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APOLLO EXPERIENCE REPORT - THE CRYOGENIC STORAGE SYSTEM

by William A. Chandler, Robert R. Rice,
and Robert K. Allgeier, Jr.

Manned Spacecraft Center
Houston, Texas 77058

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16. Abstract

A comprehensive review of the design, development, and flight history of the Apollo cryogenic storage system and of selected components within the system is presented in this report. In particular, discussions are presented on the developmental history of the pressure vessels, heaters, insulation, and selected components. Flight experience and operational difficulties are discussed in detail to provide definition of the problems and applicable corrective actions.

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APOLLO EXPERIENCE REPORT

THE CRYOGENIC STORAGE SYSTEM

By William A. Chandler, Robert R. Rice, and Robert K. Allgeier, Jr.
Manned Spacecraft Center

SUMMARY

The Apollo cryogenic storage system was designed, developed, and qualified to supply the fuel-cell reactants (hydrogen and oxygen) and metabolic oxygen to the three-man flight crew for 14 days. Supercritical storage was selected because it eliminated the need for development of venting and quantity-gaging systems for two-phase fluids in a low-gravity environment. Problems occurred in the early stages of this program in the development of pressure vessels, insulation, fans, heaters, and components; these problems resulted in changes in sources, concepts, processes, methods, or quality control. Later, problems developed in flight hardware that resulted in redesign and requalification of flight hardware. However, the development of this system, as was the case with many others in the Apollo Program, resulted in significant contributions to the advancement of the state of the art.

INTRODUCTION

During an Apollo mission, the cryogenic storage system (CSS) of the service module provides (1) oxygen for the flight crew and (2) oxygen as the oxidizer and hydrogen as the fuel for electrical power generation in the fuel-cell power generation system (PGS). This report presents a discussion of the functional and physical requirements for the CSS as it interfaces with other command and service module subsystems. Emphasis is placed on significant problems encountered during development and flight testing of the hardware and on appropriate corrective action applied to these problems.

DESIGN CONSIDERATIONS

The fluid requirements for the CSS were established from a compilation of the PGS and environmental control system (ECS) flow profiles. The PGS imposed significant reactant-purity requirements and the ECS imposed the highest system flow rates. The storage containers for the CSS are double-walled, vacuum-jacketed storage containers called dewars, named after the inventor Sir James Dewar, a Scottish physicist and chemist. Each hydrogen dewar contains 28.14 pounds of usable hydrogen and each oxygen dewar contains 323.45 pounds of usable oxygen when maximum fill conditions are met. In the four-dewar configuration, therefore, the total quantities were 56.28 pounds of usable hydrogen and 646.9 pounds of usable oxygen. The hydrogen is dedicated for fuel-cell use, and approximately 450 pounds of oxygen of the 646-pound total is consumed by the fuel cells. Nominally, ECS consumption is 1.8 pounds of oxygen per man-day, which would require a total of approximately 75 pounds for a three-man crew on a 14-day mission. The remaining 121 pounds of ECS oxygen is provided for cabin pressurization, leakage, and emergency return. To avoid venting, the CSS thermodynamic design balances the energy input caused by normal heat leak into the system with the energy removed because of the minimum-demand flow from the system. The CSS dewars, however, necessitate the use of a heat source for pressure maintenance when flow rates exceed the equilibrium flow rate.

At gravity levels below approximately 10^{-8} g, and with the temperature levels of concern here, the dominant mode of heat transfer to fluids is conduction. In such an environment, high heat rates from small areas can result in zones of fluid adjacent to the heater with significant temperature and density gradients. Such zones are said to be thermally stratified. Vehicle accelerations can suddenly mix these thermally stratified zones and under some fluid conditions can result in significant pressure decays. Obviously, forced circulation of the fluid would circumvent the potential problem of thermal stratification.

The original heaters in the Apollo dewars were concentric, perforated, hollow aluminum spheres coated with "Electrofilm" heaters. These heaters were rejected for a more positive approach that involved the use of an electric-motor-driven fan mounted at each end of a cylindrical heater element. This change reduced the weight and improved the system reliability and inflight performance.

Cryogenic Storage System Power Requirements

Electrical power is required for the CSS heaters, fans, quantity probe, and solenoid valves. The power requirements vary throughout the mission because of varying flow rates from the tanks and changing thermodynamic conditions within the tanks. The quantity-probe and solenoid-valve power requirements are negligible. The heaters use 28-volt dc bus voltage and are rated at 114.9 and 19.0 watts for the oxygen and hydrogen heaters, respectively. The fans use 115-volt, 400-hertz ac from the spacecraft inverters. The hydrogen fans use 7.0 watts, and the oxygen fans that were used in the dewars through the Apollo 13 mission used 52.8 watts.

