CHAPTER 5

APOLLO COMMAND AND SERVICE MODULE AND LUNAR MODULE ENVIRONMENTAL CONTROL SYSTEMS

by

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Introduction

The Apollo Command and Service Module (CSM) and Lunar Module (LM) proved to be highly successful space vehicles. Instrumental in the success of these spacecraft was the satisfactory and reliable operation of their environmental control systems. This chapter describes the systems and system requirements and discusses the performance of both Command Module and Lunar Module environmental control systems during the Apollo Program. The bulk of the material contained in this Chapter was orginally published in Brady and co-workers (1973), and Hughes and co-workers (1973).

The concept of the Apollo mission itself and the spacecraft that would be needed to complete it can be traced back to 1955. In March of that year, the feasibility of a one million pound thrust liquid-fueled rocket engine to launch the vehicle on its path to the moon was established. By late 1962, the broad conceptual design of the Apollo spacecraft and the lunar landing mission was complete. During 1963, formal contract negotiations for the spacecraft were completed, and by June of 1963 most of the subsystem designs for the Command Module (CM) were finalized. At the same time, critical decisions were being made concerning the Lunar Module (LM). The key items affecting its design included the decision to rotate the CSM and manually maneuver it into a docked position with the LM; that the crew would operate the LM from a standing position; and, most important for the environmental control and life support systems, that the Lunar Module would be capable of supporting the operations of two men on the lunar surface for up to 24 hours plus 24 hours in flight. Before the end of 1963, the Lunar Module mockup was completed and, in early 1964, the Block II CSM configuration was completed. The requirement for a second configuration was necessitated by a decision to execute a lunar landing and to do so by lunar orbit rendezvous, a decision which had a substantial impact on system design. The vehicles resulting from these development efforts were described and pictured in Section I, Chapter 2, *Apollo Missions.*

Command and Service Module Environmental Control System

System Requirements and Description

Briefly enumerated, the system requirements for the Apollo Command Module environmental control system (ECS) were as follows:

1. Oxygen atmosphere in the pressurized cabin of 34.5 kN/m^2 (5 psia).
2. Normal shirtsleeve mode except for critical mission phases.
3. Cabin pressure maintained at 24.1 kN/m^2 (3.5 psia) under certain defined emergency conditions.
4. Carbon dioxide (CO_2) removal by lithium hydroxide (LiOH) absorption and limited to a partial pressure of 1013 N/m^2 (7.6 mm Hg).
5. Cabin temperature maintained at $297^\circ \pm 3^\circ K$ ($75^\circ \pm 5^\circ F$) with relative humidity limited to the range of 40 to 70 percent.
6. Thermal control provided for the electrical and electronic equipment.

To accomplish these design objectives, the ECS interfaced with the electrical power system for electricity, fuel cell system for water, and cryogenic storage system for oxygen.

A schematic diagram of the ECS is shown in figure 1. For convenience of description, the system may be divided into six major subsystems: oxygen, pressure suit circuit, water, coolant, waste management, and postlanding ventilation. These subsystems interacted to meet the total ECS requirements.

The oxygen subsystem was supplied from the Service Module cryogenic storage tanks and controlled the distribution of oxygen within the Command Module. It stored a reserve supply of oxygen, regulated several levels of supplied oxygen pressure, controlled cabin pressure in normal and emergency modes, and provided for purging of the pressure suit circuit.

The pressure suit circuit subsystem provided the crew with a continuously conditioned atmosphere. It automatically controlled suit gas circulation, pressure, and temperature, and removed debris, excess moisture, odors, and carbon dioxide from both suit and cabin gases.

The water subsystem received the potable water produced as a byproduct of fuel cell operation, stored the water, and chilled or heated the water for drinking and food reconstitution. The waste water section collected and stored water extracted from the suit heat exchanger and provided it to the evaporator for evaporative cooling. Potable

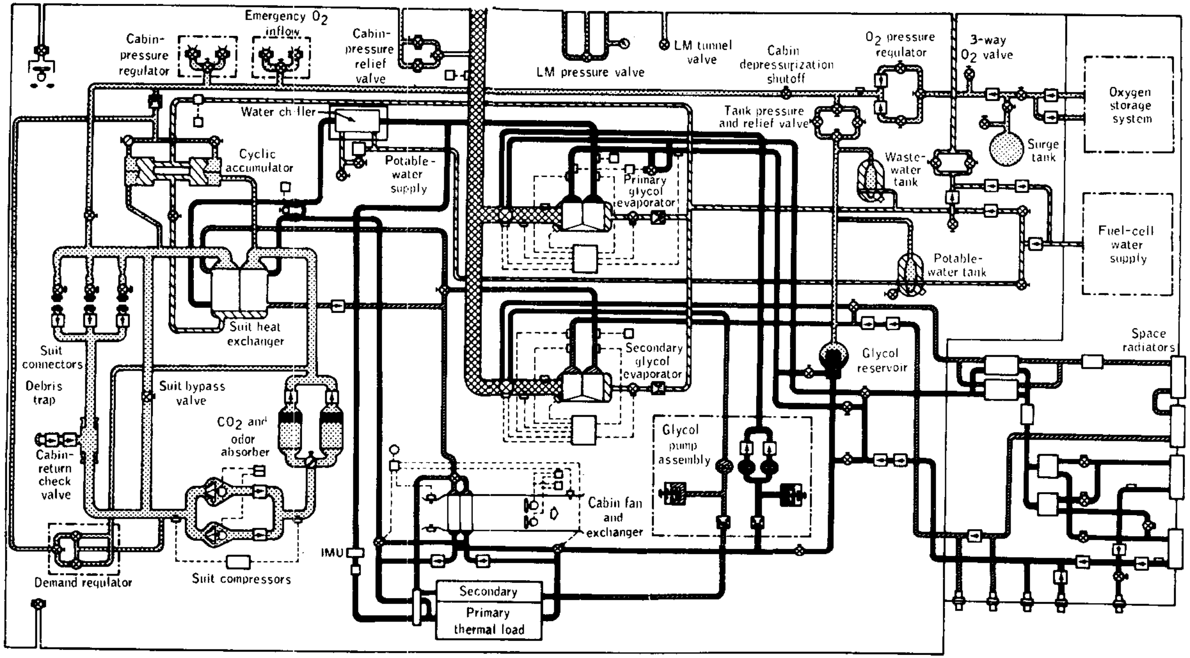


Figure 1. Apollo CSM environmental control system schematic.

water not needed for crew consumption was added to waste water storage. Water in excess of system requirements was dumped overboard through a heated water dump nozzle.

The coolant (water/ethylene glycol) subsystem supplied cooling for the pressure suit circuit, potable water chiller, and electrical and electronic equipment mounted on coldplates in the Command and Service Modules. It also supplied heating or cooling for the cabin atmosphere. Independent primary and secondary (backup) coolant loops were provided, with each loop utilizing space radiators as the basic heat rejection mechanism and water boiling from the glycol evaporator for supplementary heat rejection.

The waste management subsystem provided for dumping overboard of urine through a heated nozzle and for storage and venting of solid wastes. An interconnect capability with the waste water dump system was available as a backup for all fluid dumping.

The postlanding ventilation subsystem provided means for circulating ambient air through the cabin after landing.

Mission Performance

Oxygen Subsystem. The oxygen subsystem of the ECS, exclusive of the cryogenic oxygen system, performed satisfactorily throughout the Apollo missions. Separate regulation levels were maintained at nominal values of 690, 140, and 35 kN/m^2 (approximately 100, 20, and 5 psi), and the flow restrictors/heat exchangers demonstrated satisfactory operation for flows approaching maximum capability. No emergency cabin pressure regulation was required, and all planned depressurizations and repressurizations were without incident. Oxygen allocated to the ECS was originally 78.29 kg (172.6 lb) for a 14-day mission. Principal items were .82 kg (1.8 lb) per man-day for crew consumption and 2.18 kg (4.8 lb) per day for cabin leakage. Additional allowances were made for the extravehicular activity in the later missions. Actual consumption, as shown in table 1, proved to be less than allocations, primarily because of lower cabin leakage and crew requirements. A comparison of a typical mission with the specification requirements is shown in table 2.

