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APOLLO EXPERIENCE REPORT - POWER GENERATION SYSTEM

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16. Abstract

A comprehensive review of the design philosophy and experience of the Apollo electrical power generation system is presented. The review of the system covers a period of 8 years, from conception through the Apollo 12 lunar-landing mission. The program progressed from the definition phase to hardware design, system development and qualification, and, ultimately, to the flight phase. Several problems were encountered; however, a technology evolved that enabled resolution of the problems and resulted in a fully manrated power generation system. These problems are defined and examined, and the corrective action taken is discussed. Several recommendations are made to preclude similar occurrences and to provide a more reliable fuel-cell power system.

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APOLLO EXPERIENCE REPORT

POWER GENERATION SYSTEM

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SUMMARY

The Apollo power generation system consisted of three fuel-cell modules that were designed and qualified to generate electrical energy at a rate of approximately 2 kilowatts for a 14-day mission. The fuel cells used cryogenically stored hydrogen and oxygen as the reactants, which were supplied to the fuel cells in the form of high-pressure gases. Thermal control of the fuel cells was provided by the use of independent thermal control systems that rejected heat from radiators mounted on the skin of the spacecraft.

The Apollo fuel cell was the first practical application of a high-temperature hydrogen/oxygen fuel cell. The design, because it was selected at an early developmental stage, resulted in many inherent system-design deficiencies that made the fuel cells sensitive to operator error. Thus, many operational problems were encountered that had to be identified and resolved. The eventual solutions to the problems created new functional modes and better defined nonoperating modes of the fuel cells.

Hardware development was difficult in fuel-cell design because of the functional environment of the components. For example, electrolyte seals had to be developed that would maintain their shape and sealing capability at 500° F in a solution of potassium hydroxide. Also, a lightweight, highly reliable, long-life pump had to be developed that would operate at 200° F in a 60-psi wet-hydrogen environment. Additionally, the development of a highly reliable low-power glycol pump that could function at temperature extremes of -40° to 180° F was required.

After the fuel-cell components were designed, built, and tested, quantity production was necessary for support of the flight program. A new set of problems (such as process controls, contamination, spares production, and traceability) evolved. Although these were not considered major problems, careful control was required so that reliable flight-qualified hardware was produced.

The Apollo space flights were relatively free of fuel-cell failures. One problem that was noted early in the program was related to the secondary coolant loop. Air and particulate contamination held immobile in a one-g environment was released during the low-gravity phase of the flight. This phenomenon resulted in the loss of thermal-control capabilities for the secondary coolant loop. New checkout techniques and procedures minimized these conditions on future flights. An oscillating condenser-exit temperature was another flight problem. After many tests and analyses, the cause of the problem was determined to be another low-gravity effect that was not detrimental

to the fuel cell. Corrective inflight operations that could be used to control such oscillations were determined but never were required.

INTRODUCTION

In 8 years, the Apollo Program electrical power system progressed from the definition phase to the hardware design, system development and qualification, and ultimately, to the flight phase. Although a number of problems were encountered, resolution of the problems resulted in a satisfactory electrical power system.

The primary power generation system (PGS) that was developed had to generate electrical energy at a rate of approximately 2 kilowatts for a 14-day mission. The system had to possess adequate mission flexibility; for example, no constraints could be imposed on launch dates, photographic reconnaissance time, or navigational observation time. In addition, it had to be operationally adaptable to changing requirements for successive missions without a subsequent requirement for design changes.

High reliability and safety that were consistent with system weight were prime considerations. The concept of redundancy greatly increased the reliability of most candidate systems. Factors affecting reliability, such as multiple starts, were to be avoided, and simplicity of design was desired.

In addition to normal operational requirements, other requirements were imposed. The requirements involved operational considerations for the crewmen (minimum noise and vibration in addition to operational simplicity), integration with other vehicle systems, high heat-rejection temperature for heat-engine concepts, system volume, minimum development time, and minimum cost. After a number of electrical power systems were considered, the fuel cell system ultimately was selected. The advantages of the fuel cell system included the fuel-cell developmental status and availability, the relatively light weight of the system, and the greater degree of flexibility than existed in the other systems that were considered. The use of fuel cells in place of solar arrays resulted in simplified launch preparations and rendezvous maneuvers and the use of less fuel for attitude-control maneuvers. Also, extended periods of nonsolar orientation were possible for guidance fixes and star tracking. Batteries would be required to supply peaking power during high-load-demand periods. In addition, power to meet load demands during the entry phase (after the fuel cells were jettisoned) would be supplied by entry batteries.

After fuel cells were selected as the PGS, the mission requirements for electrical energy were refined, and a procurement specification stipulated that the PGS would have the capability of generating 575 kW-hr of electrical energy from three fuel cells at a minimum rate of 563 watts and at a maximum rate of 1420 watts per fuel-cell module.

DESIGN CONSIDERATIONS

Before the design for the Apollo PGS could be selected, the operational requirements had to be known. After the requirements were determined, a number of electrical power system designs were developed. The design that contained the best features was selected for further refinements.

Requirements

The Apollo PGS had to generate, supply, regulate, and condition all electrical power required by the command and service module (CSM) for the duration of a full mission, including recovery but excluding the life support system requirements. The specific requirement was the generation of electrical energy at a rate of approximately 2 kilowatts for a 14-day mission.

System Selection

In the process of selecting a power system to meet these requirements, all known solar, nuclear, and chemical conversion techniques were investigated individually; appropriate combinations of individual systems also were considered. Many designs that were suggested by vendors and NASA were studied and rated with respect to weight, reliability, safety, power capability, tolerance to the mission-environment profile, and mission flexibility. With respect to developmental status and availability, a requirement was that all designs were to be free of any known development-improvement requirements that might seriously impact program costs and schedules.

System Description

The system that was selected was composed of three alkaline fuel cells, one of which is shown in figure 1. The schematic diagram of the PGS (fig. 2) contains views of the three fuel-cell modules that are integrated with two hydrogen-storage tanks and two oxygen-storage tanks. Hydrogen and oxygen are used as the fuel and oxidizer. The resultant electrochemical reaction in the fuel cell produces electricity and water. The water is a byproduct and is used for the environmental control system for cooling and is consumed by the crewmembers.

