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Chapter 12

Spaceflight Water Supply

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I. General Issues

The importance of water for living creatures in general and humans in particular cannot be overestimated. The water contained in the human body (in the form of solutions and water-colloid complexes) is essential to virtually all metabolic processes and mechanisms for maintaining homeostasis. Moreover, water plays a major part in thermal regulation, especially at high ambient temperatures or when physiological heat production increases, for example, in strenuous exertion.

In the estimates of different authors, the body of an adult male is composed of 61–65 percent water.[1,2] Dehydration may have serious physiological effects. For example, water loss amounting to as little as 1 percent of body weight interferes with the functioning of various organs,[3] 10 percent loss causes serious problems, and a 20–22 percent loss is lethal.[1]

Dehydration could become a critical problem for humans in space. Numerous investigations have found that actual space flights and ground simulations alter fluid-electrolyte metabolism, reducing circulating blood volume and leading to loss of fluid and electrolytes.[4-6] A water loss of 3–5 percent in humans has been found to have serious deleterious effects on health status,[4] and this could have adverse consequences during re-entry and landing, when crewmembers undergo acceleration and are re-exposed to the Earth's gravity. For this reason, dehydration must not be allowed to occur on space flights. However, water stores substantially contribute to the launch weight of a spacecraft and must be held to a minimum. Thus, it is important to limit water consumption on the one hand and to develop efficient methods of water reclamation on the other.

A. Water Consumption Standards

The amount of water the human body needs to maintain a constant level of water balance varies as a function of environmental parameters, total heat production, and diet.

On the ground, water balance is achieved through consumption of about 2.2–2.8 liters per day by people doing light physical work in a temperate climate.[1,7] Water losses in the course of a single day amount to 1.2–1.5 liters in urine, 400–700 mL in sweat, 350–400 mL in exhaled air, and 100–150 mL in feces. When the level of exertion and/or heat production increases, so does the amount of water lost through perspiration and insensible losses. Under such conditions, if water intake does not increase proportionally, urine concentration grows. The maximum possible urine concentration for healthy adults is 1400 mOsm/L, at which the minimum daily volume of excreted urine is 1.04 liters.[8] Physiologically, it is better to maintain a higher water intake than to allow a higher urine concentration.

In a temperate climate, water loss is counteracted by the consumption of drinking water (on the average, 1.5 liters) and dietary water (0.6–1.0 liter), and by water of metabolism (0.3.–0.4 liter). Given a normal diet, every 100 kcal of energy produced as a result of metabolism produces about 0.012 liter of water. At the same time, daily human fluid intake, even in a comfortable environment, may vary widely, ranging from 2–3.5 liters according to a number of authors.[9] Strenuous exertion in a high-temperature environment requires fluid intake of 6–6.5 liters per day; if solar radiation is intense, as in a desert, for example, 6–11 liters per day are required.[9,10]

Water requirements in space are affected by many factors associated with the microclimate and gravitational environment, physical activity, diet, physiological functions, etc. The issue of water consumption standards was considered intensively by researchers in the late 1960s and early 1970s, when space flights were of short duration and size and weight constraints on the spacecraft then used were of overriding importance. At that time, most authors agreed that, in space, water intake should equal 2.0–2.5 liters per crewmember per day.[10–14]

The development of water reclamation systems for use on spacecraft drastically altered the situation with regard to water intake standards. The first such water reclamation system was flown on the Salyut-4 station in 1974. Water reclamation systems transformed moisture-containing waste products (produced by humans, hardware, or biological systems) into potable water. In this situation, it seems more reasonable to speak not of standards for water intake, but rather of standards for water supply; i.e., the quantities of water that

The Russian portions of this chapter were translated by Galina Tverskaya and Lydia Stone.

Table 1 Daily water intake of Mir third and fourth prime crews

Mir crew	Water intake, L/man/day		
	Stored	Recycled	Total
Third	0.78	1.54	2.32
Fourth	0.45	1.75	2.20

must be produced by a water reclamation system over a 24-h period.

Experience with actual space flights has supported this approach. Table 1 cites water intake data for the third (V. Titov and M. Manarov) and the fourth (S. Krikalyov, A. Volkov, and V. Polyakov) Mir prime crews. The station carried two sources of water: stored water (Rodnik system) and water reclaimed from condensates of atmospheric moisture (SRV-K system).

B. Quality of Potable and Wash Water

Initially, in order to develop hygienic principles appropriate for use of water in space, all available data on the hygienic aspects of water supply were considered, but always from the perspective of the specific properties of the spacecraft environment, the sources of reclaimed water, and the conditions under which water production processes must operate in flight. However, the basic concept for space consumption remained unchanged from standards on the ground, i.e., that humans in space, like those on Earth, need water that is safe, meets physiological needs, and has acceptable aesthetic properties.

In the Soviet Union (currently Russian Federation) parameters that have been used as standards of water quality in space were taken from "USSR State Standards on Potable Water No. 2874" and "USSR State Standards on Sources of Centralized Water Supply, Procedures for Sampling and Quality Evaluation No. 2761-57," which were in force at that time.[15,16] Water quality control also involved selective measurement of various added preservatives and substances that could migrate into the water from storage containers. Since electrolytically introduced ionic silver had been selected as the preservative for water in the U.S.S.R., the flight-qualified water standards regulated silver levels. It should be mentioned here that standards regulating silver concentrations in stored and reclaimed water on spacecraft differ from those accepted in the United States or in the U.S.S.R. for potable water on the ground (0.05 mg/L).[15,26]

A distinguishing feature of the standards for quality of stores of potable water on spacecraft is that the water must comply with the requirements during two periods, i.e., preflight and during inflight storage.

The goal of developing efficient water supply systems using water reclaimed from human wastes and by-products of hardware and biological systems presented scientists and engineers with many new problems in hygiene, chemistry, engineering, and design.

Sanitary and hygienic studies targeted the composition of sources of reclaimed water[2,7,8,10]; changes occurring in them during the reclamation process[17-20]; efficiency of elimination of contaminants[2,21]; associated effectiveness in decreasing contaminants to toxicologically safe concentrations[2,22,23]; and a toxicological description of proposed water reclamation technologies.[2,24] On the basis of experimental data, "A List of Standards for Evaluating the Quality of Water Reclaimed by On Board Water Supply Systems" was compiled and approved by the U.S.S.R. Ministry of Health in 1967.

In the course of preparing this list and in the subsequent development of national standards (1967), several assumptions were made and these should be remembered when using these documents. First, the standards regulate the quality of water meant for consumption for a period no longer than 1/70–1/50 of the mean life span of man. This is the reason why some of the contaminant levels judged acceptable are higher than those pertaining to tap water.

Second, since it is forbidden to use any construction materials not explicitly approved by the U.S.S.R. Ministry of Health for use in the potable water supply systems, the number of toxic compounds for which standards are stipulated is significantly smaller than in the United States.

Third, since the nature and quantities of organic impurities in moisture-containing wastes are highly variable and may undergo chemical transformation during treatment of the water, reclaimed water quality is evaluated in an integral fashion, on the basis of chemical oxygen demand (COD) and/or total organic carbon.[25] When COD is used as the criterion, there are two standards: one for water reclaimed from a source free of toxic compounds and the other for water reclaimed from a product that does contain toxins.

Fourth, all standards set for quality of reclaimed water should be considered absolute only as applied to water produced by a system that has been meticulously designed, repeatedly tested, and already officially certified with respect to hygienic effectiveness. During the design, development, and testing of systems, compliance with these standards should be considered in relative terms; that is, they are used to evaluate the water supply system only for technological effectiveness. The final evaluation of these water reclamation systems must involve toxicological experiments on warm-blooded animals.

Table 2 presents standards regulating the quality of reclaimed water currently used in the United States[26] and in the Russian Federation.

C. In-Flight Monitoring of Water Quality

The conclusion that reclaimed water can safely be consumed by humans is based on a set of sanitary/hygienic studies utilizing chemical, toxicological, biological, and micro-

Table 2 United States and U.S.S.R. standards of the quality of reclaimed water[26]

Parameter	Standards			
	United States		Russia	
	Potable[26]	Hygiene[26]	Potable	Hygiene
pH value	6.0–8.0	5.0–8.0	6.0–9.5	4.5–9.5
Turbidity, no more than	1[b]	1[b]	1.5[a]	–
Color, true, no more than	15	15	20	–
Taste, rated, no higher than	2	–	2	–
Odor, rated, no higher than	3	3	2	3
Total hardness, mg-equiv/L, not over	–	–	7	7
Total number of solids, mg/L, no more than	100	500	–	–
Nitrogen as ammonia, mg/L, no more than	0.5	0.5	2	10
Calcium, mg/L, no more than	30	30	100	–
Magnesium, mg/L, no more than	50	50	50	–
Sulfate-ions, mg/L, no more than	250	250	500	–
Chlorine-ions, mg/L, no more than	200	200	350	350
Nitrogen in nitrates, mg/L, no more than	10	10	10	–
Total salt content (dry residue), mg/L, no less than	–	–	100	–
Silver, mg/L, no more than	0.05	0.05	0.5	2.0
Fluorine, mg/L, no more than	–	–	1.5	–
Arsenic, mg/L, no more than	0.01	0.01	–	–
Barium, mg/L, no more than	1.0	1.0	–	–
Cadmium, mg/L, no more than	0.005	0.005	–	–
Chromium, mg/L, no more than	0.05	0.05	–	–
Copper, mg/L, no more than	1.0	1.0	–	–
Iodine, mg/L, no more than	15.0	15.0	–	–
Iron, mg/L, no more than	0.3	0.3	0.3	–
Lead, mg/L, no more than	0.05	0.05	–	–
Manganese, mg/L, no more than	0.05	0.05	–	–
Mercury, mg/L, no more than	0.002	0.002	–	–
Nickel, mg/L, no more than	0.05	0.05	–	–
Selenium, mg/L, no more than	0.01	0.01	–	–
Zinc, mg/L, no more than	5.0	5.0	–	–
Sulfides, mg/L, no more than	0.05	0.05	–	–
COD, mg O2/L, no more than	–	–	–	250
a) with no toxic substances in the source	–	–	100	–
b) with toxic substances in the source	–	–	50	–
Total organic carbon, mg/L, no more than	0.5	10	25	80
Organic acids, mg/L, no more than	0.5	0.5	–	–
Cyanides, mg/L, no more than	0.2	0.2	–	–
Phenols, mg/L, no more than	0.001	0.001	–	–
Halogen derivatives of hydrocarbons, mg/L, no more than	0.01	0.01	–	–
Alcohols, mg/L, no more than	0.5	0.5	–	–
Cations, mg/L, no more than	30	n/a	–	–
Radioactivity, pico-Curie/L	c	c	–	–
Microbiological parameter				
Maximum microbial count in 100 mL	1	1	–	–
Total bacterial count per 100 mL, no more than	1	1	10,000	100,000
Electric conductivity, x 10^{-4} S/cm, no more than				
a) purified water	–	–	1.5	1.4
b) conditioned water	–	–	1.5–7.5	–

[a] Rated against a turbidity standard of a suspension of kaolin in water, in mg/L.