Pressure Suit Circuit Subsystem. The pressure suit circuit subsystem satisfactorily accomplished all its design requirements. With the confidence gained during the program, fully suited operation was eventually limited to launch and Lunar Module jettison. No difficulty was ever encountered with the integrity of the Command Module pressure shell. Therefore, the suit loop was not used as an emergency environment for the crew. During the Command Module extravehicular activities on the Apollo 15, 16, and 17 missions, use of the suit loop was required to support two crewmen, but no problems resulted and pressure regulation was within the required 24.1 to 27.6 kN/m^2 (3.5 to 4.0 psia) range.

The original concept of using 100 percent oxygen as the cabin gas during the prelaunch and launch periods was abandoned following the Apollo 204 accident in favor of a 60 percent oxygen/40 percent nitrogen mixture with the suit circuit remaining at 100 percent oxygen. This required the inclusion of a pressure sensor to indicate suit-to-cabin differential pressure, and the direct oxygen valve was used to provide a constant 0.23 to 0.32 kg/hr (0.5 to 0.7 lb/hr) flow into the suit loop. This flow compensated for metabolic usage and suit circuit leakage with some excess flow to keep the loop at a positive pressure and provide a purge through the suit circuit relief valve. Although brief periods of negative pressure resulted from crew movement in the suits, the system was judged to perform acceptably.

Table 1
Actual Environmental Control System Oxygen Consumption

Apollo Mission Number	Duration Days:Hours	Oxygen Consumed kg	(lb)
7	10:20	46.26	(102)
8	6:03	23.13	(51)
9	10:01	44.91	(99)
10	8:00	32.21	(71)
11	8:03	37.19	(82)
12	10:05	44.91	(99)
13	5:23	13.61	(30)
14	9:00	42.64	(94*)
15	12:07	49.44	(109**)
16	11:02	48.08	(106**)
17	12:14	49.90	(110**)

*Includes 4.5 kg (10 lb) for high flow demonstration test of cryogenic system.

**Includes 11 to 13 kg (24 to 29 lb) for EVA flow and cabin repressurization.

Specification requirements called for the lithium hydroxide absorber elements to be capable of removing carbon dioxide at a maximum average removal rate of 0.064 kg/hr (0.142 lb/hr) for 24 hours [1.54 kg (3.4 lb) total for 93 percent utilization]. With two elements in parallel, the partial pressure of carbon dioxide was to be maintained at less than 1013 N/m^2 (7.6 mm Hg). Flight measurements indicated that this level was never exceeded and that carbon dioxide partial pressure seldom rose above 400 N/m^2 (3 mm Hg). For three-man operations, the elements were changed every 24 hours, but the replacement times were staggered every 12 hours to reduce the variation in carbon dioxide partial pressure levels. For single-man operations, the changeout times were lengthened proportionately.

In an effort to verify performance of the elements, chemical analyses of all of the returned elements were performed and a correlation was attempted with their length of time in service (equivalent to three-man usage). The results, indicated in figure 2, showed considerable scatter when plotted against this time variable. The figure shows how much lithium hydroxide has been turned into lithium carbonate, indicating carbon dioxide production and, thus, metabolic rate. The scatter shows that metabolic rates were different from flight to flight, but that there was a predictability within a certain band. Additional refinements were attempted to account for estimated crew metabolic rates, activity levels, and spacecraft environments. None of these was particularly successful in consolidating the data. Considering the lack of sufficient instrumentation and knowledge of actual metabolic levels, tolerances of the chemical analyses, and possibility of out-of-order use by the crew, the results appear to be representative of the element usage.

Table 2

Environmental Control System
Oxygen Consumption Breakdown

Item	Specification Requirement (14 Days)		Apollo 15 Mission (12.3 Days)	
	kg	(lb)	kg	(lb)
Crew consumption	34.29	(75.6)	22.09	(48.7)
Cabin leakage	30.48	(67.2)	2.68	(5.9)
Cabin repressurizations	5.31	(11.7)	4.08	(9.0)
One CM puncture	1.63	(3.6)	—	—
LM support	6.58	(14.5)	5.94	(13.1)
Tank bleeds			4.45	(9.8)
Cabin & WMS purges			3.49	(7.7)
EVA flow			6.67	(14.7)
TOTALS	78.29	(172.6)	49.40	(108.9)

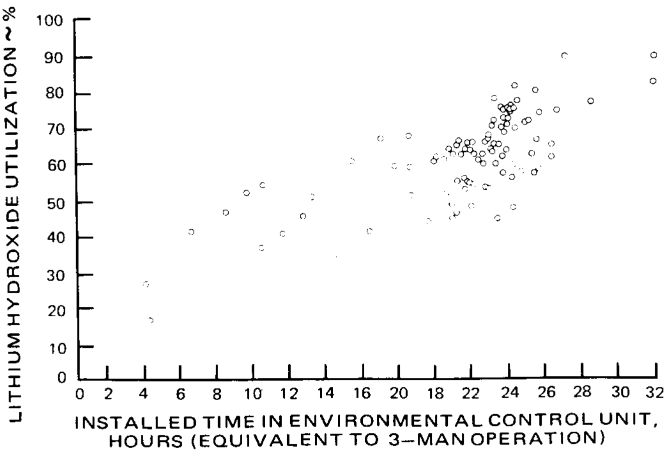


Figure 2. Apollo missions 8 to 16 returned LiOH canisters.

Water Subsystem. The water subsystem typically managed from 180 to 225 kg (400 to 500 lb) of water with normal fuel cell production rates of 0.68 to 0.91 kg/hr (1.5 to 2.0 lb/hr). Because these rates far exceeded the requirements of the crew and evaporator operation, most of the water was dumped overboard. Routine flight operation consisted of maintaining a full potable water tank and alternately filling and dumping the waste tank between limits of 10 percent and 85 percent full. On occasion, dumping was inadvertently continued until the waste tank was completely empty, and some of the potable water was dumped without adverse system effect. During later missions, the waste water tank was kept almost full at Command Module/Service Module separation to improve the spacecraft's lift/drag characteristics during reentry. A water balance for a typical mission is presented in table 3. Quantities were determined from telemetered tank quantities, calculated evaporative usage, and standard values for the lithium hydroxide reaction and metabolic oxidation. (See Section VI, Chapter 4, ***Potable Water Supply,*** for additional information.)

Table 3

Typical Environmental Control System Water Balance Summary (Apollo 15)

Initial Onboard Water	Quantity kg (lb)	
Potable tank	13.15 (29)	
Waste tank	12.25 (27)	
Subtotals	25.40 (56)	
Water gained		
Fuel cell production	235.87 (520)	
LiOH reaction	12.25 (27)	
Metabolic oxidation	11.79 (26)	
Subtotals	259.91 (573)	
TOTALS		285.31 kg (629 lb)
Final onboard water		
Potable tank	14.06 (31)	
Waste tank	23.13 (51)	
Subtotals	37.19 (82)	
Water lost		
Body waste water	43.09 (95)	
Evaporator operation	3.63 (8)	
Overboard dumping		
Waste tank	191.42 (422)	
Potable tank	7.26 (16)	
URA flushing and samples	2.72 (6)	
Subtotals	248.12 (547)	
TOTALS		285.31 kg (629 lb)

Initial onboard water + water gained = final onboard water + water lost.