Each Apollo fuel-cell module produces direct-current electrical power over a normal range of 563 to 1420 watts at a voltage of 27 to 31 volts. The module is 44 inches high and 22.5 inches in diameter and weighs approximately 245 pounds. Each module is composed of four distinct sections or systems: an energy-conversion section, a reactant-control

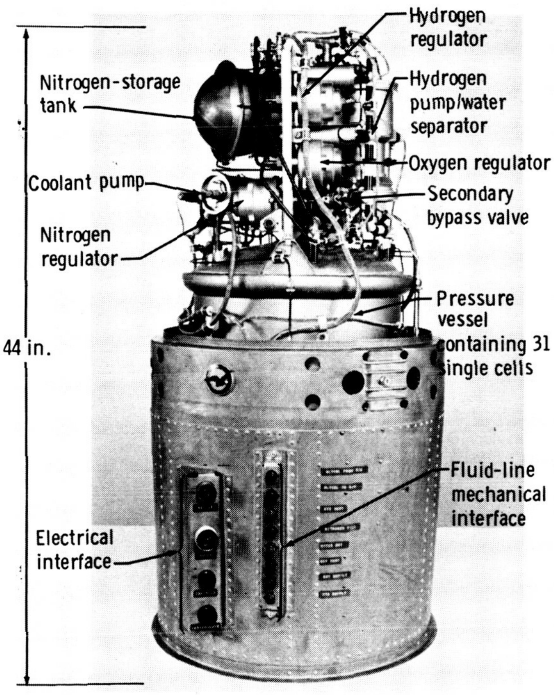
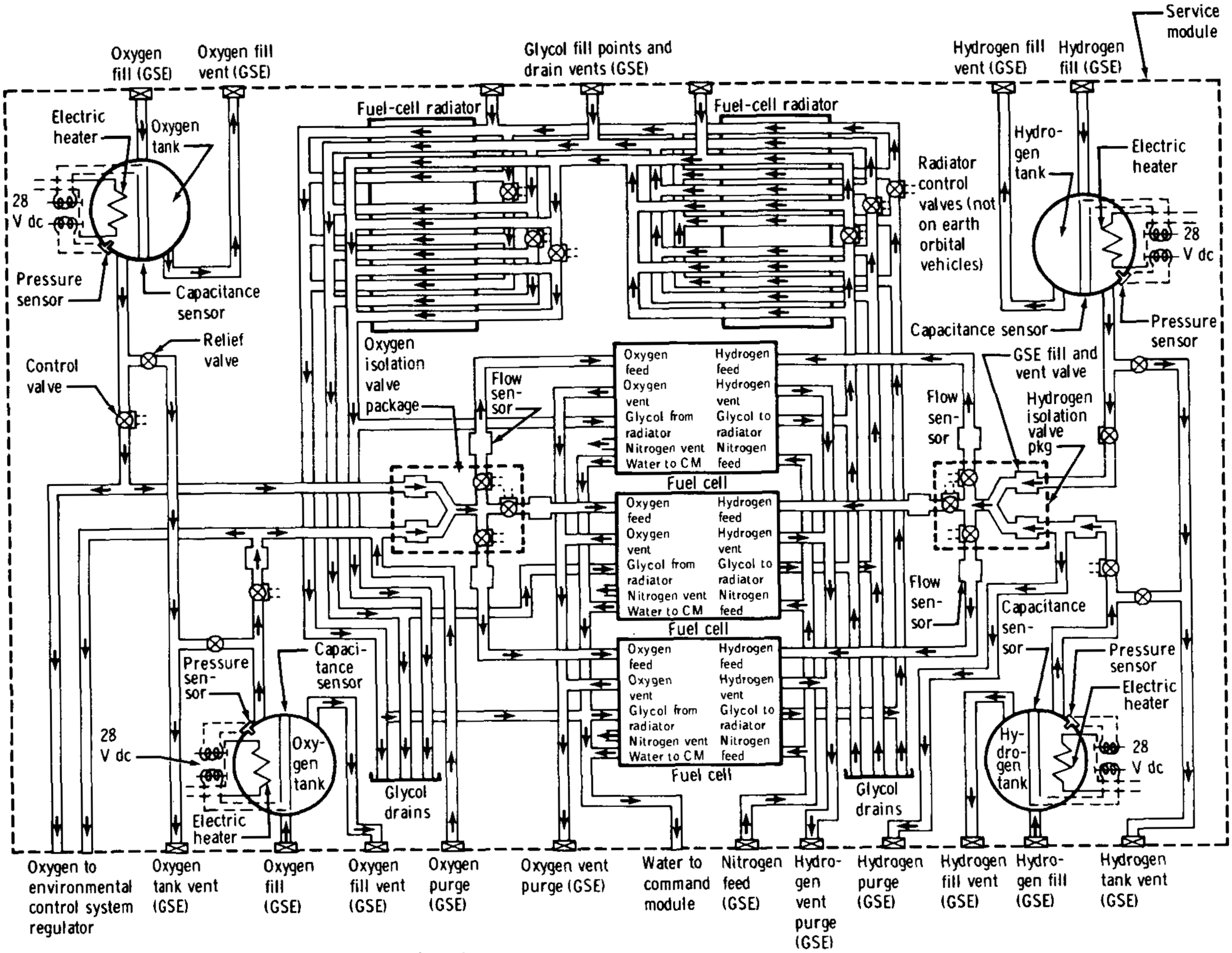


Figure 1. - Apollo fuel-cell module.



Note: GSE = ground-support equipment
CM = command module

Figure 2. - Simplified power generation system schematic.

section, a thermal-control and water-removal section, and the necessary instrumentation. Except for the energy-conversion section, all of these sections are included in the accessory portion of the fuel cell.

The energy-conversion section, shown in figure 3, consists of a cell stack composed of 31 alkaline series-connected cells and the associated gas manifolds and connecting leads. The energy-conversion section is housed in a pressurized jacket that is in an insulated support assembly. The single-cell assembly (fig. 4) converts the chemical energy of the reactants to electrical energy and byproduct water. It consists of two half cells; hydrogen is the anode and oxygen is the cathode. The electrolyte between the half cells is an 80-percent aqueous solution of potassium hydroxide (KOH). A Teflon seal around the cell contains the electrolyte in the cell and provides electrical insulation between the diaphragm portions of the electrodes. The cell operates at temperatures between 380° and 460° F and at reactant pressures of approximately 60 psia.

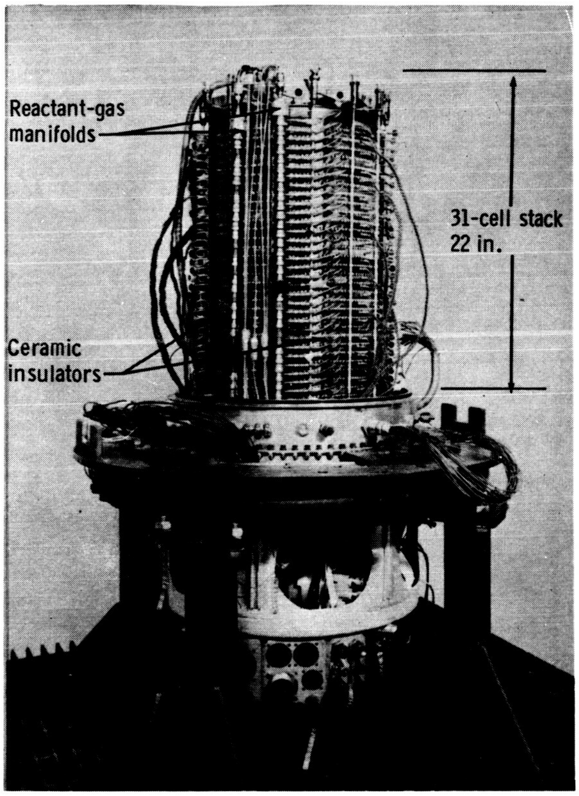


Figure 3. - Energy-conversion section.