[b] NTU or nephalometric turbidity unit.

[c] MCLs for radioactive constituents shall conform to Nuclear Regulatory Commission regulations.

Table 3 Standards for range of parameters of reclaimed water quality

Parameter, units	Potable water	Hygiene (wash) water
pH value, pH units	6.0–9.5	–
Total organic carbon, mg/L	0–25	0–80
Nitrogen as ammonia, mg/L	0–2.0	–
Ionic silver, mg/L	0.02–0.5	0.02–2.0
Microbial count, cells/mL	0–100	0–1000

biological methods and analyses of the technological effectiveness of water reclamation systems. Hygienic evaluation of the quality of water produced by a water reclamation system during the period of design, development, and operational life testing in ground-based experiments is based on criteria involving many chemical, physical, aesthetic, and biological parameters. The results of these experiments and tests are used to determine the operational lifetime of the entire water supply system and of its individual components and to specify the protocol for their use in space flight.

It should, however, be remembered that the operational lifetime of a system depends directly on the level of contaminants in the source used for water recovery, the nature and quantity of which, in turn, depend on a number of conditions and factors. Obviously, it is extremely difficult to simulate all these factors in ground-based tests. The feasible duration of a test and the amount of the water reclaimed in such cases cannot be compared with the continuous functioning of the water supply system in space; for example, the one on Mir, which was in continuous operation for 4 years and reclaimed 1500 kg of water during the flight of the third prime crew alone (366 days). In addition, it is virtually impossible to simulate, in these tests, all hypothetical situations that could affect the functioning of life support hardware, experimental equipment, or other units. This further decreases the cost effectiveness of these tests.

It is clear that, on long-duration space flights, in-flight measurements should be made of the physical, chemical, and bacteriological parameters of the potable water produced by the water reclamation system. It should be emphasized that high-quality water is one of the prerequisites for maintaining the health and performance of crewmembers exposed to the adverse effects of space. In future water supply systems involving continuous decontamination and conditioning, feedback from in-flight monitoring will ensure that the water produced meets physiological requirements.

The development of in-flight monitoring systems is complicated by the need to deal simultaneously with problems in hygiene, analytical chemistry, and precision engineering.

With respect to hygienic monitoring, size and weight constraints dictate that the minimum number of parameters must be used for water quality control. The only acceptable approach is to use integral parameters of water quality; in other words, parameters that provide information about the entire spectrum of potential contaminants.[27,29,30]

An automated system for in-flight monitoring of the quality of reclaimed water that was developed and tested by NASA in 1972 and 1973 can be considered a good prototype of such a system.[28] This system monitored ammonia and chlorine ions; pH; electrical conductivity; total, inorganic and organic carbon; and microbial contamination, including both total and viable cells. Except for the biosensor, the instrument was made from commercially available units, which were connected with tubes and pumps to operate automatically. A computer then analyzed the data obtained, initiated an alarm signal if any parameter exceeded the maximum allowable value, and activated a command to dump poor-quality water to a separate container.

In the U.S.S.R., a conductometric sensor, which signaled significant increases in level of contaminants, was added to the SRV-K water reclamation system in 1974.

In 1983, the U.S.S.R. Ministry of Health approved the "Provisional List of Parameters for Monitoring Water Quality." In contrast to the previously adopted documents, this list includes hygienic requirements not only for the water ultimately produced, but also for water quality at a number of intermediate stages of processing, making it possible to monitor individual components of the water reclamation system.[29] Two groups of parameters could thus be selected for monitoring purposes: parameters reflecting quality of water that had passed through the system as a whole; and parameters specific to each subsystem, i.e., parameters characterizing the performance of a given subsystem.[30] Table 3 presents standards for the in-flight-monitoring parameters of reclaimed water quality.

The NASA-developed instrument for monitoring the quality of reclaimed water mentioned above[28] employed a number of different procedures: potentiometric measurement of pH, ammonia and chlorine ions, conductometry, and high-temperature incineration followed by infrared detection of carbon dioxide to measure organic carbon.

The current Russian system for monitoring the quality of reclaimed water includes solid-state ion-selective electrodes for measuring ammonia and silver, potentiometric pH measurement, and potentiodynamic measurement of organic carbon. The last method was developed especially for this purpose.[31,32,146]

Conductivity has high potential as an integral parameter providing information about both organic and inorganic electrolytes in reclaimed water.[30,33,34] However, conductometry is nonspecific and, therefore, is best used in the segments of the system where ionized contaminants are most likely to occur.

D. Monitoring Microbial Contamination of Reclaimed Water

Microbiological safety is one of the most important quality requirements for potable water. This requirement cannot be overstated with regard to the quality of reclaimed water in space flight, in light of the increase in the "pathogenic potential" of microbes that takes place in the closed environments of spacecraft cabins.[35] In such environments, not only does the total level of microbial contamination increase, but also, and even more important, the proportion of pathogenic microbes with resistance to antibiotics increases.[36] Such microbial strains can spread among the crewmembers, causing a situation of "transient carriage" analogous to the spread of hospital infections.[37] In addition, alterations in the immune systems of crewmembers on long-term space flights occur in parallel to changes in the microbial status of the space environment.[38]

Current decontamination methods for reclaimed water include pasteurization and/or the addition of ionic silver.[2] These methods reduce microbial concentrations to levels compatible with applicable standards (see Table 2). However, the possibility of water becoming contaminated with environmental micro-organisms cannot be ruled out. This is especially true since the sources of water to be reclaimed are generally highly contaminated (the microbial count is 10^4 to 10^6 cells/mL, see Tables 6, 7, and 8), and there is a possibility of carryover or bypass of the purification process. In addition, the interior surfaces of closed cabins, especially those made from nonmetallic materials, tend to become coated with a biofilm,[39] making it highly likely that the surfaces in contact with the water will become contaminated.

All of the above considerations emphasize the need for the microbiological monitoring of reclaimed water.

Before turning to the analysis of existing methods for evaluating the microbiological status of reclaimed water, the species composition of micro-organisms inhabiting the cabin, the human body, and reclaimed water in the spacecraft environment (see Table 4) should be discussed. A large number of proximate methods for microbiological monitoring of the environment have been developed recently. Of great interest are immunoserological methods, particularly those utilizing fluorescent antibodies.[49,50] These methods are very sensitive and highly specific; however, this, in itself, makes it difficult to use them to monitor the quality of reclaimed water, because its bacterial spectrum, as Table 4 shows, is extremely large and variable.

Another group of methods is based on the use of nutrient media labeled with radioactive isotopes of carbon (^{14}C), phosphorus (^{32}P), and sulfur.[51-53] These methods produce good results with a pure synchronized culture; however, their reproducibility is very low when naturally occurring water and other natural environments are analyzed. In addition, since they require the use of radioactive isotopes and prolonged incubation, they are not suitable for use in space.

Methods based on bioluminescence, chemiluminescence, and fluorescence of different components of a bacterial cell are highly sensitive. These methods have been discussed by U.S. authors for use in detecting micro-organisms in reclaimed water. Levin recommended a method based on the measurement of adenosine triphosphate (ATP) by means of its bioluminescent reaction with luciferin-luciferase.[54]

The NASA-developed automated instrument mentioned above for monitoring the quality of reclaimed water[28] was equipped with a biosensor utilizing the chemiluminescent reaction of bacterial porphyrins with a luminol hydrogen peroxide mixture. Signals from incubated and nonincubated water samples were compared in order to distinguish between living and dead micro-organisms. Biosensor sensitivity was enhanced by concentrating micro-organisms on membrane filters. These procedures can detect as few as 10 microbial cells per milliliter, with a probability of 92 percent.

Other instruments using conductometry, potentiometry, and fluorescent microscopy have been designed.[55-57] However, the use of these methods presents a number of problems even on the ground; and the size, weight, and power requirements of the instruments needed to implement these methods preclude their use on spacecraft in the near future.

Another group of proximate methods uses biochemical indicators that can be dipped into the nutrient medium in which micro-organisms are cultivated.[58-60] These methods have adequate sensitivity and reproducibility, with response times between 2 and 6 h. The modification and refinement of these methods led to the development of very promising systems using paper indicator strips.[50,61] The same principle was used to develop a number of means for microbiological monitoring of reclaimed water.[62]

E. Sources of Water to be Reclaimed; Composition of Contaminants of Moisture-Containing Wastes

The following liquids are currently considered to be suitable sources of reclaimed water: humidity condensate, urine, wash water, fuel cell (electrochemical generator) by-products, and products of hydrogen peroxide decomposition. Sufficient quantities of these liquids are produced on spacecraft to meet the physiological and hygienic needs of crewmembers. For example, during Mir flights, the following quantities of liquids were produced per cosmonaut per day: 1.54–1.75 liters of humidity condensate, 1–1.5 liters of urine,[1-3] and 4.05 liters of wash water. In addition, 1-kW fuel cell produced 11 liters of water per day,[2] and the 0.8 kg oxygen obtained from hydrogen peroxide yielded 0.9 kg of water.[2]

The water vapor exuded and expired by the crewmembers forms humidity condensate in the cabin thermal regulation system. This condensate contains volatile organic and inorganic compounds. In addition to contaminants of anthropogenic origin, it also includes volatile compounds emitted from interior surfaces and products of biodegradation and pyroly-

Table 4 Generic composition of micro-organisms detected in different microbiocenoses of enclosed environments and space vehicles

Genus	Source (see reference list)									Current authors[b]
	(35)	(40.41)	(42,43,19)	(44)	(45)	(46)	(47)	(47)	(48)	
Achromobacter			W		BLSS					
Acinetobacter	SC	A, C, SC, SB	C, W, A			SB, SC	W	SC		WW-C, WW-D
Aeromonas	SC	SB, C	C, W			SB, SC	W			WW-C, WW-D
Alcaligenes										W
Arthrobacter		A, C, SC, SB	C, W							
Bacillus		SB				SB, SC			U	W
Citrobacter	SC	SB	C, W				W			W, WW-C, WW-D, U, WU, UC
Corynebacterium	SC	SB, A, C		SB	BLSS	SB, SC				
Enterobacter	SC	SC, C		SB		SB, SC		SB, SC		WW-C, C, WFC, FC, C, W
Enterococcus										WW-C, WW-D
Escherichia		SB, SC		SB[c]				SC	U	WW-C, WW-D
Flavobacterium					BLSS					
Herella			C, W	SB						
Klebsiella	SC	A,W, SB, SC		SB		SB, SC		SB		WW-C, WW-D, U, UC
Micrococcus	SC		C, W				W		U	
Moraxella	SC		C, W	SB		SB, SC	W			
Proteus		SB, SC		SB		SB, SC		SB, SC	U	WW-C, WW-D, W, WU, UC
Pseudomonas	SC	SB, SC, C	W	SB	BLSS	SB, SC			U	W, WW-C, WW-D, C,U, WU, UC, FC, WFC
Serrata				SB						
Staphylococcus	SC	SB, A, SC, C	C,W	SB		SB, SC	W	SB, SC	U	C, WW-C, WW-D, U, WU, UC
Streptococcus		C, SB	W					SB		WW-C, U, UC, WU
Yeast and mold fungi	SC	SC				SC		SC		