The hot water provided for food and drink reconstitution was greatly appreciated by the flight crews and improved the diet over the cold diet supplied on earlier space flight missions. However, while mechanical failures in the water system were infrequent, the system itself was the source of frequent negative comments by the crew. These concerned two aspects of system performance, gas in the water and problems with the sterilization injection system.

Gas in the potable water originated from two sources. Water produced as a byproduct of fuel cell operation was saturated with hydrogen gas at a pressure of 415 kN/m^2 (60 psia). When this water was supplied to the environmental control system through a 140 kN/m^2 (20 psig) regulator, approximately one liter of hydrogen per day was released. This gas was removed from the water system on Apollo 12 and subsequent missions by passing the water through a hydrogen gas separator. The separator removed about 99 percent of the hydrogen, reducing the partial pressure in the water to 4.1 N/m^2 (0.6 psia).

The other source of gas in the drinking water was oxygen from the bladder in the drinking water storage tank. This tank contained an oxygen bladder pressurized to 140 kN/m^2 (20 psig) to expell the water. Oxygen permeated the bladder material until the partial pressure was about equalized across the bladder. When the water was used by the crew in the 35 kN/m^2 (5 psia) cabin, oxygen was released. This was particularly troublesome when preparing food because large bubbles often formed in the food bags and prevented proper reconstitution. A gas separator cartridge assembly was developed for attachment to the water delivery port starting with the Apollo 11 mission. The assembly separated the free gas from the water but was only partially successful due to size and configuration limitations.

Subsequent to final design of the water system, a requirement for water sterility was placed on the system. A method was devised by which 30 cm^3 (1 ounce) of chlorine solution and 30 cm^3 (1 ounce) of buffer solution could be injected into the water system every 24 hours through a fitting containing septa. The solutions were contained in hard-case, Teflon ampoules with flexible inner bags. During development, problems were encountered with corrosion of the aluminum tubing and with chemical mixing. During the first several missions, the crews complained of a strong chlorine taste after injections. These problems were solved by (1) having the crew perform the injections just prior to the sleep period, and (2) developing the use of sodium nitrate as a corrosion inhibitor for addition to the buffer ampoules. The inhibitor was effective in preventing the chlorine from reacting with the aluminum and allowed a decrease in the concentration of the chlorine injected from 5000 mg/liter (5000 ppm) to 1860 mg/liter (1860 ppm). Use of the modified chlorine and buffer ampoule solutions began with the Apollo 14 flight. The injection procedure itself posed certain problems primarily from ampoule bag leakage. Additional preflight inspections improved this situation.

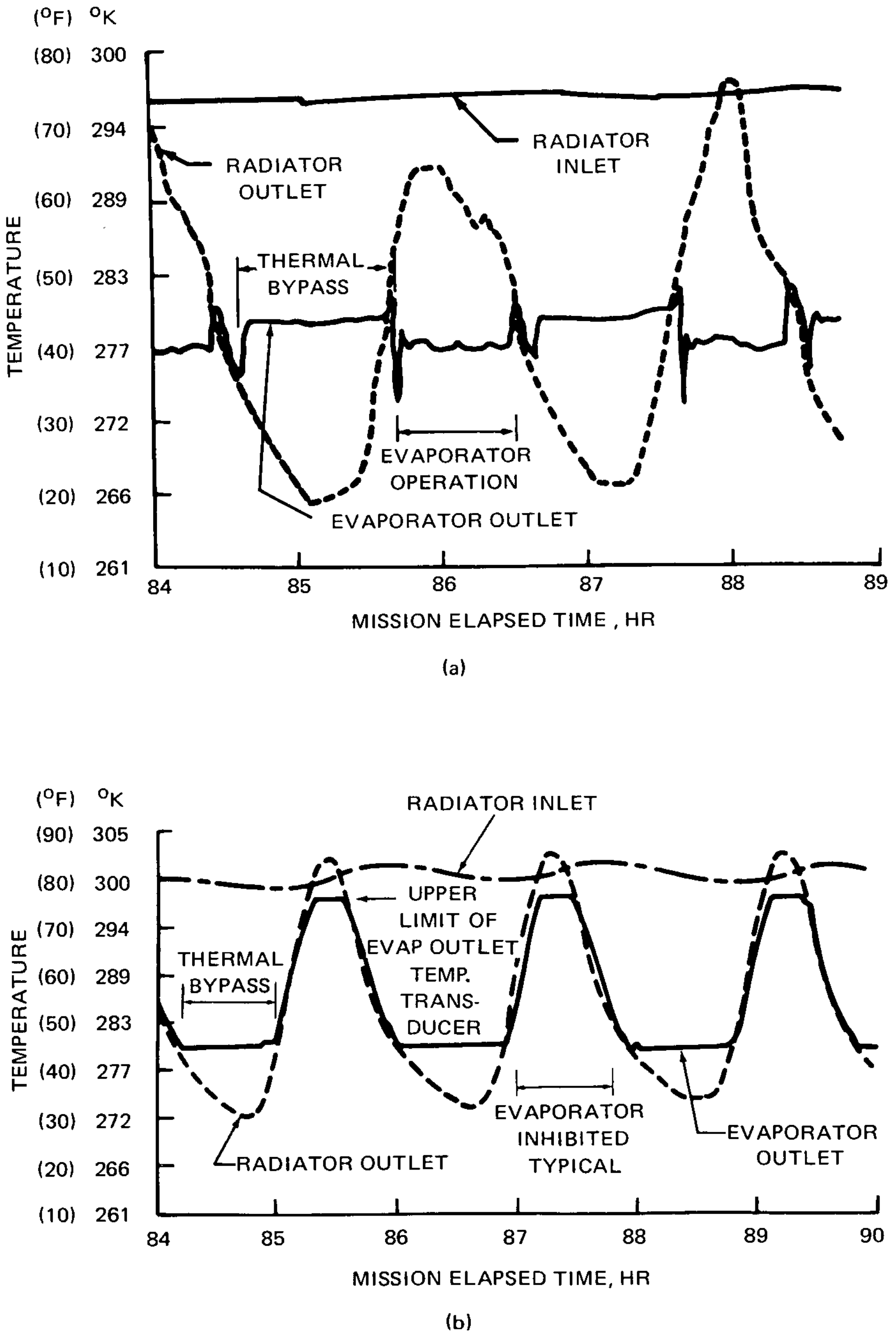
Coolant Subsystem. The coolant subsystem provided adequate thermal control throughout the missions in spite of operational limitations imposed by procedural requirements or by occasional hardware malfunctions. Early flights demonstrated that a passive thermal control (PTC) mode, accomplished by a slow, controlled CSM roll, allowed satisfactory heat rejection by the space radiators during most periods. During the translunar and transearth phases, the radiator outlet temperature seldom exceeded 283°K (50°F) and often was below 280°K (45°F). When the temperature was below 280°K the Service Module bypass valve was required to operate and control the Command Module coolant temperature to 280°K (45°F). Evaporator operation was required only during portions of launch, Earth orbit, lunar orbit, and entry, and during certain fixed attitudes which prevented effective radiator operation. Starting with Apollo 11, when steam discharge interfered with visual sightings and caused perturbations in orbital tracking and attitudes, evaporator operation was inhibited except for launch, Earth orbit, and entry. The resulting system temperature measured at the evaporator outlet exceeded the normal 278° to 283°K (40° to 50°F) range and cyclically increased during lunar orbits to 297°K (75°F) or more. Typical lunar orbit system performance with and without evaporator operation is illustrated in figures 3a and 3b. Principal impact of this excessive temperature cycling was to increase the condensation on the colder cabin surfaces after the higher temperature portions of the orbits.

The coldest coolant flowed through the suit heat exchanger for gas cooling and condensate removal and then to the cabin heat exchanger for cabin gas cooling before going to the electronic heat load. However, because the noise of the fans and the gas flow passing through the cabin heat exchanger was amplified by the cabin structure, the crews did not operate the cabin fans except during short specified periods and relied upon the suit heat exchanger for the total thermal control of the cabin gas. This mode of operation was normally adequate during translunar and transearth phases when the crews were comfortable or slightly chilly. The higher coolant temperatures during lunar orbit presented some discomfort, but the problem was not significant.