System Description

The CSS comprises the elements for the separate storage and distribution of oxygen and hydrogen. For flights through Apollo 13, the CSS contained two oxygen- and two hydrogen-storage dewars. A third oxygen dewar was added on Apollo 14 and subsequent spacecraft, and a third hydrogen dewar was added on Apollo 15 and subsequent spacecraft.

These system arrangements are shown schematically in figures 1, 2, and 3. The third tanks were required for the J-series missions on Apollo 15 and subsequent flights; however, the third oxygen dewar was added for redundancy on the Apollo 14 spacecraft after a total failure of the Apollo 13 oxygen system.

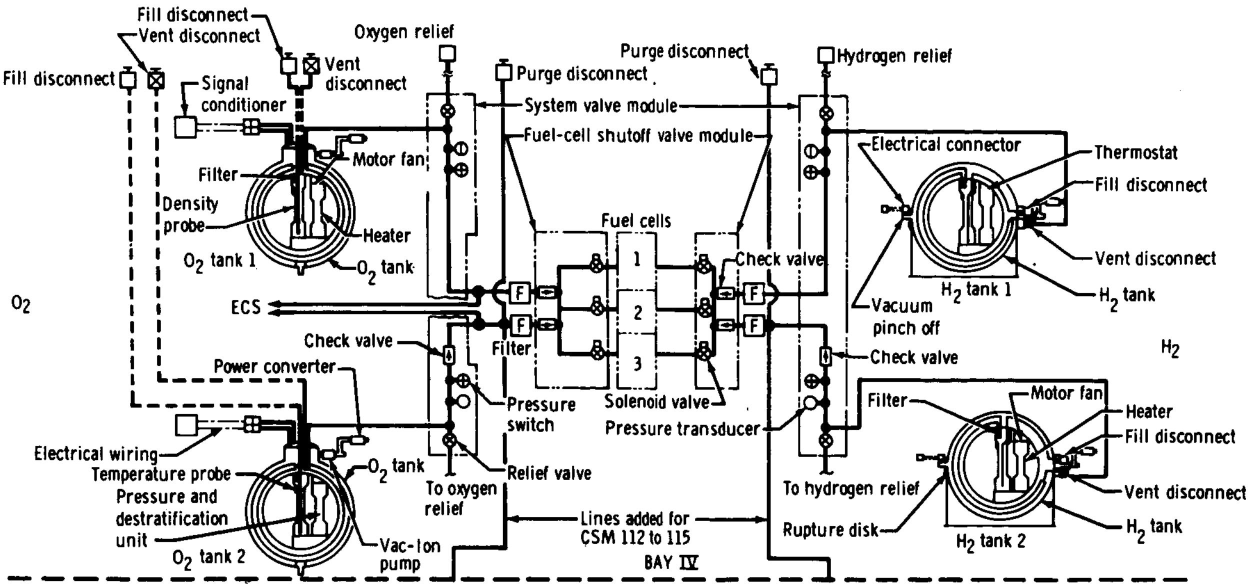


Figure 1. - Apollo 13 CSS configuration.

