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APOLLO EXPERIENCE REPORT - POTABLE WATER SYSTEM

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16. Abstract

A description of the design and function of the Apollo potable water system is presented. The command module potable water is supplied as a byproduct of the fuel cells. The cells, located in the service module, function primarily to supply electrical energy to the spacecraft. The source of the lunar module potable water is three storage tanks, which are filled before lift-off. The technique of supplying the water in each of these cases and the problems associated with materials compatibility are described. The chemical and microbiological quality of the water is reviewed, as are efforts to maintain the water in a microbially safe condition for drinking and food mixing.

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CONTENTS

Section	Page
SUMMARY	1
INTRODUCTION	1
DESCRIPTION OF THE APOLLO POTABLE WATER SYSTEM	2
Command and Service Module	2
Lunar Module	4
WATER SYSTEM MATERIALS COMPATIBILITY	5
Metallic Components	5
Synthetic Components	6
Gases	6
CHEMICAL QUALITY OF WATER	7
Water Source and Servicing	7
Fuel-Cell Water	7
Water-Use Ports	8
STERILIZATION OF THE POTABLE WATER SYSTEM	8
Medical Requirements	8
Biocide Addition	9
MICROBIOLOGICAL QUALITY OF WATER	10
Microbial Contamination	10
Maintenance of Sterility	11
CONCLUDING REMARKS	11

FIGURES

Figure		Page
1	Schematic of the CSM water management system	3
2	Schematic of the LM water management system	4

APOLLO EXPERIENCE REPORT

POTABLE WATER SYSTEM

By Richard L. Sauer and David J. Calley
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SUMMARY

The Apollo water-supply systems and the water-quality problem areas in the systems are described and discussed. The inflight water supply for the command module is a byproduct of the operation of the fuel cells designed for power generation in the spacecraft. The water produced in flight for crew use is stored in a pressurized tank which is filled from a ground-facility water supply before lift-off and is replenished in flight as required. Because there is no fuel-cell energy system in the lunar module from which byproduct water can be obtained, water is loaded into storage tanks in the spacecraft before lift-off. The system satisfies the dual purpose of providing metabolic water for the crewmen and water for a sublimation cooling process. In the command module, a buffer and an inhibitor are added to the water to minimize metal corrosion. The metal corrosion is caused by several factors: the use of ultra-high-purity water, the incompatibility of the chlorine biocide and the system, the galvanic action resulting from the selection of dissimilar metal components, and the surface imperfections in the tubing used for system construction. Other related problems are the characteristics of the command module tank-bladder material, the presence of a metal dithiocarbamate precipitate, and the release of dissolved gas from the water at the water-use ports. The resolution of these problems is described. Accumulated preflight data indicated that a significantly smaller degree of corrosion and related problems existed in the lunar module water system. A better system design and the use of a less corrosive biocide, in the lunar module water system, are reasonable explanations of the difference in problems noted in the command module and lunar module systems.

The NASA specifications for potable water require that the 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 exists when a proper biocide concentration is maintained. Preflight data gathered on the command module water demonstrated that system sterility cannot be maintained without an adequate biocide residual.

INTRODUCTION

The water-supply systems used in the Apollo Program and the water-quality problem areas that developed in these systems are described and discussed in this report.

The complexity of the systems and the requirement to maintain drinking-water sterility created several unexpected problems.

Essentially, three functions are served by the water-supply systems used in the command module (CM) and the lunar module (LM): generation and storage of a water supply, transport of water to the ports used by the crewmen for drinking and food preparation, and cabin cooling. Only the first and second functions are discussed in detail in this report. The principal difference between the CM and LM water systems is in the initial function, which is water generation and storage. Water is generated by fuel cells in the CM; however, in the LM, all required water supplies are loaded in storage tanks before lift-off. Other differences between the two systems are that provisions are made for chilling and heating of the water supply in the CM but not in the LM, and a portion of the LM water supply is used routinely for sublimation cooling of the LM cabin. In the CM, boiling of water is used only as a secondary or supplementary cooling device in place of sublimation cooling.