Early flight configurations of the evaporator showed a tendency to dry out under low heat loads and required inflight reservicing. Later modifications, which included relocated wetness sensors and trimming of the water distribution sponges, provided satisfactory units. During the Apollo 16 mission, the mixing valve was operated in a manual mode for almost the entire flight due to failure of the mixing valve controller. Less than a half dozen adjustments were required by the crew, and overall system temperature increased less than 3°K (5°F) which constituted adequate system performance.

Radiator heat load and rejection was determined by use of the total flow and radiator inlet and outlet and evaporator outlet temperature measurements. Typical heat load and rejection under favorable conditions during translunar or transearth PTC ranged between 1170 and 1470 watts (4000 and 5000 Btu/hr). Knowing the approximate electrical and metabolic heat load, the heat loss through the structure was determined. Experience from Apollo 7 and 9, both Earth orbit missions, showed that heat loss through the cabin structure varied from 380 to 675 watts (1300 to 2300 Btu/hr), depending on the extent of CM electrical load. This loss was largely due to heat shorts near the coldplates and was greater than originally estimated.

Waste Management Subsystem. The environmental control system portion of the waste management system provided for the disposal of crew waste liquids and solids. The performance of this system is discussed in Section VI, Chapter 2, ***Waste Management.***



(a)

(b)

Figure 3. Apollo coolant subsystem performance in lunar orbit with and without evaporator operation.

Apollo 13 Emergency. The Apollo 13 mission started in a routine manner with environmental control system operation proceeding normally. However, with the loss of the Service Module cyrogenic oxygen tanks, the ECS was without its main source of supply for oxygen, water, and electrical power. To preserve the remaining onboard quantities, the surge tank and repressurization package tanks were isolated, water tanks were depressurized, and the Command Module was completely powered down. The Lunar Module was activated as a "life-boat" to sustain the crew, and it operated in this capacity for approximately 83-1/2 hours until jettison prior to reentry. With certain operational restrictions imposed, the Lunar Module consumables proved adequate for all purposes except for providing drinking water and removing carbon dioxide. Drinking water was obtained from the Command Module on several occasions by briefly pressurizing the oxygen system and withdrawing water. To supplement the Lunar Module lithium hydroxide cartridges, a method was devised for CM lithium hydroxide elements to be utilized with the LM atmosphere revitalization section.

During the powered down period of operation, the temperature inside the Command Module slowly decreased and the crew noted considerable condensation within the cabin. The CM was powered up briefly for data transmittal twice during the dormant period. A summary of the temperature changes is included in table 4.

A reported inability by the crew to obtain additional drinking water and a subsequent thermal model analysis indicate that the water tanks, or more probably the water lines in the aft compartment, froze late in the powered down period. Command Module ECS operation after reactivation and during entry was satisfactory.

Dust Control

A problem encountered with the start of the lunar landing missions was effective control of lunar dust. After lunar EVA, the crewmen and the samples they had collected were covered with this fine lunar material. Despite attempts at cleanup and packaging in the Lunar Module, transfer of crew and materials back to the Command Module resulted in contamination of the CM atmosphere. This was an undesirable situation in view of the objectives of the quarantine program which sought to minimize contamination of the CM, and thereby minimize the potential hazard of contaminating the biosphere after reentry of the spacecraft. Earlier contamination testing and analysis had shown that continuous cycling of cabin gas through the lithium hydroxide elements (and filters) effectively removed particles 5 microns or even less in diameter, even though 50 percent of the flow was bypassed. Disadvantages to this automatic method were the relatively slow removal rate and introduction of additional particles whenever a dusty item was moved or disturbed. To speed up the capture of suspended material, a filter was developed for use with the cabin fans. The filter, in a shape of a pleated bag, was made from the same Armalon felt filter material used in the elements and was attached to the outlet of the fans. When used for several hours during and after crew and sample transfer, the filter was effective. An additional benefit was obtained by installing the filter shortly after launch, thereby preventing floating objects from entering the inactive fan enclosure.

To assist in removing dust from suits and sample containers, a hand-held vacuum cleaner (figure 4) was developed that used the qualified suit circuit compressor as a

Table 4

System Parameters During Apollo 13
Powered Down Period

Parameter	Units	Ground Elapsed Time (GET) ~ Hours				
		57:54 (1)	58:35 (2)	102:00 (3)	123:06 (4)	141:15 (5)
Cabin temperature	°K (°F)	288 (58)	292 (66)	284 (52)	281 (46)	279 (43)
Evaporator temperature	°K (°F)	279 (43)	293 (67)	285 (54)	281 (46)	278 (41)
Suit inlet temperature	°K (°F)	286 (56)	288 (59)	285 (53)	280 (45)	278 (41)
Pri-radiator outlet temperature	°K (°F)	274 (34)	294 (69)	288 (58)	283 (49)	278 (40)
Helium tank (near water tanks)	°K (°F)					274 (33)
Surge tank pressure	kN/m^2 (psia)	5929 (860)	5929 (860)	5254 (762)	5150 (747)	5081 (737)

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(1) Glycol pump deactivated (2 hours after accident)
(2) Instrumentation deactivated
(3) Instrumentation activated momentarily
(4) Instrumentation activated momentarily
(5) Glycol pump activated

blower. Replaceable bags were fabricated from the Armalon felt, and a brush was added to the compressor inlet. A 4.27-m (14-ft) power cable for attachment to the Command Module utility outlet enabled use in both the CM and LM. The device was effective for removing dust before transfer of the items from the LM, and reduced the contamination entering the CM. Heavy usage, however, tended to clog the inlet screen and impeller and required frequent cleaning.

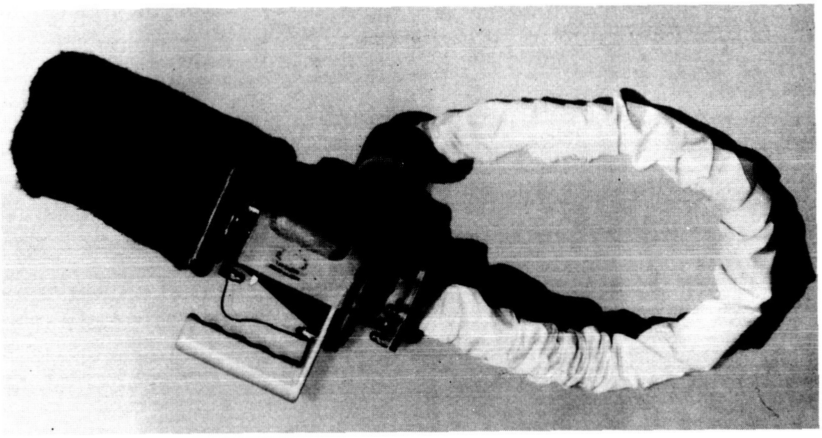


Figure 4. Hand-held vacuum cleaner.

EVA Provisions

The addition of the Service Module Experiment Bay on Apollo 15, 16, and 17 added an ECS requirement to provide extravehicular activity (EVA) capability for the support of one crewman while retrieving the experiment film containers. The system was designed to provide suit pressure control and latent metabolic heat removal.

Oxygen flow from the cryogenic system originally was limited to two restrictor/heat exchangers. In order to achieve the flow capability required for EVA, a third restrictor/heat exchanger was added in parallel, increasing flow capacity to 4.54 kg/hr (10 lb/hr) minimum. Downstream of the restrictor manifold, and upstream of the remaining ECS, a new EVA panel and life support system were added as shown in figure 5.