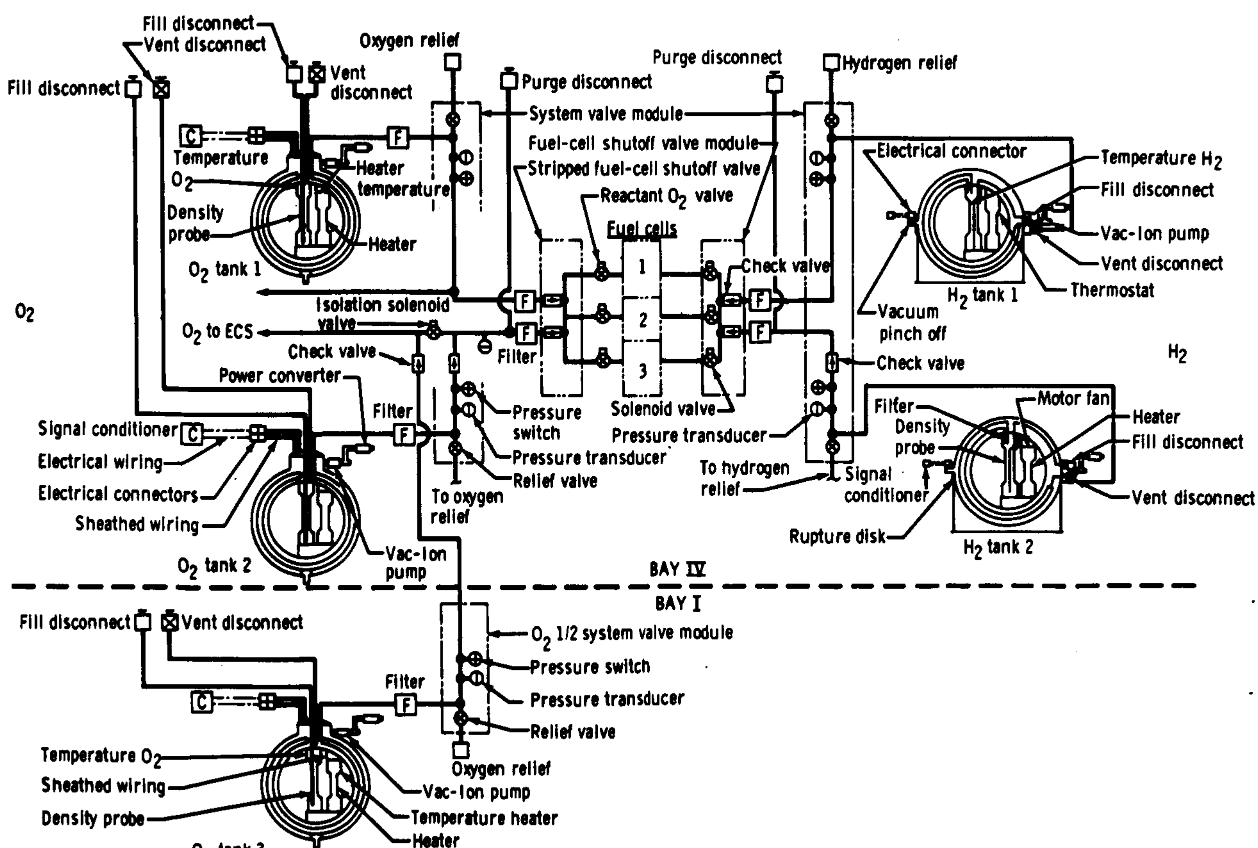


Figure 2. - The CSS configuration, redesigned for Apollo 14.

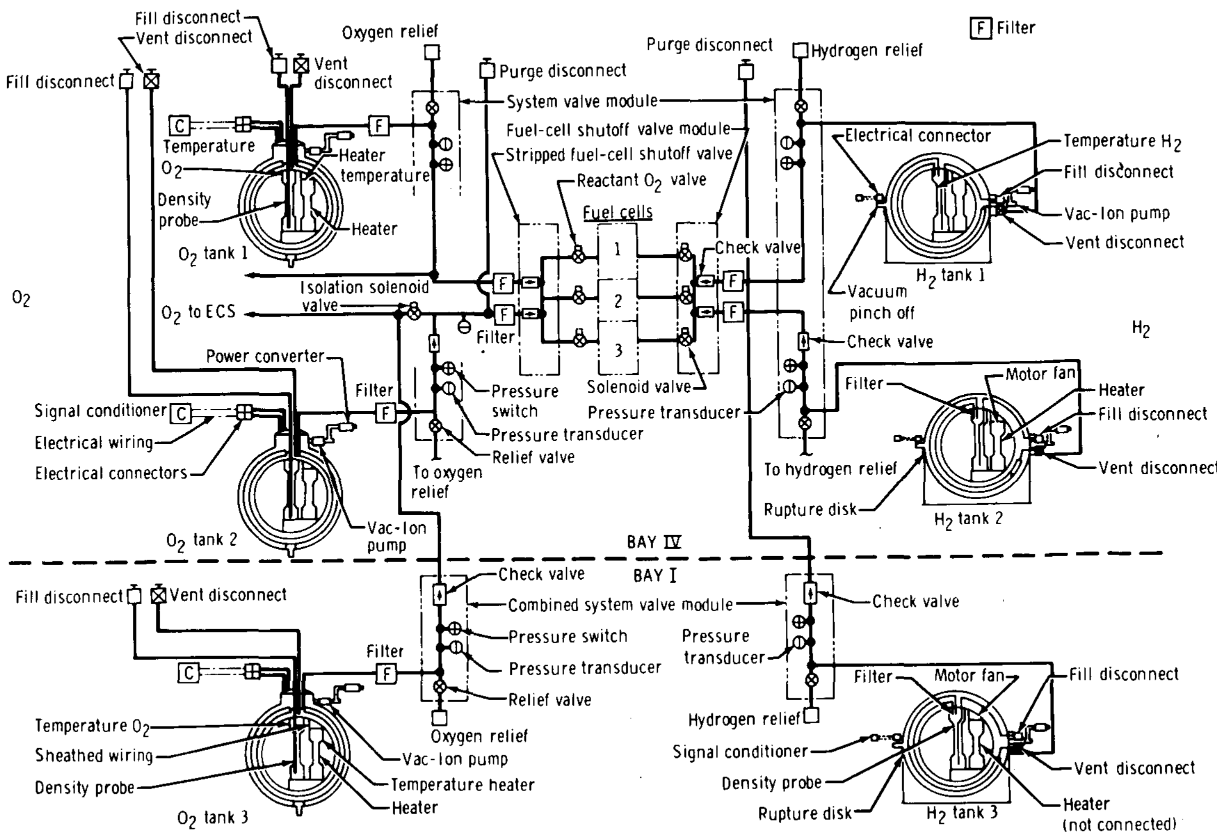
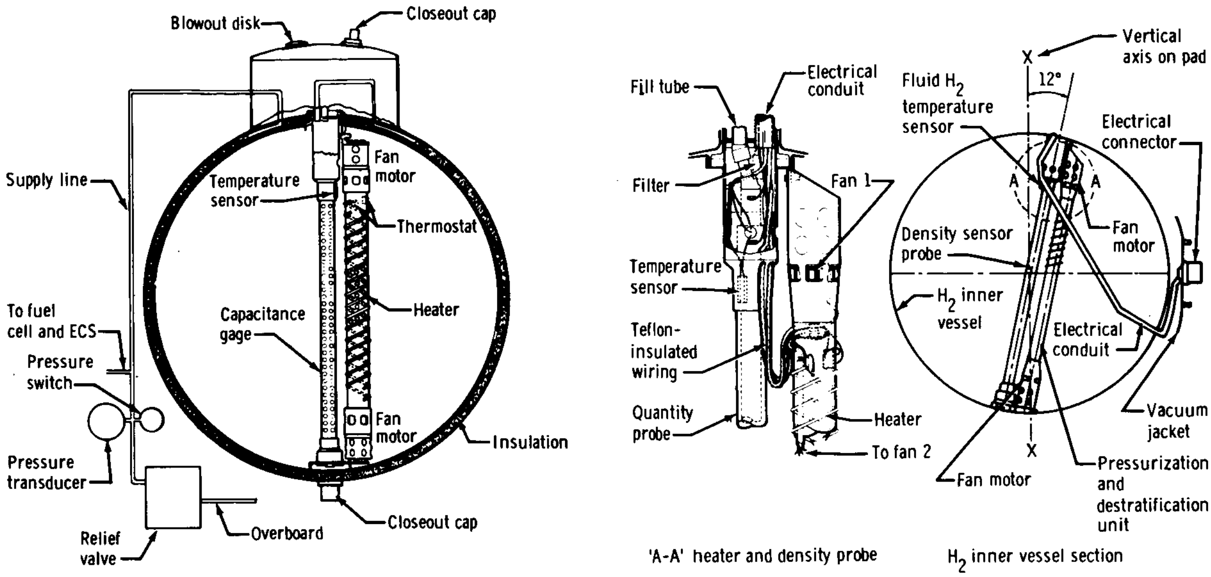