DESCRIPTION OF THE APOLLO POTABLE WATER SYSTEM

Command and Service Module

A schematic of the command and service module (CSM) water management system is shown in figure 1. Water generated by the fuel cells, located in the service module (SM), is transferred by means of a tube to a water-valve (control) panel. From the water-valve panel, water can be routed either to the potable-water tank or to the waste-water tank, and then to the food-preparation unit after passing through a heater, or to the drinking-water gun after passing through a chiller. If the potable-water tank is full, water is routed to the waste-water tank.

Water system. - The water supply from the fuel cells is adjusted to 25 psi and 74° F and is conveyed to a hydrogen separator, then to the water-control panel (fig. 1). The active portion of the separator consists of palladium-silver tubes. Hydrogen is diffused from the water through the walls of the tubes and then vented into space. The main controls on the water panel are two water-shutoff valves (one each for the potable water and waste water systems), a shutoff valve that permits access to the waste water system, the chlorine-injection assembly, a control valve to the overboard dump, and two pressure-relief controls. Fuel-cell water is supplied to both the potable-water and waste-water tanks, and excess fuel-cell water is dumped overboard if these tanks are filled. The potable water system line (line 1, fig. 1) leads to the chlorine-injection assembly, to a check valve, and to the potable-water tank. Water flowing out of the potable-water tank (by means of a bypass line and check valve) can be transferred to the chiller, heater, or waste-water tank, or dumped overboard. The chiller reduces the water temperature from 76° F to approximately 45° F. The food-preparation unit consists of a heater and two water-use ports, one for hot water and the other for chilled water. The heater has the capability to raise the water temperature to 154° F. A 25-psi pressure is maintained in the potable water system by applying oxygen to an expansion bladder in the potable-water tank.

Waste water system. - Fuel-cell water can be supplied to the waste water system only if the potable-water tank is filled. Water can be transferred from the waste-water

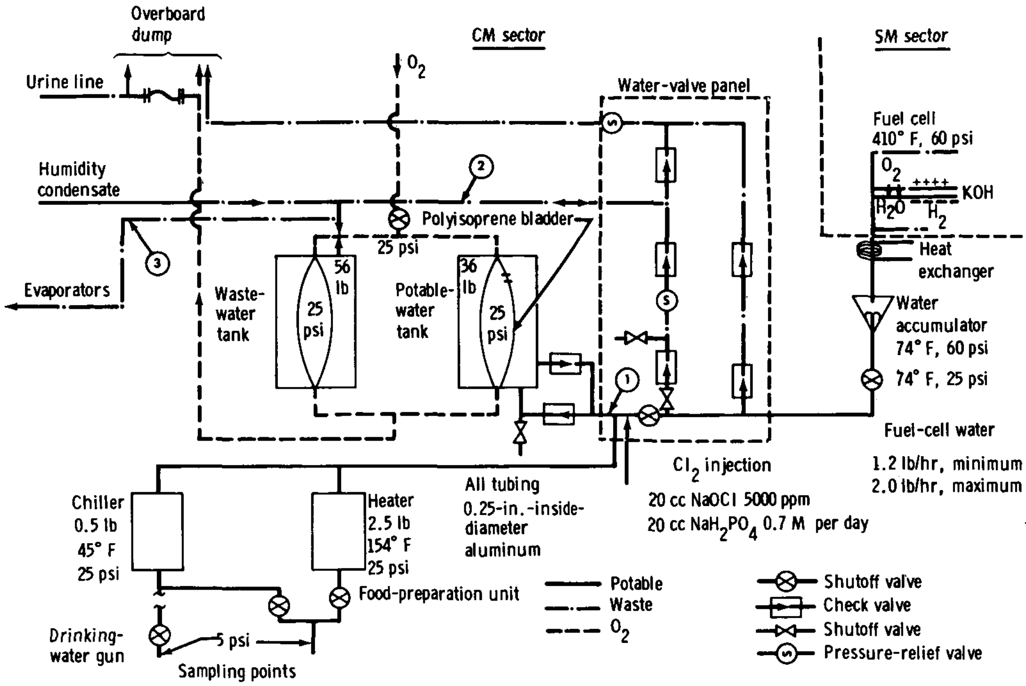

Figure 1. - Schematic of the CSM water management system.

tank by means of a service line (line 2, fig. 1) leading to the overboard-dump orifice or by means of another line (line 3, fig. 1) leading to two evaporators, which are secondary heat exchangers for the CSM water/glycol cooling system. Evaporated water is discharged into space through an orifice. The service line receives humidity condensate from the pressure suits and from the CM atmosphere. The condensate is a second source of water for the waste water system.

