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APOLLO EXPERIENCE REPORT - LUNAR MODULE ENVIRONMENTAL CONTROL SUBSYSTEM

by Richard J. Gillen, James C. Brady,
and Frank Collier

Manned Spacecraft Center
Houston, Texas 77058

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16. Abstract

A functional description of the Apollo lunar module environmental control subsystem is presented. Development, test, checkout, and flight experiences of the subsystem are discussed; and the design, fabrication, and operational difficulties associated with the various components and subassemblies are recorded. Detailed information is related concerning design changes made to, and problems encountered with, the various elements of the subsystem, such as the thermal control water sublimator, the carbon dioxide sensing and control units, the water section, and so forth. The problems associated with water sterilization, water/glycol formulation, and materials compatibility are discussed. The corrective actions taken are described with the expectation that this information may be of value for future subsystems. Although the main experiences described are problem oriented, the subsystem has generally performed satisfactorily in flight.

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APOLLO EXPERIENCE REPORT

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SUMMARY

The experiences at the subsystem level of the lunar module environmental control subsystem are summarized to assist the operational development of a future similar subsystem. The subsystem concepts used were generally well established; however, the specific hardware designs were new. As a generalization, most problems were caused by some relatively common procedure that had not been performed to the proper quality level or to a requirement that, at that time, could not be defined in sufficient detail.

INTRODUCTION

The development of the lunar module (LM) environmental control subsystem (ECS) required some improvements in the state of the art and was successfully accomplished. In the interest of preserving history and of perhaps benefiting designers of future systems, some of the development problems are recounted. It should be noted that many of the problems are of a subtle type that appear only after the hardware is used repeatedly in many different ways. In many cases, the problems were resolved by changing a procedure of use rather than by redesigning the item. This approach was used when it was felt that the unit was very sound and that the benefit of experience with a less-than-perfect unit would be better than rebuilding to get a new, untried, "perfect" device with possibly new problems. The experience gained from use of the ECS is a very significant and positive asset.

DESCRIPTION OF THE LUNAR MODULE ENVIRONMENTAL CONTROL SUBSYSTEM

This section describes the lunar module ECS from a functional standpoint. The ECS configurations of the LM-3, LM-4, and LM-5 were all substantially the same with the following exceptions.

1. The LM-3 vehicle was equipped with developmental flight instrumentation, and the ECS contained additional equipment-cooling provisions for this instrumentation.

2. The LM-5 (Apollo 11) lunar landing vehicle and later vehicles included suit-liquid-cooling provisions to enhance the crewman-cooling capability. These provisions were substituted for the cabin heat-exchanger assembly.

The complete schematic diagram of the LM-5 ECS is shown on prime contractor drawing LDW 330-55000, which can be obtained from the NASA Manned Spacecraft Center (MSC), Houston, Texas. This drawing shows part numbers and detailed fluid and electrical schematics.

In summary, the LM-5 ECS was divided into the following functional sections.

1. Atmosphere revitalization section (ARS)
2. Oxygen (O_2) supply and cabin pressurization section (OSCPS)
3. Heat transport section (HTS)
4. Water (H_2O) management section (WMS)

Atmosphere Revitalization Section

The ARS (fig. 1) removes heat, moisture, odors, and carbon dioxide (CO_2) from the suit circuit of the two astronauts and provides the required atmosphere circulation. One of the two suit fans circulates the warm, moist, suit-circuit gases through the backup heat exchanger to the primary heat exchanger. The backup unit is a suit gas-to-water sublimator and is used only if the primary coolant circuit fails. The primary heat exchanger is a gas-to-coolant fluid (water/glycol) unit. The gas, which has been cooled below the dewpoint, enters the selected water-gas centrifugal separator. (An identical unit is provided for redundancy.) These rotary devices are powered by the suit-circuit gas stream. The water is coalesced and thrown to the periphery where it enters a pitot tube, through which the water is delivered first to the WMS and then to the HTS for use in heat rejection.

The suit gas may next be reheated, if required, by warm water/glycol in a regenerative heat exchanger activated by a manual valve. The regenerative heat exchanger is functional only on the primary cooling circuit. Each crewman has a suit-isolation valve, which is normally open except during extravehicular operations. These fast-acting suit-isolation valves close automatically if the suit-circuit pressure becomes dangerously low. This safety feature functions if the space suit of one crewmember is torn or otherwise malfunctions while the cabin is depressurized. The crewmember with the good suit can then take corrective action.

Flexible hoses deliver the conditioned gas to each astronaut and return the gas to the ECS for processing again. The gas is normally diverted to the pressurized cabin for circulation and is returned to the ARS through the cabin-gas return check valve. The gas next enters the primary replaceable filter cartridge that contains lithium hydroxide (LiOH) to remove carbon dioxide and activated charcoal to remove odor. A secondary filter cartridge, which is identical to the cartridge used in the backpack or

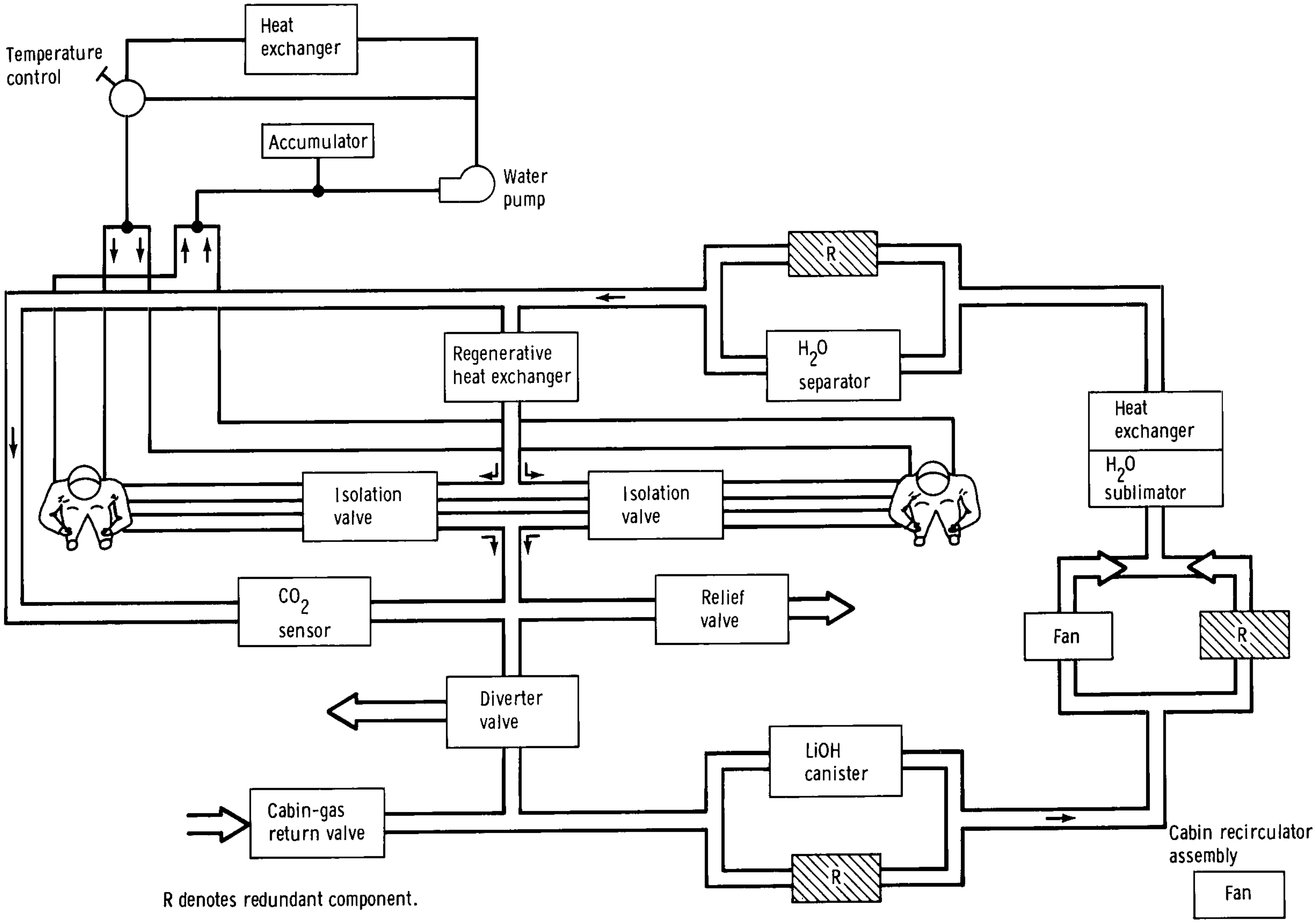


Figure 1. - Atmosphere revitalization section simplified schematic.

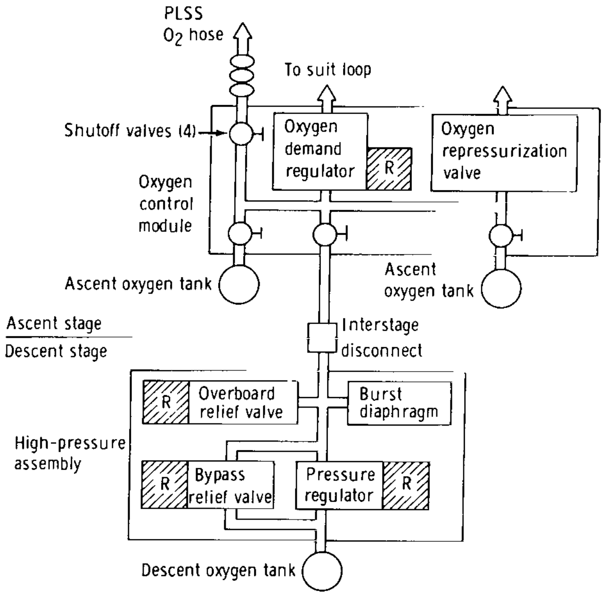
portable life support system (PLSS), is normally used only when the primary cartridge is being changed. This cartridge change is preplanned to occur at a convenient time in the mission. A carbon dioxide sensing device is included in the ARS to assess the condition of the cartridges. Other items of instrumentation are provided to ensure optimum subsystem operation and safety.

Supplemental cooling also is provided to the astronauts for periods of high metabolic heat rates by circulating cool water through plastic tubing, which is a part of the undergarments. The same undergarments provide cooling during extravehicular operations. The liquid-cooling assembly uses a pump, an accumulator, and a temperature control valve to bypass the cooling water around the liquid-to-liquid heat exchanger.

Oxygen Supply and Cabin Pressurization Section

Gaseous oxygen is stored in the LM descent stage for use during the descent and lunar stay phases, and a small amount of gaseous oxygen is stored in the LM ascent stage for use during the lunar ascent phase and during rendezvous and docking with the command module. A simplified schematic of the OSCPS is shown in figure 2. The 2800-psi descent oxygen supply is regulated to 900 psi by redundant regulators. Redundant bypass relief valves protect the descent oxygen tank against overpressurization. Redundant low-rate overboard relief valves protect the section downstream of the regulators against excessive pressure caused by a defective regulator or by flow through the bypass relief valves. A reseating burst disk provides high-rate relief for failed-open regulators.

The descent oxygen supply and the redundant ascent oxygen supply are manifolded through manual shutoff valves located in the cabin. The shutoff valves are mechanically interlocked to prevent the premature use of ascent oxygen. The 900-psi descent oxygen is available for backpack recharge through appropriate valves and fittings.



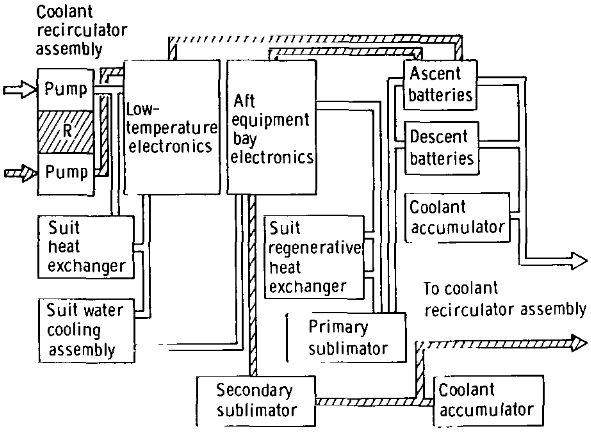
R denotes redundant component.

Figure 2. - Oxygen supply and cabin pressurization section simplified schematic.

Suit-circuit absolute pressure (and, therefore, cabin absolute pressure) is controlled by two manually selected, redundant regulators, both of which are normally activated. These automatic aneroid valves have electrical interlocks with the cabin repressurization valve to permit cabin depressurization when desired. The cabin repressurization valve can be manually or automatically actuated to restore cabin pressure rapidly. A cabin relief and dump valve is provided on both LM hatches for automatic overpressure control and for controlled cabin depressurization.

Heat Transport Section

Heat from various sources is rejected by the sublimation of water (ice) to space vacuum. Two closed loops carry a circulating solution of 65-percent water and 35-percent corrosion-inhibited ethylene glycol through heat exchangers and electronics cold plates and through the respective sublimators. Figure 3 is a simplified schematic of the HTS. The water/glycol is circulated at the nominal 250-lb/hr primary loop flow rate by one of two pumps. The suit heat exchanger and the low-temperature electronics cold plates are cooled in parallel. Next, the flow passes to the liquid-cooled-garment heat exchanger and then to the high-temperature electronics cold rails. These cold plates and cold rails are carefully arranged in a series-parallel network with necessary flow control orificing to provide the proper thermal environment for each electronic unit.



R denotes redundant component.

Figure 3. - Heat transport section simplified schematic.

The primary sublimator rejects the collected heat, and the coolant absorbs the waste heat from the batteries before returning to the filter and to the pump, at which point the circuit is complete. The secondary coolant loop is substantially the same, except that the primary guidance equipment is not cooled and only a single pump is provided. As previously noted, the suit loop is cooled by a backup sublimator and not by the secondary coolant circuit.

Water Management Section

The WMS is schematically illustrated in figure 4. The LM water is stored in one large descent tank (332-pound capacity) and two ascent tanks (42-pound capacity each). Each tank has a bladder pressurized with nitrogen (N_2) to expel the water in zero gravity and to force the water upward from the descent stage in one-sixth gravity during the lunar stay. Series-redundant water pressure regulators provide reduction of the pressure to a level compatible with sublimator requirements and permit suit-circuit condensate to be effectively pumped by the water separators. A backup set of series-redundant water pressure regulators is provided for secondary coolant-loop operation.

The water used for PLSS refill, for drinking, for food preparation, and for fire extinguishing is tapped off through a dispenser located upstream of the pressure regulators. Water and iodine are mixed at the time of LM water loading to give a low iodine concentration for bacteria control.

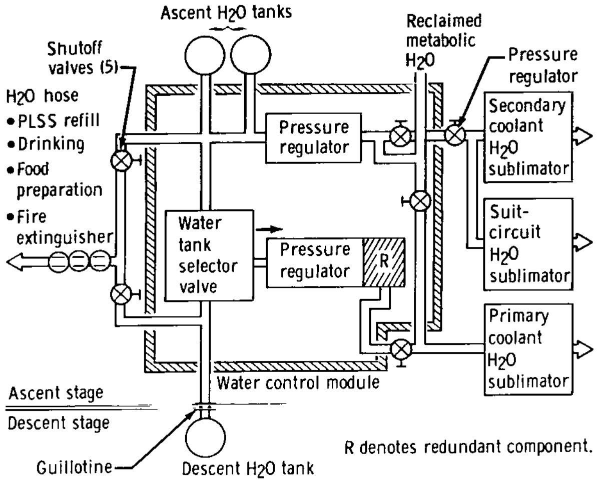


Figure 4. - Water management section simplified schematic.