Figure 3. - The CSS configuration, redesigned for Apollo 15.

Under normal conditions, the dewars are depleted uniformly so that, at any time during the mission, emergency quantities of each fluid are available in each dewar. Equal depletion is maintained automatically by a feature of the heater logic; however, the internal heaters had to be operated occasionally in the manual mode to balance the quantities.

Cutaway views of both the oxygen dewar and the hydrogen dewar are shown in figure 4. Each dewar consists of an inner pressure vessel and an outer vacuum shell with evacuated multilayer insulation in the annulus between the two concentric spheres. The inner pressure vessel contains a capacitance probe for fluid-quantity measurement, a heater element to provide energy to the fluid for pressure maintenance, and temperature sensors that provide an indication of bulk-fluid temperature.

The individual dewars are equipped with check valves for automatic isolation in the event of an external leak. Where additional dewars were installed, they were incorporated into one side of the two existing parallel loops (figs. 1, 2, and 3).



(a) Oxygen tank. (b) Hydrogen tank.

Figure 4. - Apollo 13 tank designs.

DEVELOPMENTAL DIFFICULTIES

Pressure Vessels

The storage of supercritical hydrogen and oxygen required judicious selection of pressure-vessel materials. A materials screening program led to the selection of type 5Al-2.5Sn titanium alloy for the hydrogen storage and Inconel 718 alloy for the oxygen storage. These materials were selected because they had attractive combinations of weight, strength, ductility, and compatibility over the operating temperature ranges. In the early CSS program developmental stages, several titanium-alloy pressure-vessel problems occurred. One problem was control of material grain size during the forging process, which resulted in a high rejection rate of forged parts and in schedule slippage. The problem was attributed to a lack of adherence to accepted standards in temperature control of parts during forging; the problem was finally resolved by changing the forging vendor.

One hydrogen pressure vessel failed prematurely during a gaseous-nitrogen proof-pressure test. A failure analysis was conducted on the vessel fragments, and it was concluded that the vessel had failed because of room-temperature creep. Subsequently, creep tests performed on standard tensile specimens indicated that no creep occurred below a stress level of 75 percent of the actual yield strength. The problem was resolved by increasing the pressure-vessel wall thickness from 0.032 to 0.044 inch, thus reducing the stress levels below the creep threshold. This wall thickness increase resulted in a working-stress level of approximately 52 percent of tensile yield strength based on the certified yield strength of the material.