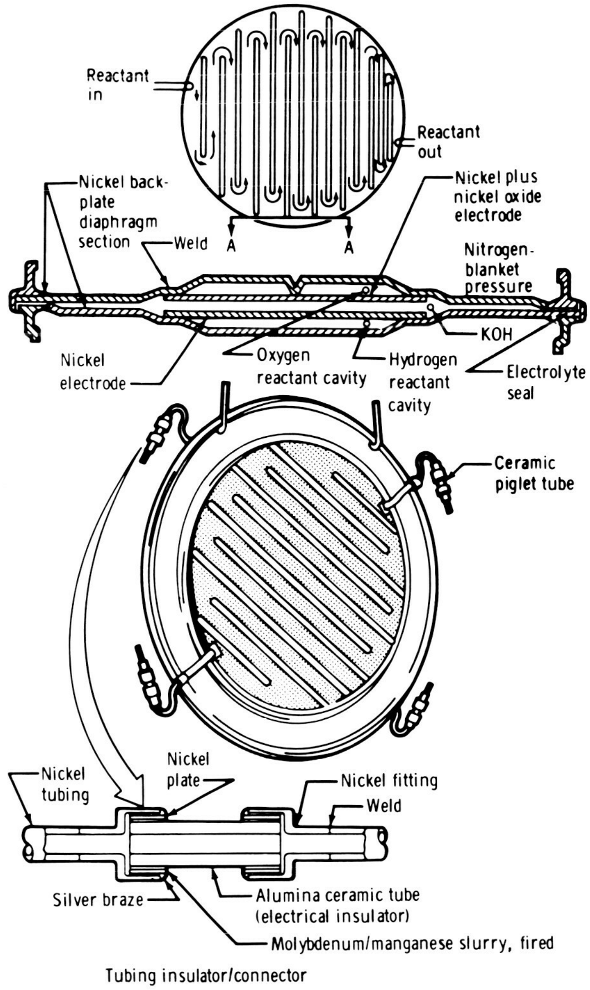


Figure 4. - Single-cell assembly.

The components that form the accessory section are mounted on a Y-frame (fig. 5). The accessory section consists of a nitrogen pressurization system, three regulators, a primary loop (hydrogen and water vapor), a secondary loop (glycol and water), heat exchangers, motor-driven pumps, and plumbing. A condenser connects the two fluid loops.

The pressurization system consists of a gaseous nitrogen (GN_2) storage tank that operates at a nominal 1500 psi, supplies a reference pressure to the reactant regulators, and supplies makeup nitrogen to the blanket-pressure tank. The GN_2-blanket-pressure tank operates at a regulated 52 psi and provides an inert atmosphere and constant pressure on the fuel-cell-stack assembly.

The primary coolant loop contains hydrogen and water in the form of superheated steam at 60 psi and 430° F. The excess steam is condensed in the 160° F condenser. Then, the liquid/vapor/gas mixture enters the hydrogen pump/separator unit (fig. 6) that separates the liquid water out of the stream by centrifugal action and pumps the gaseous hydrogen back to the fuel-cell stack. The water-separator portion of the pump is shown in cross section in figure 6. Gaseous hydrogen and water enter the rotating housing and separation screen in the separator assembly. The water is trapped in the

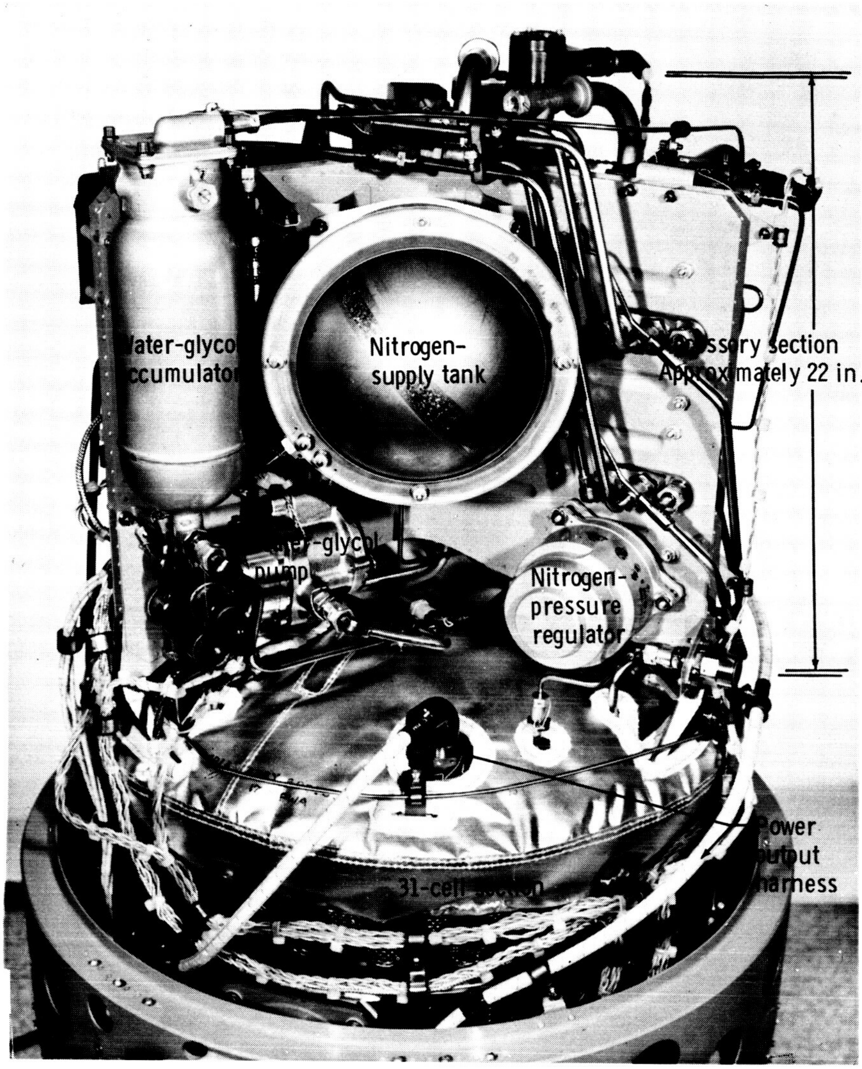


Figure 5. - Fuel-cell accessory section.

separation screen because of surface tension and is forced down into the pitot-tube pickup area by the centrifugal force that is generated by the rotating screen and housing. The pickup end of the pitot tube is stationary and is submerged in the liquid water. The rotation of the water along with the rotating housing produces a 2-psi ram pressure in the pitot tube; this pressure is transmitted by the water to the water-removal-valve diaphragm and spring. This process causes the valve to open and water to be expelled from the separator into the pitot tube. If a gas bubble enters the pitot tube, the ram pressure is lowered sufficiently to cause the water-removal valve to close. Then, the gas bubble is forced through the pitot tube and out the unsubmerged end. The actual operation consists of a continuous flow of water and gas bubbles through the pitot tube, during which time the periodic opening of the water-removal valve occurs, depending on the degree of submersion of the ram end of the pitot tube.