[a]Legend: atmosphere of the space cabin (A); biological life support system (BLSS); C, humidity condensate; fuel-cell by-products (FC); surface of the human body (SB); surface of the space cabin (SC); nonpreserved urine in storage (U); urine condensate (UC); water recovered from humidity condensate (W); water recovered from fuel-cell by-products (WFC); water recovered from urine (WU); contaminated wash water (WW-C); decontaminated wash water (WW-D).
[b]Obtained in collaboration with A.N. Viktorov, L.B. Zagibalova, K.V. Zarubina, and L.A. Vinogradova.
[c]Detected in the pharynx.

sis of polymers, paints, and varnishes. Various researchers have detected from 70–350 compounds in the humidity condensate of spacecraft cabins.[2,22,23,63]

Table 5 presents data on compounds detected in the humidity condensate of the Soviet space vehicles Vostok, Salyut, and Mir. The chemical composition of the condensates tends to vary quantitatively. Another feature is the presence of significant quantities of organic compounds, as revealed by chromatography and levels of COD, permanganate oxidizability, and total organic carbon. Of these contaminants, the most important are ethanol, acetic acid, ethylene glycol, and, occasionally, methanol. Inorganic compounds, with the excep-

Table 5 Physical properties, chemical composition and bacterial contamination of spacecraft cabin humidity condensate

Parameter, units	Space vehicles and mockups			
	Vostok[2]	Salyut mockup	Mir mockup	Mir station
COD, mg O_2/L	144–240	72–2880	150–375	437–1500
Permanganate oxidizability, mg O_2/L	25–30	19–81	33–81	–
Total organic carbon, mg/L	–	26–590	56–137	333–503
pH value, pH units	6.0–6.9	1.6–7.8	6.8–7.3	6.0–7.2
Specific electrical conductivity, x 10^4 S/cm	–	1.4–6.6	1.2–2.3	1.0–2.1
Transparency, cm	Turbid	10–20	30	–
Turbidity, mg/L	–	0.0–25	0–2	0.75–2
Odor, scored	3	1–4	5	4–5
Color (cobalt), deg	–	5–40	–	15
Total hardness mg-equiv/L	0.2–0.3	–	0.1–0.3	0.56
Nitrogen as ammonia, mg/L	70–160	15–275	17–33	13–32
Nitrogen as nitrates, mg/L	0.6–1.0	0.25–0.4	0	0.3
Nitrogen as nitrites, mg/L	–	0.9–1.15	0.04–0.25	0.03–0.0008
Chlorides, mg/L	3–22	1.9–50	0.8–2.8	2.55–3.69
Sulfates, mg/L	3–5	1–18	1–4	1–5
Calcium, mg/L	4–29	3.5–8.2	0.4–0.8	1.2–3.4
Magnesium, mg/L	–	0.2–4.8	0.1–0.8	–
Potassium, mg/L	–	0	0	–
Sodium, mg/L	–	0	0	–
Alcohols, mg/L	330–2500	–	–	–
Ethanol, mg/L	–	0.1–342	8–136	186–634
Methanol, mg/L	–	0.4–8.2	1.6–8.2	14.9–32.1
Propanol, mg/L	–	0.15–0.3	0	0
Butanol, mg/L	–	–	0–0.6	0–5.7
Isoamyl alcohol, mg/L	–	–	0	0–4
Ethylene glycol, mg/L	–	–	5.6–35	1.6–22.4
Organic acids:	15–27	–	–	–
Acetic, mg/L	–	0.8–98	17–48	0–47
Butyric, mg/L	–	0.1–1.2	0–1.6	1–13.7
Propionic, mg/L	–	0.01–1.1	0	0
Valeric, mg/L	–	–	0	1.1
Caproic, mg/L	–	0.15–18	0–3.8	0–19
Microbial contamination, x 10^3 cells/mL	–	2–800	2–380	0.06–4.5

tion of ammonia, are not present in significant amounts.

Humidity condensates tend to be highly contaminated by micro-organisms, probably because the latter form in the air conditioning system. Virtually all of the spacecraft cabin air circulates through this system, and the moisture condensed from the air is highly contaminated with environmental and human microflora. This process is markedly facilitated by microgravity. Table 4 presents a list of microbial genera occurring in humidity condensate.

Of all the sources of reclaimed water, urine is the most contaminated (see Table 6). Urine is a complex mixture of substances belonging to different chemical classes. Approximately 200 different compounds have been identified in urine.[64] The major organic substances are urea, uric acid, creatinine, amino acids, and lactic acid. The nitrogen in urea accounts for 85–89 percent of total urinary nitrogen, with other nitrogen-containing compounds, including ammonia salts, comprising the remaining 10–15 percent. Daily urine samples may contain as much as 16 grams of such salts as chlorides, sulfates, and phosphates and as much as 1.1–2.8 grams of amino acids. Volatile components of urine easily enter reclaimed water, making it unsuitable for drinking, with amines presenting the greatest danger. Moreover, alcohol, phenol, indole, furane, and pyrrole from urine may readily infiltrate the spacecraft cabin atmosphere. All these compounds are toxic and cannot be permitted in reclaimed water. Some of the salts in urine are in a supersaturated state.

Urine acts as a nutrient medium highly conducive to the growth and development of microorganisms, which may significantly alter its chemical composition and produce unde-

Table 6 Chemical composition of daily urine and condensate obtained during low-temperature evaporation in the water recovery system SRV-M

Chemical compounds and parameters, units	Urine[54]	Urine condensate[a]
Water, percent	95	99.9
Urea, mg/L	2000–35,000	0–17
Sodium chloride, mg/L	8000–10,000	1.2–2.8
Creatinine, mg/L	500–2400	–
Phosphates, mg/L	2000–13,000	–
Ammonia, mg/L	400–1200	0.5–2.5
Hippuric acid, mg/L	100–2500	–
Uric acid, mg/L	200–1200	–
Sodium, mg/L	4000–9000	–
Potassium, mg/L	2000–3300	–
Calcium, mg/L	200–970	1–2
Magnesium, mg/L	60–200	6–9
Sulfur as SO_4, mg/L	1800–3600	–
Inorganic sulfates, mg/L	1210–3030	0–30
Oxalic acid, mg/L	15–30	–
Nitrogen as amino acids, mg/L	180–530	–
Purine bases, mg/L	15–45	–
Phenols, mg/L	17–420	–
Volatile fatty acids, mg/L	≤ 60	–
Citric acid, mg/L	200–1000	–
Dry residue, mg/L	32–184	–
Nitrogen as nitrates, mg/L	–	0–0.2
Nitrogen as nitrites, mg/L	–	0.07
Iron, mg/L	–	1.9–32
Ethanol, mg/L	–	2.3–47
Methanol, mg/L	–	2.5–4.3
Acetic acid, mg/L	–	5.7–15.2
Acetaldehyde, mg/L	–	0–4.2
Acetone, mg/L	–	0–8.3
Total organic carbon, mg/L	11,800 ± 660[b]	10–78
COD, mg O_2/L	17,590 ± 1510[b]	70–100
Electric conductivity, x 10^{-4} S/cm	–	0.08–1.4
Odor, rated	–	5
Transparency, cm	–	30
pH value, pH units	–	3.7–6.4
Microbial contamination, 103 cells/mL	–	0.6–15

[a]Current authors' data.
[b]From Ref. 66.

sirable toxic substances. The main source of these substances is urea, which accounts for 25 grams of daily urine. Decomposition of this amount of urea through microbial action may produce as much as 14 g of ammonia. When untreated urine is stored under ambient conditions, the microbial count increases rapidly and may reach 10^{12} cells/mL. Microscopic fungi may also develop. Thus, if urine is to be used for water reclamation, it needs to be preserved to maintain chemical and microbiological stability.

Wash water recirculated after washing the face, hands, and body, as well as other sources of reclaimed water, contains many contaminants, mainly organic compounds, including detergents [for instance, katamin AB (alkyl dimethyl benzyl ammonium chloride) mixed with amine oxide, lactic acid, urea, and lipids]. Suspended substances are also present in substantial quantities. The main inorganic contaminant is sodium chloride. High microbial contamination is characteristic of wash water; thus, detergents should have disinfectant properties in order to stabilize the microbial level at (9-32) × 10^3 cells per milliliter. Table 7 lists the physical-chemical

Table 7 Physical-chemical parameters of wash water obtained on a mockup of Mir (data obtained in collaboration with A.A. Berlin)

Parameter values, units	Minimum–maximum
pH value, pH unit	6.5–8.1
Transparency, cm	0
Color, deg.	10–20
Odor, rated	0–5
Specific electrical conductivity, x 10^{-4} S/cm	2.2–6.0
Total hardness, mg-equiv/L	0.4–1.0
COD, mg O_2/L	1000–1750
Total organic carbon, mg/L	224–914
Urea, mg/L	62–166
Chlorides, mg/L	21–110
Detergent+disinfectant, mg/L (katamin AB+amine oxide)	120–340
Suspended substances, mg/L	750–1000
Sulfates, mg/L	28–31
Nitrogen as ammonia, mg/L	7–49
Nitrogen as nitrates, mg/L	0.25–0.31
Nitrogen as nitrites, mg/L	0.07–0.09
Microbial contamination, x 10^3 cells/mL	10–32

parameters of used wash water obtained in a mockup of Mir.

The least contaminated sources of reclaimed water are fuel cell by-products and water formed from the decomposition of hydrogen peroxide. The by-products of fuel cells (electrochemical generators) typically contain gaseous and dissolved hydrogen. At normal barometric pressure, hydrogen is biologically inactive; nevertheless, U.S. astronauts who drank water containing gaseous hydrogen complained of flatulence and bloating. The exact physical-chemical properties of by-products from fuel cells may vary as a function of fuel cell type. Table 8 presents data on the composition of by-products of electrochemical generators with different types of fuel cells.

II. Fill-and-Draw Water Supply Systems

The most reliable space flight water supply systems are those in which potable water is brought from the Earth (so-called "fill-and-draw" systems). Compliance with hygienic standards is assured by methods of preservation and/or by stabilization of the chemical and microbiological parameters of the water. Obviously, water that is to be preserved should start off by having acceptable aesthetic properties, as well as acceptable levels of chemical and biological toxins; and preservatives that are added should not negatively affect quality. The preservative should produce a sustained and reliable antimicrobial effect, stabilize taste and physical-chemical properties, be nontoxic to humans, not react with structural materials, and be compatible with the water supply system.[65]

Physical methods of water disinfection [e.g., heating (boiling or autoclaving), ultraviolet irradiation, ultrasonic and microwave treatments] are of limited utility for treating water stores because they do not produce a residual effect and thus cannot stabilize basic parameters of water quality or ensure bacteriological safety in the case of secondary contamination.[66] Nevertheless, in the Russian Federation, autoclaving is used to treat water in survival kits for use by cosmonauts who are forced to perform unscheduled landings in off-target area.[2] To exclude the possibility of contamination, this emergency water supply is never touched during flight, making autoclaving an acceptable method of water preservation.