TECHNICAL HISTORY

The technical history is presented first for some general items that apply to the system as a whole or for items which cut across several subsystems. Next, the history of subsections is given for the HTS, the ARS, the OSCPS, and finally, the WMS. No attempt was made to arrange these by severity of the problem. All problems were significant at the time they were reported.

General

Interstage disconnects. - Interstage disconnects (LSC-330-505) are used between the ascent and descent stages to provide a flow path for high-pressure oxygen from the descent-stage oxygen tank to the environmental control subsystem in the ascent stage and to provide coolant flow paths for the descent-stage cold rails. Normally, service fluid lines between spacecraft stages are routed through cutter assemblies if the spacecraft stages are required to separate during mission life. At the time of separation, the cutter assembly shears the lines (ensuring safe separation) and allows external leakage to occur at the sheared interfaces. Shearing of the glycol lines would have required the installation of a shutoff valve (manual or electrical) in the supply to the descent stage and a check valve in the return line to prevent loss of glycol after separation. Because of possible impact ignition, it was also considered unsafe to shear the oxygen line that contained 900-psia oxygen. The glycol coolant loop is serviced at the builder's plant; and, because normal ground checkout required separation of the ascent/descent stages, it was more feasible to use disconnects to eliminate deservicing and reservicing of the coolant. Furthermore, the disconnects provide an automatic seal to prevent loss of fluid from either half of the disconnect after staging.

The interstage disconnects were designed without retention mechanisms so they could be simply pulled apart. This method ensured minimum resistance to ascent/descent-stage separation. Coupling of the ascent (structure mounted) disconnect half to the descent (structure mounted) disconnect half is maintained by squib bolts, which connect the two stages.

The original design used a single compression seal and was successfully certified with flight bracket assemblies. From the beginning of vehicle assembly and checkout at the manufacturer's plant, it was noted that this particular design was susceptible to damage during vehicle installation unless extreme care was taken. Subsequent installation efforts at the NASA John F. Kennedy Space Center (KSC) verified the damage susceptibility; and it was necessary to add a redundant seal (fig. 5) to the LM-3, LM-4, LM-5, and LM-6 coolant-loop disconnects to ensure no external leakage. The redundant seals were not used on the oxygen disconnects because the higher pressure (900 psia) provided a much better seal than the lower pressure (20 psia) glycol disconnects. It was also found that the redundant-seal method used was ineffective at pressures above 50 psig. Starting with the LM-7 vehicle, a redesigned disconnect (fig. 6), which had built-in redundancy and also provided better protection to the sealing surfaces, was used. This design was certified by test and installed in the remaining vehicles. To date, this design has shown a high resistance to handling and installation damage.

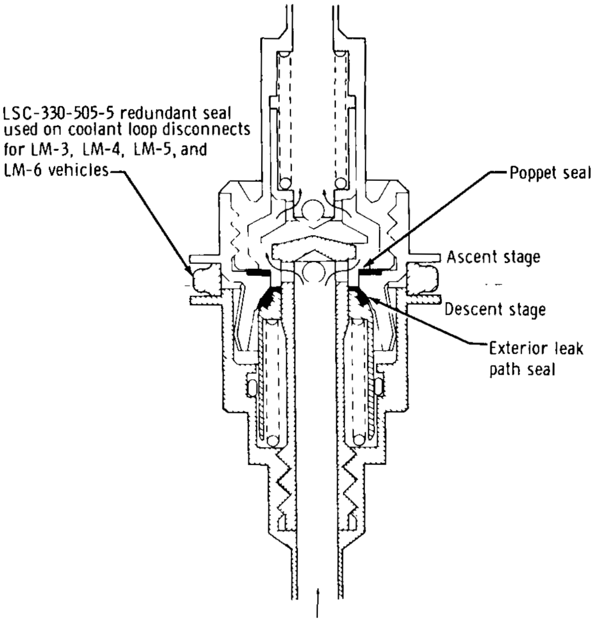


Figure 5. - Original design of interstage disconnect.

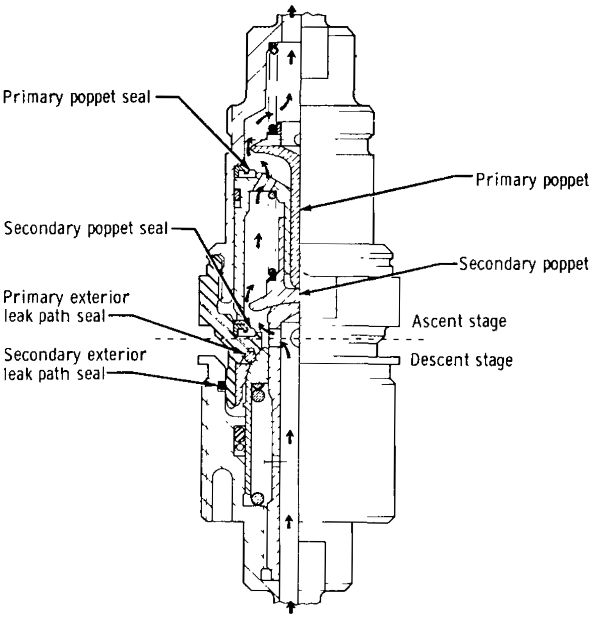


Figure 6. - Final design of interstage disconnect.

Battery configuration change. - The early LM vehicle design depended on fuel cells for electrical power generation. The reactants for the fuel cells (hydrogen and oxygen) were to be stored in the supercritical state, and it was planned to use the cryogens as a heat sink.

After approximately 2 years of design work and studies, the power source was changed to batteries, the hydrogen was eliminated, and the oxygen storage method was changed to high-pressure gas. The ECS requirements and responsibilities were changed significantly at this time (approximately March 1965). High-pressure gaseous oxygen pressure regulators and relief valves were required, and the high-pressure oxygen storage tank in the descent stage became a new ECS responsibility. Previously, the ECS oxygen requirements had been supplied from the common cryogenic oxygen descent-stage tank. While these changes were being considered and identified, a series of studies was performed to determine the new requirements for sizing water and oxygen consumables. Mission parameters were updated and varied to examine and to understand the vehicle and mission penalties associated with the changes. Implementation of the changes produced a large impact upon the ECS. New designs were required for a large descent-stage gaseous oxygen tank (approximately 48-pound capacity at 3000 psi) and two ascent-stage gaseous oxygen tanks (approximately 2.4-pound capacity each at 900 psi). New designs were required for the high-pressure gaseous oxygen pressure regulator and for the relief valves in the descent stage. Changes to the water tank designs were not required. In response to the late start, all of these changes were pursued vigorously to shorten the development cycle.

In contrast to the large impact that the change to batteries had on the ECS, there was an early change to incorporate a redundant cooling loop. The redundant-loop change affected many hardware items but was implemented shortly after the subcontracts were initiated, and this change was easily accommodated.

Reliability considerations. - Reliability analyses performed for each subsystem by the contractor resulted in Failure Mode and Effect Analyses and Single Failure Point Summary documents. During the course of the contract, these were periodically refined and improved in detail. The degree of detail was upgraded as more and more knowledge of the hardware was gained. These documents served the useful purpose of identifying for management those areas of subsystem design in which operational risks would be encountered and also identified the severity of the risk. For example, most equipment was adequately backed up by redundant components, and failure would result in nuisance-type situations rather than in hazardous conditions. These documents dealt with design and operations and were not of the probability assessment type. The cause-and-effect type of reliability approach was found by management to be more useful than dealing strictly with abstract numbers of mean time to failure.

The reliability program also included shelf-life control. Problems were encountered in implementing effective shelf-life control. The original plan by which this program was established failed to set up strict controls, such as periodic checking of the stored equipment. Based upon observations of shelf-life control, it is felt that future programs should implement strict controls early in the program by providing for periodic testing or periodic operation of equipment, by applying a conscious consideration of shelf life when evaluating each engineering change (after configuration control is established), and by requiring that positive actions are established for all hardware when the shelf-life limitation is reached.

The failure reporting portion of the reliability program also had some significant aspects. Every out-of-specification condition was formally documented from the time manufacturing of a component was completed. Thus, development problems and in-process checks and calibrations were not reported, but all acceptance test (and subsequent) problems were reported. A report was accepted and closed only when a comprehensive analysis of the cause was documented and corrective action was initiated. The prevailing philosophy of "every failure has a cause" required a comprehensive investigation into the failure causes. Accurate reporting proved helpful many times in referring back to a problem. All failure reports were reviewed by top management at the Flight Readiness Review and required closure or a satisfactory explanation to remove constraints to flight release. A failure report "explanation" meant that, although the failure was not completely closed, there was a satisfactory explanation for a specific spacecraft as a result of extra testing, isolation of the problem to a specific lot, and so forth.

Flight instrumentation. - The operational instrumentation installed in the ECS provided minimum information concerning performance. The vehicle penalties for instrumentation were significant, and only data that were considered to be vital were provided. The instrumentation requirements were established early and included a number of valve position indicators. These valve position indicators were switches that caused a closed or open circuit to stimulate a telemetry signal, depending upon the position of a valve handle. In retrospect, these data have not proven very useful; and the weight, power, and volume penalties could have been better allocated to instrumentation for subsystem performance. The valve position indicators are perhaps useful where an inadvertent electrical actuation is possible; but, for manually selected valve positions, they are redundant to a voice link for verification of proper subsystem configuration.

Very small plunger travel was used to actuate the switches, and this made precision alinement necessary. The switch design was also found to be susceptible to change in performance (actuation force) with a change in ambient pressure. Many switches were found to have defective internal springs, which changed their performance.

These switches were also difficult to install properly in some valve designs. In one application (suit-isolation valves), more than a half dozen indirect measurements (with cumulative tolerances) were required for the switch installation because, as a result of inaccessibility, there was no simple, direct way to measure the installation shimming required.

Several switch applications were deleted from the system where operational experience indicated that the function provided could not justify retention of the device. In other cases, a change was made to increase the overtravel, giving more positive switch action.

Modular concepts. - Modular packaging concepts were used in several places where certain groupings of equipment appeared desirable. Some of the advantages and drawbacks experienced are discussed.

The major package in the LM ECS was the suit-circuit assembly (LSC-330-190 package), which contained the necessary atmosphere processing equipment — such as valves, heat exchangers, carbon dioxide removal elements, suit fans, and instrumentation — for the suit circuit. Interfaces with the electrical power system, with telemetry signals, with the water system, with the coolant system, with the cabin gas, with the suit gas umbilical hoses, and with the oxygen supply were required. A summary of components and interfaces for the ECS packages is given in table I.

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 throughout the program. Whenever equipment was modified or changed, the certification testing program was modified accordingly. "Delta" qualification runs, which caused the same

TABLE I. - COMPONENT MAKEUP OF LM ECS ASSEMBLIES

Component	Environmental control subsystem package, LSC-330-						Total
	190	192	290	390	392	490	
	Suit-circuit assembly	Suit coolant assembly	Coolant recirculation assembly	Oxygen control module	High-pressure oxygen control assembly	Water control module	
Heat exchanger	3	1					4
Water separator	2						2
Fan and motor	2	1					3
Valve	9	1	6	5	5	9	35
Pressure regulator				2	2	3	7
LiOH canister	2						2
LiOH cartridge	2						2
Transducer and switch	10		2	4			16
Fluid interface connection	19	4	4	7	3	12	49
Pump and motor		1	3				4
Accumulator		1					1
Flow control orifice	1	2					3
Voltage regulator		1					1
Filter			1	4			5
Total per assembly	50	12	16	22	10	24	134

basic package to be subjected to a number of different qualification test runs, were required in many instances to qualify the revised equipment. The interdependence of packaging and functional effects was adequately demonstrated by tests, but a great number of tests and a considerable amount of time were required.

It had been planned to replace the entire package in the field if any component required change for any reason. Changing an entire package was a fairly lengthy process, and a large number of tests were required to verify that all the components within the replacement package were functioning properly after installation. For this reason, the practice of changing individual components with the package installed, wherever possible, was adopted. This practice, which was successfully performed on a number of occasions, saved much time in the vehicle cabin and thus generally avoided schedule slips. Because of the dense packaging, however, removal and replacement of components within an installed package was a difficult task. On each occasion, practice runs were made on a bench package at the subcontractor's plant to establish a suitable procedure (to ensure that no damage would be done) and to train the person who was to make the change. The exact procedure to be followed in the flight vehicle was developed and, in a sense, "qualified" before authorization was given to proceed with replacing the flight item. These procedures included the necessary reverification tests.

Dense packaging caused practical problems that required the expenditure of extra time and effort as the penalty for minimizing cabin volume usage. It is not reasonable to assume that complex packages can be installed and never require a component change; therefore, it appears that the trade between time and packaging convenience must always be carefully weighed and understood. Packaging was less complex for other areas. (Coolant pumps, filters, and valves were designated as the LSC-330-290 package; the cabin oxygen control module, consisting of valves and pressure regulators, was called the LSC-330-390 package; water system valves and regulators were designated the LSC-330-490 package; the high-pressure oxygen control module with pressure regulators and relief valves was designated the LSC-330-392 package; and the liquid-cooling provisions for the crewmen were designated the LSC-330-192 package.)

Pump packaging was quite successful with no particular complications. The oxygen and water module packages used complex castings, into which the necessary active elements were fitted. Integral manifolding and the lack of numerous tubes and fittings are the main features of the casting approach. This concept worked quite well for the oxygen modules. However, for the water system module, a number of design changes were necessary; and the inflexible configuration caused by the casting concept led to add-on valves, capped bosses, and similar modifications to achieve minimum-impact changes. For the water system module, the use of a casting proved to be an encumbrance because the casting design became fixed before the design requirements became firm. However, this problem was not experienced with the oxygen modules, and the screw-in components were very easily replaced and retested.

Heat Transport Section

Water/glycol formulation. - The coolant fluid caused several problems even though the application was considered to be well within the state of the art. Initially, the fluid, which was formulated to give the following mixture, was specified to be the same as that for the command and service module.

Material	Parts by weight
Ethylene glycol	62.5
Distilled water	As necessary to make 100 parts
Triethanolamine phosphate	1.6
Sodium mercaptobenzothiazole (NaMBT)	0.9

By using an identical fluid in both spacecraft, the problems of logistics and of ground-support equipment could be minimized.

During the development of the heat transport components, it was found that additional specific heat capacity was required, which necessitated revising the formulation to one containing more water and less ethylene glycol. This change improved the specific heat from 0.72 to 0.86 Btu/lb°F.

This change also increased the freezing point from approximately -65° to -2° F, but the antifreeze protection was not needed in the LM ECS because the coldest temperatures encountered are from sublimation of cooling water (in ice form) to space vacuum. The modified LM water/glycol formulation was as follows.

Material	Parts by weight
Ethylene glycol	35.0
Distilled water	As necessary to make 100 parts
Triethanolamine phosphate	1.6
Sodium mercaptobenzothiazole	0.9

With the change to the modified coolant, which was made in August 1965, it was necessary to adjust the pH of the mixture to a higher value in order to keep the corrosion inhibitors in solution. The appropriate pH was determined experimentally by the spacecraft prime contractor.