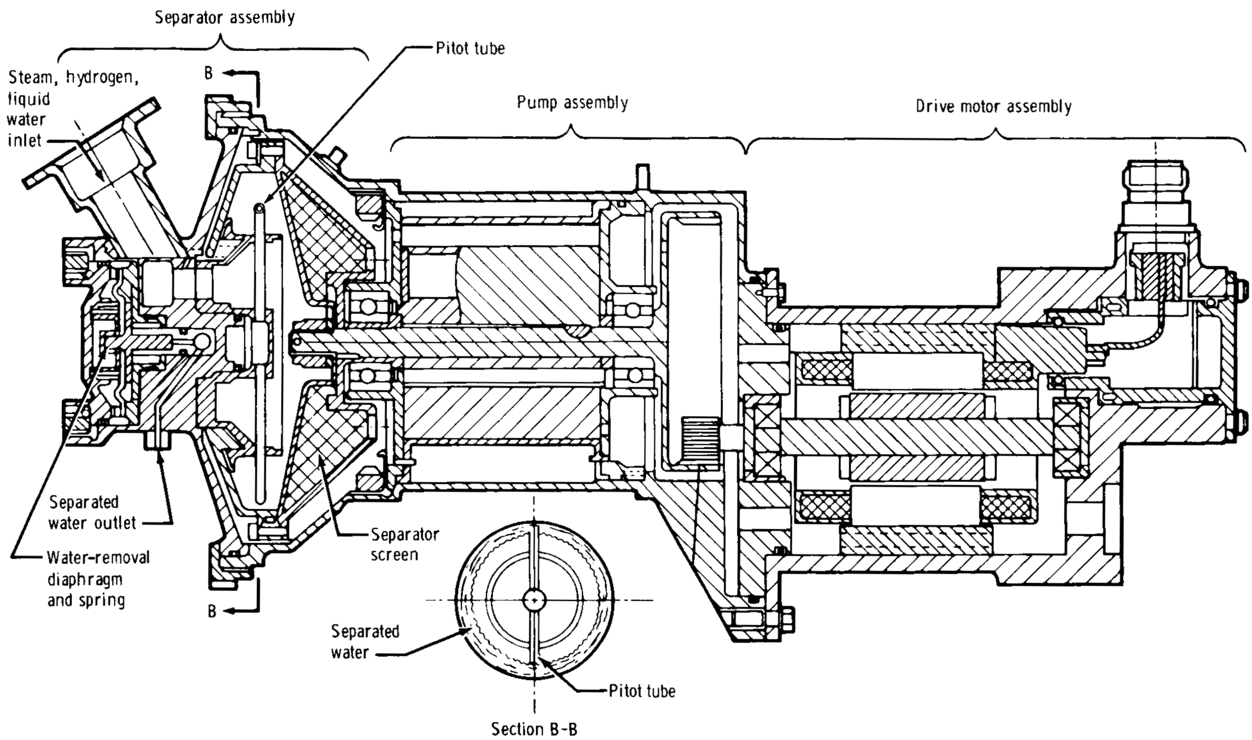


Figure 6. - Block II hydrogen pump/separator.

DEVELOPMENT AND FLIGHT-TEST DIFFICULTIES

During the initial system development of the PGS, a number of problems occurred that necessitated further component development. During the early flight tests of the PGS, additional problems were noted that resulted in the need for improvements in service procedures and for further system refinements.

Component Development and Production

Development problems were encountered during the transition from prototype hardware to production-type components that would meet the mission requirements. Many of these problems were unique to the fuel-cell operations and required that new technology be developed.

Electrolyte seal. - As a result of cell peripheral electrolyte-seal leakage, a considerable delay occurred in the early stage of development. After an exhaustive survey of materials, Teflon was selected as the seal material. The seal had to contain the highly concentrated potassium hydroxide, which is very corrosive (especially at 400° to 500° F). Also, the seal had to contain the pressure and act as an electrical insulator. At elevated temperatures, formed Teflon has a tendency to return to its original shape. Also, the surface of the seal is slick, which enables it to slip or extrude (cold flow) through two parallel sealing surfaces. The critical temperature at which these phenomena occur is close to the operating temperature of the cell (500° F). Because no other material met the seal requirements, a decision was made to accept the relatively small electrical-performance penalty by operating at lower temperatures (nominally 400° to 425° F). Also, the flat-cell seal design was changed to an L-configuration, as shown in figure 4, and both mating surfaces were roughened to allow for better containment. This action virtually eliminated all seal leakage problems.

Cell flooding. - The two half cells (electrodes) that form the single-cell assembly (fig. 4) are composed of dual-porosity sintered nickel formed from nickel powder that is pressed into sheets. The liquid-electrolyte-to-gas reactant interface is maintained within the sintered nickel by means of a controlled 10.5-psi pressure differential between the electrolyte and the reactant compartments. If either the hydrogen or oxygen gas pressure is more than 2.5 psi below or 15 psi above the electrolyte pressure, a breakdown of the liquid/gas interface possibly would occur.

During the preprototype design stage of the single cells, many electrolyte leaks developed across the electrode interface as a result of pressure differentials that caused flooding, allowing KOH to enter the reactant cavities. The result was the failure of the individual cell to maintain an electrical load. The manufacturing procedure was changed so that the porosity of the nickel electrodes was more uniform, thus increasing its bubble pressure and decreasing its susceptibility to flooding. Also, a coating of lithium-impregnated nickel oxide was added to the electrolyte side to inhibit oxidation; by this method, the configuration was controlled during operation. These changes constituted modest improvements, but the fundamental problem of ground-test cell flooding caused by gas-pressure imbalance remained throughout the program. This ground-test operational effect was minimized by the improvement of ground-support-equipment (GSE) gas distribution systems and operational test procedures and by careful handling.

Dendrite formation. - During qualification testing, it was discovered that, after two 400-hour mission duty cycles, the fuel cell shorted out internally during shutdown. Nickel ions dissolved from the oxygen electrode into the electrolyte and formed nickel dendrites when reduced at the hydrogen electrode. Eventually, the dendrites bridged the space between the hydrogen and oxygen electrodes (fig. 4) and resulted in electrical short circuits that were internal to the affected cell.

It was determined empirically that the reaction rate was temperature and time dependent. Because this was a well-defined failure mechanism, the failure mode was circumvented by means of operational procedures. A criterion was established requiring the removal of the fuel cells from the spacecraft if an equivalent life of 840 hours (based on an operating temperature of 400° F) accumulated before launch. Fuel-cell operation during the buildup and checkout of spacecraft was minimized; as a result, no fuel cells have been removed from spacecraft because of the equivalent-life operational rule.

Pressure vessels. - Titanium proved to be an excellent pressure-vessel material for fuel cells; however, a higher degree of quality control was required during the manufacturing process than was imposed originally. Two titanium pressure vessels are used on each fuel cell: one on the GN_2-storage tank and one on the GN_2-blanket-pressure-tank assembly. Contamination and inadequate process control caused the tanks to have defective welds that resulted in failures. The two components that were affected and the welds that were involved are shown in figure 7.