Only chemical methods of decontamination have a residual effect, making them suitable to preserve water for use in space. Researchers have investigated such well-documented disin-

Table 8 Composition of fuel cell by-products

Parameter, units	Data of Chizhov and Sinyak[2]	Data of present authors	
		M ± m	(Min.–max.)
pH value, pH units	4.5–10.0	7.46 ± 0.53	(6.65–8.45)
COD, mg O_2/l	6.4–88	4.97 ± 1.73	(2.5–10)
Permanganate oxidizability, mg O_2/l	0.8–27	–	–
Total organic carbon, mg/L	–	1.06 ± 0.24	(1–2)
Nitrogen as ammonia, mg/L	0–0.52	0.08 ± 0.006	(0–0.18)
Nitrogen as nitrates, mg/L	0.12–0.25	0	
Nitrogen as nitrites, mg/L	0.007–0.025	0	
Calcium, mg/L	0	–	
Magnesium, mg/L	0–1.42	–	
Potassium, mg/L	0–117	0	
Sodium, mg/L	0–4.5	–	
Chlorides, mg/L	0–2.84	–	
Sulfates, mg/L	0	–	
Acetone, mg/L	0.5–1.0	0	
Methanol, mg/L	0.5–24	0	
Ethanol, mg/L	0.5–6.0	0	
Total hardness, mg-equiv/l	0	0.11 ± 0.07	(0–0.32)
Electrical conductivity, x 10^{-4} S/cm	–	3.47 ± 0.5	(0.4–17.9)
Microbial contamination, cells/mL	0–106	150 ± 10.6	(0–600)
Hydrogen:			
Gaseous, mL	–	232 ± 19.1	(5–700)
Dissolved, mL		12 ± 2.9	(6.2–15)

fectants as chlorine and its derivatives, ozone, iodine, heavy metals, and, in particular, silver and its derivatives. The investigators eventually had to reject most of the above disinfectants for a number of reasons. Chlorine must be used in doses so high (20–50 mg/L) that it affects the taste and odor of the water. Ozone does not produce a prolonged residual effect. The level of most heavy metals needed to kill bacteria is above the maximum permissible concentration with respect to toxicity.

Silver is a promising disinfectant. Bacterial loading studies of the bactericidal effects of various silver preparations have revealed high effectiveness. For example, 84–96 percent of E. *coli* cells died within 1 h, and 100 percent died within 6 h, after being added to water containing silver.

During the design and development of water supply systems, it was found that ionic silver tended to react with the materials used for the storage containers. In some cases, aluminum alloys were corroded, whereas, in others, silver was absorbed by the walls of the container.

Studies of samples of preserved water after prolonged storage, as well as after long-duration space flights, showed that silver levels diminished during storage and, at the termination of the storage period, had diminished from an initial level of 0.2 mg/L to 0.06–0.09 mg/L.[65]

The rate of silver absorption varies as a function of the ratio of the container surface area to volume; therefore, current Russian spacecraft water storage systems use spherical containers with volumes of up to 210 liters (the Rodnik system).[20]

The use of materials with minimum capacity to absorb ionic silver (Teflon® and similar materials, passivated stainless steel, and titanium) and water containers having optimal volume capacities, allows storage time to be extended to 2 years without the addition of more preservative.

American specialists followed another approach to water storage for space missions. On Apollo missions, sodium hypochlorite and monosodium phosphate were used to preserve stored water. The water system was regularly injected with ampoules containing sodium hypochlorite (5000 mg/L) and an aqueous solution (0.7 M) of sodium dehydrogen phosphate.[67] On the lunar module, water disinfection was achieved through the use of iodine (at a concentration of 10 mg/L).[2] Iodine is also used to preserve water on Space Shuttle flights. A packed bed of irradiated anion exchange resin provides iodine in quantities no less than 2.0 mg/L and no more than 4.0 mg/L at a flow rate of 12–60 lb/h flowing to the storage tanks. Such beds are also used at outlets to prevent back contamination.

III. Water Reclamation

A. Characteristics of Water Reclamation Systems

The weight of fill-and-draw water supply systems increases dramatically with mission duration, making them unfeasible for extended missions. Thus, water supply systems using water recycling or water reclamation had to be designed. Designers of such systems had to contend with the fact that, because of the lack of the liquid-gas interface in microgravity, extraction, rectification, and flotation processes cannot be used in space.

In light of the diversity and complexity of the chemical composition of human wastes, it is not possible to develop a water reclamation system that uses only a single method. Rather, the system should include a number of processes, as dictated by the chemical composition of the sources of reclaimed water and the type and amount of power available on the spacecraft.

It is very likely that it will not be possible to develop a single type of system that can be used in all situations. For example, a water supply system for a lunar spacecraft with fuel cells as components of the life support system would not be efficient on an extended mission space station; on such stations water should instead be reclaimed from human wastes and other moisture-containing by-products. On short-term flights, it would be difficult to use the radiation method, for example, since it requires that crewmembers be protected from ionizing radiation. At the same time, on extended flights on which power will be generated by nuclear reactors, the radiation method might be particularly cost effective.

When designing water reclamation technologies, it is important to consider how their behavior in microgravity differs from that on Earth. In the Earth's gravitational field, because of the difference in liquid and gas densities, the gas-liquid interface is stable; consequently, boiling, condensation, gas-liquid separation, and other processes occur normally. In microgravity, these mechanisms are disrupted. For example, in boiling, vapor bubbles do not separate and float to the surface but instead accumulate at the container wall, impeding heat transfer. In condensation, heat transfer is also impaired if special measures are not taken to remove the accumulating film of condensate. Thus, membranes, cyclonic separators, or centrifuges have to be used in microgravity to create artificial interfaces.

B. Design Principles for Water Reclamation Systems

The selection of water reclamation methods depends largely on the chemical and microbiological composition of waste products that serve as sources of reclaimed water. According to Kulskiy,[68] all contaminants in spacecraft wastes can be classified into six groups on the basis of particle size. Optimal methods can be identified for eliminating the contaminants in each group as a function of the type and amount of power available (thermal, electric, ionizing radiation, or solar radiation).

As a rule, a water reclamation system should include the following stages: 1) stabilization of physical-chemical and microbiological composition of waste products–decontamination and preservation; 2) removal of all impurities from the liquid media–filtration; 3) mineralization of resulting water using macro- and trace elements; 4) water preservation; and 5) water heating and/or cooling.

Stage 2 may include the process of transformation–oxidation of all organic components in the wastes and their subsequent demineralization.

These stages may be modified as a function of the use to which the reclaimed water is going be put. For example, stage 3 is unnecessary for wash water; stages 3 and 4 (mineralization and preservation) are unnecessary when reclaimed water is to be used for electrolytic generation of oxygen.

C. Pretreatment (Stabilization) of Wastes

Waste products used as sources for reclaimed water create a medium conducive to microbial proliferation. Microbial growth and development induce decomposition of organic and inorganic compounds, forming compounds of new classes, including ammonia, acetic and butyric acids, hydrogen sulfide, and others. In addition to their toxic effects on humans, these substances may degrade the hardware of the reclamation system. For example, urea transformation causes pH to shift toward alkaline values, causing sediments (e.g., calcium phosphate and magnesium hydroxides) to form and be deposited on membranes, tubes, valves, gas-liquid separators, sorption beds, and other elements of the reclamation system. Another consideration is the abundant offgassing of volatile compounds, which requires additional units for trapping and removal. Gaseous compounds, such as methane and nitrogen, can shield the surface of absorbers and intensify channel formation in the beds, thus reducing the dynamic capacity of ion-exchange resins and activated charcoals. Additionally, sediments and gaseous compounds may increase hydraulic resistance in the lines of the system and interfere with the functioning of the water pumps. For this reason, one of the stages of stabilization of moisture-containing human wastes is their decontamination and subsequent preservation.

It should be noted that moisture-containing wastes (even if they have been decontaminated) contain substances with unpleasant odors. It is thus desirable to bind volatile compounds to form thermally stable compounds or to expose them to partial transformation (oxidation) during the decontamination stage.

In summary, the stabilization unit should decontaminate and preserve wastes, as well as bind ammonia and other volatile compounds to form stable compounds. Methods of waste decontamination and preservation are described in detail in Chapter 13 of this volume.

D. Filtration (Removal of Suspended and Colloidal Impurities)

Virtually all moisture-containing wastes generated on manned space flights that are used as sources for water reclamation contain colloidal and suspended particles, as well as microbes. Removal of dispersed particles from these wastes typically precedes other stages of processing. Almost all processes used for this purpose on the ground can be used in space, with the exception of sedimentation and flotation, which will not work in microgravity. The most suitable process for waste clarification is filtration. Wastes are passed through porous partitions under the action of pressure gradients or centrifugal forces. Nonregenerable filters have been found to be more effective in extracting water from waste products.

Filter cartridges using filtration and precipitation have been employed successfully to clarify weakly contaminated wastes. The problem is that the process flow rate decreases rapidly for wastes that are strongly contaminated with suspended particles, demanding frequent replacement of filters.

Filters operating according to the bulk filtration principle are more suitable for strongly contaminated wastes. Such filters clarify by precipitating suspended particles in filter pores as a result of cohesion and adsorption. Normally, they consist of multiple layers made of different materials so that pores diminish in size from layer to layer; e.g., felt and nonwoven fabric, belting fabric, filter cardboard, and synthetic membranes. To clarify used bath and laundry water containing significant quantities of fats, the multilayer filters also include hydrophobic materials, such as wool.[69]

Waste clarification by filtration can be accelerated through contaminant coagulation. This method of clarification involves the agglomeration of colloidal and dispersed particles and neutralization of their Z-potential through adsorption of multicharged ions on their surface and coagulant hydrolysis. Coagulants containing multicharged cations (e.g., aluminum sulfate or iron compounds) are used to remove negatively charged colloidal particles. Activated silica is used for positively charged colloids. The process can be accelerated and the amount of coagulant needed can be reduced by using high-molecular-weight flocculants; e.g., polyacrylamide or quaternary ammonium bases of the B-2 or BA-3 type. The degree of coagulant hydrolysis depends on the pH value of the water being clarified and its buffer properties, which, in turn, are a function of its alkaline reserve. For example, the optimal pH range of hydrolysis is 4.95–5.4 for aluminum sulfate, 6.4–7.0 for sodium aluminate, and 9.0–10.5 for iron salts. Organic flocculants can be used to clarify water with a low alkaline reserve and at a low temperature.

Filtering centrifuges equipped with an automatic precipitate discharge unit appear more promising for use in separating coagulated suspensions. However, methods to desiccate the sediments–either to extract more water or to preserve them for further storage–must be developed as well.