Safety features, consistent with simplicity, were added to enhance problem detection and backup provisions.

1. The EVA panel pressure gage was monitored for high pressure oxygen [1030 kN/m^2 (>150 psia)] by one of the two crewmen in the cabin.

2. The suit control unit (SCU) orifice controlled the flow rate to 5.0 ± 0.5 kg/hr (11.0 ±1.0 lb/hr) at 280°K (45°F) with 690 ± 35 kN/m^2 (100 ±5 psia) at the umbilical inlet. In the event of a severed umbilical, reverse oxygen flow from the suit was limited by the

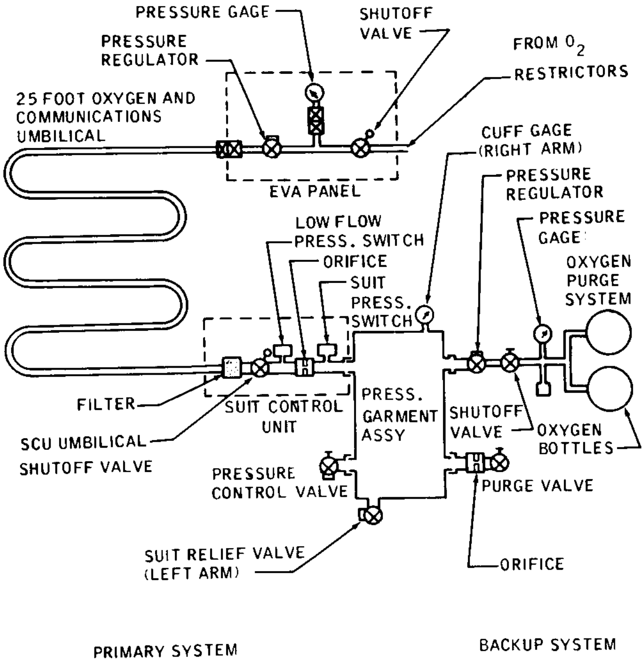


Figure 5. EVA life support system.

orifice. This allowed time [6.9 kN/m^2 (1 psi) drop in 80 seconds] for the EVA crewman to close the SCU shutoff valve.

3. The pressure switch upstream of the orifice in the SCU activated a warning tone in the EVA crewman headset should the umbilical pressure drop below 415 kN/m^2 (60 psig), indicating a low flow condition [2.7 kg/hr (6 lb/hr)]. Use of the pressure switch as a means of low flow detection was possible since flow rate through the orifice was sonic, and therefore, a function of upstream pressure.

4. The pressure switch downstream of the orifice in the SCU also activated the warning tone in the EVA crewman headset and gave warning of low suit pressure [less than 23.4 kN/m^2 (3.4 psig)].

5. The pressure control valve (PCV) controlled the suit pressure to 26 ± 1 kN/m^2 (3.80 ± 0.15 psig). The PCV was designed so that suit pressure would not fall below 20 kN/m^2 (3.0 psia) in the event the PCV failed in the open position.

6. A backup oxygen purge system (OPS) provided up to 3.6 kg/hr (8 lb/hr) oxygen flow for 30 minutes. A purge valve controlled the flow for this system, utilizing either a high flow or low flow setting.

Although no telemetry was added for the EVA hardware, existing telemetry and crew data readouts indicated the system performance as given in table 5 was normal. No flight problems were encountered with the EVA system, and the EVA crewmen commented that thermal conditions were adequate for the time and metabolic rates involved.

Table 5

EVA System Performance

Parameter	Units	Apollo Mission Number		
		15	16	17
Suit circuit pressure	kN/m^2 (psia)	26.9 (3.9)	25.9 (3.8)	25.5 (3.7)
EVA suit pressure	kN/m^2 (psia)	27.6 (4.0)	26.5 (3.8)	25.9 (3.8)
EVA panel pressure gage	kN/m^2 (psia)	2068 (300)	2068 (300)	2413 (350)
Calculated EVA flow at vacuum [using restrictor delta P at 294 °K (70°F)]	kg/hr (lb/hr)	5.0 (11.0)	4.6 (10.2)	4.7 (10.4)
EVA duration	minutes	31	73	58

Program Considerations and Recommendations

Redundancy Utilization. The requirements for reliability dictated that practically all components with moving parts have redundancy or backup provisions. In the oxygen system, which was especially critical for life support, all regulators and relief valves had parallel redundancy and both were used together. In addition, regulators contained relief features set slightly above regulation setting to allow for a failed open regulator. Each regulator had a separate isolation capability. Redundancy for electrical switches, electrical circuits, and manual shutoff valves was not normally provided. Therefore, backup provisions were made for items essential to crew safety or mission success.

Very few hardware failures resulted in required use of redundant components, but backup provisions were used to extend the capability of the ECS. For example, the secondary glycol loop proved useful for warming the crew during prelaunch when chilldown of the primary glycol loop by ground support equipment was necessary for equipment cooling. The manual backup provision on the glycol temperature valve was used when the controller failed during the Apollo 16 flight. The suit loop, usually considered as a backup for cabin cooling and ventilation, bacame the prime system because the crew preferred to keep the cabin fans off. The secondary glycol loop was never required as a backup for the primary loop. However, it proved useful during flight as a means of cold soak prior to reentry. In this mode of operation, the coldest fluid of the secondary loop was sent to the suit heat exchanger. Again, accomplishing this without hardware changes was made possible by backup provisions such as bypass and isolation valves.

Material Age Life Investigation. The specification design age life for the Command and Service Module environmental control system was three years. It became apparent that much of the hardware manufactured for the program would exceed this specification life, particularly since several spacecraft were nearing or had already completed installation and checkout and were scheduled for storage because of program changes. Such was the case of CSM 111, designated for the Apollo Soyuz Test Project (ASTP).

An age life analysis investigation was initiated. Each material, its application, failure criticality, and rationale for age life extension, was listed and reviewed by material and subsystem personnel. As a result of the review, the static age life of most materials was extended to ten years. Also as a result of the study, specific valve positions were identified to reduce material "set" during any storage periods.

Problem Summary and Recommendations

During the Apollo flights, several environmental control system problems were experienced. None of the problems can be classified as a major anomaly and none affected crew safety or mission success. Minor problems, however, encompassed almost all aspects of ECS operation and can be used as a valuable source for identifying system weaknesses and recommending future improvements. The listing in table 6 includes all of the more significant problems encountered in the flight program, corrective action applied, and recommendations for future design.

Lunar Module Environmental Control System

System Description

The Lunar Module environmental control system was comprised of four main sections: atmosphere revitalization, oxygen supply and cabin pressure control, water management, and heat transport.

The atmosphere revitalization section (ARS) consisted of a suit circuit assembly and suit liquid cooling assembly. The ARS is illustrated in figure 6. The suit circuit assembly was a closed-loop recirculation system that cooled and ventilated the two pressure garment assemblies (PGA) through flexible umbilicals. The suit liquid cooling assembly circulated water through, and controlled the temperature in the liquid cooling garment, circulated cabin gas via a cabin fan when required, and removed lunar dust from the cabin after ascent from the lunar surface.

The oxygen supply and cabin pressure control section (OSCPCS) stored gaseous oxygen, supplied oxygen to and maintained pressure control of the suit circuit and cabin, and provided refill oxygen to the portable life support system (PLSS). A schematic of the OSCPCS is shown in figure 7.

The water management section (WMS) supplied water for drinking, food preparation, cooling by heat transport section sublimators, and refilling the PLSS water tank. Figure 8 is a diagram of the WMS.

The heat transport section (figure 9) contained the hardware that heated or cooled the gas flow to the PGAs and cabin, cooled the electronic equipment and batteries, and rejected heat to space. It consisted of a primary coolant loop for normal operation and a secondary loop which cooled critical equipment in the event the primary system failed. A water/ethylene glycol solution circulated through each loop.