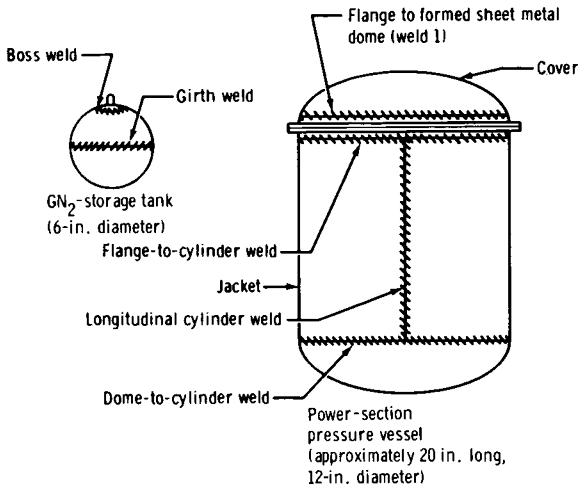


Figure 7. - The GN_2-blanket-pressure tank and power-section pressure-vessel assembly components and welds.

The first indication of a titanium-weld problem was a GN_2-storage-tank girth-weld failure that occurred during a component-acceptance test. The cause of failure was oxygen contamination of the weld caused by the use of improper procedures for a girth-weld repair. Because of the sensitivity of pressure-vessel failure during flight and the resultant damage that could have been caused by such a failure, a thorough review of all procedures and processes that had been implemented was made, and all titanium welds were inspected for flaws. Because of the hydriding that occurred in many of the titanium welds, all of the high-pressure storage vessels were rejected. As a result, improved procedures were implemented that included the requirement for the new GN_2-storage tanks to be welded inside a hard chamber (instead of a bag) that had a capability of vacuum purge and inert-gas backfill. The dewpoint was controlled to -30° F maximum. A single weld pass was allowed (previously, two passes were allowed), and no weld repairs were permitted. Each tank was X-rayed, the inside and outside surfaces were inspected visually, and the welds were dye-penetrant-inspected before and after a proof test of 3000 psi and a tank helium-leak check. The weld specification was revised to prohibit high-density inclusions. The quality-control samples were required to be with the tanks during the weld and stress-relief operations. All the procedures were reflected in the traceability records that were made more specific. When applicable, similar procedures were incorporated into the production of the GN_2-blanket-pressure tanks. The precautions that were taken have resulted in no recurrence of failures in fuel-cell pressure vessels after acceptance tests were conducted.

Ceramic-insulator leakage. - Each fuel cell has a hydrogen and oxygen reactant inlet and a hydrogen and oxygen reactant outlet (fig. 4). The inlets of the cells are joined to form a manifold (that is, the hydrogen inlets of the 31 cells are joined with a common supply), as are the outlets, as shown in figure 3. The piglet tubes between each cell and its manifold are isolated electrically by means of ceramic insulators (figs. 3 and 4), to maintain the desired series electrical connection.

During the acceptance test of one fuel cell, excessive hydrogen was detected in the GN_2 blanket, indicative of leaking ceramic insulators in hydrogen piglets. This indication was confirmed by means of additional tests. It was shown that the manufacturer had produced one lot of these insulators for which a high-temperature bake cycle and assembly leak-check procedures were omitted. The fuel cells that had insulators from this lot were recalled; the insulators were replaced with properly processed ones. All insulator records were reviewed for quality control to ensure that necessary tests and procedures had not been omitted. More stringent quality-control procedures were instituted, and the ceramic-insulator leakage problem did not recur.

Ground Tests

Ground tests indicated that the PGS could operate while the fuel cells were integrated with the spacecraft systems during extreme environmental conditions. During these tests, incompatibilities were noted in the reliability of the components in the integrated systems; definition and correction were required.

Accumulator. - An accumulator (fig. 8) is provided as part of the water-glycol coolant system to maintain a constant coolant pressure, regardless of the volumetric changes associated with coolant temperature variations. This pressure control is accomplished by imposing a regulated nitrogen-blanket pressure on the coolant system by the use of a flexible bladder.

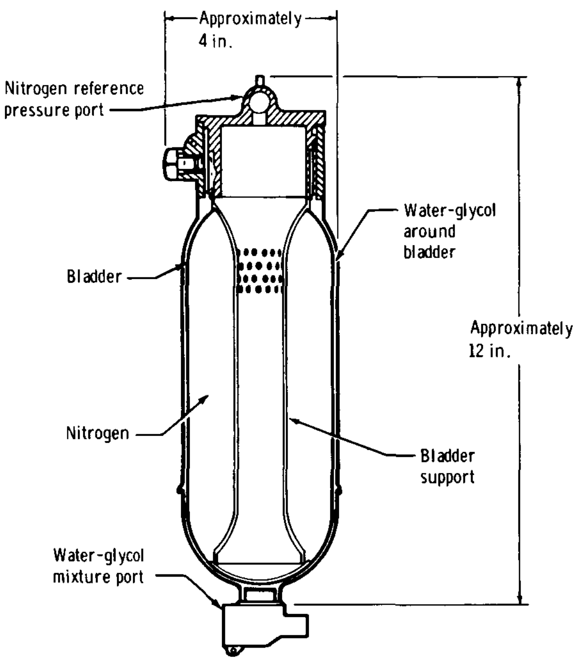


Figure 8. - Coolant accumulator assembly.

During early system tests, it was determined that the accumulator size was not sufficient to function as a pressure-control device for the total temperature range of the fuel cell. The problem was noted during boilerplate 14 tests, at which time the coolant pressure increased because thermal expansion of the water-glycol extended the accumulator bladder to its limit. A larger accumulator was added to production fuel cells, and the problem did not recur.

Cell separation. - The electrolyte, 80 percent KOH, is a porous solid at ambient temperature. Therefore, small quantities of reactant gases can permeate the electrolyte as it dries and hardens during shutdown of the fuel cell. The early shutdown depressurization procedure was accomplished by opening the reactant-gas purge valves and rapidly reducing the cell pressure. When the cells are rapidly depressurized, the forces exerted by the expansion of the trapped gases can break the bond between the electrode and the solidified potassium hydroxide. This process is called cold popping. On restart of a cold-popped cell, the trapped reactant gas forms a bubble between the electrolyte and the electrode. It manifests itself as a reduction in the active electrode area, with a resultant loss of performance.

The occurrence of cold popping was virtually eliminated by careful adherence to a controlled, slow depressurization of the cell reactant gases, which allowed the reactant trapped in the solidifying electrolyte to diffuse out.

Water-glycol pump. - Several problems were associated with the coolant pump (fig. 9), including leakage and failure to start. The leakage was noted first during tests on spacecraft 012. The leakage was caused by a damaged seal surface under the motor-to-housing O-ring seal. Although initially the damaged area under the seal was not large enough to cause leakage, corrosion of the damaged area outside the seal was augmented by the air environment. This augmentation caused an enlargement of the damaged area and the growth of a large crystal under the O-ring seal, allowing leakage. To prevent recurrence of the problem, all water-glycol pump housings (356T6 aluminum) were electroless nickel plated to resist damage or corrosion. No recurrence of this problem was noted.