The efficacy of filtration can be increased, and the weight of water reclamation systems can be reduced, if electrocoagulation is used.[68,70] The advantages of this method are accelerated coagulation of dispersed contaminants through use of an electric field, independence of the process from the alkaline reserve of the wastes, and the low level of electrolyte contamination of the resulting water. When electrocoagulation is used to clarify water, the best results are obtained with aluminum electrodes having an electrical field intensity of 50–100 W/cm and a processing time of 6 min. This treatment provides a high level of clarification from suspended particles and detergent. Permanganate oxidizability of the filtrate does not exceed 50–90 mg O_2/L when either fat-based soaps or quaternary ammonia-based detergents are used. The use of electrocoagulation as part of a water supply system prevents the formation of gaseous by-products of electrolysis (primarily hydrogen), which constitute 3 percent of processed wastes by volume. This requires that cathode depolarization electrocoagulants be developed.

At the present time, the use of modern ultrafiltration hardware is being considered for clarification of moisture-containing wastes in future life-support systems.[71,72,147] The operational life of ultrafilters can be increased through the use of tangential-convective filtration and the method of wet oxidation to process concentrates. An advantage of this method is that it ensures that the water will be free of endotoxins. To achieve this goal, ultrafilters can also be used to follow sorption.

E. Removal of Soluble Contaminants from Moisture-Containing Wastes

1. Sorption

Sorption is widely used for decontaminating weakly contaminated waste products, such as humidity condensates. This method is cost effective; ensures 100 percent water extraction from wastes; and utilizes minimum power, which is required only to transport the wastes. The sorption method entails waste filtration through a series of beds of granular ion-exchange resins and molecular sorbents, which remove both electrolytes and molecular impurities. The most effective ion-exchange resins are synthetic cation- and anion-exchange resins, polymers that are not soluble in water, or organic solvents containing chemically active groups that participate in chemical exchange reactions with the ions of dissolved contaminants. To remove dissolved salts from water and ensure the necessary degree of purification, cation-exchange resins are used in acidic form and anion-exchange resins are used in basic form.

Typically, mixed beds of ion-exchange resins are used. However, in some cases, there are separate layers of cation- and anion-exchange resins. First, acids form through exchange on the cation-exchange resins. The specific acids generated depend on the anions that had been in the solution. Along with the solution, these enter the anion-exchange resin bed, where they are neutralized through anion exchange.

Ion-exchange processes occurring on mixed sorbent beds are not self-sustaining because of the depletion of ion-exchange resins, which must be either replaced or regenerated. In water supply systems, depleted sorption filters are usually replaced, since regeneration of the ion-exchange resin would complicate the system and diminish the amount of water extracted from waste products. In water supply systems, the sorption method is used to recover water from humidity condensates and used wash water. Cation-exchange resins of the polymerized type with highly acidic or alkaline functional groupings are used most frequently in water reclamation systems. Such ion-exchange resins have a high exchange capacity and satisfactory kinetic characteristics for sorption of ions with molecular weights to 300–350. They also meet radiation and mechanical stability requirements. Ionite consumption is mainly a function of the extent to which the waste is contaminated with ionic impurities. In humidity condensate, the level of such impurities is 3–4 kg/m^3, whereas they increase to 4–5 kg/m^3 when wash water is used.[71] For purposes of designing water reclamation systems, the performance characteristics of ion-exchange filters can be derived by computing ion exchange dynamics for various sorption isotherms and kinetic conditions.[73]

To decontaminate wastes containing molecular impurities, sorption systems use molecular sorbents and, especially, activated charcoals. Processes of waste decontamination using adsorption are very similar to ion-exchange processes. For this reason, the two process types are often combined in a single subassembly, in which electrolytes are first removed from wastes through ion exchange, and then are passed through adsorption filters for removal of organic molecular impurities. This sequence of operations is highly efficient and minimizes the consumption of materials.

Because of the type of contaminants in air moisture condensates, only small-pore activated charcoals are used to decontaminate them. Certain synthetic activated charcoals (PAU-SV, FAS) and granular charcoals (PC) are very efficient because they have high equilibrium constants for the low-molecular-weight, aliphatic, organic contaminants present in condensates.

To decontaminate wash water, activated charcoals with well-developed mesoporosity and microporosity (e.g., SKT-7C) are preferable. In ion-exchange resins, the dynamic capacity of sorbents is a function of contaminant levels in the wastes and is determined by the profile of their adsorption isotherms. The adsorption isotherms for most contaminants in weakly contaminated wastes are linear; i.e., the amount of contaminants adsorbed increases in proportion to concentration. For strongly contaminated wastes, adsorption can be described by Lengmuir's, Freindlich's, and other more complex isotherms.

There are no rigorous mathematical models of the dynamics of adsorption for moisture-containing wastes, although an attempt has been made to describe the dynamics of adsorption of binary mixtures.[74] In most cases, the sorption properties of multicomponent mixtures, such as actual waste products, can be approximated by a single hypothetical compound; and a mathematical model of sorption dynamics can be used to describe the process. An example of such an approach can be found in Zolotareva et al., [75] in which mathematical modeling was employed to determine the optimal proportion of ion-exchange resins and adsorbents in a filter for air moisture condensate, with the operational lifetime of the water supply system used as the criterion for optimum performance.

The efficiency of sorbent systems for decontaminating wastes is not high because of the presence in the wastes of such organic compounds as low-molecular-weight alcohols, aldehydes, and urea. Decontamination of air moisture condensate requires amounts of sorbent equal to 3.0–4.0 percent of the volume of the processed decontaminated water. Wash water provides a slightly better ratio of 1.0 percent.

Greater efficiency can be attained with chemisorbents, such as activated charcoals impregnated with catalysts of dehydration of organic compounds. For example, nickel, platinum, and other metals of the platinum group act as efficient chemisorbents of most organic compounds. Chemisorption of alcohols, aldehydes, and organic acids are accompanied by dehydration.[76] Chemisorbents can sustain catalytic and electrocatalytic processes of oxidation of organic compounds with the involvement of absorbed oxygen.[77] The addition of catalysts of this kind to the sorption filters of waste decontamination systems may increase their capacity by several hundred percent, improve the quality of decontaminated water, and decrease the adjusted weight of the water supply system. The sorption method was used extensively in the first generation of water reclamation systems;[79–82,69] however, the adjusted weight of reclamation systems can be minimized only by using stationary decontamination processes.

2. Electrochemical Methods

One such stationary process is electrodialysis with ion-exchange membranes to remove electrolytes from wastes. This process involves treating wastes with direct or pulsating electrical current in a chamber bounded by selectively permeable cation-exchange and anion-exchange membranes. The current causes the impurities of the contaminant ions to migrate through the ion-exchange membranes toward the cathode and anode of the electrodialysis unit, removing them from the waste solution.

Electrodialysis is energy efficient and can readily be implemented in microgravity. The use of electrodialysis to decontaminate air moisture condensate was discussed by Armstrong[83] while Hansen and Berger[84] discussed its use for wash water decontamination and urine demineralization. These authors did not evaluate this method very highly because problems with use in a regenerative life support system and because it was used in combination with a relatively ineffective adsorption process for organic contaminants. Further studies demonstrated that electrodialysis units with ion-exchange fillers in desalinization chambers are well suited for use in decontaminating air moisture condensate. Glueckauf[85] showed that such systems can function like ion-exchange filters with continuous electrochemical regeneration. A maximum concentration technique proposed for decontamination of radioactive wastes[86] provided 98–99 percent water reclamation. In this case, power consumption was no more than several voltampere-hours per liter (VA-h/L).

Electrodialysis was investigated as a method of urine demineralization during the development of an electrochemical water reclamation system.[85,87,143] In this system, electrodialysis was employed to demineralize urine pretreated by electrodialysis for oxidation of organic contaminants. The method allowed extraction of approximately 90 percent of water from waste products, with power consumption of 25–35 VA-h/L. A prototype of the electrochemical water reclamation system was developed and successfully used in 30-day tests; however, a toxicological analysis of the reclaimed water detected the presence of oxidizing agents.

The combined use of electrochemical oxidation for organic contaminants and electrodialysis for deionization seems very promising for the design of a stationary system of water reclamation from condensates. A prototype was discussed in Putnam,[88] in which an attempt was made to implement both processes in one electrodialysis unit. However, it is more efficient to use a separate unit functioning as a short-circuited electrochemical cell to remove organic compounds.[89, 145]

In the design of electrochemical water reclamation systems, special attention must be given to the structuring of electrode processes specifically for use in microgravity and closed environments.[144] Gaseous by-products of electrode reactions in electrodialyzers are reclaimed through the use of the principle of a hydrogen electrodialyzer,[90] and solid ion-exchange electrolytes are reclaimed in combination with porous, catalytically active electrodes.[91]

3. *Reverse Osmosis*

Reverse osmosis, a universal method for removing organic and mineral contaminants from water, is one of the most promising methods for decontaminating wash water. Water is subjected to pressure exceeding osmotic pressure, which forces it through semipermeable membranes that are selectively permeable for water. Asymmetric membranes with 10-nm pores in the active layer are currently used most extensively. The permeability of asymmetric semipermeable membranes is optimal. Because of the simplicity of the hardware required, low power consumption, high selectivity with respect to most wash water contaminants, and a 95–97 percent water reclamation rate, this process is the most suitable one for decontaminating moisture-containing wastes when large quantities of water must be processed daily. The use of reverse osmosis has been investigated for wash water decontamination .[92–94] The best results have been obtained with polysulfonic and polyamide membranes. It has been noted that use of the nonionogenic surfactant, Triton X-100, makes it possible to maintain the selectivity of semipermeable membranes for a sustained period. It is recommended that reverse osmosis take place at high temperatures (50–75 °C) to diminish power consumption. Selectivity of 98–99 percent has been attained for inorganic compounds and 80 percent for organic compounds. This difference is mainly attributable to low selectivity for urea. The apparatus used has an effective membrane surface area of 0.3–0.38 m^2. The rate of water reclamation is 90–97.5 percent. Power consumption at a temperature of 53 °C is 10 VA-h/kg. Slightly poorer results are obtained when dynamic semipermeable membranes are used.

To ensure that the water processed through reverse osmosis is of adequate quality, the permeate should be exposed to additional sorption decontamination. To extend the performance of semipermeable membranes, reverse osmosis is usually combined with clarification processes; e.g., ultrafiltration.[95] The chief problem confronting designers of water systems using reverse osmosis is increasing the useful life of semipermeable membranes. If such systems are to become components of spacecraft life support systems, this parameter will have to be improved.

4. *Distillation*

Distillation is a universal method for purifying moisture-containing wastes. This method is suitable for reclaiming water from all sources except condensates, in which the major contaminants are volatile compounds. It is most efficient for water reclamation from urine. Since urine contains unstable organic compounds that disintegrate upon boiling (at normal barometric pressure) and strongly contaminate the condensate, distillation must take place at a temperature no greater than 65 °C. There are more than a dozen distillation technologies for recovering water from urine.[2,69,96,97,139] At present, the development of membrane distillation,[98,99] distillation with a thermal pump,[100,101] and distillation with catalytic oxidation in the vapor phase[13,26,102,103] are undergoing intensive study.