The new coolant was successfully used until June 1969, shortly before the Apollo 11 flight, when a precipitate problem was encountered on the LM-5 vehicle. During routine fluid sampling for cleanliness and fluid property maintenance, a large number of precipitate crystals were found to be present. A number of fluid exchanges were made, and special filtering was performed; but the crystals rapidly reformed again. In the intensive investigations into the problem, it was found that a relatively minor change in a corrosion inhibitor had been made a few months before. A higher purity mercaptobenzothiazole (MBT) was introduced instead of the previously used commercial grade chemical. The commercial grade fluid produced a hazy solution during preparation, which required approximately a week to let the haze form and then required filtering to remove it. This slow manufacturing cycle was improved by using the higher purity chemical. During the investigation into the crystal problem, it was determined that the commercial inhibitor contained a small amount of sodium sulfite as a stabilizer. Sodium sulfite was added to the LM-5 fluid, but the crystal formation still persisted even after repeated flushes with the modified-purified fluid. The amount of sodium sulfite involved was 2 percent (weight) of the NaMBT, which makes up 0.9 percent (weight) of the finished water/glycol. Thus, a stabilizing agent in the amount of 0.018 percent had been omitted. As discovered on the LM-5 vehicle, this quantity would not, of itself, inhibit or dissolve the crystals. The crystals were identified as the disulfide decomposition product of the NaMBT. Because there was no indication of any damage to the tubing or other system components caused by corrosion, the main problem seemed to be whether the particles would degrade system flow rates, clog the system filter or system orifices, or abrade the pump. Bench testing was conducted with two different pump-filter packages for endurance; and, although the filter plugged both times and the automatic relief valve bypassed the filter, the pumps performed normally. The pumps were dismantled and showed no unusual wear. The crystals were observed to be rather fragile in character and apparently were readily passed through the pumps. No clogging of the flow-balancing orifices occurred during bench tests. Gross precipitate was formed in the laboratory, and the fragile nature of the precipitate allowed it to pass through the finest orifices used with only a minute pressure head. Based on all these tests, the LM-5 vehicle was flown with the crystals present, and no problems were encountered.

Subsequent vehicles were drained, flushed thoroughly with water and with isopropyl alcohol, then refilled with water/glycol formulated with the previously used commercial grade inhibitor. This fluid has again proved more stable and is a satisfactory coolant. The investigations showed clearly that subtle amounts of unknown "impurities" other than sodium sulfite in the commercial product have a crystal-inhibiting and crystal-dissolving action. A contract (NAS 9-9956) was let to continue the investigation into determining the nature of these impurities and also to investigate what system effects (flow rates, etc.) may cause disulfide crystals to form.

Sublimator developments. - The development of the sublimators for heat-load rejection caused probably the most significant design problems of the LM ECS. The relative simplicity of sublimator operation might give a misleading impression of the difficulties involved in the design and manufacture of the device. Simplicity is apparent in the cutaway view (fig. 7) and in the expanded section shown in figure 8. The early problems were difficulty in brazing the porous plates and in achieving a good bond without plugging the pores with braze material. Materials were changed as were brazing techniques. The early units were also showing performance degradation rates (with usage time) that were not encouraging; and, also, the initial performance was below expectations. Loss of porosity of the plates directly reduces performance, and this seemed to be the problem.

Porous plates with higher permeability were used; and several other improvements in fabrication were tried, including welding of fins to the porous plates to eliminate brazing problems. Performance improvements were made by increasing the density of heat-transfer fins in the coolant passages. Additionally, to meet performance requirements, it was required to control the installation of porous plates so that the finer pore orientation was always facing the steam vent passage.

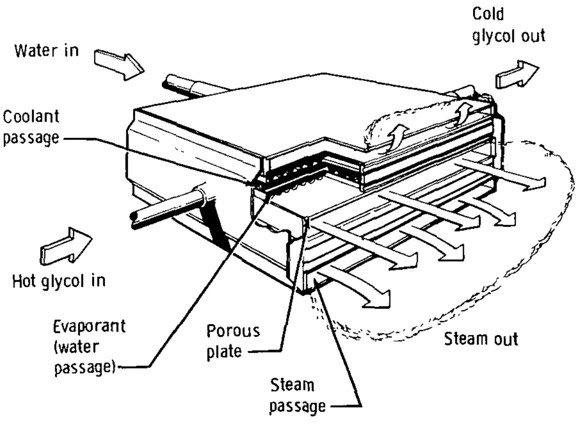


Figure 7. - Cutaway view of water sublimator.

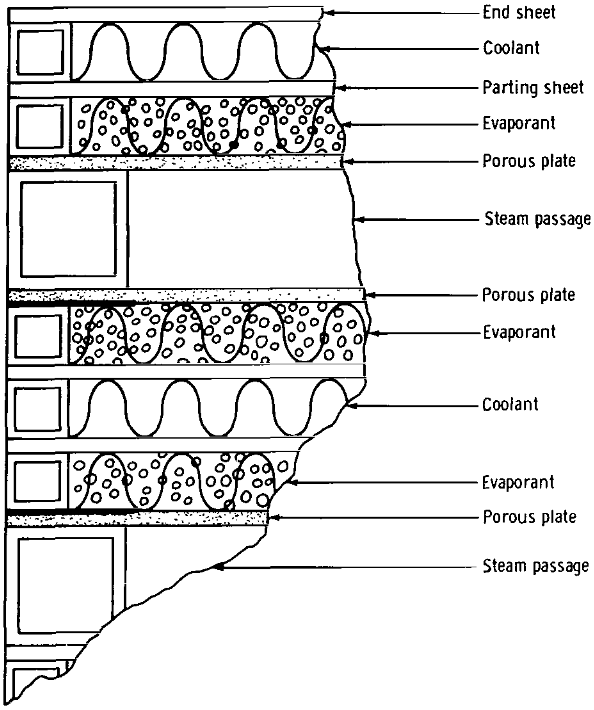


Figure 8. - Expanded section of water sublimator.

Chlorine was added to the stored water to act as a biocide. The chlorinated water produced unacceptable performance in the sublimators. Formation of a chlorine-based residue on the steam-passage side of the porous plates caused a depression of the freezing point, and water breakthrough occurred. Testing was performed by using iodine as the biocide, and these tests showed that iodine was acceptable.

Performance degradation history was taken from measured data on a Saturn sublimator used for instrument unit electronics cooling. Degradation was found to occur as a result of the slow accumulation of corrosion products during storage. Degradation during operation was found to be related to the cumulative water quantity boiled per square foot of surface, and this was caused by corrosion and by the slow blockage of pores with particulate matter.

To guarantee specified performance at the time of a mission, a higher performance is required at the time of acceptance testing. The magnitude of this performance margin was established by tests and analyses. The most sensitive parameters were the duration of operation and the quantity of water used per square foot of sublimation surface. The sublimator plates and assemblies were stored in a dry nitrogen environment to minimize degradation for as much of the manufacturing and checkout process as possible.

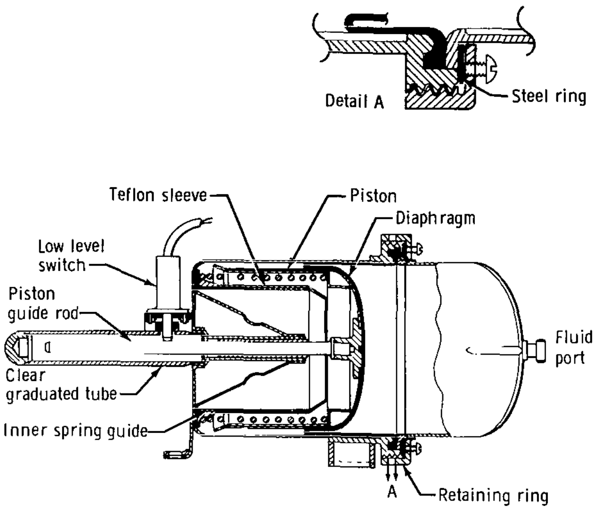
Flight experience with the sublimators has been very satisfactory on LM flights to date. Performance has been very stable and has followed preflight predictions.

Quick disconnects. - Quick disconnects were used in the heat transport section for convenience in making and breaking several connections. Several problems that were caused by loss of the lubricant within the connectors occurred.

Whenever a draining operation was required, isopropyl alcohol was used following draining to flush the residual water/glycol from the system. Removal of the lubricant by the alcohol prevented free action of the moving parts and thereby caused incomplete sealing. Leakage resulted when these units were subjected to gaseous leakage checks, although it was felt that the liquid coolant would not leak because of the lubricity properties of the liquid. However, in practice, any unit showing gaseous leakage was removed and replaced to guarantee a leak-free system. To prevent replacement time, the ground-support equipment interface quick disconnects were redesigned to allow reapplication of lubricant following alcohol exposure.

It was also found that the plasticizer in Buna-N elastomers used in the quick disconnects was shrunk by the isopropyl alcohol after a certain period of alcohol exposure as determined by testing. The alcohol flush times were controlled to values less than the critical exposure times.

Accumulator designs. - A water/glycol accumulator that would maintain acceptable leakage at the flanges proved difficult to build. An accumulator unit is illustrated in cutaway view in figure 9. The diaphragm forms the sealing gasket, and slight irregularities in the molded diaphragm result in uneven and inadequate sealing forces. The size of the flange groove was reduced to achieve the proper bead squeeze. The metal shoulder on the flange had to be redesigned to control the amount of diaphragm squeeze. The use of higher torquing of the screws on the retaining ring around the flange was also implemented. The screws had to be added because high torquing of the retaining ring itself created relative displacement of the top and bottom shells, which tended to wrinkle the diaphragm. After the screws were added, leakage problems seemed to be well in hand.



Note: Accumulator shown full.

Figure 9. - Coolant accumulator (item LSC-330-210).

Approximately a year later, a large crack was discovered at the angle section of a retaining ring. Investigation into this problem revealed that the material (aluminum alloy 2024T4) was subjected to stresses above those allowed for stress-corrosion control. All accumulators were recalled, the ring material was changed to aluminum alloy 7075T7351, and the cross section was thickened in the affected area to reduce stress levels.

It is important to note that the stress-corrosion problem was brought on by the solution of a totally unrelated problem. Higher and higher stresses were imposed on the unit by incrementally increasing the squeeze on the diaphragm bead for sealing purposes. Problems with stress corrosion were common in a number of subsystems in the LM. In this case, the material in all of the glycol accumulator retaining rings was greatly overstressed; however, only one unit failed. It appears that stress corrosion may or may not occur even when the stresses are well above the "threshold" values. However, the uncertainty associated with stress corrosion is such that adherence to threshold stress levels is the only safe approach.

Sublimator breakthrough problems. - The initial redundant cooling loop contained no water/glycol accumulator. An "accumulator effect" was designed into the system by an interface with the water system. This design required that the secondary coolant loop be maintained at a subatmospheric pressure to accommodate expected thermal expansions and contractions and to provide a pressure compatible with the water system in case the secondary cooling system were activated.

Figure 10 illustrates the general arrangement of the redundant cooling system and the water system. The interface of these two systems is at the puncture disk, and activation of the secondary cooling loop included puncturing of this disk so that the water system could serve as an accumulator. The use of ganged valves ensured that the selection of the proper water valves drove a pointed plunger through the puncture disk. Because this was an irreversible step that left the systems with some intermixed fluid and required special cleaning, the actuating mechanism was arranged to prevent inadvertent puncturing of the disk. Despite this design and the use of warning flags during ground operations, there were several instances early in the program when the disk was punctured during factory operations.

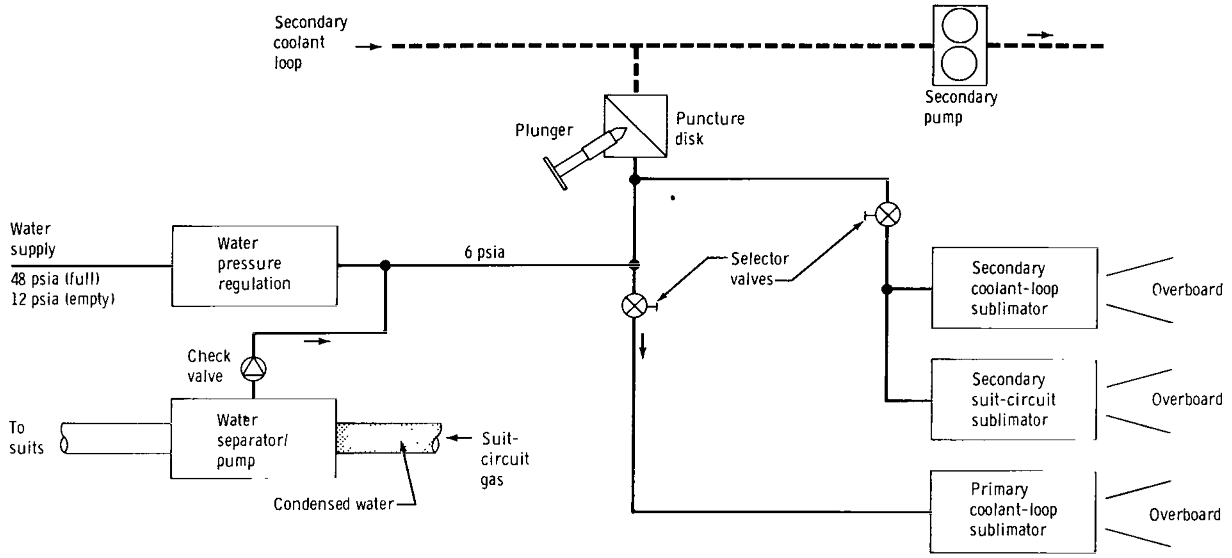


Figure 10. - Simplified diagram of original design of redundant cooling loop/water system.

This configuration was sensitive to the absolute pressure in the water/glycol loop. A high pressure caused water/glycol to enter the waterline feeding the secondary sublimators. Development testing indicated that the sublimators had an acceptable tolerance to the ethylene glycol (commonly used as "permanent" antifreeze). The pressure in the secondary water/glycol system was established by filling it with hot, deaerated water/glycol and then sealing it off. When the system cooled to ambient temperatures, it was at a subatmospheric pressure (approximately 5 psia).

Thermal-vacuum testing on a lunar module test article (LTA-8) provided the first opportunity for testing with complete spacecraft systems. A very slight leak existed, and the pressure that was locked off in the secondary coolant loop slowly rose. During the "hot case" secondary loop operation, the disk was punctured and the secondary sublimators failed. The glycol had caused sufficient lowering of the freezing point of the sublimator feedwater to prevent an ice layer from forming, allowing the water to break through and to freeze in the steam duct. To eliminate this interface between the water system and the secondary water/glycol loop, the design was changed by adding an accumulator. The puncture disk and waterline were removed, and plugs and caps were installed to isolate the systems.

Pump noise. - The coolant pumps, which are located in the cabin, have produced high noise levels. Surveys have shown that the pumps are not noisy in themselves, but the vanes produce pulses of fluid flow which excite the coolant lines and (sometimes) the cabin structural panels to which the tubes are attached. The coolant is carefully deaerated to prevent the formation of gas bubbles, which could cause cavitation or flow blockage. This removal of gas lowers the bulk modulus, which aggravates the noise problem. Several methods of quieting the pumping noise were investigated and evaluated. An expansion device that produced a significant reduction in noise was included downstream of the pump on later vehicles.

The noise experienced on missions was somewhat distracting, both because of the intensity and because of an apparent change in frequency on occasion. This frequency changing has not been completely understood, but it is felt that reducing the overall noise level will make any such occurrences less noticeable.

The pulsing of flow can be detected by slight, periodic pressure changes of approximately 10 psi. The mechanical stresses caused by these pulses within the system components were determined to be insignificant. Because these fluctuations at 400 hertz produced "noisy" data, the pump discharge pressure transducer was electrically damped. The pressure ripple at 400 hertz results from the 6000 rpm of the four-vaned pump.