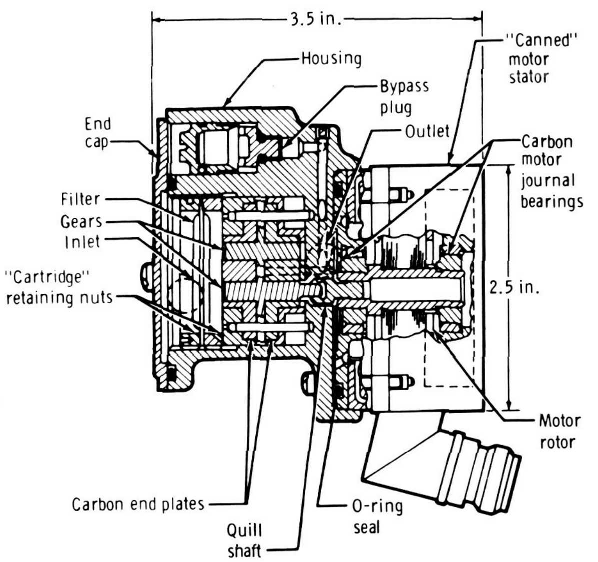


Figure 9. - Block II water-glycol pump.

During tests on spacecraft 2TV-1, the water-glycol pumps failed to start after being dormant for several weeks. By investigation, it was determined that the pump was sticking. The sticking was caused by deposition of nickel phosphate in the pump gears, which was caused by the presence of chlorides in the coolant. The water-glycol mixture that was used for servicing the 2TV-1 radiators did not require a chloride analysis. A sample of the water-glycol mixture that was used was analyzed; the chlorine content was 37 parts per million. Concentrations of greater than 25 to 30 parts per million are considered to be intolerable from a corrosion standpoint; consequently, the chlorine content was limited during servicing to 5 parts per million maximum.

During the normal acceptance tests of new hardware, several of the water-glycol pumps tended to stick during the first start. By investigation, it was shown that, during a final flush and dryout procedure before storage, a residue was left on the shaft and that the shaft could not rotate because the pump has a low (4 inch-ounce) starting torque. After the water-glycol pumps were started, the residue was dissolved and no further problems occurred. A new rinse and dryout procedure that eliminated further problems of this type was incorporated.

Hydrogen-vent port. - Two reactant purge ports, one for hydrogen and one for oxygen, are provided on each fuel cell to allow the purging of impurities (nonreactant gases) that may accumulate in internal cell reactant cavities. Under extreme thermal conditions, during the spacecraft 008 tests on the original spacecraft design, the water vapor condensed and froze at the purge-port opening, preventing further hydrogen purging. Two heaters were added to subsequent flight vehicles; these heaters are connected electrically in parallel for redundancy. Each heater has two elements that operate at 2 watts per element. The heaters are activated 20 minutes before a fuel-cell hydrogen purge and are turned off 10 minutes after purge termination.

Water relief valve. - The fuel cell does not have a water relief valve as such; however, the environmental control system (ECS) has such a valve that interfaces with the fuel cell system. Through this valve, water is removed that is generated by the fuel cell when both ECS water tanks are full and the water pressure exceeds 45 psia. Failure of this valve to relieve and vent water causes the fuel cell to absorb an excessive amount of water, thus requiring increased volume and resulting in cell flooding and subsequent failure.

Certain ground conditions of the ECS could cause back pressures in excess of 45 psia that would be applied to the fuel-cell water supply system as a result of the water head pressure caused by the one-g force of the earth. This problem was avoided by verification of the position of the ECS tank-valve switches (three) and by the placement of a redline maximum value (12 to 15 pounds) on the amount of water in each tank. This problem has not occurred.

Hydrogen pump/separator. - The fuel-cell hydrogen pump/separator (fig. 6) serves two functions: it circulates moist hydrogen from the fuel-cell stack through the condenser, regenerator, and inline heater and back to the stack; it removes the condensed water from the hydrogen loop and discharges this water to the spacecraft water-collection tanks of the ECS. The hydrogen gas that is pumped through the motor eliminates the need for shaft seals in the hydrogen pump and cools the motor. Because the hydrogen is saturated with water vapor, many electrical problems were caused until a satisfactory waterproofing epoxy insulation was found and a satisfactory method of application of the epoxy was developed.

Flight Experiences

Anomalies occurred on the early Apollo short-duration flights in both Block I and Block II fuel cells. During later flights of longer duration, the effects of zero g, coupled with the thermal cycling, were a problem in the operation of the fuel cells. The anomalies were corrected, and operational procedures were incorporated that resulted in satisfactory fuel-cell performance.

Block I flight anomalies. - The only Block I fuel-cell anomaly was on spacecraft 011 (the first use of fuel cells on an Apollo flight), which had two operable fuel cells (numbers 1 and 3). Fuel cell 2 had been rendered inoperative before launch because of a checkout-equipment-wiring error. During the latter portion of the flight, the condenser-exit temperatures of fuel cells 1 and 3 were out of regulation (high), although the overall performance was unaffected. It was concluded that the cooling capacity of the secondary coolant loop was reduced, and the most likely cause was attributed to inadequate radiator servicing that resulted in coolant-pump cavitation. To prevent recurrence of the problem, a coolant-system compressibility test was designed to identify entrapped air in the PGS radiators to verify adequate system servicing. A maximum of 8 cubic centimeters of air at a temperature of 120° F and at a normal operating pressure of 54 ± 2 psia was allowed. The compressibility checks were performed twice on all vehicles after the occurrence of the problem on spacecraft 011: once just after coolant-system servicing and again as late as possible before a launch. The application of these procedures virtually eliminated the possibility that preflight leaks or gas bubbles of significant volume would occur in the fuel-cell secondary coolant system. As a result, this problem was eliminated.

Block II flight anomalies. - When the CSM was maneuvered into lunar orbit, extreme operational conditions were encountered as a result of exposure of the fuel cells to transient thermal conditions.

Condenser-exit temperature: The condenser-exit temperature (TCE) sensor is a functional part of the secondary water-glycol coolant loop (fig. 10), the output of which is used to maintain a temperature equilibrium in the water condenser of the hydrogen system. This allows a constant water-vapor pressure in the inlet-hydrogen manifold throughout the operating power range of the fuel cell, which, in turn, controls the water content of the electrolyte.

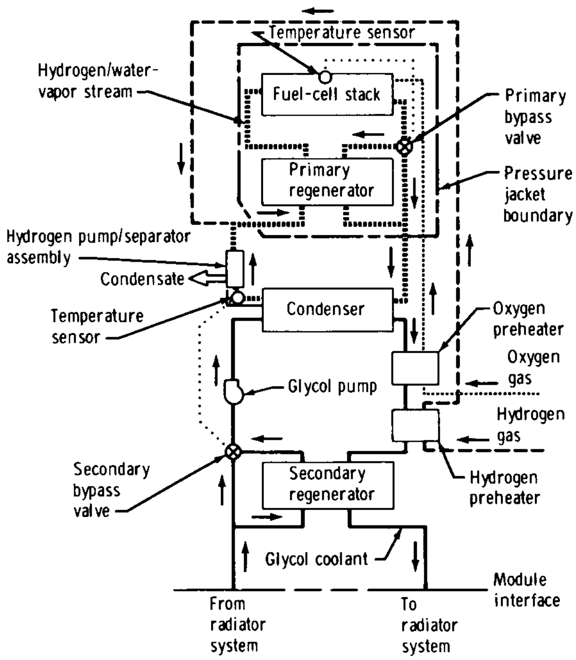


Figure 10. - Schematic diagram of fuel cell system.