Methods of membrane evaporation with a diffusion gap and evaporation through hydrophobic porous membranes[99] are also under study. The major disadvantage of membrane methods is the high power expenditure (because of a relatively low coefficient of heat utilization) and the limited useful life of membranes (because of accumulation of deposits of organic and inorganic suspended particles on their surfaces). The useful life of semipermeable and porous membranes can be extended significantly by combining hydrophilic and hydrophobic membranes at the interface,[104] while their cost effectiveness can be increased by using a thermal pump of the refrigerant or thermoelectric type. This may help decrease power consumption to 300 VA-h/kg and extend the life of a distiller to tens of thousands of hours. The method of membrane distillation is the simplest and most reliable but requires greater quantities of expendables. Analyses of different variants of a spacecraft water supply system designed to function automatically for 500 days[105] showed that the method of membrane evaporation with vapor compression is the most suitable for reclaiming water from urine and other wastes. The most power-efficient methods of urine distillation are those utilizing heat produced by water vapor condensation.

Information about a new generation of water supply systems for a space station prototype can be found in Brose and Jackson.[106] In these systems, water is reclaimed from urine and concentrate in a reverse osmosis device through vapor compression. The reclamation device was manufactured and tested by the Hemtrick Co. It is a very sophisticated device with automated process control. Wastes are distilled in a rotating still at ambient temperature. Evaporation at subatmospheric pressure and vapor compression are provided by a vapor compressor located in the same device. Prolonged testing demonstrated that power consumption was 150 VA-h/kg with 90 percent of the water reclaimed.

In terms of performance, the use of a thermoelectric pump for reclaiming water from urine is similar to the vapor-compression method. The pump operates on the basis of the Peltier effect, the principle that a temperature rise or fall at the junction of two dissimilar metals carrying a small current will be proportional to the magnitude of the current. The heat of condensation is reclaimed by having this junction occur at the heat-transfer surface, separating the evaporator and condenser. Distillation providing phase separation in microgravity is performed in a rotating still. Extended tests of the system prototype showed that 90 percent of the water could be reclaimed at a power consumption of 250–300 VA-h/kg.

These distillation methods for recovering water from urine do not produce a condensate of adequate quality, since it typically still contains volatile organic and inorganic compounds. Sinyak and Chizhov have developed an oxidative-catalytic distillation method for contaminant oxidation in the vapor phase.[102,103] A water supply system using this method consumes minimum quantities of expendables. Water vapor and volatile compounds are passed through a heterogeneous catalyst layer (e.g., hopcalite), where they are oxidized at a temperature of 150 °C, to form carbon dioxide, nitrogen, sulfur dioxide, and water. In open-loop devices of this type, atmospheric oxygen is used as the oxidizer, while closed-loop devices use oxygen bound in the catalyst. In the latter case, the catalyst should be regenerated regularly.

The results of analyses of alternative processes for recovering urine from water[26] for use in an orbital space station water supply system[96] suggest that a distillation method involving catalytic oxidation of contaminants in the vapor phase is most suitable. This method has the lowest reduced weight, power consumption, and size because of the use of radioisotopic sources of thermal energy.[107,108]

5. Other Methods

In addition to the methods discussed, other procedures theoretically can be employed to recover water on spacecraft. However, for one reason or another, these procedures remain inadequately studied or are not being considered for incorporation in future reclamation systems. These include ozonization,[68] impulse processing,[70] catalytic oxidation in the presence of hydrogen peroxide,[109] radiation[110] and photochemical[2] oxidation, microbiological methods,[2,136] and others.

F. Artificial Mineralization of Reclaimed Water

Water reclaimed from moisture-containing wastes is virtually devoid of minerals and, thus, cannot be used for drinking on long-duration flights. Demineralized water does not taste very good, which decreases water consumption by crewmembers.[111] Some authors maintain that prolonged consumption of demineralized water may cause cardiovascular disorders.[112,113,142] In light of such adverse effects of microgravity as reduced water consumption and potential cardiovascular deconditioning, it becomes critically important to provide space crews with potable water containing a full complement of minerals.

The lowest acceptable level of total mineral concentration in reclaimed potable water is 100 mg/L total salts, with no less than 20 mg/L calcium, and no less than 10 mg/L magnesium.[114]

Demineralized reclaimed water can be enriched using reagent methods; i.e., solutions or tablets containing essential minerals can be added to the water,[115,116] or through dissolution of natural or artificial minerals.[117]

The reagent method of artificial mineralization of reclaimed water was tested in a year-long bioengineering study conducted in the U.S.S.R.[78] The method most suitable for artificial water mineralization in space flight depends on flight duration. For example, for flights no longer than 70 days, the addition of reagents seems to be justified;[118] whereas, for longer-duration flights, methods that do not require active participation by crewmembers are preferred. Shikina et al.[116] discussed various methods for artificial enrichment of reclaimed water that require dissolution of natural and artificial minerals. The major disadvantage of these methods is that it is very difficult to control salt concentrations in drinking water; thus, they can fluctuate to values outside the recommended range. A higher level of mineralization can be achieved if a mineral created by roasting dolomite at 700 °C is added to potable water.[119] However, this mineral, if allowed to remain in the water for a prolonged period, may increase its pH value to more than 9.0, requiring pH adjustment.

The recommended level of mineralization can be attained in reclaimed water through the use of plastic granules containing all physiologically important salts.[120] However, this method has the disadvantage of being nonstationary.

Another method of mineralization that can be employed to provide the recommended salt levels involves dissolving natural minerals in desalinated water that has been pretreated with carbon dioxide.[121] This method has been used extensively in preparing drinking water in arid zones. However, it cannot be readily incorporated in a life support system for use in microgravity. For this purpose, membrane methods of artificial mineralization based on dialysis and electrodialysis are under development.[84,85,122] The electrodialysis method appears attractive for use on spacecraft because salt concentrations may be adjusted by varying the current density. A disadvantage of the method is that it involves osmotic transfer of the solvent to the concentrate, necessitating the development of compensatory measures for use when there are pauses in the operation of the water supply system.

IV. Water Reclamation Systems

The multiple sources of water in the life support system of manned spacecraft complicate consideration of different design concepts for water supply systems. Water from different sources can be processed in separate systems and/or mixed together and processed in a single system. The former approach makes it possible to gradually increase the closure of the water reclamation process, as is currently being done on space station Mir. The overall design concept for such systems involves modular design of different units and their maximum standardization.

Each water reclamation subsystem is associated with one or more devices in which moisture-containing waste products are collected. For example, the subsystem for reclaiming water from air moisture condensate is associated with a cooling/drying component, which controls the temperature and humidity of the spacecraft cabin and collects air moisture condensate. The subsystem for water reclamation from wash water is associated with shower and wash-basin facilities, whereas the subsystem for recovering water from urine is connected with the commode.

The subsystem for recovering water from air moisture condensate[71] using the sorption method of decontamination includes the following processes. The air moisture condensate that builds up in the cooling/drying component is pumped out to the condensate separator, where it is separated from the gaseous phase. The separated condensate is collected in the interior of a bellows pump and periodically fed to the decontamination subassembly, which contains a series of beds of ion-exchange resins and activated charcoal. To prevent microbial proliferation on the sorbents, small quantities of bactericidal sorbents containing silver or iodine are sometimes added to the first and last beds.[123]

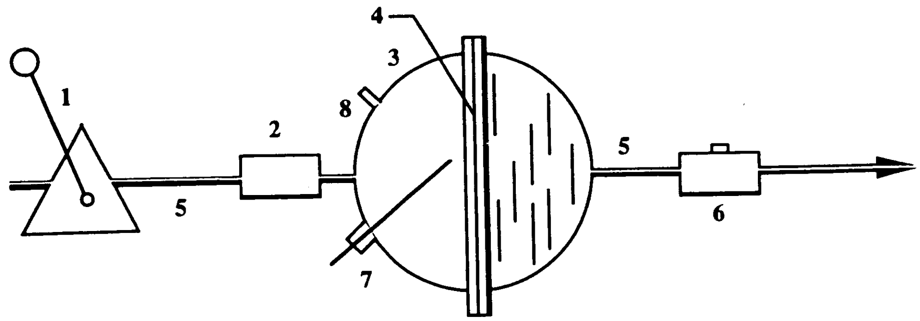
Decontaminated condensate is fed to the conductivity sensor, where its ionic strength is measured and then, depending on the measured value, is passed either to the water conditioning subassembly or to the reprocessing water container. The water is conditioned by enriching the demineralized water with calcium, magnesium, potassium, sodium, bicarbonates, and trace elements (fluorine and iodine), as well as oligodynamic quantities of silver or milligram doses of activated iodine. Reclaimed water that meets the requirements for reclaimed potable water[124] is transported to the potable water container, from which it is dispensed to the crew through a dispensing and heating subassembly, where it is pasteurized and, if necessary, cooled. The subsystem for recovering water from air moisture condensate can also be used for final decontamination of this condensate and of by-products of carbon dioxide hydration forming in the Sabatier or Bosch reactors.[26,125]

Early design configurations for water reclamation systems involved reclamation of potable water from urine.[2,69,78] Today, because of psychological considerations, it is considered preferable to use the water reclaimed from urine in the oxygen supply system. One of the modifications of the subsystem for recovering water from urine through membrane evaporation includes urine collection and separation from carrier air and preservation by the addition of chemicals, distillation at normal barometric pressure through a polymer membrane surface, final purification, and disinfection of the condensate.[71] This design is highly reliable, since it contains no very complicated devices and since the phase interface is created by a polymer membrane. Sometimes the diffusion gap is maintained by a slightly positive pressure, dispensing with the need for a bellows pump. Reliable performance of the system depends on use of the appropriate type and quantity of preservative, which can inhibit bacterial hydrolysis of urea and also bind volatile compounds, e.g., ammonia. Membrane distillers have the disadvantage that their performance declines during long use, requiring regular replacement. The performance of membrane distillers can be improved significantly by the use of hydrophobic membranes.[104] Water reclamation by membrane distillers is as high as 80–90 percent.

The reclamation of water from spent wash water has been emphasized because the relative amount of water used by a crew for personal hygiene is very high. On interplanetary flights, systems based on filtration, (e.g., clarification by ultrafiltration, reverse osmosis to remove dissolved contaminants, and sorption for final decontamination) are the most efficient.[95,126] On long-term orbital flights, where expendables can be resupplied, processes based on clarification using filter cartridges and final decontamination by sorption are more cost effective.[127]

One variant of the design configuration for recovering water from wash water includes the following stages: water from the shower is separated in a centrifugal or cyclonic separator and fed to the waste storage subassembly, then it passes through a preliminary filter into a pump and then into an ultrafiltration device for clarification. A high-pressure pump moves the clarified wastes into a reverse osmosis device. The permeate undergoes final decontamination through sorption and is disinfected by ionic silver or ultraviolet irradiation. The concentrate from the reverse osmosis device undergoes further concentration, along with urine, by distillation. According to different authors, water reclamation from hygiene water varies from 90–97.5 percent.