Atmosphere Revitalization Section

Liquid-cooled-garment provisions. - A crew complaint in December 1968 indicated that the LM-4 suit cooling was marginal during the altitude-chamber run at KSC. Design and checkout data reviews showed that the LM-4 suit cooling portion of the ECS was performing somewhat better than specification, and the suits themselves were found to be within specification. Several methods of providing cooling performance improvements were investigated to see if the gas cooling could be extended. The design cooling capacity is 520 Btu/man-hour for steady-state operation. It was concluded that only minor improvements could be realized with the gas cooling approach. A system design change was made quickly to provide chilled water from the LM for circulation through the liquid-cooled garments. This method of cooling provides a large increment of cooling capacity. Even with the worst-case (warm water) situation, a 1200-Btu/man-hour metabolic load can be comfortably handled; and 2000-Btu/man-hour loads can be accommodated for at least short periods, although heavier perspiration is experienced.

The design that was adopted for liquid cooling was not optimized; instead, maximum usage was made of existing components to make the unit available for LM-5, the first lunar landing vehicle (Apollo 11). The cabin heat exchanger was removed not only to provide a location for the new unit (designated the LSC-330-192 package) in the cabin, but also because the cabin temperature control range provided by the cabin heat exchanger was a rather small value. This follows the trend of both Gemini spacecraft and the Apollo command module ECS experience, in which the cabin temperature control provisions have been quite small compared to the capacity of suit-circuit heat exchangers. Typically, after the design has proceeded as far as vehicle thermal-vacuum testing and flight, there has been enough confidence to delete or to deactivate the cabin heat exchangers. The design selected also removed the cabin temperature control valve and one cabin fan. The remaining cabin fan was retained for contingency purposes to enable cabin atmosphere mixing and purging necessitated by the loss of carbon dioxide removal capability. The liquid-to-liquid heat exchanger that was associated with the cabin heat exchanger was relocated and replumbed to chill the water with cold water/glycol. As a sidelight to the deletion of the cabin heat exchanger, the cabin temperature sensor was no longer located in any gas stream and thus sensed a temperature in a remote corner of the cabin. It had been observed that a waterline temperature closely approximated the cabin temperature (because the water is routed through the cabin, giving a considerable dwell time); therefore, the water temperature was used as cabin temperature by flight controllers. This procedure saved relocating the sensor to a location which would receive good airflow of representative cabin-gas temperature.

The water pump used in the LSC-330-192 unit is a PLSS design and uses 16 volts dc. A voltage regulator was designed to drop the LM 28-volt dc power to the correct voltage. This voltage regulator was the only new item designed for the LSC-330-192 package. A glycol valve was modified to bypass the circulating water around the liquid-to-liquid heat exchanger for crew comfort. This design provides water at the same temperature for both crewmen; and, if one is overchilled, he can disconnect the water umbilical at the suit. A schematic diagram of this unit is shown in figure 11.

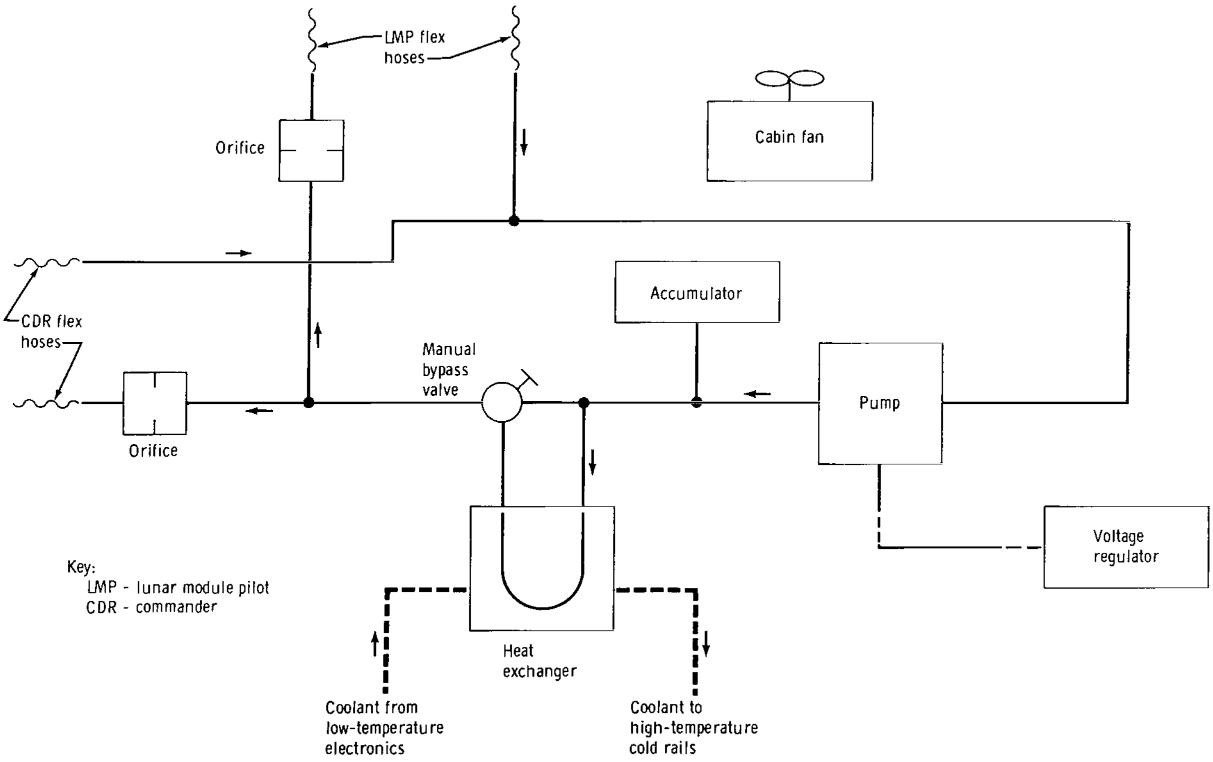


Figure 11.- Schematic diagram of the LSC-330-192 package.

Water separators. - The water separators underwent several changes to achieve specified performance. Considerable early development testing was performed to reduce the gas-side pressure drop and still achieve water pumping capability. Later, the assembly was redesigned to improve the pitot tube (water pump) efficiency, the bearing supports, and the assembly method. In later stages of development, several of the gas inlet vanes were blocked to give the gas stream impinging on the turbine blades of the rotating drum a higher velocity. In addition, the blade angle was changed, and the water pitot probe was again modified. Wire mesh was added to the drum to assist the coalescing of the droplets. A cutaway view of the flight configuration is shown in figure 12.

All the development changes were aimed at improving the pumping capability with low gas-flow rates. During qualification testing, the unit experienced a failure to start following a shutdown. In this condition, the ullage water that is retained within the unit settles to the bottom and creates a high resistance to rotation when restart is attempted with a low gas-flow rate at minimum system pressure. Clearances were revised, drain provisions were added, and additional inlet guide vanes were blocked. This design was then qualified by test for flight.

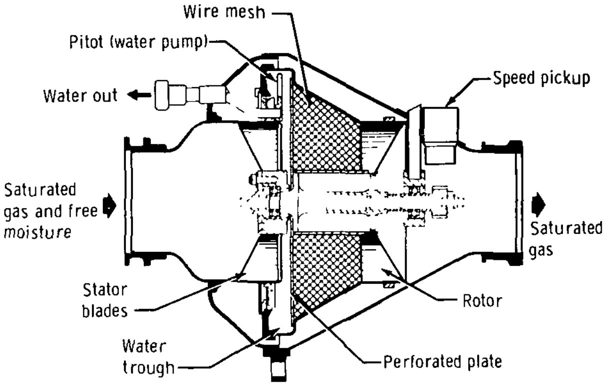


Figure 12. - Centrifugal water separator (item LSC-330-109).

During the flight of Apollo 11, waterdrops were sprayed onto the crewmen on several occasions. The subsequent investigations identified several possible reasons, but the cause was finally determined to be water separator overspeed. The gas-flow was considerably in excess of specification as a result of better-than-specification performance of the suit fans and because of lower-than-nominal system-pressure drops. At high speeds, the water in the trough splashes; and some is carried downstream and into the suits. A simple orifice plate was added to the primary lithium hydroxide cartridge to return the gas-pressure drop to specification value in order to provide necessary water removal efficiency. Because the secondary lithium hydroxide cartridge is smaller than the primary cartridge and produces a pressure drop compatible with proper water separator performance, this snap-in item, which is illustrated in figure 13, was not required for the secondary cartridge.

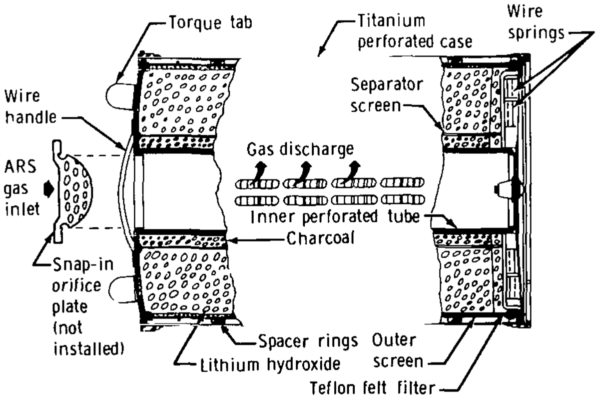


Figure 13. - Primary LiOH cartridge (item LSC-330-122).

Suit-isolation valves. - During the safety reassessments following the Apollo spacecraft fire in 1967, a completely new valve was developed and provided for isolation of the suit gas umbilical hoses. The change provided electrically actuated, fast-acting valves that automatically closed both supply and return hoses of both crewmen if suit-circuit pressure dropped below a safe level. Use of the valve guaranteed that at least one crewman would be protected (pressurized) and enabled to reopen his hoses manually, to close the hatch (which was presumably open in order to get a low cabin pressure in the first place), and to repressurize the cabin. The previous design was manually actuated only and provided protection for one less failure than the solenoid actuated design. This change was made rather late in the program and proceeded without major problems. Sluggish operation on several units required a minor change of materials to retain clearances after repeated usage.

A cutaway view of this valve is shown in figure 14. The cabin repressurization valve could be automatically actuated by means of the switch shown on the cutaway only if the repressurization valve was in the automatic mode. This switch was later removed as an unnecessary function.

Actuation of the suit-isolation valves was initially achieved by a suit-pressure transducer, which activated relays through signals from the caution and warning subsystem. This design was changed to activate the relays directly from a snap-acting pressure switch. This change improved the reliability and simplified the overall design. Originally, the transducer signal was compared with a preset voltage level in the caution and warning subsystem, which triggered the relay that applied the voltage to the isolation valves when the suit-circuit pressure decreased below the present level.

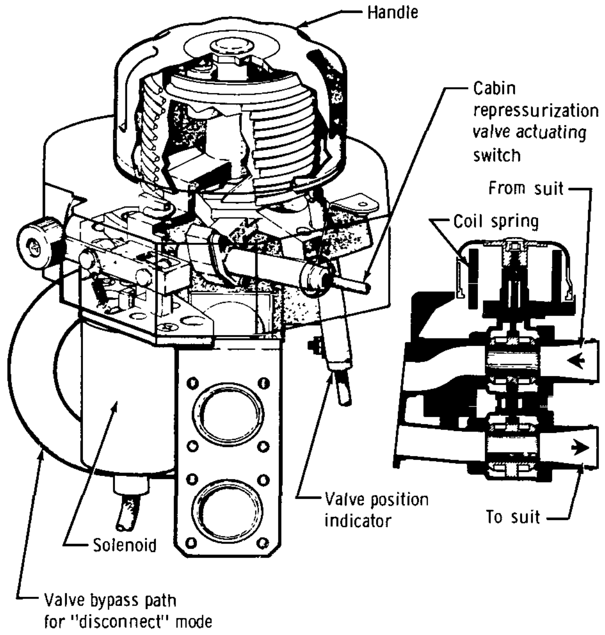


Figure 14. - Suit-isolation valve (item LSC-330-138).

Carbon dioxide sensor. - A number of problems were encountered with the carbon dixoide sensor used in the LM ECS, and the unit was frequently criticized. Despite the criticisms, the flight performance was generally good and provided useful data. The functional schematic diagram of the carbon dioxide sensor is shown in figure 15.

This instrument was initially Government-furnished equipment and was later turned over to the contractor to be supplied as contractor-furnished equipment. When the unit was retested to prove compatibility with the LM vibration levels, vibration problems were encountered. Other sensitivities were detected in the course of further ground testing, and design changes made are discussed in the following paragraphs.

The unit was mounted on vibration isolators to help attenuate the vibration environment. In addition, a more rugged infrared (IR) source (lamp) was used; and the unit case was ruggedized. The unit was designed to have a dc ground; but, because this was incompatible with the LM caution and warning system, an ac ground (resistance-capacitance network) was added to delete electromagnetic interference (EMI) sensitivity.

If water entered the unit, it could bridge a narrow gap and set up a galvanic corrosion cell, which would then degrade the optical filter layers and seriously degrade the sensitivity of the unit. An epoxy-type coating was added to cover the metal surface near the filter and thus eliminate the galvanic cell action.

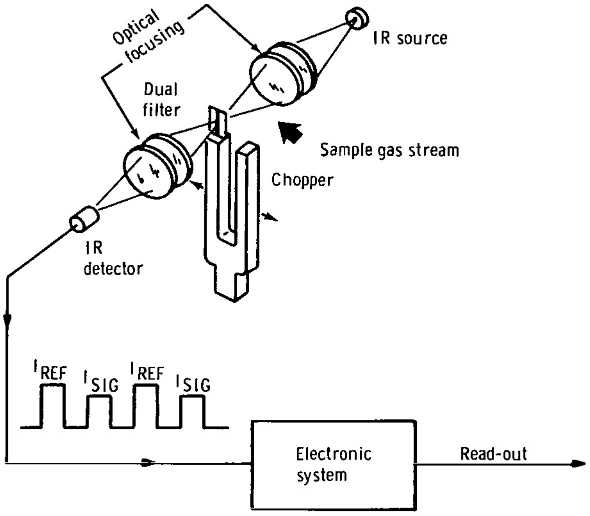


Figure 15. - Simplified system diagram of a CO_2 sensor.

Calibration changes with time and temperature were traced to outgassing of the conformal coating in the electronics section. Because the outgas products absorbed IR energy at the same wavelength (4.3 microns) that carbon dioxide does, elimination of the resultant distorted signals required a change to the conformal coating material. In addition, a trim resistor and a thermistor were added to the circuitry for temperature compensation.

Flight performance indicated satisfactory operation except for several momentary excursions during engine firings and several instances when water is believed to have been introduced into the sensor. Solids or liquids which interrupt the optical signal appear as large amounts of carbon dioxide and distort the signal. The unit will return to normal operation after the water dries.

Lithium hydroxide. - Cartridges containing lithium hydroxide are located in the suit-circuit assembly to provide chemical control of carbon dioxide. During the program, several significant design changes were made.

The early design allowed the granular lithium hydroxide to abrade when the unit was subjected to vibration, and "dust" that was generated and evolved with the effluent gas was very caustic and irritating to eyes, nose, and throat tissues. The design was changed in early 1966 by compressing the granules tighter within the container so that relative motion was inhibited. The packing procedure was also changed to load only a fraction of the cartridge, then vibrate lightly to pack the granules, load some more, vibrate, and so forth until the unit was properly filled. Figure 13 shows the flight configuration in cutaway view.

Polyurethane foam was the material that was used to compress the granules. This material, which was selected to give uniformly high loading, was durable even under required storage vacuum and temperature conditions. Following the Apollo spacecraft fire in January 1967, the use of polyurethane foam for compressing lithium hydroxide granules was prohibited. Although fire testing of this design was successfully passed, the presence of the polyurethane foam represented an immeasurable hazard, which was judged to be undesirable.

The ensuing redesign considered other "foam rubber" materials of the fireproof class (Fluorel foams) along with metallic springs and washers to achieve the chemical bed compression loading. Because the fireproof foams were not too well developed at that time, the metallic spring design was adopted and qualified for use. The filter material contained in the cartridge was changed from Dacron to Teflon felt at the same time.