Table 6

Mission Problem Summary

Problem Description	Apollo Mission	Cause	Mission Impact	Corrective Action	Recommendation for Future Systems Design
Oxygen Subsystem					
High oxygen flow (procedural error)	Most	Manual overboard dump valve remained open	Increased O_2 usage	None	Include time-to-close feature in manual purge valves
Slow oxygen tank repressurization	9	Valve indicator misaligned—valve partially closed	None	Preflight inspection	Include greater detent identification or integral position indicators
Cabin fans					
(a) Noisy	All	Lack of noise suppression	Discontinued most fan use	None	Add acoustical design requirements
(b) Failed to operate	9	Foreign objects in fan area		Inspection	Protect fan inlet and outlet with screens
Toggle pin failure—main regulator shutoff valve (postflight)	15	Tolerance buildup allowed pin movement	Unknown	Inspection of all valves	Increase review of detail design of vendor parts
Discrepant CM/LM ΔP gage readings	15	Valve position arrow chipped off	Confusion during integrity check	Metalcal arrow substituted	Design indicators into manual devices
Pressure Suit Circuit Subsystem					
Return filter screen partially plugged	All	Cabin debris from manned operations	Required daily crew cleaning	Incorporated in crew procedures	Design filters for accessible cleaning or replacement
Free water in suit hoses	7; 15	Prelaunch degradation of suit heat exchanger condensate flow	None (droplets minor)	Improved servicing techniques	Minimize use of sintered plates or design for in-place restoration to original flow
LiOH elements sticking in ECU canister	16	Adverse operating conditions—temp control failure and flow valves mispositioned	None	Preflight fit check requirements tightened; crew procedures revised	Design for contingency conditions; use automatic valves to minimize crew operation

Table 6 (Continued)
Mission Problem Summary

Problem Description	Apollo Mission	Cause	Mission Impact	Corrective Action	Recommendation for Future Systems Design
Coolant Subsystem					
Evaporator dryout	7, 8, 9	Wick sensor location not representative of wick wetness	Manual reservicing required	Relocated sensors; removed sponges locally near sensors	Adequately develop test liquid systems in 6 axes to verify operation in zero gravity
Evaporator dryout	10	Microswitch misadjustment	Manual reservicing required	Added preflight inspection	Limit switches should be individually verified after installation. Functional tests inadequate
Evaporator outlet temperature high	10	Backpressure valve boot lost elasticity	None (recovered satisfactorily)	None	Adequately attach nonmetallic flow devices to the driving mechanism
Radiator proportioning valve system switched over to backup	7, 17	Electrical bus transient	None	None	Design electronics to be unaffected by short bus transients
Condensation on cold coolant lines	All	Lines not fully insulated	None	Increased line insulation	Provide adequate insulation for lines operating below dew point. Locate coldest lines away from electronics if possible
Primary accumulator quantity decayed	11	Valve not fully closed due to excessive knob play	None	None	Provide greater detents, eliminate all play between knob and valve
Glycol temperature exceeded control tolerance	11	Bearing failure in control valve drive mechanism	None (recovered satisfactorily)	None	Use limit switches on control valves to prevent continuous drive signals when valves are on end stops
Same	17	Gear lashup in drive mechanism due to pitch diameters not tangent	None (recovered satisfactorily)	None	Same

Table 6 (Continued)
Mission Problem Summary

Problem Description	Apollo Mission	Cause	Mission Impact	Corrective Action	Recommendation for Future Systems Design
Coolant Subsystem (Continued)					
Higher than expected radiator outlet temperatures	15	Lunar attitude holds and possible radiator coating degradation during launch	Increased cabin condensation and excessive temperature excursions	None (Launch procedures unique to Apollo 15)	Protect thermal coatings from mission contamination if possible, configure for minimum attitude hold impact
Glycol temperature controller failed in automatic mode	16	Silicon controlled rectifiers (SCR) turned on without a gate drive signal	Manual control required with increased condensation and LiOH element swelling	Controllers screened to determine condition of SCR's	Include proper part derating and parts application in electronics design phase
Water Subsystem					
Leakage during crew installation of quick-disconnect	7	Threads crossed	Water leaked while dumping	Threads inspected	Use automatic and built-in systems to minimize crew operations
Gas in potable water	All	Fuel cell carrier gas and bladder permeability	Crew discomfort	Added hydrogen separator and gas separator cartridge assemblies	Eliminate bladder and gas blanket type tanks, provide adequate gas separators
Hot water valve leakage	12, 14	Tolerance buildup with heated water	None	Added hot water expulsion tests	Provide system checkout in all operational modes
Potable water tank failed to fill	15	Contamination on check valve seat	None	None	Verify system cleanliness and filter all fluids entering the spacecraft
Leakage at chlorine injection port	15	Threaded septum retaining nut worked loose	Water (1 quart) leaked into cabin	Revised assembly requirements	Include locking features on threaded components

Table 6 (Continued)
Mission Problem Summary

Problem Description	Apollo Mission	Cause	Mission Impact	Corrective Action	Recommendation for Future Systems Design
Water Subsystem (Continued)					
Chlorine and buffer ampules leaked when injected	15, 16, 17	Inner bag breakage due to bonding problems and pinching between wall and end plate	Required additional crew time and cleanup	Added inspection requirements and revised crew procedures	Provide automatic or semi-automatic systems to reduce crew operation
Waste Management Subsystem					
Urine filters partially clogged	12	Urine breakdown due to overnight storage	Required replacement with spares	Revised crew procedures; added larger filter for mission requiring storage	Anticipate contingency requirements during initial design
Urine dump line partially frozen	14	Undetermined	Urine backup — temporary blockage	Revised crew procedures to minimize flush and require gas purge	Minimize lengths of dump lines; provide adequate heater and orifice sizes
Miscellaneous					
Vacuum cleaner failed to operate	16	Dust accumulation between turbine wheel and housing	Cleanup time lengthened	Revised crew procedures	Adequately protect all fans with filters
Instrumentation calibration shifts, erratic operation and failures	Many	Contamination, internally and externally generated; corrosion, electronic failures	Backup instrumentation utilized, flight procedures modified	Internal epoxy coating added; inlet filters provided; corrosion displaced by cycling; modified design	Protect pressure sensors with filters including static sense lines, since contamination migration may occur in zero gravity

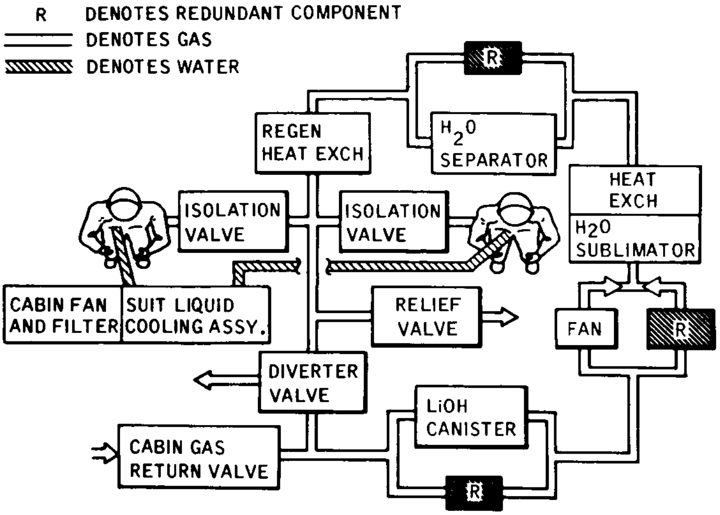


Figure 6. Atmosphere revitalization section.