Titanium hydride formation, growth, and spalling were found to be the cause of failure of the vent-disconnect welds on an early hydrogen engineering model. By subsequent analyses of other hydrogen-tank failures, the hydride formation was found not to be restricted to only the vent-disconnect region, but occurred in other plumbing lines as well. No hydride formation was found in the pressure vessel. The problem was found to be affected partially by process and procedural variables. However, optimizing the processes only delayed the start of formation. With controlled variables, the life expectancy could be increased only from approximately 200 to approximately 400 hours total exposure. The problem was finally resolved by replacing the titanium plumbing lines with type 304L stainless-steel tubing. After this change, hydrogen test article 0015 was exposed to a hydrogen atmosphere for more than 2000 hours and there was no evidence of hydride formation.

A number of methods for joining the titanium-alloy pressure vessel to the stainless-steel tubing were investigated. These methods ranged from explosive bonding to brazing. Tests of some of these types of joints under simulated service conditions indicated that coextrusion was the superior method. Subsequently, many tests were performed on the coextruded combination. These tests simulated both fabrication and service conditions. After successful testing, redesign was implemented and production was initiated using the coextruded transition joints with stainless-steel plumbing lines. Nine transition joints failed leak check after a cold shock in liquid hydrogen before assembly. These failures were found to be caused by a fabrication process error, which was subsequently corrected. The coextrusion method proved to be very successful, with the exception of one joint leak that occurred during the Apollo 12 mission (discussed in the section of this report entitled "Flight-Hardware Problems").

Both the titanium-alloy and the Inconel pressure vessels were welded by electron-beam welding. An initial problem was the lack of required acceptable reliability and confidence levels before the process could be approved. In addition, no specifications or criteria were available to use as reference material in the design of the weld joints. Also, there were conflicts between customer requirements and the manufacturer's projected specifications regarding the postweld treatment for stress relief. These problems were solved by a complete and meticulously detailed test program to qualify the electron-beam welding process and to prove its value as a space-age technique.

The significant problems in the development of the electron-beam welding process for this application were the machining of the joints and the preparation of the surfaces (because of the extremely small tolerances for gap and mismatch) and operator error in making the weld itself. The quality of the weld was found to be related directly to the experience of the electron-beam weld operator. A 0.010-inch offset of the electron beam from the joint could result in an incomplete fusion that, in some cases, could not be detected by X-ray inspection techniques. A borescope was used for weld inspection, and the results of the nondestructive proof-pressure test were proof of the quality of the vessel.

Heaters and Fans

The original heaters were concentric aluminum spheres that were perforated with lightening holes to reduce weight. The heater was a high-resistance film (Electrofilm) that was sprayed over the aluminum spheres. This approach was rejected in favor of the fan and heater combination, which reduced weight and provided fluid mixing. In the fan and heater approach, a fan was installed at each end of a perforated, cylindrical tube. The heater element was brazed in a "barberpole" manner around the tube, as shown in figure 4. The fans provided adequate mixing of the fluid to minimize stratification and significantly increased the ability to transfer heat.

The electric motors used in the Apollo dewars were developed for another purpose and adapted to this application. However, considerable effort was required in redesign, quality control, and contamination control before an adequate degree of reliability was achieved. Among the redesign changes were an increase in air gap between the rotor and the stator, the addition of a sleeve over the rotor, and bearing changes. The motors were redundant; one was mounted at each end of the heater tube.

Insulation

The insulation schemes for the Apollo dewars were developed through extensive analytical efforts and optimized by a comprehensive test program. The test program was conducted by use of removable outer shells that were clamped together; then the entire assembly was placed in a vacuum chamber. This configuration permitted rapid modification of the test article. The results of these tests led to the conclusion that a vapor-cooled shield would be required to achieve the specification thermal performance. The vapor-cooled shield provides an intermediate cold-boundary layer within the insulation. The shield consists of a layer of 0.004-inch-thick aluminum foil, to which the vapor-supply line is cemented. The aluminum foil readily conducts heat, which is intercepted by the supply fluid and carried downstream away from the storage vessel. The insulation scheme that was selected consisted of alternate layers of aluminum foil, Dexiglas paper, and preformed fiber-glass strips. The oxygen dewar had eight sequences of insulation, and the hydrogen tank had 28 sequences. One insulation sequence consisted of six layers: three of aluminum foil (each 0.0005 inch thick), two of paper, and one of fiber glass. The vapor-cooled shield was placed midway between the inner and outer vessels. This insulation scheme was later changed in the hydrogen tanks for two reasons: to improve thermal performance within acceptable limits and to reduce weight. The first insulation scheme was completely load bearing; that is, the total fluid and pressure-vessel loads were transmitted uniformly through the insulation to the outer shell. The method that was used to insulate the hydrogen tanks for Block II spacecraft was semiload bearing; that is, straps of load-bearing insulation encircled the pressure vessel (contacting only a small percentage of the pressure-vessel area) and contacted the outer shell at specific points where the load was transmitted to a girth ring. Insulation interspaced between the straps consisted of gold-coated H-film and a vapor-cooled shield. This design has provided excellent thermal performance, and near the end of the production program, all the dewars were rated significantly better than the required specification heat-leak rate.