Functional components. - The following key functional components are used in the CM water management system.

Potable-water tank: The potable-water tank serves two purposes: a water-storage container in case of fuel-cell failure and an equalization tank to provide water during peak-demand conditions when the water demand rate exceeds the fuel-cell production rate for brief periods. The cylindrical vessel holds a maximum of 36 pounds of water and is fabricated from 6061 aluminum alloy. An oxygen-filled polyisoprene bladder maintains a pressure of approximately 25 psi in the tank and throughout the system. The oxygen that keeps the bladder inflated is obtained from a common SM supply that also provides oxygen for metabolic consumption and for power generation. Because free hydrogen in the water diffuses through the bladder material, a low-rate gas bleedoff is provided to prevent a buildup of diffused hydrogen, which could result in an explosive hydrogen/oxygen mixture in the oxygen plenum.

Waste-water tank: The waste-water tank provides storage for water that can be supplied to the water evaporators in case of a failure of the primary cooling system radiators. The tank holds a maximum of 56 pounds of water and is similar in design and operation to the potable-water tank.

Water chiller: The chiller, which has a water-storage capacity of 0.5 pound, reduces the temperature of the water from 76° to 45° F for the drinking-water gun and the food-preparation unit. The tubes of the heat exchanger in the chiller are made of stainless steel (type 347), and all other components in the chiller are made of stainless steel (corrosion-resistant type 316L). Chilling is provided by the spacecraft water/glycol cooling system.

Food-preparation unit: The food-preparation unit transfers hot or cold water in 1-ounce aliquots into dehydrated-food packages. The unit includes an electrical heater and two metering faucets. The heater holds 2.5 pounds of water and maintains the water temperature at 154° F. The heater consists of a stainless-steel (type 347), corrosion-resistant reservoir shell that contains copper (ASTM B 152-58) baffles and tubes.

Drinking-water gun: A drinking-water gun is connected to the water system by 70 inches of Viton flexible hose.

Lines: All hard lines in the system are fabricated from 0.25-inch-diameter 6061 aluminum tubing.

Biocide: Sodium hypochlorite (NaOCl) was used as a biocide for the CSM water supply system. The NASA potable-water specifications require that the minimum residual chlorine concentration be 0.5 mg/liter as chlorine.

Lunar Module

The LM water management system (fig. 2) differs in several aspects from the CM system. The LM system is designed to supply drinking water and water for sublimation cooling. The drinking-water gun provides water for drinking and food preparation. However, no provisions are made for chilling or heating potable water on board the LM. The sublimation unit is used as a heat exchanger to chill the cooling fluid for the cabin and various LM electrical components.

Three storage tanks, filled before lift-off with deionized water, meet all water demands. The large storage tank (tank 1), which holds 400 pounds of water, is located in the LM descent stage. The descent-stage tank supplies all water for the LM during the lunar-orbit descent phase and during the surface-exploration phase. During the ascent phase and the LM/CSM rendezvous and linkup phase, all water requirements are met by the two

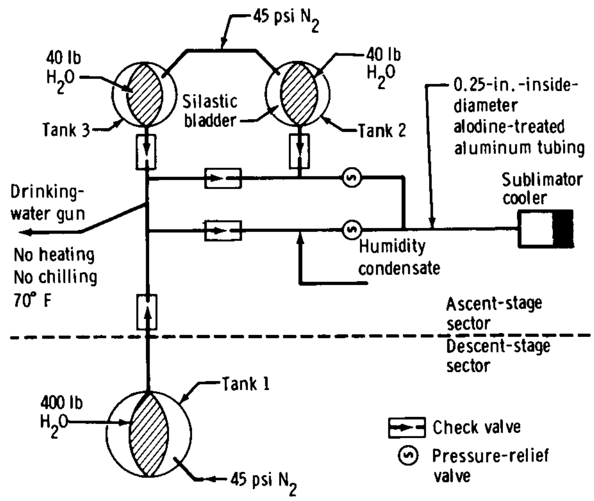

Figure 2. - Schematic of the LM water management system.