Condenser-exit temperature anomalies were noted on all flights except the Apollo 8 mission. The anomalies were in two categories. The first anomaly was evident on the Apollo 7 and 9 missions and was characterized by TCE excursions to higher-than-normal temperatures, which were indicative of restricted secondary-coolant bypass-valve travel. By analysis of the data, it was shown that the restriction was caused by coolant-loop contamination on both flights. The coolant system had a history of chronic contamination. The combination of the coolant, coolant-corrosion inhibitors, and aluminum plumbing caused the formation of a gelatinous product after dormant-stand periods of more than 3 months during which no loop circulation occurred. The gelatinous product, released in a zero-g environment during flight, restricted the fluid travel in certain critical control valves and caused mission-constraint problems. The servicing procedures were revised for all subsequent spacecraft that had not already been serviced. Thereafter, the coolant systems were serviced with water-glycol at the NASA John F. Kennedy Space Center rather than at the spacecraft manufacturing facility to reduce the dormant-stand time. Also, the coolant-sampling schedules were revised to include the requirement for more frequent sampling of the coolant loops. If any samples were questionable, the coolant loops were flushed with fresh water-glycol while the radiator panels were vibrated manually in an effort to shake adherent contamination loose. The flush and vibration operations apparently minimized the contamination because this type of anomaly was noted in only one of the fuel cells on the remaining Apollo flights. Spacecraft 107 (Apollo 11) and the subsequent spacecraft were retrofitted with fuel cells that had a modified Block I secondary-coolant bypass valve in place of the Block II valve. By means of testing, it had been shown that the Block I retrofit valve was far less susceptible to contamination than was the Block II valve. The TCE excursions of this type did not occur in fuel cells that were installed in spacecraft subsequent to that used on the Apollo 9 mission.

On the Apollo 10 mission, 18° F amplitude (peak-to-peak) TCE oscillations at a frequency of approximately 2 cycles per minute were noted in fuel cell 2 during lunar orbital flight (fig. 11). Fuel cell 2 was operating at a load that was higher than normal at the time because of the pump circuit problem in fuel cell 1 that caused the temporary electrical isolation of that fuel cell. The overall fuel-cell performance was unaffected, but the caution-and-warning alarm for low TCE was tripped repeatedly and had to be reset manually every 5 minutes, creating a nuisance for the crewmembers. The oscillations tended to damp out at radiator exit temperatures of 110° to 120° F and recommence at temperatures of 60° to 80° F. Five separate instances of the oscillations occurred. After an extensive examination of the flight data, the presence of a periodic disturbance was noted in the TCE and was characterized by a 1.5° to 2.0° F drop over a 2-second period with an approximate 10-second recovery time to the original temperature (fig. 12). Periodic disturbances were present on this fuel cell throughout the Apollo 10 flight. Typically, the disturbances were 8 to 10 minutes apart and increased to a frequency of 4 to 5 minutes at loads above 30 to 35 amperes on the affected fuel cell and served as the trigger mechanism for the oscillations. The other two fuel cells were unaffected. By the use of computerized analytical studies and ground tests at the NASA Manned Spacecraft Center (MSC) Thermochemical Test Area (TTA), it was shown that TCE oscillation was a function of load and radiator temperature and that induced oscillations could always be damped out by reducing the fuel-cell load. Both the analysis and test program confirmed that the oscillations were not divergent and caused no damage to the system. The only concern was the effect of the repeated caution-and-warning alarms on the crewmembers.

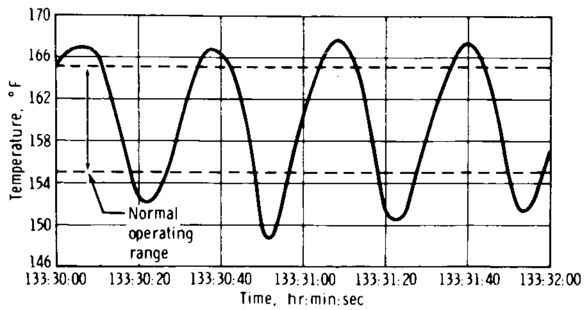


Figure 11. - Typical fuel cell 2 condenser-exit temperature oscillations during lunar orbit.

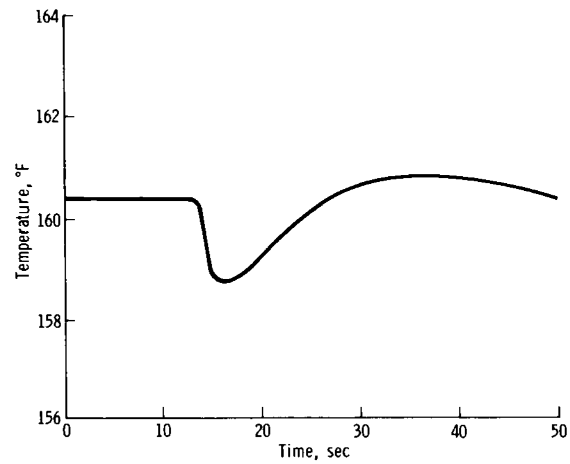


Figure 12. - Typical fuel cell 2 TCE disturbance.

An extensive review of all previous flight data resulted in proof that this type of disturbance occurred in at least one fuel cell per spacecraft on all Block II flights. Extensive investigation of the cause of the TCE disturbance was indicative that water slugging out of the primary (hydrogen) loop condenser in a zero-g environment was the most probable cause. Because of the absence of a gravity field, the water probably did not leave the condenser in a uniform manner, but tended to accumulate at the condenser-exit plenum until some critical level was reached, at which time the subcooled water was released in the form of a fairly large globule. Presumably, the subcooled water contacted the TCE probe and the secondary-loop bypass-valve-control sensor, causing the control disturbance and resulting valve oscillations under the high loads and low radiator temperatures that occurred in lunar orbit on the Apollo 10 mission.

Provisions were made in flight procedures to unload a fuel cell that exhibited an oscillating TCE. Through the Apollo 16 mission, however, no other fuel cell has demonstrated this phenomenon, probably because all three fuel cells have shared loads throughout all other missions.

Hydrogen pump: During the Apollo 10 mission, a short circuit in the alternating-current pump package of fuel cell 1 caused the associated circuit breaker to trip open. The breaker would not reset; thus, a permanent short was indicated. Fuel cell 1 was removed immediately from the bus because both the hydrogen and coolant pumps were inoperative. This fuel cell was maintained in an operative standby mode by placing it on the bus when the fuel-cell-stack temperature reached 370° F and open circuiting it when the stack temperature reached 420° F. After the hydrogen-pump failure in fuel cell 1, the maintenance of this fuel cell in the operative standby mode was accomplished by periodic loading, which caused the concentration of water in the electrolyte to increase eventually to approximately 33 percent. At this concentration, the fuel cell soon would have flooded if water could not have been removed. A continuous hydrogen purge was initiated to reduce the water concentration after approximately 167 hours of the flight. After 3 hours, at which time the fuel cell was sufficiently dry, the purge valve was closed and the hydrogen vent-line heater was turned off.