Outer Shells

The original outer shells were chemically milled in a waffle pattern to reduce the outer-shell weight. This approach was deleted and a monocoque outer shell was adopted, primarily because of manufacturing costs. The first monocoque outer shells were

0.012 inch thick and had buckling problems. Subsequently, the thickness was increased to 0.020 inch, and better contour-tolerance control was implemented.

Adequate thermal performance of insulation is dependent upon achieving and maintaining a pressure level within the insulation to minimize gas conduction. Normally, the insulation is evacuated at an elevated temperature to boil off residual surface gases. When the insulation cools, a stable vacuum of 1×10^{-5} torr or lower is achieved.

During Block II qualification tests, it was found that vibration caused a degradation in the vacuum level. This problem was corrected by the installation of Vac-Ion pumps on the outer shells of all tanks. The Vac-Ion pumps have proved successful in maintaining a good vacuum, and they also provide a check on the annulus vacuum level. Previously, thermal-performance degradation could be checked only after servicing with the cryogenic fluid. The Vac-Ion pump package consists of a 1-liter/sec vacuum pump and a high-voltage-output dc-to-dc converter. The converter high-voltage output is supplied to the Vac-Ion pump through shielded high-voltage wires.

Most of the problems associated with the Vac-Ion pump package were of a random nature and usually occurred because of improper handling on the part of operators. However, one major problem occurred: electromagnetic interference (emi) caused by corona conditions in the converter. This problem was first discovered at NASA Kennedy Space Center before the launching of the Apollo 7 mission. By pulling various component fuses, the problem was isolated to the Vac-Ion pump package. The Vac-Ion pump packages were emi tested in a vacuum chamber, and air-leak paths from high-voltage areas were present in both the pump and the converter potting. At altitude, leakage through these paths causes corona conditions. Development of better vacuum-potting techniques allowed the pumps to be requalified for flight.

FLIGHT-HARDWARE PROBLEMS

Only three flight problems that occurred in the CSS are considered significant enough to report here. These problems occurred on Apollo flights 9, 12, and 13. In addition, the performance of the CSS during the Apollo 14 mission is discussed because Apollo 14 was the first flight to use the redesigned oxygen dewars following the oxygen-tank failure on Apollo 13.

Apollo 9

During the Apollo 9 flight, a failure occurred in the automatic pressure-control system of the hydrogen tank. The pressure-control system, shown schematically in figure 5, primarily consists of two pressure switches, one in each tank system. These switches are installed in a series-parallel arrangement with a motor switch and the associated circuitry. The logic of this system is that both pressure switches must close to activate the heaters; however, the opening of one pressure switch will deactivate the heaters. The first indication of failure occurred at a ground elapsed time (g.e.t.) of 93 hours, when the heaters failed to activate at the lower limit of 225 psia. At this time, the heaters in hydrogen tank 1 were in "AUTO" and the hydrogen tank 2 heaters

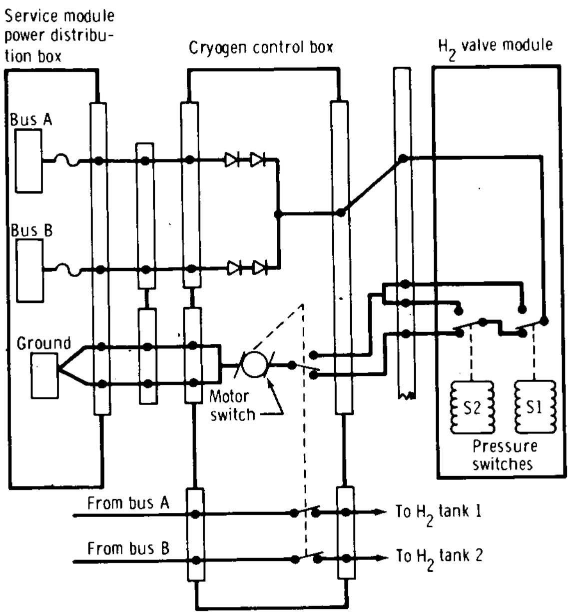


Figure 5. - Schematic of the hydrogen tank automatic pressure-control system.

were "OFF." This failure could have been caused by either of the pressure switches or the motor switch failing to close. The tank 2 heaters then were placed in the AUTO position with no effect, and the tank pressures decayed to approximately 210 psia. At this time (95:43 g. e. t.), the tank 2 fans were turned on to arrest the pressure decay. The fans in tank 2 were then turned off at 100:13 g. e. t. When the lunar module was undocked (101:22 g. e. t.), the tank heaters came on and pressurized the tanks to approximately 270 psia. The automatic cutoff point was passed, and the crewmen were required to deactivate the heaters. This failure mode requires that both pressure switches fail closed or that the motor switch fail to open. It should be noted that this second failure mode is in conflict with the first failure mode.