During the Apollo 10 (LM-4) flight, an unusually high rate of carbon dioxide increase, followed by a decrease, was noted. (See the section entitled "Flight Experience.") The LM-4 LiOH cartridge, which was returned in the Apollo command module for analysis by the manufacturer, became the first item of LM equipment to be returned for postflight analysis. Following chemical and X-ray diffraction analyses, it was finally concluded that variations in the chemical conversion rates combined with carbon dioxide sensor tolerances accounted for the flight performance variations. No evidence of channeling or breakthrough was found, and no design changes were deemed necessary. Figure 16 shows the flight data combined with test data from ground-test cartridges. It can be seen that performance variations that reflect widely varying rates of increase had been experienced. Subsequent flight performance predictions were made for optimistic and pessimistic variations to account for the dispersions seen in test. The peaks seen at 6 and 7.7 hours were typical of closed suit-loop operation and were caused by a combination of reduced suit-loop mass flow and an increase in carbon dioxide partial pressure. Future designs should attempt to maintain system pressure and flow during suited and unsuited operations.

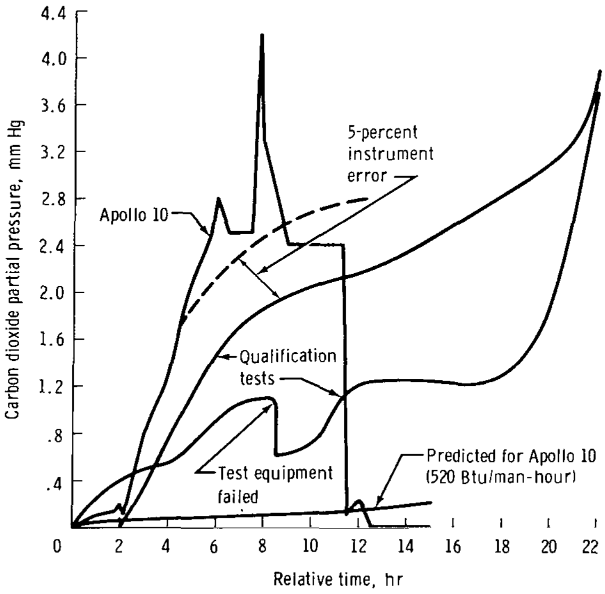


Figure 16. - Lithium hydroxide cartridge performance curves.

Suit-circuit fans. - The suit fan motors were initially manufactured by a vendor to the main subcontractor. Problems were experienced both in failures of the power transistors and in consistently getting the correct rotational direction as a result of improper phasing of the integral inverters. This development was eventually taken over by the main subcontractor, and design changes were established to correct the problems.

Bearing problems were caused by (1) contamination, which required improved cleaning; (2) inadequate lubrication, which necessitated changing from G-300 to Andok-C grease; and (3) bearing race brinelling, which required an improved fixture to pull bearings. Particulate contamination during the manufacturing operation was corrected by revised techniques and by design changes. The fan wheel rubbed during early testing, and clearances were changed slightly. Shimming was used to prevent the inducing of loads into the fan scroll from the ductwork.

In late 1968, an EMI suppression filter within a suit fan electronics package was found to have an intermittent open circuit during KSC checkout. The problem was traced to overheating of the EMI filters when heavy electric leads were soldered on. The overheating caused failure of a solder joint within a capacitor. The change to heavy-gage wire was made as a result of wiring safety reviews following the spacecraft 204 accident at KSC in 1967. The configuration of the radial flow fan-motor assembly is shown in figure 17 and a motor cutaway view in figure 18. Details of the EMI filter configuration and wiring arrangement are shown in figure 19.

It was desired to test the units in place within the vehicle to save time. A bench test program was set up in an effort to determine whether the capacitor lead would be intermittently open, but the tests were unsuccessful. The tests used X-ray, rf energy, and an "rf sniffer." The X-ray approach was unsuccessful because the problem joint was too inaccessible in the installation. Imposing rf energy on the power leads proved to be only partially successful because it would not consistently generate enough rapid local heating to cause a capacitor open circuit. These bench tests were tried on units which had been intentionally failed as well as on some good units. The rf sniffer, which would detect radiated electromagnetic noise, could not consistently detect a problem in intentionally failed units because of poor accessibility of the probe.

The design solution for the filter problem was to move the heavy-wire connection point farther from the capacitor lead and to install a wiring lug that was better suited to the heavy wire. A method was developed to remove the suit fans (two per vehicle) from the vehicle installation and to replace them with redesigned

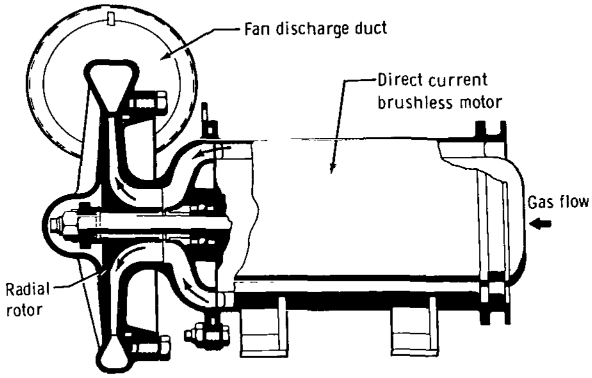


Figure 17. - Suit fan-motor assembly.

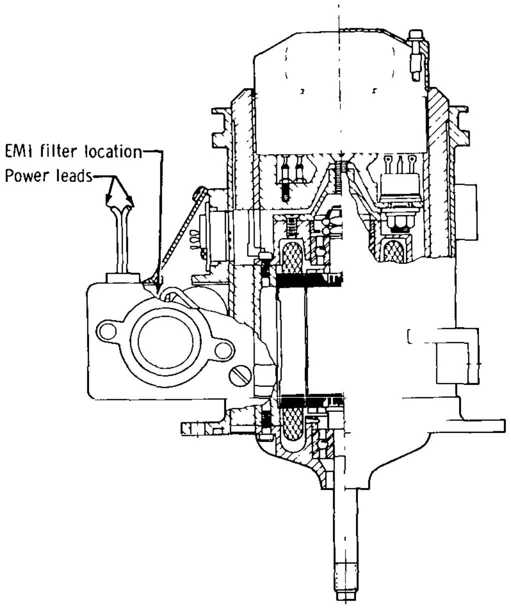


Figure 18. - Cutaway view of suit fan motor.

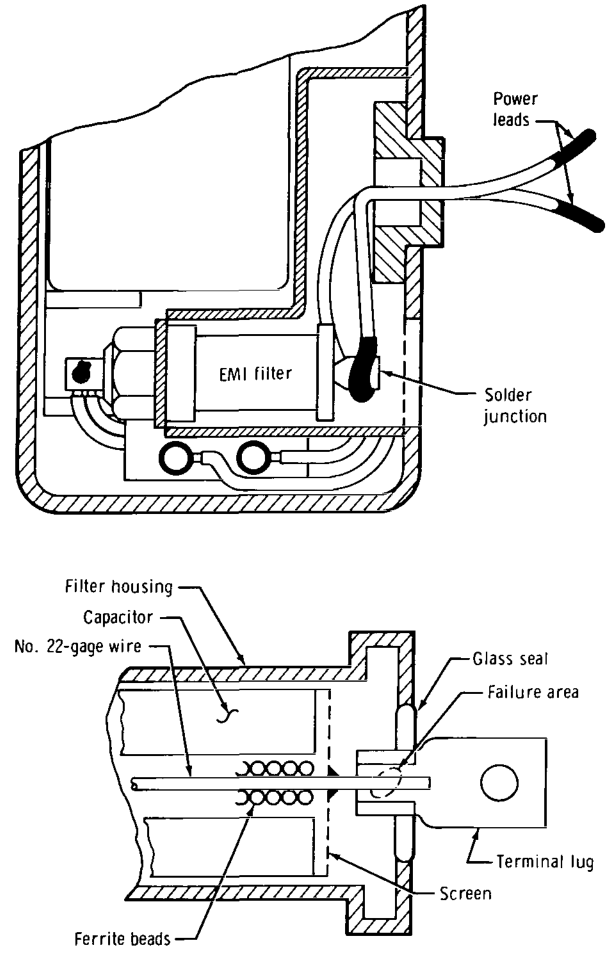
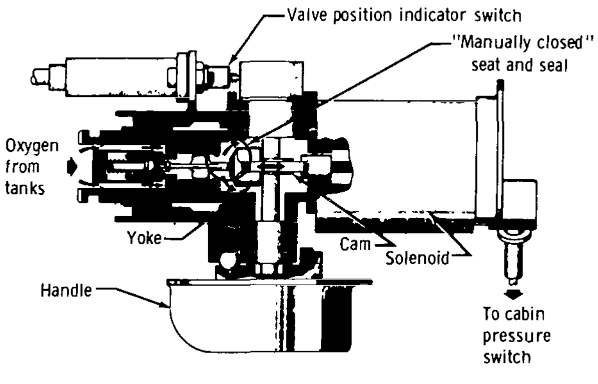


Figure 19. - Suit fan EMI filter configuration.



Note: Valve shown in "auto" position.

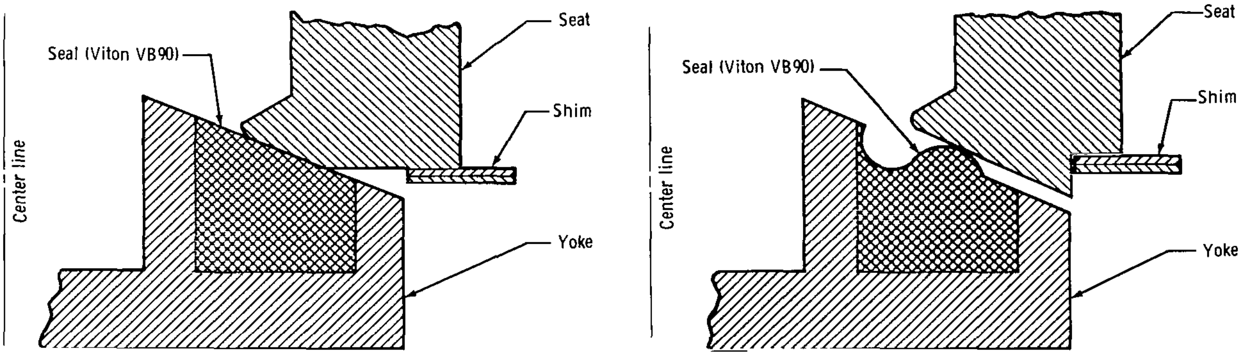
Figure 20. - Cabin repressurization and emergency oxygen valve.

units. This procedure proved to be successful when done by one specific, meticulous assembly technician. The potentially faulty fans were replaced on the LM-3 (Apollo 9) vehicle at KSC, thus saving many days of replacement and checkout time that would have been required for replacement of a complete ARS package. The highly skilled technician was presented a "Snoopy" award for his effort. The exact method and the technique required to perform these replacements were practiced and perfected at the subcontractor's plant before they were performed on the flight vehicle.

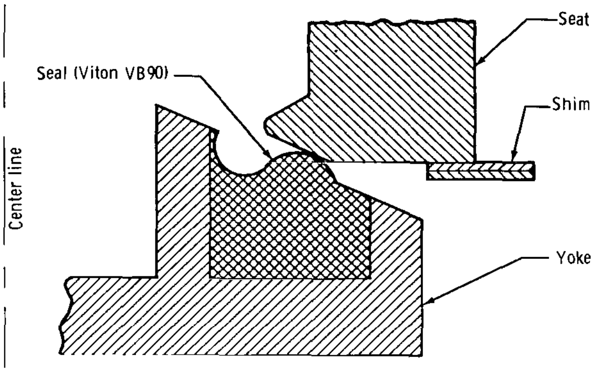
Oxygen Supply and Cabin Pressurization Section

Cabin repressurization and emergency oxygen valve. - The cabin repressurization and emergency oxygen valve is used to repressurize the cabin and can be actuated manually or automatically by a solenoid in response to low cabin pressure. During design feasibility testing, the manual-close seat was found to be susceptible to permanent setting, and the seat material was changed from Viton B to Viton VB90. The configuration is illustrated in figure 20 and is designated configuration A (fig. 21(a)).

During production acceptance testing prior to the endurance phase of qualification, leakage again occurred in the manual-close mode. Inspection revealed that the seat had cracked as a result of compressive loads. The seat was redesigned to a wave-type shape (configuration B, fig. 21(b)) to allow required compression with lateral material expansion. This configuration was subjected to verification tests followed by formal certification tests. During the vibration-temperature testing of the certification program, the valve again leaked in the manual-close mode. It was determined that tolerance buildup was allowing the valve poppet to load unevenly and to move laterally during vibration. A design change was made to the seat length to provide better centering and to resist lateral movement. Certification testing was completed with no additional leakage problems. Configuration C (fig. 21(c)) is the final seat and seal design.



(a) Configuration A. (b) Configuration B.



(c) Configuration C.

Figure 21. - Seat and seal details — cabin repressurization and emergency oxygen valve.

The cabin repressurization and emergency oxygen valve, a high flow-rate device, is located in the cabin immediately behind the lunar module pilot. When the valve position is changed from "close" to "auto" or from "auto" to "close," a sharp, loud report occurs. This "bang" is caused by high-pressure gas expanding to produce a shock wave. Testing of the valve demonstrated adequately that no equipment damage is incurred; but the noise has been startling to the crew, particularly when their helmets are off. Several design modifications were considered, but no changes were directed. The very satisfactory functioning of the existing design was felt to be a distinct asset and the flight crew recommended retaining the design and providing proper alerting of the crews. This has become an expected noise during activation/deactivation of the LM subsystems and during extravehicular activity (EVA) preparations.

Demand regulators. - The oxygen demand regulator (LSC-330-306) is one of two parallel-redundant units that are used to provide suit-loop and cabin pressure control. The regulator (fig. 22) is basically a balanced rocker/poppet design with calibrated springs working against an aneroid bellows for absolute pressure control. A failed-open regulator is overridden by the closure of a redundant manual seat. The aneroid chamber is isolated from the regulated pressure chamber, and each chamber is connected to the suit loop by a separate line.

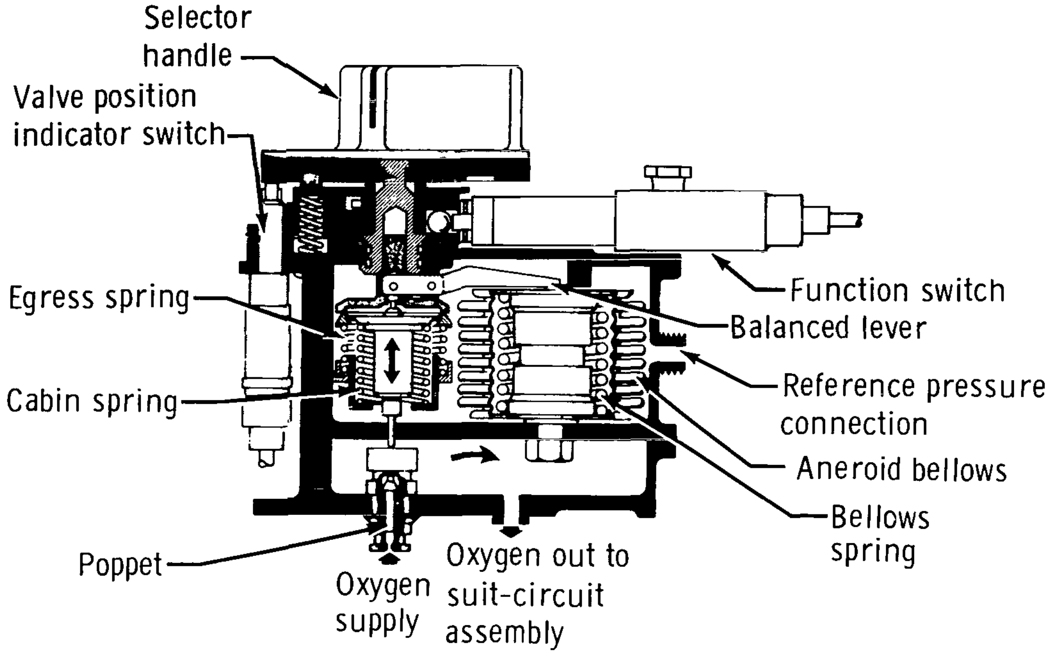


Figure 22. - Cutaway view of oxygen demand regulator.