Mission Performance

Cabin Leakage. The Lunar Module was pressurized after transposition and docking. During the translunar coast of the vehicles, the pressure decay of the LM was monitored. The rate of pressure loss was used to evaluate the leakage of the cabin in space. The range of leakages obtained for Apollo 11 through 17 was between 14 and 23 gm/hr at 35 kN/m^2 (0.03 and 0.05 lb/hr at 5 psia). The maximum allowable specification leakage of oxygen from the LM cabin to space was 90 gm/hr (0.2 lb/hr) at a total pressure of 35 kN/m^2 (5 psia). Thus actual leakage rates that existed were generally between one-seventh and one-fourth of the allowable specification rates.

Consumables. Careful predictions were made in advance of lunar surface missions of the quantities of water that would be required, based on planned Lunar Module usage and planned lunar surface activities. The predictions compared well with actual usage data.

Water consumption for a typical mission during which a total of 181.4 kg (399 lb) of water was used was subdivided as follows: approximately 1 kg (2.3 lb) for the sublimator fill, 22 kg (48 lb) for PLSS water refills, 4.5 kg (10 lb) for drink bag fills, and 3.7 kg (8.2 lb) for metabolic nonreclaimables.

The oxygen consumption was the total of the oxygen consumed due to crew metabolic consumption, leakage, cabin pressurization, and PLSS refills. The oxygen consumption rate was equal to the sum of the metabolic rates of each man [Joules/hr (Btu/hr)] multiplied by 0.07052 kg/J (1.64 x 10^{-4} lb/Btu). This was based on a respiratory quotient (RQ) of 0.82. The oxygen consumption due to leakage was a function of the vehicle configuration.

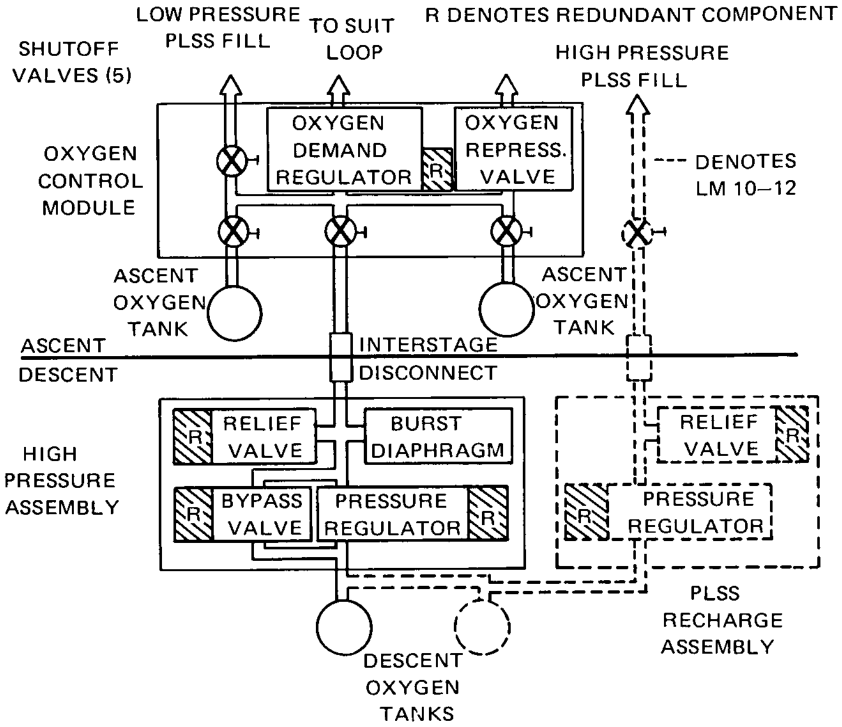


Figure 7. Oxygen supply and cabin pressure control section.

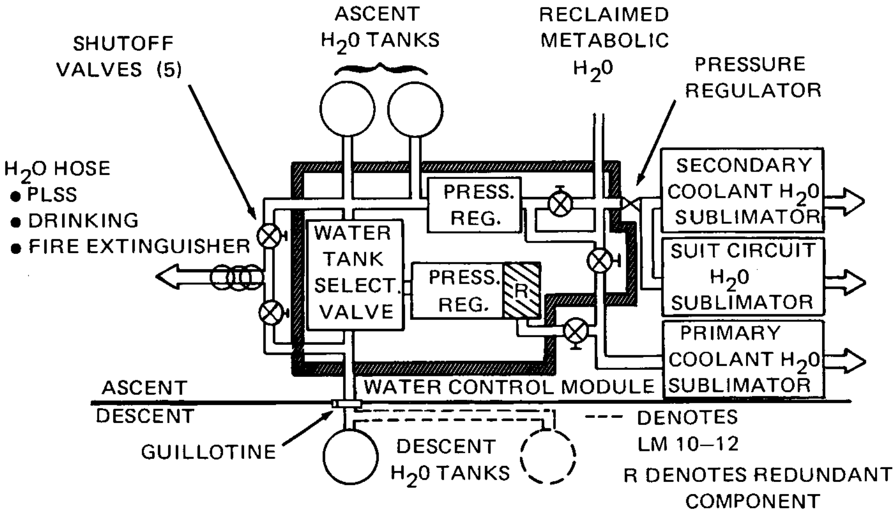
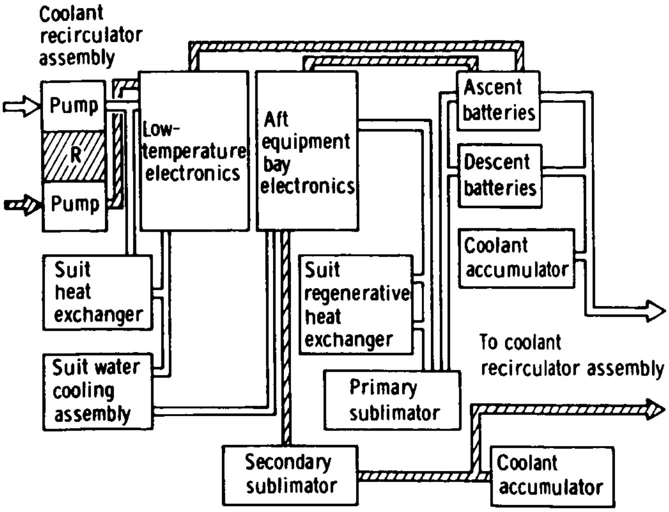


Figure 8. Water management section.



R denotes redundant component.

Figure 9. Heat transport section.

The total descent oxygen consumed for the Apollo 17 mission was 21.2 kg (46.6 lb). This compared very well with the preflight prediction of 20.7 kg (45.5 lb). Comparable values for the Apollo 11 flight were 8.6 kg (19 lb) consumed versus 10 kg (22 lb) predicted. The higher predicted value for Apollo 11 can be attributed to conservative estimates of expected crew metabolic levels during earlier flights.

Apollo 13 Emergency. The Apollo 13 mission was aborted approximately 56 hours after launch. The Apollo 13 mission started in a routine manner, however, the Service Module cryogenic oxygen supply was lost and the environmental control system in the Command Module was without its main source of supply for oxygen, water, and electrical power. To preserve the remaining onboard quantities, the surge tank and repressurization package tanks were isolated, water tanks were depressurized, and the Command Module was completely powered down. The Lunar Module was activated to sustain the crew. This support was required for about 83½ hours, which was nearly twice the duration of the planned Lunar Module utilization.

Early assessment of the problem indicated that with no cabin repressurizations, oxygen was not a critical consumable. However, since only 154 kg (338 lb) of water was available in the Lunar Module, it was decided to utilize Command Module water for drinking and food preparation and to limit the heat loads by activating a minimum of electronic equipment. Power levels were maintained between 350 and 400 watts for most of the Apollo 13 flight by limiting the operation of the electrical equipment. The greatly reduced thermal loading resulted in cabin temperatures between 286° and 289°K (54° and 60°F). The low power level resulted in an average water consumption rate of 1.6 kg/hr (3.5 lb/hr) and approximately 132 kg (290 lb) of water was consumed during the mission.

