NCDC* Group IVc NCDC Group IVd NCDC Group IVe	2:2	1.1×10^6
17	Negative	0:2	

* NCDC = National Communicable Disease Center
**TNTC = Too Numerous to Count

seven of nine missions. No determinations were made after the Apollo 13 and 14 missions. Chlorine concentrations ranged from zero in the Apollo 15 and 16 missions to as high as 6.0 mg/liter in the Apollo 10 drinking water gun sample. The postflight samples for microbiological analysis were taken simultaneously with those for chlorine residual determination. As can be seen, there were occasions when there was both a biocide residual and an indication of viable microbiological contamination. It is noted that the biocide depletion rate in the system is proportional to the area-to-volume ratio. Therefore it is probable that while postflight analysis indicated the presence of biocide (in effect the presence of biocide in the water tank because of sample volume), the biocide level was nil in the water use ports and interconnecting tubing where there is a high area-to-volume ratio. This could account for microbial growth in these portions of the system and the positive analyses. Because of the requirement for a biocide contact time and the immediate reduction of the biocide upon sample collection (sodium thiosulfate) it is possible to have an indication of a biocide concentration and still have viable organisms present.

Table 10

Postflight Chlorine Residuals in Command Module Potable Water System

Apollo Mission	Postflight Chlorine Residual, mg/l		Time Lapse Since Last Inflight Chlorination, hr
	Drink Gun	Hot Water Port	
7	0.13	Not determined	25
8	2.0	0.1	17
9	2.0	1.0	40
10	6.0	0.5	27
11	0.8	0.05	29:30
12	Not determined	0.125	35:30
13	Not determined	Not determined	
14	Not determined	Not determined	
15	0.0	0.0	25
16	0.0	0.0	30
17	0.01	0.01	32

Summary and Conclusions

The Apollo potable water system satisfied the dual purpose of providing metabolic water for the crewmen and water for spacecraft cooling. The overall performance was good. Although design and operational difficulties existed, these were not insurmountable despite the complexities of the unconventional type of water system required for space travel.

The problems documented in this chapter were successfully resolved in the Apollo Program. These efforts led to numerous technological advances including those in the following general areas.

1. Selection and evaluation of new types of water system materials.

Metallics: Evaluation of corrosion resistance of certain metal alloys, their physical characteristics as water system components, and their compatibility with biocides.

Nonmetallics: Endurance and permeability characteristics of polymeric membrane materials; material compatibility with water, gases, and biocides; and taste and odor problems related to material use.

2. Selection and evaluation of water biocides.

3. Selection and evaluation of physical and chemical corrosion inhibitors.

4. Importance of sanitary engineering concepts in the design, development, and testing phases of potable or multiuse water systems.

The information, equipment, and instrumentation developed in the Apollo Program will contribute toward the needs of future space flight missions. In addition, this technology may have useful application in municipal, industrial, and private water conservation programs.

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