40-pound water-storage tanks (tanks 2 and 3), which are located in the ascent stage. The LM descent stage is separated from the ascent stage before lift-off and remains on the lunar surface. Storage tank 2 is used exclusively to supply water to the sublimation unit. A check valve prevents the transfer of water from tank 2 to the drinking-water gun. Tank 3 provides drinking water and, if required, supplies water to the sublimation units. Essentially, the entire LM water management system is fabricated from alodine-treated 6061 aluminum and 0.25-inch-diameter tubing. The following key functional components are used in the LM water system.

Water-storage tanks. - The three LM water-storage tanks are made of aluminum, and the water supply in these tanks is stored in silastic bladders. The space between the bladders and the tank shell is pressurized with nitrogen at 45 psi.

Sublimation units. - The sublimation units are heat exchangers that chill the water and glycol for the LM various components. Basically, the units consist of sintered nickel plates that form a barrier between the water (either liquid or solid) on one side and the space vacuum on the other side. A thin ice film develops at the inner side of the plates and sublimates and passes through the plates into space.

Disinfectants. - Iodine was selected as a disinfectant for the LM water management system because chlorine caused operating problems with the sublimation units. The NASA potable-water specifications require that the minimum residual iodine concentration be 0.5 mg/liter.

WATER SYSTEM MATERIALS COMPATIBILITY

Metallic Components

Corrosion was found initially at the following three points in the CM: the inlet tube to the heater, the tube just in front of the connection to the hose of the drinking-water gun, and the section of tubing between the chlorine-injection point and the potable-water tank. An investigation revealed that a pitting-type corrosion was occurring throughout the system. It was noted that pits occurred at points of surface imperfections in the 6061 aluminum tubing. Because of the corrosion, nickel, cadmium, and manganese were present in the water supply at levels in excess of the NASA criteria existing at that time.

It is believed that the corrosion was primarily attributable to the following factors.

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

2. The incompatibility of the biocide with the system (for example, the capability of chloride ions to penetrate the passivating oxide layer formed on aluminum tubing)

3. The selection of materials for system fabrication

a. Dissimilar metals connected in electromotive series (for example, the interconnection of aluminum and copper produces an electromotive force of approximately 2 volts)

b. Internal tubing-surface imperfections which provide sites for active localized corrosion

Tests indicated that fuel-cell water when combined with sodium hypochlorite and sodium dihydrogen phosphate (NaH_2PO_4) at the concentration levels used in the spacecraft produces considerable corrosive action on aluminum. Nickel, cadmium, manganese, and (to a lesser extent) other metals are released into the CM water supply as a result of corrosive activity and the attendant deterioration of the nickel-copper brazing and the aluminum-alloy tubing. In the CM, in addition to the problems that corrosion imposes on maintaining system integrity, corrosion also is a sink for biocide (chlorine) and results in a rapid loss of residual biocide. To solve the incompatibility problem, sodium nitrate was tested and found to be acceptable as a corrosion inhibitor.

The interaction of iodine with aluminum has caused, to a significantly lesser extent, corrosion in the LM water system. The presence of nickel in samples taken from the ascent-tank use port and the presence of cadmium in samples taken from the descent-tank use port are evidence of this corrosion. However, corrosion has proved to be of a minor nature, and inhibitors were not deemed necessary.