Sufficient lithium hydroxide cartridges, the carbon dioxide control system of the spacecraft, were not available in the Lunar Module to sustain the crew. The primary and secondary cartridges supplied in the Lunar Module were used until the carbon dioxide level reached approximately 2000 N/m^2 (15 mm Hg). Since additional lithium hydroxide was needed, a means was developed for adapting the Command Module elements for use in the Lunar Module system. Figure 10 shows the system ultimately devised.

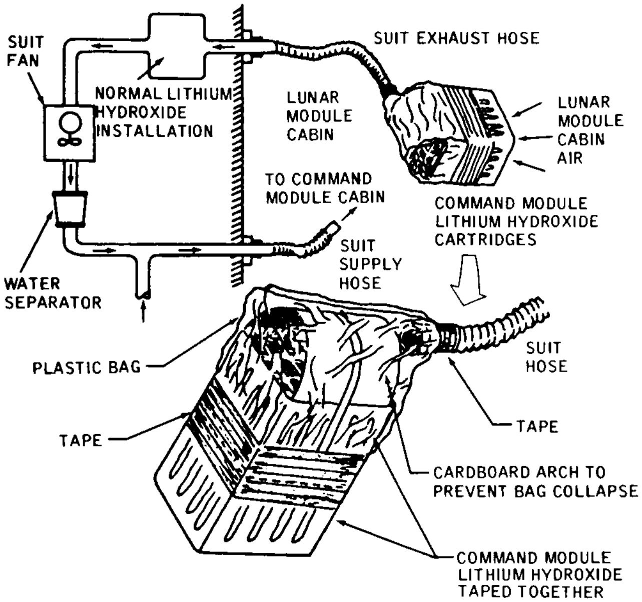


Figure 10. Supplemental carbon dioxide removal system.

Space suit return hoses were taped to plenum chambers, constructed by the crew from onboard documents and tape, and attached to the Command Module environmental control system elements. Cabin gas drawn through the elements by the atmosphere revitalization system was successfully scrubbed of carbon dioxide. After about 20 hours of operation, an additional unit was stacked on each original cartridge to improve the removal of carbon dioxide. With this configuration, the indicated carbon dioxide level was maintained between 13 and 240 N/m^2 (0.1 and 1.8 mm Hg). This special procedure was used for 47 hours until the Command Module was activated and the Lunar Module jettisoned.

Flight Problems

The problems encountered during flight were not serious in terms of crew safety or mission success. Two of the more interesting problems involved the water separators and oxygen demand regulators.

Water Separator. During the Apollo 11 and 12 flights, the crews reported free water in their suits during lunar operations. Prior to the Apollo 12 flight, a thermal and system analysis indicated that the most probable cause of the problem was bypass flow through the separator selector valve, a part of the water separator. The problem could not be reproduced during ground tests. However, during Apollo 12, free water was again reported in the pressure suits.

Following the Apollo 12 flight, a detailed bench test was again performed to identify the problem. It was found that the suit loop gas flow drove the separator too fast, resulting in water carryover. To correct the difficulty, an orifice was incorporated in the primary lithium hydroxide cartridges to limit the suit loop flow in future vehicles.

The Apollo 13 and 14 crewmen reported no free water. However, the indicated separator speeds read "High" during some flight periods. In fact, in certain suited configurations (for example, helmets and gloves removed), pressure resistance in the suit was lowered and gas flow became unacceptably high. Therefore, the operating procedures were modified to maintain adequate flow resistance during all modes of operation.

Oxygen Demand Regulator. Suit circuit and cabin pressures were controlled by two oxygen demand regulators which sensed suit circuit pressure and supplied oxygen. The regulators normally operated concurrently. Two pressure ranges could be selected: cabin mode and egress mode.

While the cabin was being depressurized prior to the third lunar excursion during the Apollo 17 mission, the suit circuit gas pressure increased above a normal regulator lockup. The situation was cleared by manual shutoff of one of the two parallel oxygen demand regulators. The mission was completed with exclusive use of the second regulator. Postflight data review indicated that the pressure rise could have been caused by inadvertently bumping the regulator out of its "Egress" position or by contamination between the regulator poppet and seat.

Experience

The experience gained in the development and operation of the LM environmental control system may prove to be useful in the design of future systems. The following sections relate the more important derivatives of the program.

Instrumentation Adequacy. The initial system design incorporated instrumentation to allow assessment of system performance and mode of operation during mission phases. However, since the crews were expected to follow the specified procedure and flight timelines, certain instrumentation was deleted. As a result, there were periods of uncertainty. For example, the exact position of a valve might have been unknown to ground controllers. Moreover, ground-to-crew communications to verify performance were limited by mission and scientific activities.

Additional instrumentation would have been useful to provide engineering determination of flight discrepancies. This lack of data was aggravated as the vehicle was nonrecoverable and postflight verification was not possible.

Component Redundancy. The Lunar Module ECS was designed with sufficient redundancy in critical life support areas to provide a "fail operational, fail safe" design. The hardware performed successfully throughout the Apollo flights. Only during the last flight, previously discussed under flight problems, was a redundant component required.

Redundancy considerations were simplified by the multiple function component design. Hardware complexity and costs were high compared to single function components. For system design where weight, volume, and manual operation are premium design requirements, the use of multiple function components should be considered in lieu of multiple single function components.

Modular Construction. Modular packaging concepts were used in several places in the ECS where groupings of equipment appeared desirable. The major package in the Lunar Module ECS was the suit circuit assembly which contained the necessary atmosphere processing equipment. The suit circuit assembly was densely packaged to accommodate the required hardware in the allotted space. Use of the modular concept was necessary because of the weight and volume constraints, but this led to a number of problems.

It had been planned to replace the entire package in the field if any component required change. Changing an entire package was a relatively long process. A large number of tests were required to verify that all the components within the replacement package were functioning after installation. For this reason and wherever possible, the practice of changing individual components with the package installed was adopted. This practice, which was successfully performed on a number of occasions, saved time in the vehicle cabin and generally avoided schedule delays.

Subatmospheric Design. The Lunar Module environmental control system was designed for optimum performance when operated at subatmospheric pressure and zero to one-sixth Earth gravity. As this equipment could not be operated at sea level pressure, considerable ground checkout problems and lengthy test flows resulted. For example, the suit and cabin pressure control system, designed for absolute pressure maintenance, would not function unless the suit circuit or cabin pressure was reduced to, or below, the system control pressures. This design prevented normal system operation unless the vehicle was placed in a vacuum chamber and its ambient pressure reduced to effectively zero. Inadvertent operation of the suit and cabin fans at pressures greater than 70 kN/m^2 (10 psia) required considerable analysis and tests to certify that the affected hardware was acceptable for flight. Nevertheless, some fans were replaced.

In order to simplify ground checkout and limit test errors which result in hardware replacement or reverification, future design efforts for spacecraft environmental control systems should include requirements for normal operation at sea level environments.

Summary

The performance of both the Command Module and Lunar Module environmental control systems during the Apollo Program was highly satisfactory. Only minor problems were experienced. These systems provided the astronauts with the necessary life sustaining functions, with as much added comfort as possible. The knowledge gained in the system design and performance should be beneficial to the development of future trouble-free systems.

References

The bulk of the information in this chapter appeared in the following two articles:

Hughes, D.F.; Owens, W.L.; and Young, R.W.: Apollo Command and Service Module Environmental Control System – Mission Performance and Experience. ASME Paper No. 73-ENA-29, American Society of Mechanical Engineers (New York), 1973.

Brady, J.C.; Browne, D.M.; Schneider, H.J.; and Sheehan, J.F.: Apollo Lunar Module Environmental Control System – Mission Performance and Experience. ASME Paper No. 73-ENA-28, American Society of Mechanical Engineers (New York), 1973.