Because there are three components in series (two pressure switches and one motor switch), there is no possibility to identify positively which component failed. Because the second failure would have required that both pressure switches fail closed, there is reason to believe that there was a probable intermittent failure of the motor switch or its circuitry.

As a result of the automatic-pressure-control-system failure, the hydrogen-system pressure was controlled by operating the fans in a manual mode throughout the remainder of the mission. This manual mode was the recommended contingency procedure, and no constraints to the mission resulted from this type of operation.

During the postflight investigation, a determination was made that terminal board number 9 (part number MD417-0018-0001) had 16-gage wire to supply the motor switch with power. There was a history of one intermittent-type failure using this type of terminal board with 16-gage wire. An intermittent open failure between selected pins could have been responsible for both the closed and the open modes of failure. During the investigation of the 16-gage-wire terminal boards, a discrepancy was found in the manufacturing process and corrective actions were instituted. Additionally, the suspect boards were removed from the program on a criticality basis, and this problem never recurred.

Apollo 12

During the Apollo 12 cryogenic loading, approximately 51 hours before the scheduled launch, the performance of hydrogen tank 2 was found to be unacceptable because the tank filled much slower than normal and had a higher than normal boiloff rate during the thermal stabilization period. By visual inspection of the tank, a thick layer of frost was noted on the tank exterior, indicating a loss of vacuum in the annulus. The tank was replaced with a tank from the Apollo 13 spacecraft, and cryogenic loading was completed satisfactorily.

A failure analysis, performed before launch, resulted in identification of the cause of the vacuum loss: a leak in the bimetallic titanium/stainless-steel transition joint. The leak resulted from an incomplete bond in the joint, which permitted hydrogen to leak from the inner tank into the annulus. Investigation revealed that improper inspection of the bimetallic joint during manufacture had allowed voids between the metal surfaces to pass unnoticed. The failed joint was manufactured in lot 3B, and lot 3A also was suspected of having poor-quality joints. The reason for this suspicion was the random location of the joints in the lots that failed the inspection process. These failures had escaped detection under the quality system that was in use at the time and, as a result, they were not reported. Only four other tanks from these two lots remained in the program; these tanks were recalled for replacement of the questionable bimetallic joints.

The following corrective actions were taken to ensure that no more bad joints would pass inspection.

1. A special chemical and inclusion analysis was conducted for the raw material.

2. Metallurgical samples were taken from the ends and middle of each billet.

3. A new ultrasonic inspection against a standard was instituted.

4. All failures were to be reported and examined for their lot location.

Apollo 13

During the Apollo 13 mission, oxygen tank 2 failed at 55:53:20 hours into the mission and subsequently caused the loss of the complete cryogenic oxygen system. The mission was aborted and the crewmen were returned safely. To solve this problem, an Accident Investigation Board was formed. Based on flight analysis and ground test data, the board reached the following conclusions:

1. Two protective tank-heater thermal switches failed closed during an abnormal detanking procedure used on the pad. The failed switches allowed continuous ground-support equipment (GSE) heater power to be applied, which led to severe damage of the fan-motor wire insulation.

2. The failure of the thermal switches was caused by a design incompatibility between the switches and the GSE power.

3. The detanking problem that occurred during the countdown demonstration test was the result of loose or misalined fill-line plumbing components within the tank.

4. A fire was started by electrical short circuits in the wiring to the fan motors inside oxygen tank 2 shortly after the fan circuits were energized for the seventh time.

5. Burning of the insulation proceeded for approximately 80 seconds before reaching the pressure-vessel electrical conduit, through which all electrical tank wiring passes. The heat from the burning insulation first caused failure of the Inconel conduit and ultimately led to the failure of the vacuum dome and to separation of the bay IV structural panel.

6. The internal component design of the tank is such that possible damage can go undetected. Furthermore, the plumbing parts have tolerance allowables that can build up so that normal detanking is prevented.

7. The design of the warning system for indicating the position of the reactant valves to the fuel cells does not allow detection of individual valve closures to any fuel cell, a condition that existed during this incident.

As a result of the Apollo 13 failure, the cryogenic oxygen dewar was redesigned to include the following items.

1. The fan motors were removed to minimize the amount of combustible materials within the dewar and to reduce potential ignition sources.

2. The Teflon-insulated wire was replaced with stainless-steel-encased wire with refrasil (SiO_2) and magnesium oxide (MgO) insulation to minimize the amount of combustible materials within the dewar.