The original design was highly sensitive to vibration while the demand regulator was operating within its pressure-control regions. Various aneroids and mass-balancing techniques were employed before the design was acceptable. The final design did not completely eliminate the increased leakage during vibration, but the suit-loop oxygen volumes are such that negligible pressure rise would occur during the vibration periods.

On several occasions, the oxygen demand regulators were contaminated by water, which produced corrosion following system checkout problems at the factory. These problems, which were always associated with testing the suit circuit "wet" by using the metabolic simulator (which introduces steam into the ECS), were identified only after some length of time following the incidents. In some cases, excessive water has been introduced as a result of metabolic simulator problems or by test errors with other related ground-test equipment that blocked the water discharge from the separators. The result was that water collects at the low point in the system where the oxygen regulator discharge tube attaches to the suit circuit. Testing is performed at 5 psia; and, at the completion of testing, water is driven upward into the demand regulators when the pressure is returned to sea level. Subsequent drying operations (evacuation and purge) were ineffective in removing the water from the regulators; and corrosion resulted, particularly on the aneroid bellows. The relationship between the water separator area of the suit circuit and the oxygen demand regulators is shown in figure 23. The use of steam in the metabolic simulator was finally discontinued during all factory operations to avoid moisture problems.

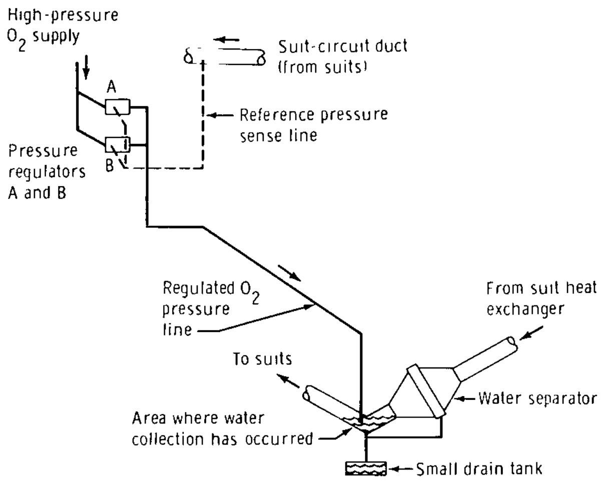


Figure 23. - Elevation schematic of demand regulator/suit circuit.

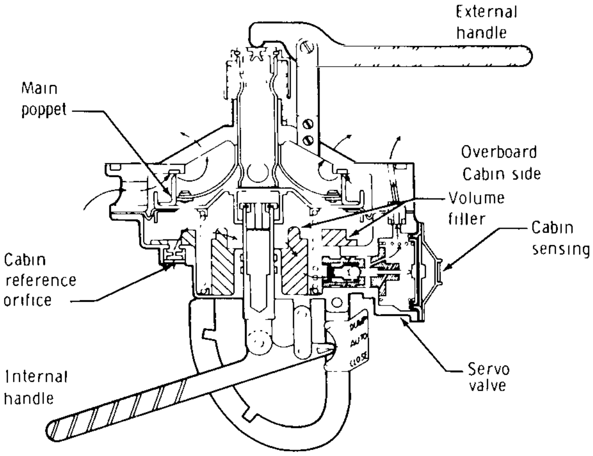


Figure 24. - Cabin dump and relief valve (item LSC-330-307).

Cabin dump and relief valve. - Two (redundant) cabin dump and relief valves (LSC-330-307) are used in each LM vehicle. Each valve provides cabin pressure relief at 5.6 ± 0.2 psid and is sized to prevent overpressurization of the cabin from any single failure of high-pressure oxygen lines or components. Manual actuations are provided to allow depressurization of the cabin when desired and also to close off the main poppet if the servo control fails open. A section view of the valve is shown in figure 24. The cabin dump and relief valve has three modes of operation, as follows.

1. The "dump" mode mechanically lifts the main poppet, allowing manually controlled cabin depressurization.

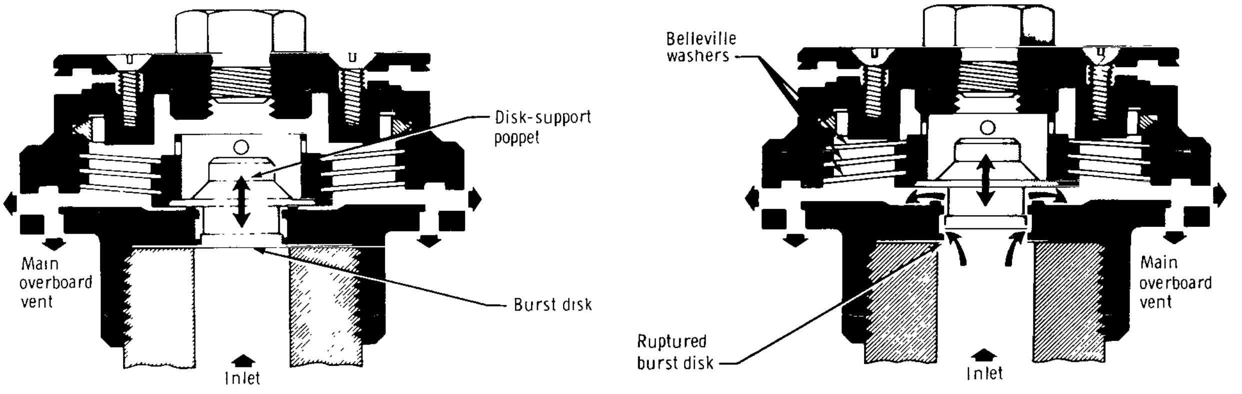
2. The "auto" mode allows the servo valve (which is referenced to cabin and external environments) to control pressure by equalizing the servo chamber pressure with external pressure, allowing cabin pressure to force the main poppet open. Once the servo valve reseat pressure is reached, the servo valve closes; and the servo chamber is returned to cabin pressure by pressure inbleed through the cabin reference orifice that causes the main poppet to close.

3. The "close" mode is provided to allow manual closure of the main poppet if the servo fails open. Overboard leakage for this failure is limited to 1 lb/hr by the cabin reference orifice.

During initial certification testing of the cabin dump and relief valve, the leakage rates were out of specification following vibration-temperature exposure. Teardown indicated that a material used as a volume filler in the servo chamber was cracking and generating particle contamination that lodged in the servo valve seat, preventing full closure of the servo valve. The filler material, which was necessary during development tests to achieve the proper dynamic responses of the valve, was changed from an expanded molded foam (like styrofoam) to gaskets formed from a silicone rubber compound. Certification was completed with no additional design changes.

High-pressure regulation and relief. - The high-pressure oxygen control module (designated LSC-330-392) in the descent stage used a combination of three modes of pressure relief. Redundant bypass relief valves provided low-rate relief to the section downstream of the pressure regulators. Redundant low-rate overboard relief valves provided pressure relief, if necessary, during translunar coast. The low-rate overboard relief valves were set to operate at a pressure higher than the pressure at which the bypass relief valves operate. A reseating burst disk provided high-rate relief at the highest relief pressure. By design, none of these relief valves should ever be required to function during a mission.

One of the most significant features of this module was the incorporation of the reseating burst disk, which was an early design change that allowed retention of enough oxygen to provide one cabin repressurization following a burst-disk rupture. The reseating burst disk provided a significant degree of safety for the crew if a burst disk ruptured during a lunar EVA period. This assembly is shown in the normal sealed mode (fig. 25(a)) and in a flow mode with the disk ruptured (fig. 25(b)). The Belleville washers would reseat the disk-support poppet when the upstream pressure was reduced.



(a) Normal sealed position.

(b) Open position.

Figure 25. - Burst-disk relief assembly.

Water Management Section

Iodine compatibility. - All the water used in the LM is loaded before launch, and medical requirements exist for maintaining the water free of viable organisms for health reasons. This requirement evolved because there is an interconnection between the potable (drinking and food preparation) water and the reclaimed (from respiration and perspiration) metabolic water. (Notwithstanding the foregoing, it is considered likely that a biocide would be required even if there were no interconnection because of uncertainties in long-term water storage and the necessity of maintaining an acceptable microbiological condition.)

Tests at the main subcontractor facility showed that the sublimators could not perform using chlorine (introduced as sodium hypochlorite). In a hard vacuum, a greenish residue (identified as chlorine hydrate) slowly formed on the ice layer. After a period of time, the increased concentration of the chlorine hydrate lowered the melting point of the ice below 32° F. This melted the ice and caused water to run freely through the porous plates and to freeze in the vacuum space.

Iodine was next tried as a biocide and found to be compatible with the sublimation process. Development testing of other portions of the water system and with metallic and nonmetallic materials showed generally good stability and only slight corrosion from the use of iodine. Corrosion which results with iodine concentrations of about 15 ppm is essentially the same as that which occurs with water alone.

Tests were performed to show that a proper iodine concentration could be maintained for approximately 30 days. The medical requirement was that at least a 0.5-ppm iodine residual had to be present when the last water was consumed, which could be approximately 30 days after tank servicing. No onboard test devices were planned because of the rather cumbersome checking techniques required of the crew. Further ground-test results began to show wide variations in iodine depletion rates. The variables involved seemed to be inseparable, and the data were reviewed carefully several times before a pattern apparently emerged. The final conclusion was that the initial exposure of the water tanks to iodine resulted in an acceptably slow depletion rate, but that repeated exposures caused progressively faster depletion rates. The corrective measure was to avoid loading water containing iodine except for the flight load. The descent water tank configuration is illustrated in figure 26. The ascent tank is similar but is more spherical in shape.

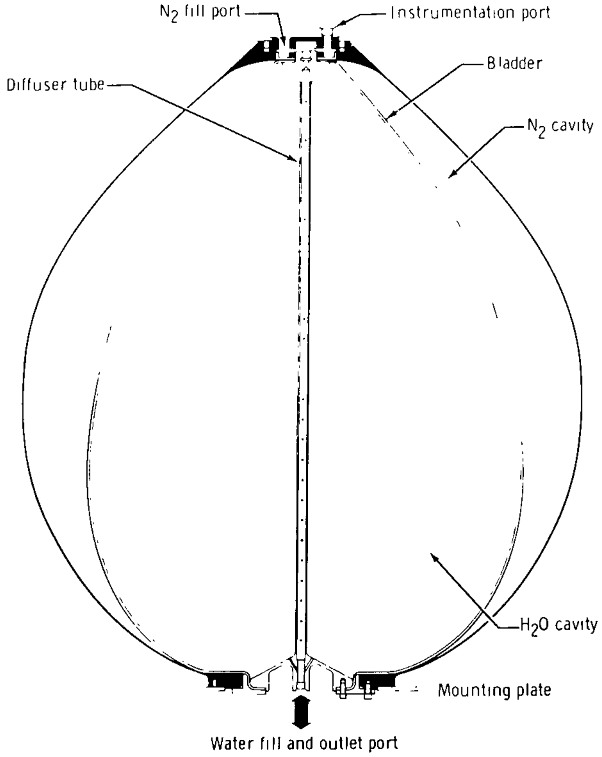


Figure 26. - Descent water tank (item LSC-330-404).

The mechanism of iodine depletion was found to be the diffusion of iodine vapor from the water, through the silicone rubber bladder, and into the surrounding nitrogen gas space. Water vapor also permeates the bladder, as does the nitrogen pressurant gas. The humid iodine vapor attacks the anodized aluminum tank wall; and, as the anodized coating is corroded, more 6061-T6 aluminum is exposed. The exposed aluminum readily reacts with the iodine. As the iodine is depleted, the vapor pressure is reduced and more iodine vapor permeates the bladder to maintain an equilibrium vapor pressure, thus depleting the iodine in the water. The anodized aluminum standpipe that is immersed in the liquid side is consistently uncorroded, but the tank walls show definite corrosion with the amount dependent upon exposure time.

Exposure history was not readily apparent as the cause of iodine depletion, because of the many variables of testing. Tank shells and tank bladders were often shifted from test to test (because not many test items were available for use) and reexposed. Exposure times and concentrations of iodine varied considerably. It was felt for a time that the bladder material reacted with the iodine, and "seasoning" of bladders was tried at several hundred ppm. Bladders which had been exposed to ethyl alcohol appeared for a time to cause fast iodine depletion. Until that time, the iodine was introduced in tincture form (iodine in ethyl alcohol) because the ease of dissolving iodine in alcohol made the testing more convenient. Testing was changed to use water solutions of iodine only. Only after the tank shell exposure histories were carefully arranged in order did the depletion test results appear consistent.

The water tanks on the LM-3 (Apollo 9) vehicle had been exposed to iodine in the altitude-chamber testing at KSC; thus, early depletion of the iodine was predicted. A bacteria filter was affixed to the water dispenser for that flight. The filter was not used on the LM-4 vehicle because the water tanks were not exposed to iodine before the flight water was loaded.

Tank bladder adhesions. - Silicone rubber bladders were used in the water tanks for zero-gravity expulsion. It was found that a bladder, when maintained in a collapsed state for a considerable period, would adhere to itself (adjacent folds, for example); and, when subsequently expanded, it would be weakened or damaged. This adhesion was of the nature of a fusion of the rubber. To prevent adhesions, the bladders were subsequently maintained in an expanded state by the application of several psi of dry nitrogen pressure on the waterside. Whenever the bladder configuration was changed (inflations or deflations), a record was entered in a "Limited Life Log" in accordance with established program requirements. Pressure cycles on the tank itself were likewise recorded for a comparison to allowable life cycles. The life limitations were based upon previous test experience and engineering judgments.

During checkout operations at KSC, a bladder tear was discovered on the LM-7 vehicle. The subsequent investigation failed to identify the specific cause of the failure, which could not be traced to a material defect or to improper pressure application or other handling problems. To ensure that flight tanks did not have tears, an X-ray examination was implemented after the water was loaded for flight. Gas leakage checks had routinely been used to show that no tear existed just prior to waterloading.

This is an example of the "explained" category of failure reports. No fault could be found with the bladder design or with the manner in which it was used. Special tests were implemented, however, to verify that the flight units were free of defects after completion of prelaunch preparations.

Redundant water regulator and particulate contamination. - Particulate contamination and corrosion were experienced a number of times during development and checkout. In general, the corrective measures were to progressively reduce the exposures to water and to dry the system more thoroughly following use. Even minor corrosion results in the generation of large amounts of particulate contamination. Significant water system corrosion was found in the first several LM vehicles, including the LTA-8. The corrosion occurred in the tubing interior, where the alodine coating had been destroyed when the gamah fittings (tube connectors) were swaged in place. Chromic acid flushes to replace the coating followed by water flushes to clean the system were required.