Water reclamation systems in which there are separate sub-



1. hand air pump
2. safety valve
3. potable water container
4. elastic partition
5. air hose
6. water hose
7. mouthpiece
8. drain

Fig. 1 Flow chart for a spacecraft water supply system using water stores.

systems for each water source seem to be preferable from the standpoint of low launch weight, but they are too complicated as a result of the presence of a large number of components, and their maintenance and servicing are time-consuming. According to Hall et al.,[96] maintenance work performed on the life support system by the crew costs about 35,000 U.S. dollars per hour, increasing the cost of life support. An alternative approach to water supply system design, involving the reclamation of water from a mixture of waste products, including solid wastes, has been considered. An integrated system of waste processing utilizing radioisotopic thermal elements (RITE), can treat a mixture of urine, feces, wash water, air moisture condensate, packaging material, food debris, and garbage.[108] Such systems are discussed in greater detail in Chapter 13 of the current volume.

V. Water Supply Systems on Manned Spacecraft

The Vostok and Voskhod spacecraft used stored water supplies.[128] Water tanks were made of polymer films and other elastic materials housed in metal containers (see Fig. 1). Potable water was preserved using silver compounds or ionic silver at a concentration of 0.1 mg/L. The outlet nozzle was filled with silver-impregnated, activated charcoal to enhance the reliability of water disinfection and deodorization. A cosmonaut could obtain water simply by sucking on the nozzle. The water supply subsystem, as well as other Voskhod life support subsystems, was designed to sustain one cosmonaut on a 12-day flight. The amount of water provided, including dietary water, was 2.2 kg/day.[128]

The Soyuz water supply system also used stored water preserved with ionic silver. The major component of the system was a tank consisting of two hemispheres separated by a polymer membrane. Water sufficient to fill the entire tank was pumped into one of the hemispheres, stretching the membrane to the container wall. When water was needed, a cosmonaut would use a hand pump to create air pressure on the membrane. Then he pushed a button valve on the nozzle to dispense water. Air pressure in the device was controlled by a valve.

Most of the water for the Apollo water supply system was produced by fuel-cell cryogenic hydrogen and oxygen (Fig. 2). This water was used for drinking and food rehydration. Air moisture condensate was used for thermal regulation. A small store of water was brought from the Earth.

The Apollo command and lunar modules were each equipped with their own water supply systems,[67] which differed in design. In the command module, potable water was supplied by a system utilizing fuel-cell water, whereas water stores were used in the lunar module, which had no fuel cells (see Fig. 3).

Water from fuel cells located in the service module entered the command module through a water pipe. Before it reached the command module, it was cooled to 24 °C and its pressure was decreased from 4.2–1.7 atm. On Apollo 1 through 11, a hydrophobic-hydrophilic filter that separated gas from liquid was used. A special hydrogen separation device was used on Apollo 12 and subsequent flights. This device consisted of a silver-palladium tube, through which hydrogen was diffused from the water and vented overboard.

Water was dispensed into a container, where it was stored and used for food preparation. Potable water was supplemented with sodium hypochlorite, which helped to maintain its aesthetic, physical-chemical, and bacteriological parameters.

In the lunar module, potable water was stored in three containers. On the lunar surface, the astronauts used water from the main 181-liter container located in the lunar lander. During ascent from the Moon's surface and during docking with the command module, they used water stored in two 18-liter containers. The space between the walls of the container and the water membrane was filled with nitrogen at a pressure of 3.2 atm. Water was preserved with iodine. Seven days prior to launch, a solution of iodine at a concentration of 30 mg/L was added to the system. After a 1-h soak, the system was filled with deionized water containing 10 mg/L of iodine and

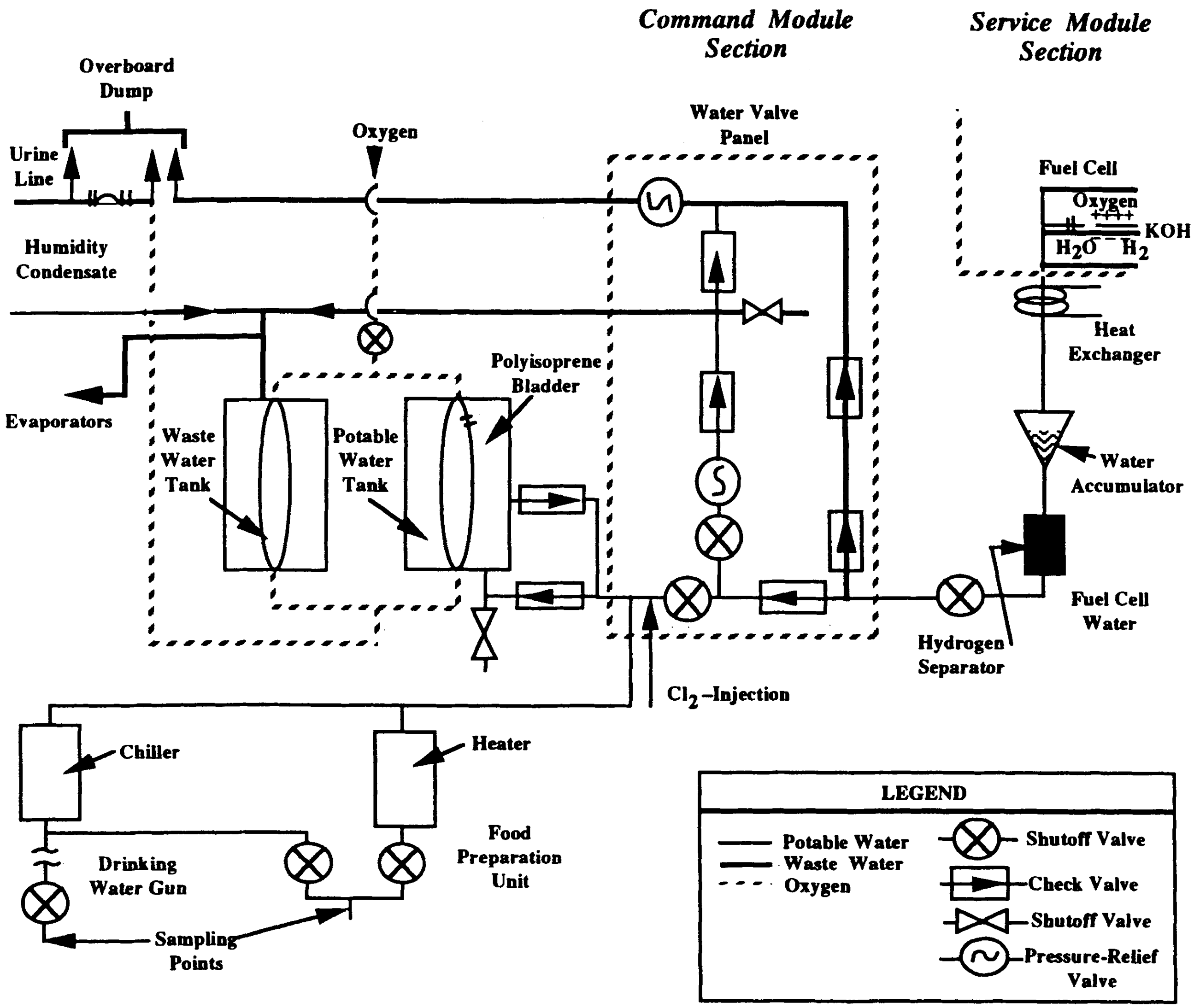


Fig. 2 Apollo Command Module water supply system.[67]

this water was actually consumed by astronauts.

The water supply system for the Space Shuttle[129] is, in many respects, similar to that of Apollo with fuel cell water as the primary water source. The maximum production rate was 11.34 kg/h when the three fuel cells were under maximum power demand. The fuel cells produce a hydrogen-enriched water, which is passed through a matrix of silver-palladium tubes to remove 95 percent of the hydrogen. The excess hydrogen is vented overboard, and the potable water is fed into storage tanks.

Water storage consists of four stainless steel tanks.[130] Each has a usable capacity of 74 kg and weighs 17.9 kg dry.[131] The potable water is routed from the potable water tank to the galley system, which is in the cabin middeck (working) area. The galley has a dispenser for drinking water and water to mix with rehydratable food. The system provides chilled water at 7–10 °C or water heated to a selected level as high as 49 °C, all at a maximum flow rate of 27 kg/h.

The water management system is serviced on the ground before each mission. The water supplied by the ground support equipment is deionized and iodinated. New and refurbished systems are treated with concentrated iodine solutions of 25–50 mg/L of water. The solution is drained after a 3–4 h soak and refilled with water containing about 6 mg iodine per liter of water. For normal ground servicing of the water supply system, treatment is with deionized water with sampling before iodine addition. After this initial sampling, a solution containing iodine at levels of 5.0–10.0 mg/L water is injected. Dilutions by residual water results in an iodine concentration of 3–5 ppm.

In-flight iodination is achieved by passing the water through a packed bed of iodinated anion-exchange resin. The concentration of iodine is maintained at a level of 2.0–4.0 mg/L. Tests of the effectiveness of this method have found elevated microbial counts in only 46 of 853 water samples.

On Skylab flights, the water supply system utilized stores of deionized water. The system provided all the water used by the crew for drinking, food rehydration, washing, house-