Synthetic Components

In the LM, a problem of rapid iodine depletion was found, caused by interaction between iodine and the silastic membranous material used in the LM water tanks. The primary cause of this depletion was the diffusion of iodine through the bladder material. Evidence indicates that the silastic bladder acts as a semipermeable membrane and that the rate of membrane permeation of the iodine increases with increasing iodine concentration and time of exposure of the bladder to iodinated water. To solve the permeability problem, the following procedural changes were instituted for the loading of the LM water tanks.

1. Iodinated water was not placed in the tanks during ground-based testing.

2. The loading of iodinated water into the tanks was delayed until the latest possible time before launch.

Interaction between the biocide and the membranous material in the LM has not caused the objectionable taste and odors as did the interaction between the chlorine and the original neoprene hose connecting the drinking-water gun to the water system in the CM. The extent to which chlorine-polyisoprene interaction affects the CM water taste and odor is unknown; however, organic precipitates have been found in the water system. The precipitate, a metal carbamate, was found to be a curing agent that was used in the polyisoprene tank bladders.

Gases

The degassing 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 of the water for drinking or food preparation. Techniques to perform gas/liquid separation in zero-gravity conditions (such as bagging and centrifugation) were not effective. A hydrophobic/hydrophilic water/gas separator, which performed with reasonable success during the Apollo 11 mission, is being used along with the palladium-silver hydrogen separator that was used during the Apollo 12 and subsequent missions.

The following are the two major sources of dissolved gases in the CM water.

1. Hydrogen gas released from fuel-cell water as the water passes through cascaded pressures from 60 psi (fuel cell) to 5 psi (cabin atmosphere)

2. Diffusion of oxygen, used as a pressure balance in the water tanks, into the water supply (Data on dissolved oxygen concentrations in the delivered fuel-cell water are not available.)

Similar degassing problems have occurred at the use ports of the LM. The gases are believed to have consisted either of nitrogen diffused into the water supply from the balancing plenum of the potable-water tanks or of entrained air in the water supply at the time of servicing. A source of dissolved gases that is common to the LM and the CM is ground-support-equipment water that is not degassed before being loaded on board the spacecraft.

CHEMICAL QUALITY OF WATER

Water Source and Servicing

The water placed on board the spacecraft for the Apollo missions was drawn from the resources of the city of Cocoa, Florida, and was purified to ultrahigh quality at the launch site. The city water was filtered through particulate filters, charcoal filters, and then through two mixed-bed ion-exchange units until the water had a resistivity of 18 megohms. Then, the water was filtered through 0.22-micron bacterial filters and was loaded into a water-servicing unit for subsequent transfer to the spacecraft.

The water was loaded into the servicing units in a closed system that eliminated exposure to the atmosphere. Once loaded, each servicing unit had the capability of recirculating water through the bacterial filters. On-site measurement of the pH and electrical conductivity was necessary to avoid atmospheric contamination of the highly purified water. Sample containers were designed to prevent the entry of any extraneous contaminants, and an anodized aluminum container (impregnated with Teflon) was found to be satisfactory for this purpose.

Fuel-Cell Water

Service module fuel-cell assembly. - The fuel cells are the only components interrelated with the water system that are located in the SM. Fuel cells consist of two chambers, separated by porous-nickel electrodes, and contain concentrated potassium hydroxide (KOH) liquid electrolyte. One of the chambers is filled with oxygen (cathode), and the other chamber is filled with hydrogen (anode); pressure in both chambers is maintained at 60 psi. Oxygen is diffused through the electrode into the hydrogen-filled chamber, wherein the two gases react chemically to produce electrical power to meet the requirements of the CSM. Extremely pure water is a byproduct of the chemical reaction. The fuel cells operate at approximately 410° F and 60 psi and produce water at a nominal rate of 1.2 lb/hr. The water-production rate depends on the power drawn from the cells and may increase from the nominal rate to as much as 2.0 lb/hr for brief periods. Before fuel-cell water is transferred to the CM, the water is cooled to 74° F and the system pressure is reduced to 25 psi.

Chemical composition. - Chemically, the fuel-cell byproduct water is as pure as distilled water, but the water is saturated with hydrogen gas. The total dissolved solids in this water averages 0.73 mg/liter, and the average pH is 5.6.