During checkout of the LM-4 vehicle at KSC, a water pressure regulator malfunctioned; and corrosion of some of the internal parts was apparent. During the investigation of the problem, the sensitivity of the regulator design to particulates was a major finding. Several bench test series were run with water which was intentionally contaminated. The tests imposed difficult conditions by varying system parameters and by running for long durations. The general findings were that, even though analysis showed that the design was sensitive to malfunctions caused by particulates, the units functioned satisfactorily in test. Two regulators in series apparently provided sufficient redundancy that additional protection (waterline filters) could not be justified. The primary water system already contained two regulators in series, but the backup system had only a single regulator. A redundant regulator in the backup system was added at that time, effective on the LM-5 and subsequent vehicles. This was a field modification kit added downstream of the LSC-330-490 water control module. The redundant regulator (designated LSC-330-433) had interior working parts identical to the existing LSC-330-415 regulators. A schematic view of the regulator is shown in figure 27.

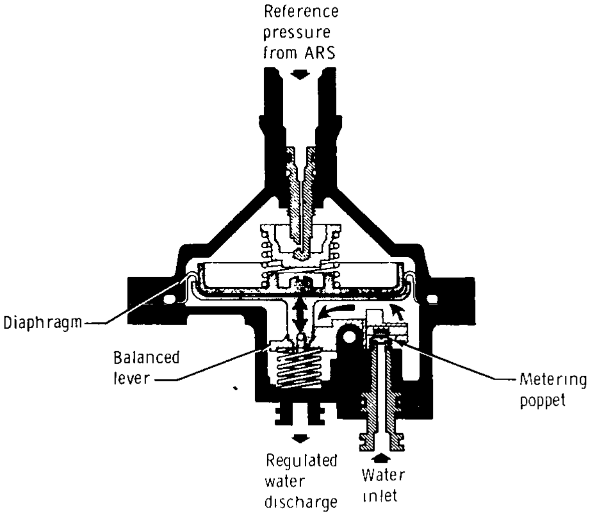


Figure 27. - Water pressure regulator — functional schematic.

Water pressure regulators that would meet the tight specification performance requirements were difficult to manufacture and assemble. The large counterbalanced diaphragm assembly would sometimes become misalined, and disassembly and hand matching of parts was the practice. Once a unit had passed acceptance testing (indicating that all specifications were met), the subsequent performance was good. Flight performance was without flaw.

Corrosion in the WMS, which resulted in particulate contamination, was not so severe that structural integrity was threatened. Only light, surface-type corrosion was found; however, this was significant from a particulate contamination standpoint.

Extensive testing was performed to demonstrate the effects of iodinated water upon material stability in the WMS. These tests basically showed that the use of iodine in the concentrations required for water sterility purposes was no more detrimental than the use of water itself. Metallic and nonmetallic materials were tested, including dissimilar coupled samples; and the materials showed good overall resistance to corrosion.

Bacteria filter. - A requirement that no viable organisms be deposited on the moon as a result of systems operation was placed upon the LM ECS. The crewman condensate enters the sublimator water feedline and is eventually vented overboard as low-pressure steam. Micro-organisms contained within this line will not necessarily be killed by the vacuum nor filtered out by the sublimator porous plates. Furthermore, the contact time of the condensate and the iodinated stored water would not guarantee a bacteria "kill," particularly of spore-type micro-organisms.

A small-pore (0.22 micron absolute) filter was developed for the waterline to retain the bacteria mechanically. The unit was to be placed in location A as illustrated in figure 28. Placement in location B was also possible but would require twice as many filters for the redundant water separators.

Problems with gas blockage, which increased the pressure drop and effectively blocked the fine filter, were encountered. The gas in the water came from the water-supply tank, which became saturated with nitrogen at approximately 48 psia shortly after filling. The water pressure regulator settings could not be increased to force more water through the filter because of the limitations imposed by the sublimator and by the water separators. Additional pumping head requirements on the water separators would increase the suit-circuit gas pressure drop and thereby require revision to the suit fans. High water-supply pressure would cause sublimator breakthrough.

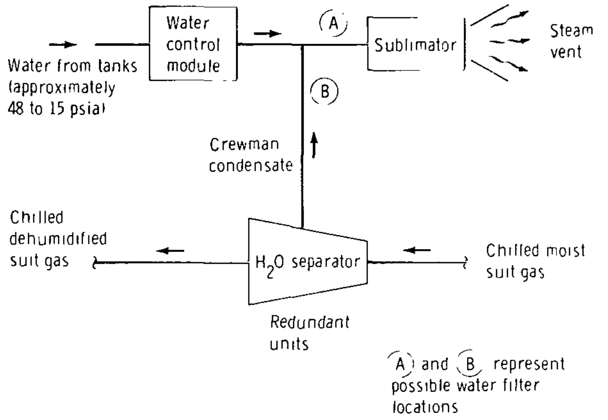


Figure 28. - Water bacteria filter locations.

The Interagency Committee on Back Contamination (ICBC) reviewed the status of the developments and recommended relaxing the requirement concerning bacterial deposits from this source. A bacterial filter was used on the LM cabin dump valve for the Apollo 11 mission. The requirement for this filter was deleted for later missions, and the cabin gas was dumped directly overboard at the times of lunar exploration.

Compliance with the ICBC requirements was difficult (if not impossible) with the existing hardware. Later developments could have been pursued to possibly provide a hydrophobic/hydrophilic filter for water filtering. Also, if the ICBC requirements had been imposed early in the development, they probably could have been accommodated within the basic design.

Gas solubility. - Although gas is mixed with the water, it has not been a problem in LM usage. On the LM-4 (Apollo 10) vehicle, there was a crew comment concerning the gas that they encountered in the drinking water; but it was not regarded as a problem. Gas has caused no problems in water pressure regulation or in sublimator operation.

The gas, which is nitrogen, enters the water by permeating the tank bladders following servicing. The water is not deaerated before loading because the nitrogen will saturate it anyway after loading. The water is probably saturated with air at one atmosphere in the ground servicing equipment. The only concern about gas saturation occurred after tank loading the first few times because the water quantity measurement device (WQMD) is basically a pressure transducer. As permeation takes place, the pressure of the sealed-off gas supply slowly decreases, causing a decrease in the WQMD reading and falsely indicating a slow water (or gas) leak. The rate of decrease and the level-off point, based on previous test observations and theoretical gas saturation data, have been furnished to flight controllers. Pressure decay rates greater than those predicted indicate a leak, while rates less than predicted indicate the permeation phenomenon rather than leakage.

Orifice problems. - The water pressure regulators were set to control their outlet pressure from 0.5 to 1.0 psi greater than suit-circuit pressure. This was necessary to provide the water pressure required for sublimator operation. The pressure-sense lines, which provided the reference pressure, contained small orifices at the suit-circuit end. These orifices were provided originally to preclude loss of suit-circuit pressure if a sense line should break.

During altitude-chamber manned testing at KSC on the LM-3 vehicle, it was noted that the water separators were performing poorly. Eventually, the carbon dioxide indications became high; and there were crew complaints of being warm and humid. The high carbon dioxide indications resulted from water being forced into the sensor because of the location of the sensor tubes. It was subsequently determined that the orifice in the water regulator sense line was plugged; and some unknown pressure was trapped in the sense line, causing an artificially high reference pressure. This caused the sublimator supply pressure to be abnormally high, which required the water separators to pump against a high head pressure. Under these conditions, little or no condensate would be pumped out of the suit circuit. The factory checkout method verified all functions of the sense line except whether it was actually open to the suit circuit. With the unit in place, these orifices and protective screens were carefully removed to avoid particulate contamination in the suit circuit on the LM-3 vehicle and on all subsequent vehicles. The decision to remove the orifices was based on the extraordinary high reliability of the system plumbing.

The failure to detect the blocked orifices at the factory resulted from checkout limitations that were imposed by certain aspects of the spacecraft system design. For example, the main checkout restriction imposed by the design was caused by the suit fans, which could accept full bus voltage only at operational (reduced) pressures. At sea level pressure, the fan voltage had to be dropped to 15 volts by ground-support equipment to avoid overheating the fan motors. Actual testing involving the suit circuit was thus restricted to KSC, where the manned altitude-chamber test was run. It was always desired to detect all faults at the factory before shipment of the vehicle. The factory checkouts were made as complete as possible, but sometimes they left some small portion of the system incompletely tested until later.

A similar restriction on checkout, because of design, was the absolute pressure regulation of some devices. This deferred end-to-end pressure regulation tests to KSC, where subatmospheric pressures were finally encountered. If all pressure control could have been gage-type or differential-type control, the checkout job could have been more thoroughly performed at the factory.

CERTIFICATION TESTING PROGRAM

General Scope

The ECS design concept of modularized subassemblies led to an early decision to perform certification testing at the module level for examining and verifying all possible component interactions during dynamic testing. Because it had been stipulated that any field failure of a single component would require replacement of the complete module or lowest replaceable element, it is reasonable to assume that certification should be performed at the same vehicle replacement level of assembly.

Feasibility testing. - Design feasibility tests were conducted at the component and subsystem (module) levels. The component level tests were primarily used to verify design and to establish performance curves, and the subsystem (module) level tests were performed to identify component interaction and to verify that system design performance requirements were met. The hardware used was virtually production grade and was made from controlled procedures and drawings.

Design verification testing. - Because production-type hardware was used during feasibility testing and very little redesign was required following feasibility tests, the design verification test requirement was deleted.

Formal qualification. - Two sets of flight hardware were subjected to logic-group (module) testing. One set of hardware was tested to design limit certification levels consisting of mission-design-extreme environments, and one set was subjected to two normal mission-level environment tests plus ground environment tests.

Design changes resulting from component failures during initial certification testing, plus component additions and redesign imposed by changes in system requirements, were responsible for incorporating a delta qualification program following the initial logic-group qualification program. The delta qualification of new and modified hardware assured a more realistic certification by using the original modules as test beds (or fixtures) during testing.

Man-rating. - To certify the life support section of the ECS, a complete test facility was built at the prime contractor site. The man-rating test facility consisted of a vacuum chamber, a vacuum system, a data system, and a life support section of the LM ECS, which was installed in the simulated LM cabin of the vacuum chamber. The facility was designated the LM Internal Environment Simulator (IES).

Using the IES, the ECS man-rating was accomplished in two steps. The first step (phase I) used some preproduction hardware which differed from production hardware only in physical layout. The second step (phase II) used production hardware which was modified to provide instrumentation points necessary for gathering parametric data. Although no design changes or modifications were identified during these tests, valuable crew familiarization and confidence were attained. Following these tests, the test chamber was moved to the NASA Manned Spacecraft Center, where it was used for further evaluations and provided some flight crew familiarization.

Thermal-vacuum tests. - To ensure compatibility between all subsystems during vehicle exposure to expected environments, the LTA-8 vehicle was built and installed in a special thermal-vacuum chamber, in which six manned tests were run at design-extreme metabolic and thermal loads to verify flight worthiness.

Feasibility Testing and Design Verification Testing

The original concept for hardware development was to conduct feasibility testing on preproduction hardware for the purpose of component and part selection, performance evaluation, and design concept verification. These tests — which included performance, fluid compatibility, endurance, and thermal exposure — were conducted on the component, logic-group, and system levels of hardware buildup. Satisfactory completion of feasibility testing released hardware for production. Design verification testing would then be conducted with production hardware. As the hardware development phase progressed, the preproduction hardware had the appearance of production hardware; that is, very few "hogouts" or heavyweight items were made for feasibility purposes. Therefore, critical portions of the design verification testing were included in the design feasibility program.

No definite limit was set on quantities of hardware required to undergo feasibility testing. At least three of each item went through component, logic-group, and system level feasibility testing.

Several hardware redesigns were required to meet feasibility test requirements. The following paragraphs indicate the type of redesigns required to meet specific test requirements.

Performance. - The water separator (LSC-330-109) had excessive water carry-over. The pitot tube was redesigned to prevent splashing. Nine stator vanes were blocked to increase the velocity of the suit gas through the separator for increasing the starting torque.

The primary sublimator (LSC-330-209) could not meet the required thermal performance. The manufacturing process of brazing the fins to the porous plate was changed to welding to increase the sublimation area. Control of the installation of porous plates was required so that the finer pore orientation was always uniformly in the same direction. The suit fan (LSC-330-118) rotor profile was changed, and the motor efficiency was increased to meet performance requirements.

Structural. - The water/glycol accumulator (LSC-330-210) pressure curve was nonlinear. A spring guide was added to prevent the spring from dragging. The LiOH canister cover (LSC-370-127) was redesigned to meet torque requirements.

Leakage. - The water check valve (LSC-330-401/492) seating arrangement was changed from a spring-loaded poppet to a flapper-type poppet, the oxygen shutoff valve (LSC-330-304) seat was changed to an aluminum hard seat, and the poppet material was changed to Kel-F to meet leakage requirements.

Stability. - The cabin dump valve (LSC-330-307) main poppet spring preload was increased to meet vibration requirements. (See fig. 24.)

Endurance. - The suit fan (LSC-330-118) motor bearing grease was changed to Andok-C, and the percent of grease fill was reduced to meet endurance requirements. The cabin fan (LSC-330-102) motor bearing grease deteriorated and was changed to G-26 lubricant.

Qualification Testing

Design limit testing. - Design limit testing was performed to verify the functional capability of ECS components during or following subjection to environmental loads approaching the ultimate levels for which the equipment was designed. One complete set of production flight hardware was subjected to the following environments.

1. Humidity and temperature (combined)
2. Salt atmosphere (noncabin hardware)
3. Sand and dust
4. Vibration
5. Acceleration
6. Thermal vacuum
7. Shock
8. EMI (as applicable)
9. Burst pressure (as applicable)

Most hardware failures that occurred during testing were caused by improper test setups (i.e., incorrect polarity at the test equipment/test item electrical interface and excessive test item leakage rates as a result of contamination introduced from test instrumentation, test area environments, and test fluid/gas supply sources) and improper manufacturing procedures, all of which could have caused component failure during normal operation, even without the design limit test environments. Hardware failures that were attributable to the actual test environments and that require subsequent redesign were few. The following paragraphs indicate — by test environment — the failed components, the fixture mode, and the redesign necessary to successfully complete qualification.

Electromagnetic interference: Some cases of radiated and conducted EMI which occurred during this test resulted in adding suppression to some electrical components and in modifying test requirements for those which bordered on test limitations. The out-of-specification conditions in many cases involved switching circuitry and not the components directly, so no failed hardware listing is made.

Vibration (lunar ascent/descent and earth-launch loads): The cabin pressure switch (LSC-330-323) failure modes were out of specification, and contact chatter was of sufficient duration to cause activation of hardware in the circuit. Redesign of this unit included shock mounting and slight changes to the specification pressure bands for activation and deactivation.

Functional (operational, cycles): The water check valve (LSC-330-401/492) failure mode was excessive reverse leakage caused by contamination of the check valve seat. Redesign incorporated a much softer flapper-type seat which had a greater surface area and less susceptibility to contamination.

The suit-circuit diverter valve (LSC-330-112) failure mode was an increase in handle torque beyond the specification limits and was caused by burring of the valve-shaft sleeve. Redesign resulted in replacement of the sleeve with one made from a higher Rockwell number (hardness) material.

Subsequent to design limit qualification completion, many hardware design changes were incorporated to increase reliability and to delete flammable materials. Where applicable, delta qualification testing was performed to ensure that hardware operation was not affected.

Endurance qualification testing. - The endurance qualification testing, which consisted of two mission simulations plus ground checkout time, was performed to verify the functional capability of ECS components during or following subjection to normal environmental loads. One complete set of production flight hardware was subjected to the following environments.

1. Integration and checkout (cycles, operation)
2. Vibration and temperature
3. Thermal and vacuum
4. Corrosive contaminants
5. Oxygen atmosphere (oxygen, temperature, humidity)
6. Shock
7. Acceleration

The failures that occurred during this certification test were (for the greatest part) characteristic of long-term operation, test rig induced contamination, and improper manufacturing procedures. As in design limit qualification, the failures that were directly attributable to the certification environment loads were few. The following paragraphs indicate by test environment the failed component, the failure mode, and the redesign necessary to complete endurance qualification successfully.