3. The five-piece fill tube was replaced with a single tube.

4. A temperature sensor was added to monitor the heater temperature.

5. The internal filter was placed external to the tank.

6. The bulk-fluid temperature sensor was relocated in the boss area (fig. 6).

These changes are illustrated in figure 7 and, as can be seen, few components were unaffected. In addition, the oxygen reactant valves were replaced with valves that contained no Teflon.

Because the fan motors were deleted from the tanks, the thermal performance of the heater depends to a large extent on the effective gravity level. This occurs because the heat from the heater must be transferred to the fluid primarily by natural convective processes. Obviously, the conditions that dominate these processes cannot be duplicated in a terrestrial environment. This problem, together with the fact that the first flight of this new system would be a lunar mission, dictated that extensive analysis, checkout, and testing programs be conducted. The analytical effort required by this redesign was concentrated on the stratification and heat transfer in low-gravity (10^{-6}g to 10^{-8}g) levels.

Because of the technical risk involved with the fan-motor removal, a parallel approach was taken. An external pump to circulate and mix the oxygen was designed and qualified. This pump was designed with a magnetic coupling so that none of the electrical components were in contact with the oxygen.

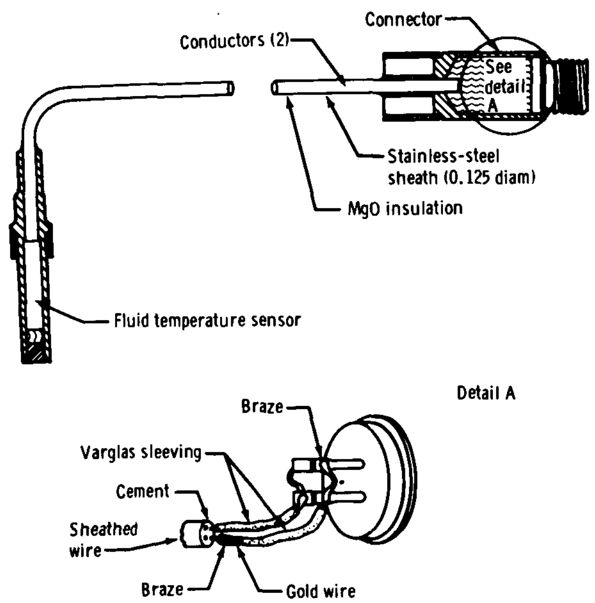


Figure 6. - Fluid temperature (O_2) electrical connector.

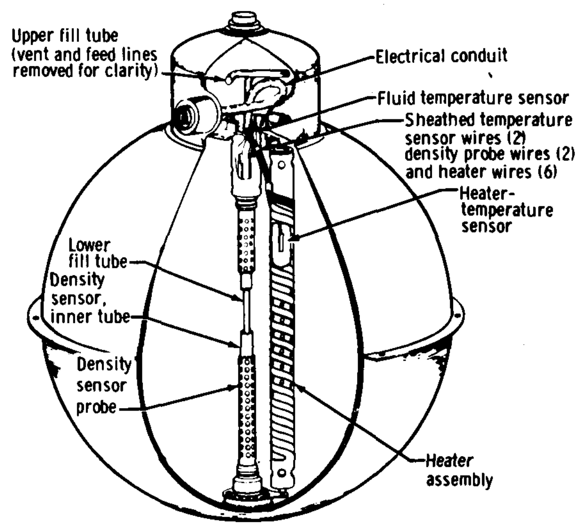


Figure 7. - Redesigned Apollo 14 oxygen tank.

Because of the open issue of forced convection at low densities, a third tank was added to the Apollo 14 system to ensure that, even in the event of a failure of one of the tanks, a return could be made without entering fluid density regions that had not been previously encountered in flight with no fan-motor operation. A flight demonstration test was conducted during the Apollo 14 mission, and the subsequent analysis resulted in the following conclusions.

1. The alternate design approach using an external circulation pump is not required on Apollo 15 and subsequent spacecraft.

2. Large thermal gradients exist on the heater, and the specific temperature profiles are strong functions of gravity level.

3. The location of heater-temperature sensors is critical in flight systems.

4. Stratification does not affect the thermal efficiency of the system.

CONCLUDING REMARKS

The successful development of the Apollo cryogenic storage system resulted in significant technological developments for cryogenic applications, particularly in fabrication and welding of pressure-vessel shells, metallurgy associated with titanium creep and hydride formation, application of bimetallic joints, application of vapor-cooled shields in high-performance insulation, and vacuum acquisition and retention. Most of these advances are directly applicable to other required cryogenic developmental programs, such as the space shuttle.

Additionally, the results of preflight analytical predictions, flight data, and subsequent analytical correlations have contributed much data on heat transfer and stratification of cryogens at low-gravity levels. Analytical tools have been developed and correlated with flight data to such an extent that a high degree of confidence now exists in the analytical approaches.

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