One problem associated with the fuel-cell water is the reaction that appears to occur between the storage-tank membranous bladder material and the fuel-cell water. After chamber tests, analyses for total solids, turbidity, and particulates indicated that the water failed to meet these specifications because of the presence of a yellow, granular material. This material was identified as Bis-(pentamethylenedithiacarbamate) Ni (II) and was previously referred to in the discussion on synthetic components as a metal carbamate. It appears only after fuel-cell water has collected in the water-storage tank.

Water-Use Ports

The significant problems associated with the water-use ports of the CM and LM have been related to the failure to deliver adequate biocide levels, caused by interaction with system components, and to the transport to the use ports of dissolved gases from the fuel cell and from the gas-pressurized water-storage tank. The attrition of disinfectant levels is directly related to the problems of corrosion, the interaction of disinfectant with membranous materials, and the presence of viable organisms, tastes, and odors in the water. The presence of quantities of gas in the water supply transported to the use ports caused difficulty in the direct use of the ports to acquire drinking water or food-preparation water.

STERILIZATION OF THE POTABLE WATER SYSTEM

Medical Requirements

The bacteriological criteria used by the NASA for potable water systems requires the total absence of viable organisms (sterility). The criteria do not specify indicator organisms. The design characteristics of the water system, possessing several potential sources of contamination, offer little restraint preventing microbial entry and proliferation in the water. Little is known about the interrelationship between microorganisms and man in the spacecraft environment. In addition, a remote but real chance exists 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.

In the development of biocide systems for the CM and LM, the size, weight, and power requirements of the systems were limited severely by the spacecraft design, which precluded the use (in the Apollo Program) of other than chemical treatment for disinfection. With the implementation of chemical sterilization, it has been confirmed that the chemical systems that were selected for use (chlorine in the CM, iodine in the LM) interacted with metallic components and membranous materials in the water system. As a result of these interactions, problems of corrosion, taste, odor, and loss of residual biocide were generated. Thus, the need for water-quality criteria oriented toward preservation of system integrity and the health and esthetic needs of the crewmen are evident.

Biocide Addition

System sterilization for the CM. - Both preflight and inflight system-sterilization procedures are used for the CM water system. Approximately 5 days before lift-off, the water system of the CM is filled with deionized water containing 12 mg/liter sodium hypochlorite as chlorine. After an exposure of 4 hours, the system is drained and flushed with water that has been deionized by means of a mixed-bed ion-exchange system. After flushing, the system is filled with deionized water. Three hours before lift-off, 20 cubic centimeters of sodium hypochloride (5000 mg/liter as chlorine) and sodium dihydrogen phosphate buffer (0.7 molar) are injected into the spacecraft system.

Inflight sterilization of the CM potable water system is performed in the following steps.

1. Approximately 10 percent ullage is produced in the potable-water tank by withdrawing water through the drinking-water gun or food-preparation unit. (This step is required in order to permit a flow of fuel-cell water past the biocide-injection point and into the potable-water tank.)

2. A solution containing 1860 mg/liter sodium hypochlorite as chlorine is injected from a 20-cubic-centimeter ampule.

3. The contents of a 20-cubic-centimeter ampule of sodium dihydrogen phosphate buffer solution (0.297 molar) and sodium nitrate corrosion inhibitor (0.217 molar) is injected.

4. The injected solutions are flushed into the potable-water storage tank by flowing fuel-cell water past the chlorine-injection port and into the tank (fig. 1). Most of the biocide and buffer passes the service line branching point and is carried into the storage tank. However, a small fraction may remain in the injection tee or may be diffused into the service line.

5. After a 10-minute contact time, an ampule of water is withdrawn through the injection point. As a result of withdrawal, a chlorine solution which may be in the service line is pulled back into the main line where the chlorine can be transferred into the storage tank by the fuel-cell water.

6. Before the water is used, an additional 20-minute period is required to allow the biocide, buffer, and inhibitor to disperse in the potable-water tank.