Circuit analysis, inverter testing, and review were indicative that the failure probably was a phase-to-phase short circuit in the hydrogen-pump stator windings, probably caused by insulation breakdown. Because the motor windings are exposed to hot, wet hydrogen, the limited life of the motors is attributed to the basic design. In endurance testing, the minimum length of time before a motor stator failed was 1000 hours; the maximum time before a failure was 3960 hours. Except for a major redesign of the hydrogen pump, no procedural or design changes could be identified that would enhance the reliability of the pump. Consequently, the use of the pump was retained throughout the flight program without hardware changes. This type of failure did not occur in any flight fuel cell other than in the one on the Apollo 10 mission.

Hydrogen purge flow and pressure excursion: After the extended purge of the flooded fuel cell on the Apollo 10 spacecraft, the hydrogen-supply flow failed to shut off completely. Normally, hydrogen flow should have decreased to zero in less than 1 minute; however, the flow rate decreased very slowly. The purge valve was reopened, and the flow rate increased to the upper limit, which was indicative that the purge valve was functioning. The valve was closed again, but the flow decrease was still very slow. After approximately 30 minutes, as the flow rate approached zero, the regulated hydrogen pressure for fuel cell 1 began to increase and reached a maximum pressure of 72 psia before it decreased slowly to the normal pressure of 62 psia (fig. 13).

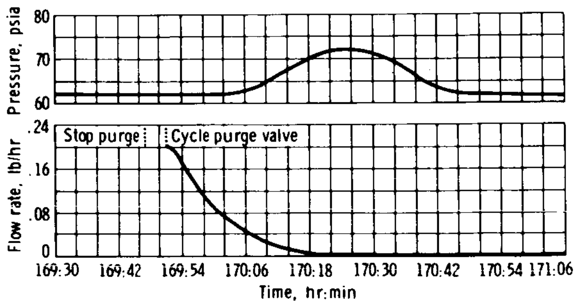


Figure 13. - Hydrogen flow rate and pressure after purge.

A test program was conducted at the vendor facility to test the flight hardware under simulated environmental conditions at the time of failure. During the tests, the regulator temperature reached -23° F in 5 minutes and reached -100° F in 15 minutes during hydrogen purges. At a temperature below -10° F, both the regulator supply and relief (vent) valves, also a part of the regulator assembly, leaked because the seals stiffened and did not conform to the seats. Proper sealing was restored when the regulator temperature increased to -10° F.

The test results were indicative that the extended hydrogen purge in flight without a hydrogen-preheat capability created low temperatures in the regulator; the consequent leakage of both regulator seats was the reason for the continued flow. Both the purge line and the vent line are vented overboard through a common header, and the header is protected from freezing by the heaters that were discussed previously. In this instance, the heaters were turned off when the purge valve was closed; thus, the continued vent through the regulator caused cooling and subsequent freezing in the overboard vent line. Normally, the regulator controls overpressure by venting on the downstream side. Consequently, blockage of the vent line caused an increase in regulated hydrogen pressure. Subsequently, tests at the TTA resulted in proof that subcooled hydrogen can be purged safely and continuously for at least 9.5 hours if the reactant-preheat capability is maintained.

A change was incorporated in the Apollo Operations Handbook requiring that the vent-line heater be kept on for 10 minutes after the termination of a hydrogen purge. Extended hydrogen purging was not required after the Apollo 10 mission.

Hydrogen gas in potable water: Gaseous hydrogen (GH_2) in the spacecraft potable water was a problem on all manned Apollo flights. The operation of the fuel-cell pump/separator causes expulsion of water that is free of gas except for the natural absorption of GH_2 in water at 60 psi and 160° F. When the environment of the water is changed to that of the potable-water tank (25 psi, 80° F), 3×10^{-6} pound (10.3 cubic centimeters) of gaseous hydrogen is expelled from each pound of water that is collected from the fuel cell. The theoretical GH_2 liberation value was shown and verified in controlled tests at the MSC.

The hydrogen that was entrained in the potable water posed no hazards to the crewmen or missions but did represent a nuisance when the water was used by causing uneven water-flow slugging and some physical discomfort to the crewmen from the gas accumulation in their digestive systems. A hydrogen-gas separator was added to the ECS potable water system to reduce the occurrence of this problem.

CONCLUDING REMARKS

During the course of the Apollo Program, the fuel cell was proven to be a rugged, reliable, and versatile electrical-power-generation device. The fuel cell operated satisfactorily during spacecraft launch/boost vibration, in zero g, and in a space/vacuum environment. The fuel cell met all electrical demands that were imposed on it from low (translunar coast) to high (Apollo 10 two fuel-cell return) power levels.

The experience gained from the ground- and flight-test phases of the Apollo fuel-cell program was indicative of certain hardware design and operational sensitivities that, although not considered major problems, required a great deal of time and effort to correct or work around. Some of the problems were unique to the fuel cell; other problems were caused by integration with other spacecraft systems.

Operational errors caused the costly failure of several fuel cells during early servicing and checkout operations in the Apollo Program. The high frequency of this occurrence was caused by the complexity of the fuel cells and their sensitivity to off-design conditions. After the fuel cell was operating and was on internal spacecraft reactants, the system operated reliably.

Contamination, particularly in circulating-fluid systems (for which hardware tolerances are critical), was a serious problem for spacecraft subsystems, as evidenced by the chronic contamination of the fuel-cell coolant loops caused by the formation of a gelatinous product after dormant-stand periods during which no loop circulation occurred. These problems were minimized before subsequent flights by means of ground flush and vibration procedures that (presumably) removed most of the gelatinous product from the coolant loops.

The fuel-cell condenser-exit-temperature disturbance that occurred during the Block II flights is believed to have been caused by a condensation phenomenon in the zero-g environment. Enough evidence was produced during ground tests to verify this as the most likely cause of the disturbance. The apparent instability of the fuel cell under these conditions was shown by a mathematical model that represented the fuel-cell module.

The redundancy philosophy that was instituted by the fuel cell system designers resulted in system and mission flexibility. The value of redundant powerplants was evident during the Block II flights, during which a fuel cell was shut down and had no effect on the accomplishment of the mission objectives.

To preclude similar problems on future spacecraft and to provide a more reliable fuel-cell power system, the following recommendations are made.

1. System selection/design criteria should include susceptibility to damage as a result of operational errors. To supplement these criteria, ground-support equipment should be designed so that, when a hardware failure occurs, the mode of failure will preclude damage to the spacecraft hardware. Also, thorough training programs on fuel-cell operation should be conducted for engineers and technicians who perform field operations in this area to ensure adequate protection in case of off-design conditions.

2. System and spacecraft interfaces should be defined carefully, and the definition should be adhered to during subsystem design and integration phases.

3. The compatibility of circulating fluids with system hardware must be verified thoroughly by ground testing.

4. All fluid loops should have filters installed upstream of all critical components.

5. Critical automatic control devices, such as the transducer used to control the water-vapor pressure in the hydrogen loop, should be used in a manner that will preclude control-sensor operation in a two-phase-fluid medium.

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