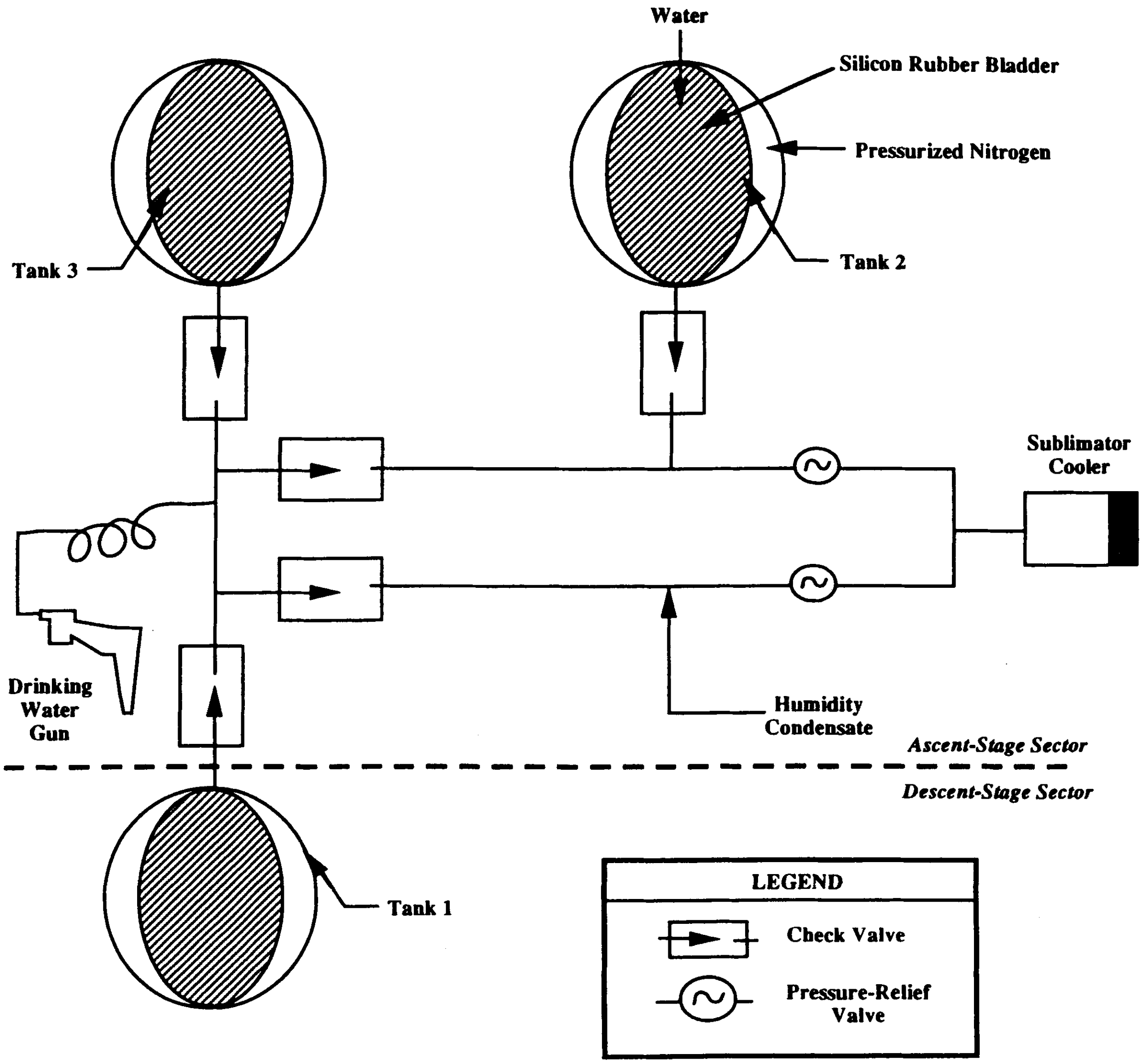


Fig. 3 Apollo Lunar Module water supply systems.[67]

keeping, and waste management.[132–135] The total amount of stored water was approximately 3000 kg. This water was stored in 10 stainless steel tanks, each with a capacity of 268 kg, which were located in the front portion of the orbital workshop module of the station along its interior perimeter.

Each container was equipped with a bellows membrane, through which water was forced from the container under pressure of gaseous nitrogen. To prevent water freezing on unmanned flights, each container was provided with an electric heater. Water was stored at a controlled temperature not above 13 °C. Cold water for drinking and cooking was maintained at 7 °C and was dispensed in 14.8-cm^3 portions by means of a valve. Hot water for cooking was heated to 65 °C and was dispensed in portions of 29.6–177.4 cm^3. Wash water was maintained at 52 °C.

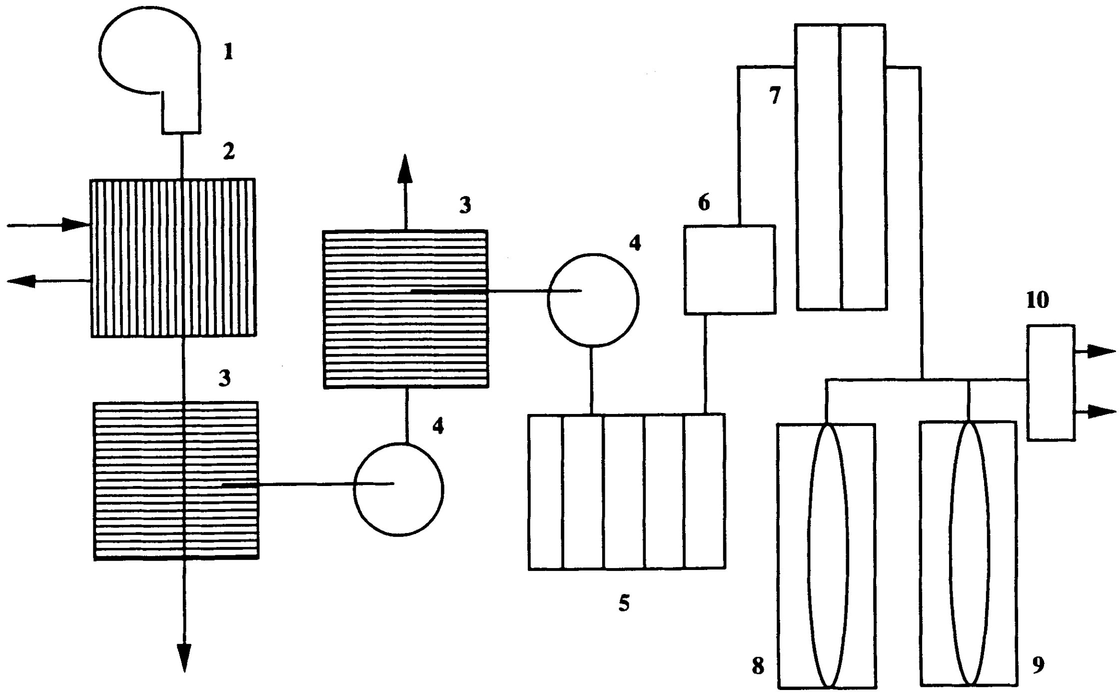
Water use by the crew, consisting of three astronauts, included 10.9 kg/day for drinking and cooking and 3.2 kg/day for personal hygiene and housekeeping. During the three Skylab flights, the crews consumed 1812 kg of water.

The water supply system included water storage tanks, devices for microbial monitoring, and devices for water distribution and dispensing.

Waterlines containing cold and hot water for beverages, drinking water, and to reconstitute dehydrated food were placed under the dining table, which accommodated three crewmembers. At each seat was a nozzle that delivered drinking water. In the center of the dining table, there was a valve for water delivery for rehydrating food. Dehydrated food items were stored in plastic bags, into which cold or hot water could be injected. After water injection, the bags were shaken to prepare beverages, which the astronauts drank through the same opening used to input the water.

Water was piped to the table from the tanks through rigid pipes or flexible tubes. There was a separate line with a heater to the commode, which delivered 50 mL of water at a time, and another line to the washing facility.

Skylab also carried water supplies for the water-cooled extravehicular activity space suits. In addition, water was pro-



1 - fan
2 - cooling-drying unit
3 - gas-liquid separators
4 - pump
5 - sorbent columns
6 - conductometric sensor
7 - mineralization unit
8,9 - potable water tank
10 - water dispenser and heating device

Fig. 4 Potable water recycling system using humidity condensate.

Table 9 Quality of recovered water after five flights on Salyut-6

Parameter, units	Standard	Flight 1	2	3	4	5
pH, pH units	6.5–9.6	7.5	7.0	7.8	7.5	7.1
Transparency, cm	30	30	30	30	30	30
Odor, rated	2	0	1	0	0	0
Taste, rated	2	0	1	0	0	0
Total hardness, mg-equiv/L	7	1.6	2.1	5.2	2.8	1.6
Nitrogen, as ammonia, mg/L	2.0	0.2	0.3	0.4	0.2	0.2
Bichromate oxidizability, mg O_2/L	100	30	21	22	25	30

vided for use in the event of a fire.

In addition to the main water tanks, the station also carried a special container with water to be used in various experimental studies. There was a portable container holding 12 kg of water for contingency situations.

Emphasis was placed on the level of microbial contamination of water supplies, which were preserved by means of iodine. Before launch, iodine was added to every container in concentrations of 12 mg/L. Iodine concentration was measured regularly during water sampling. Since the iodine concentration diminished as the flight continued, additional amounts were administered to bring it up to the requisite levels.

The water supply for the Salyut station (beginning with Salyut-4) included both stored water supplies and water reclaimed from air moisture condensate.[20,136,137] Stored water was preserved using ionic silver at a concentration of 0.2 mg/L. The Rodnik system was used starting with the fourth expedition on Salyut-6. This system could be used repeatedly by replenishment from water tanks delivered by cargo vehicles. The Rodnik system accommodated the delivery, storage, transfer, and distribution of about 410 liters of potable water.

The configuration of the system for recovering water from air moisture condensate (SRV-K) included gas-liquid phase separation, water decontamination, enrichment with minerals, preservation with ionic silver, and heating. Reclamation was based on sorption with ion-exchange resins (cationites and anionites) and activated charcoal. The former were used to remove ionized compounds, and the latter removed organic (nonelectrolyte) compounds (Fig. 4).

The water reclamation system provided cosmonauts with cold and hot (to 80 °C) water, which they used to prepare hot drinks; e.g., tea, coffee, or fruit juices. Reclaimed water was used, also, to rehydrate freeze-dried foodstuffs. Some of the hot water was used for personal hygiene.

At the end of each flight, reclaimed water samples were delivered to a laboratory on the ground for analysis. Table 9 presents data obtained from the measurement of water reclaimed by the SRV-K system.

Salyut-6 crewmembers rated the taste and odor of stored water supplies, as well as water reclaimed by the SRV-K system, as good. It should be emphasized that cosmonauts seemed to prefer hot water from the reclamation system to the stored cold water. Beginning with the second expedition, average consumption of hot water in the form of tea, coffee, and juices was 1.50, 1.22, 1.14, and 1.04 L/man/day compared to cold water consumption, which was 0.63, 0.57, 0.66, and 0.61 L/man/day, for crews 2–5, respectively.

The operation of the SRV-K water reclamation system confirmed the efficiency of using water reclamation systems on spacecraft. Use of these systems make possible large decreases in the launch weight of life support systems and the amount of cargo that must be delivered to orbital stations from Earth.

The water supply system for Mir flights provides both stored water supplies and reclaimed water. Water stored in the Rodnik system is dispensed by a special pump and a water container. Water is reclaimed from air moisture condensate, urine, and spent wash water. Water is reclaimed from air moisture condensate by a sorption system resembling the one used on the Salyut stations. Water is extracted from urine by membrane, low-temperature evaporation, and subsequent condensation and sorption. The resultant condensate (distilled water) is used to generate oxygen in an electrolysis system. If necessary, water reclaimed from urine, after mineralization and preservation, can be consumed by cosmonauts. However, for psychological reasons, cosmonauts obtain the water they need from the Rodnik system.

In the future, when a carbon dioxide hydration system becomes operational, the water it generates will undergo sorption so it can be used by the crew. Sorption processes, in which a mixture of katamin AB and amine oxide has been used as a detergent and disinfectant, are used to recover water from wash water.

During Mir flights, water reclamation from water containing human wastes (wash water, urine, and perspiration) was accomplished for the first time in space.

As soon as a biological component is incorporated into the life support system, the water supply system will reclaim water from condensates produced by algal reactors and greenhouses, since all wastes will probably be transformed by bioengineering systems.[138]

Water supply systems for Space Station will probably also include reclamation of water from all moisture-containing wastes.[140,141] Potable water will be reclaimed from air moisture condensate. Plans call for urine and used wash water to be reclaimed to obtain wash water. Feces is not a suitable source of water because its moisture content is low and difficult to extract. The final selection of a process to be used for the reclamation system has not yet occurred.

The design of water supply systems for flights to Mars will depend on the design of life support systems and propulsion systems selected for the spacecraft. In any event, any system selected will have to meet the requirements of maximum reliability and high closure of water reclamation for extended missions.

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