7. The sterilized water is withdrawn for consumption through the drinking-water gun and 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.

System sterilization for the LM. - Iodine was selected as the biocide for the LM water management system because it was noted that chlorine caused operational problems with the sublimation units. The NASA potable-water specifications require the minimum residual iodine concentration to be 0.5 mg/liter.

Only preflight sterilization procedures are used on the LM water system. Approximately 7 days before lift-off, the water management system is filled with a 30-mg/liter iodine solution. After 1 hour, the system is drained and refilled with deionized water, to which a 10-mg/liter iodine solution has been added. This solution is left in the LM tanks and is used to supply water during the lunar mission.

MICROBIOLOGICAL QUALITY OF WATER

Microbial Contamination

The problem of microbial contamination in the water system of the CM has been related almost totally to preflight detection of aerobic organisms in the hot-water port and the drinking-water gun. Bacterial growth has been detected during the interval immediately before a final chlorination before lift-off.

Several types of organisms have been identified in cultures from the use ports (for example, Flavobacterium sp., Staphylococcus epidermidis, Sarcinia sp., and Corynebacterium sp.). Flavobacterium sp. has been observed the most frequently and in the highest numbers. All of these species have been detected before the preflight chlorine injection. Postflight samples taken from the drinking-water gun consistently have had zero bacterial counts, and either zero or nominal counts (20 organisms per 100 milliliters) have been recorded for samples taken from the hot-water port. Preflight and postflight testing of all sample ports for coliforms, anaerobic bacteria, yeasts, and molds also resulted in a zero count. This condition can be attributed to the 24-hour inflight chlorination schedule.

Samples of the LM water supplies can be taken only during the preflight period because the LM stages are jettisoned in the course of the mission. Tests for coliforms, anaerobic bacteria, yeasts, and molds have been made on the LM water-supply samples drawn during the preflight period. Flavobacterium sp. has been found in a water supply prepared for transfer to the LM; however, after iodination, no organisms of any kind were found in this water supply, either before or after transfer into the LM. Bacterial growth has not been obtained from any samples taken after preflight iodination procedures have been completed.

Maintenance of Sterility

The single common-use water dispenser provided for the three Apollo crewmembers offers no protection from microbial transfer from crewman to crewman. The CM water dispenser is attached to a 70-inch-long Viton hose. The water in the hose has little or no residual biocide after remaining unused for extended periods. Consequently, bacterial growth may occur.

It has been noted that maintenance of system sterility cannot be achieved in the absence of residual biocide. Connections, valves, metering dispensers and O-rings in water systems may harbor bacteria that rapidly recontaminate the water. Also, back contamination at use ports occurs. Bacterial growth in the water storage tanks has been unexpectedly rapid. During CM chamber tests when no biocide was used, bacterial levels of to 6×10^6 organisms per 100 milliliters were found during the period of 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, hose, or other carbon compounds.

CONCLUDING REMARKS

The overall performance of the command and service module and lunar module water systems has been good. Although design and operational difficulties in the Apollo Program existed, the difficulties were not insurmountable despite the complex and unconventional type of water system that is required for space travel. The design and operational problems that were experienced on the two water systems are of considerable interest to industry, not only because of the uniqueness of the systems, but also because of the technology that is being developed and applied to problem solving.

The problems documented in this report have been successfully resolved in the Apollo Program. However, some concern exists that, as the timespan of space missions is increased, problems that are potentially adverse over a comparatively short period of time may evolve into serious problems during longer missions. During the Apollo Program, much of the technology was developed to meet future water-supply needs in spacecraft. The information, equipment, and instrumentation developed in spacecraft programs can be applied effectively to municipal, industrial, and private water-conservation programs. Technological advances described or cited in this report are found primarily in the following general areas.

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

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

   b. 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. The importance of sanitary-engineering concepts in the design development and testing phases of potable or multiuse water systems

In recognition of the rapidly increasing need for new technology in modern water-supply management, a conscious effort will be made to make meaningful contributions to modern ecology. It is the intent of the NASA to continue to design and develop high-quality potable-water use and recycle systems for the space program.

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