Vibration (lunar ascent/descent and earth-launch loads): The cabin relief valve (LSC-330-307) had excessive leakage, which was attributed to contamination. Disassembly revealed that the foam material used as a volume filler had cracked. Redesign resulted in replacement of the foam material with molded silicone rubber.

Integration and checkout (endurance qualification): The water check valve (LSC-330-401/492) failure mode was identical to the failure which occurred during design limit testing. The redesigned unit used to complete design limit qualification was also used in the retest for this qualification.

The suit-circuit diverter valve (LSC-330-112) failed to return to the egress position during electrical actuation. The failure was identified as a jammed detent ball between detent and shaft. Redesign resulted in a modification of the shaft detent cavity.

The secondary glycol-loop sublimator (LSC-330-224) failed to meet performance criteria after 100 hours of operation. The failure was attributed to excessive braze flowing, incorrect porous-plate orientation, and particulate contamination. Redesign of the sublimator involved installing the porous plate by welding instead of brazing, modifying manufacturing procedures, and using MSC-approved water.

Subsequent to endurance qualification, many hardware design changes were incorporated to increase reliability and to eliminate flammable materials. Where applicable, delta qualification was performed to ensure that hardware operation had not been affected.

Integrated Subsystems and Vehicle Testing

Internal environment simulator. - The IES test program was generated to man-rate the LM ECS prior to man-rating at the vehicle level. The test facility consisted of a vacuum chamber, a cabin volume pressure shell, all ECS components which were required for life support, and cabin wall temperature control to simulate mission thermal loads.

The IES test program comprised four tests: one unmanned, one contractor manned, and two manned by MSC astronauts. The following summary covers test objectives of each test.

Test 1 (unmanned): Test 1 was designed to provide assurance of specification performance of the ECS when exposed to design environments. Minor problems associated with the metabolic simulator caused deviations from test procedures, but adequate data were compiled to enable proceeding to manned testing.

Test 2 (manned — contractor pilot): Test 2 was designed to man-rate the ECS and to provide confidence for continued manned testing. The contractor pilot provided sufficient subjective comments before, during, and after the test to "debug" the test procedures adequately and to identify possible hazards to man. This test was highly successful, and only minor procedure changes were made prior to the next test.

Tests 3 and 4 (manned — MSC astronauts): Tests 3 and 4 were identical to test 2, and the only anomaly which occurred was in a negative suit-pressure relief valve (special ground-test item). During cabin depressurization, the suit circuit was noted to be following the cabin pressure. After recycling the cabin pressure, this ground-test valve sealed off properly; and no recurrence of this anomaly occurred.

The only performance characteristic worthy of note was a temperature rise between a point directly upstream of the suit-isolation valve and the suit inlet. This temperature rise (approximately 9° F) was apparently caused by conduction across the isolation valve (a single two-port valve which controls the "cold" flow into the suit and the "hot" return flow from the suit) and between the suit supply and return umbilical hoses. Even though this heat loss was not predicted, the suit inlet temperature was below specification level; and no redesign was required. With the exception of the aforementioned minor anomalies, the IES test program was satisfactory.

Special testing. - The liquid test rig (LTR) was a geometrical reproduction of the lunar module environmental control subsystem HTS and WMS and was designed to provide a means for testing various configurations to determine heat-transfer characteristics and flow distributions for various cold-plate heat loads and flow conditions. This program was conducted in two distinct configurations, one being the LM-1 vehicle system (a flight development vehicle which had additional cold-plated equipment and an automated water system for unmanned flight) and the other being a LM-4 vehicle system (a lightweight lunar landing vehicle with all development equipment removed).

The flow balance phases of LTR testing were satisfactorily completed for both the LM-1 vehicle and LM-4 vehicle configurations. The only noteworthy test discrepancy was during the special test described in the following paragraph.

A special test was conducted to verify the capability of the water/glycol ground-support equipment to adequately remove particulate contamination from the water/glycol to below specification levels before and after vehicle servicing. Review of the test report showed that water/glycol samples were taken prior to LTR servicing; but, because of inadequate quantities of water/glycol after system servicing, no samples were taken. At test completion, the water/glycol was drained from the LTR and reported to be qualitatively "very dirty."

The successful flight operation of the HTS and the WMS would tend to indicate that the LTR program was highly successful, but one major vehicle anomaly that occurred during subsequent ground testing indicated an area of inadequate certification. This vehicle problem, which should have been identified during the LTR testing, was the breakthrough of the secondary loop sublimators of the LTA-8 vehicle. (See previous discussion under "Sublimator breakthrough problems.")

Lunar module test article. - The following paragraphs describe tests performed on the lunar module test article.

Thermal vacuum: To verify design requirements for the Apollo lunar module before manned flight, a special lunar module test article, designated LTA-8, was built and installed in a space simulation vacuum chamber. Because the LM program called for orbital flights prior to a lunar landing, the LTA-8 test program also was set up in two phases. Each test program was designed to provide environments and time lines simulating expected mission loads. Although the following summaries for each test phase show that few hardware problems were encountered during manned testing, those which did occur more than justify the importance of manned-integrated systems testing.

The LTA-8/LM-3 configuration (manned earth-orbital simulation — cold case): The LM test article was installed in the space simulation chamber, and the thermal environments were stabilized for the cold extreme of expected temperatures. The ECS anomalies which occurred during the cold test were for the most part connected with special ground-test hardware, procedure errors, and instrumentation anomalies. Descriptions of two significant failures follow.

The water separator (LSC-330-109) failed to start (during the second manning phase) until the third attempt. It was concluded that residual water from the previous manning phase was causing excessive friction which counteracted the low (gas flow) torque, thereby preventing a startup of the water separator. This problem had been identified during component testing; and a redesigned water separator, which develops more starting torque from the same gas flow, was certified for use in flight vehicles.

The carbon dioxide sensor (LSC-330-150) was indicating carbon dioxide partial pressures greater than 30 mm Hg during the second manning phase. Postflight analysis indicated that the sensor had failed because of environment incompatibility. Subsequent sensors for flight use were redesigned to reduce sensor susceptibility to moisture, to vibration, and to known circuit problems.

The LTA-8/LM-3 configuration (manned earth-orbital simulation — hot case): The space simulation chamber was stabilized for the hot extreme of expected flight temperatures. As in the cold test, most failures or anomalies were in special ground-test hardware and instrumentation. One significant failure, which justified major system redesign, is summarized in the following paragraph.

The secondary water/glycol loop (a backup life support and black-box cooling system) was designed to use the potable water system as an accumulator. Selection of the secondary loop punctured an isolation disk between the water system and the secondary glycol loop; and, at the same time, water was supplied to the secondary loop sublimators. During LTA-8 testing, the secondary loop glycol pressure was greater than the water system pressure at the time of secondary loop startup, causing the water/glycol mixture to enter the potable water system and to be supplied to the secondary loop sublimators. Because a water/glycol mixture has a freezing temperature below that of water, no ice layer was formed on the sublimator plates and breakthrough occurred.

As a result of the failure, the secondary glycol loop was redesigned, the potable water/glycol loop interface was removed, and a glycol accumulator (LSC-330-210) identical to the primary loop accumulator was installed. This configuration was certified in the subsequent LTA-8/LM-5 tests. With the exception of the secondary glycol loop failure, all ECS test objectives were satisfactorily completed.

The LTA-8/LM-5 configuration (manned lunar landing simulation): The LTA-8/LM-5 thermal-vacuum tests were performed to verify that the LM-5 vehicle thermal design and thermal control system were adequate for worst-case (predicted) lunar landing environments. The ECS performed within predictions for both the hot and cold mission simulations. The only anomaly which occurred was an out-of-specification temperature for the cabin temperature control valve (LSC-330-203). Because a subsequent design change eliminated the cabin heat exchanger and temperature control valve, no discussion of the test anomaly is given.

The LTA-8/LM-3 and LTA-8/LM-5 thermal-vacuum tests satisfied the following test objectives:

1. To demonstrate the capability of the vehicle environmental control system to provide a habitable environment in the cabin and pressure suit with the equipment operated in the earth-orbital and lunar landing mission-oriented thermal-vacuum environments

2. To demonstrate the capability of the WMS to supply water to the boilers properly in quantities consistent with heat levels generated by the equipment operating in all modes consistent with representative earth-orbital and lunar landing mission-oriented thermal-vacuum environments

3. To demonstrate the capability of the primary HTS to accept and to effectively dissipate the thermal loads generated by the electrical equipment and a crew when operated in modes consistent with earth-orbital and lunar landing mission-oriented thermal-vacuum environments

4. To demonstrate that the cabin pressure-shell leak rate will not exceed 0.2 pound per hour (The leakage shall be measured before the first manning, when the crew is not in the cabin, with a cabin pressure of 4.8 ± 0.2 psia and the vehicle operating in a representative earth-orbital and lunar landing mission-oriented thermal-vacuum environment.)

5. To demonstrate that, during unmanned and manned operations, the cabin atmosphere and suit loop contain no contaminants which would have an unacceptable physiological effect on the crew

6. To demonstrate the capability of the secondary HTS to accept and effectively dissipate the heat generated by electrical equipment, mounted on redundant cold plates and cold rails, when operated in modes consistent with earth-orbital and lunar landing mission-oriented thermal-vacuum environments

7. To show acceptable cabin depressurization operation under cold lunar conditions with the antibacteria filter installed on the cabin relief and dump valve (Cabin depressurization from 5.0 psia to 0.08 psia through the forward relief and dump valve shall not require more than 310 seconds.)

8. To show that the primary lithium hydroxide cartridge can be replaced while the cabin is depressurized and while the crew is supported by the vehicle environmental control systems

9. To determine the cabin temperature gradient, with and without cabin fan operation, when crew activity is at a low level

VEHICLE AND ACCEPTANCE TESTING

Acceptance tests were conducted on all deliverable ECS components or assemblies to provide assurance that the equipment performance was within the limits of the design parameters and that the equipment was free from material, construction, workmanship, and functional deficiencies. Prior to vehicle installation, most equipment received a preinstallation test to ensure that no damage had occurred during handling, shipment, or storage.

The vehicle level of acceptance consisted primarily of tests conducted on equipment installed in the vehicle, from individual section level to "fullup" (complete) systems test. A Customer Acceptance Readiness Review (CARR) was conducted on each vehicle for increased levels of testing. Phase I CARR was conducted after subsystem installation and served to identify constraints to subsystem testing. Phase II CARR was conducted prior to the start of Final Engineering Acceptance Tests (FEAT). Phase III CARR was conducted after FEAT to assess the readiness of vehicle acceptance and to obtain authorization to ship.

The basic intent of acceptance testing was to "wring out" completely an item on a component level. Unique test functions were generally impractical on the vehicle level. These tests were performed on the component or module only and included such tests as vibration, thermal cycling, proof pressure of tanks, and indepth component performance. Test functions were repeated only when the previous test results were violated by a change in stimuli or by a different installation procedure. In general, test functions on a component were reduced as the component progressed to the next level of assembly.

FLIGHT EXPERIENCE

Lunar Module 1 (Apollo 5)

The primary objectives for the LM-1 vehicle mission were to flight-verify the ascent and descent propulsion systems and the abort staging function. Because the vehicle was unmanned, only the ECS thermal control and its supporting functions were used during the mission. Life support hardware was included in the vehicle but was deactivated.

The glycol temperatures remained within predicted values throughout the mission. No anomalies were observed during the mission; however, ascent water tank number 2 instrumentation indicated a small leak prior to launch. No water leakage was detected, and a leak of the tank pressurant gas was suspected. The degree of leakage would not compromise the mission because water sufficient to complete the mission and pressurant gas were known to be available.

Lunar Module 3 (Apollo 9)

The ECS was activated three times and operated normally during the 26 hours of manned operation. All ECS operating procedures required for the lunar mission were verified. All components functioned according to plan with the exception of a valve position indicator on the LM pilot suit flow control valve, which gave erratic indications. This position indicator provides information for ground controllers and does not control any system operations.

The crew reported that the cabin noise was excessive during helmets-off operation. The noise was caused primarily by operation of the cabin fans and the glycol pumps. The flight procedures were changed to limit cabin fan operation at the discretion of the crew, and a noise reduction survey was initiated for the glycol pumps. A design change was made, effective on later vehicles, to reduce pumping system noise.

Lunar Module 4 (Apollo 10)

The ECS was activated for approximately 12 hours and performed satisfactorily. Loss of cabin pressure during LM jettison provided an opportunity to evaluate the ECS under a rapid decompression failure. The automatic functions of the suit loop were verified when the suit loop locked up at 4.4 psia. Additionally, satisfactory performance of the cabin pressure control logic was verified. This unplanned situation represented a severe test of the ECS, and all ECS functions were nominal.

The primary lithium hydroxide cartridge was returned to earth for analysis because of an indicated high rate of carbon dioxide increase, followed later by a decrease. Chemical and X-ray diffraction analyses of the cartridge indicated no evidence of cartridge malfunction. It was concluded that the lithium hydroxide chemical conversion variations, combined with sensor tolerances, accounted for the flight performance.

The crew reported that the drinking water contained gas. The nitrogen, used to pressurize the water system prior to launch, penetrates the tank bladder and slowly saturates the water at the fill pressure of 48 psia. As the absolute pressure is reduced, the dissolved nitrogen is released. The water hose and connecting plumbing were not serviced with water, and this entrapped air initially added to the problem. Prelaunch procedures were changed to include servicing the water hose and connecting plumbing.

The crew reported that the cabin was noisy, primarily because of the glycol pump. One cabin fan was used for approximately 30 minutes and was then turned off because it was not needed. The use of molded earpieces significantly attenuated the glycol pump noise.

Lunar Module 5 (Apollo 11)

The ECS satisfactorily supported all lunar operations with only minor exceptions. Depressurization of the cabin for the EVA required more time than predicted. The data indicate that the cabin pressure transducer was reading high at the low end of its range; consequently, the crew could have opened the hatch sooner if the true pressure had been known. Additionally, the requirement to use the bacteria filter which snaps onto the cabin dump valve was deleted for future missions. It was known that this filter slows down the gas flow, thus extending the cabin dump time slightly.

The carbon dioxide sensor output became erratic after lunar ascent. The carbon dioxide sensor samples the suit-circuit supply gas from a vent line connected to the condensate drain tank that was used during lunar surface activities. It is probable that some free condensate entered the sample line and was drawn into the carbon dioxide sensor. Any free water in the optics section of the sensor will disturb the IR signal and cause erratic performance. To preclude the introduction of water into the sensor from the drain tank, the vent line was relocated upstream of the suit fan on later vehicles.

During the sleep period on the lunar surface, the crewmen reported that they were too cold to sleep. Analysis of the conditions experienced indicated that, once the crewmen were in a cold condition, there was not enough heat available in the ECS to return them to a comfortable condition. In addition to the required procedural changes which were designed to maintain heat in the suit circuit, hammocks were provided for subsequent missions to improve crew comfort and to reduce heat conduction from the crewmen.

CONCLUDING REMARKS

Several generalized conclusions can be made from the development experience of the lunar module environmental control subsystem. The development problems of the state-of-the-art advances received considerable attention, and these were successfully overcome.

The discovery of a defect or an out-of-tolerance condition was followed by the determination of its cause. The most positive corrective action was then instituted to prevent recurrence, and this method of control proved to be successful.

Most of the problems experienced were caused by some human, small error which resulted in an imperfection in a unit. The system of checks and rechecks was quite successful in uncovering defects during ground testing as evidenced by considerable successes in flight.

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