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REDESIGN OF THE APOLLO CRYOGENIC STORAGE SYSTEM

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An assessment of the Apollo 13 mission resulted in establishing new and revised requirements for the design of the oxygen tanks and the associated spacecraft system.

Areas to be discussed include new system requirements, system changes to Apollo 14, revised operational requirements, instrumentation, operational redlines, component isolation modes, and return enhancement capabilities. In order to show the relationship of the cryogenic system to the spacecraft, a short description of the system may be useful.

General System Description and Requirements (Basic Apollo)

The basic Apollo cryogenic system consisted of two each oxygen tanks and hydrogen tanks. The system includes related controls, check valves, filters and shutoff valves as shown in Figure 1.

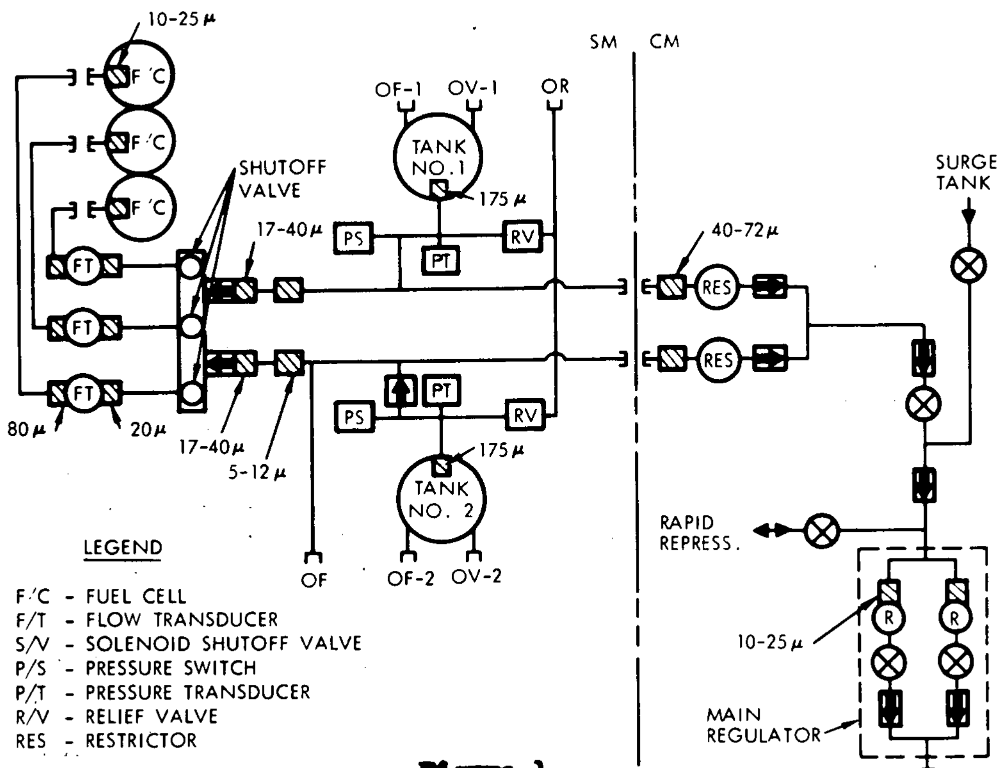

Figure 1

Oxygen is provided for pressurization of the command module and for crew metabolic consumption. Oxygen and hydrogen in an 8:1 ratio is also provided as reactants to the fuel cells for the generation of spacecraft electrical power. Useful stored consumables are 320 pounds of oxygen per tank, and 28 pounds of hydrogen per tank. The basic design concept for the cryogenic system allows for an emergency return with the loss of either one hydrogen tank, or one oxygen tank, or both. The hydrogen and oxygen systems for the basic Apollo are stored in Sector IV of the service module as shown on Figure 2.

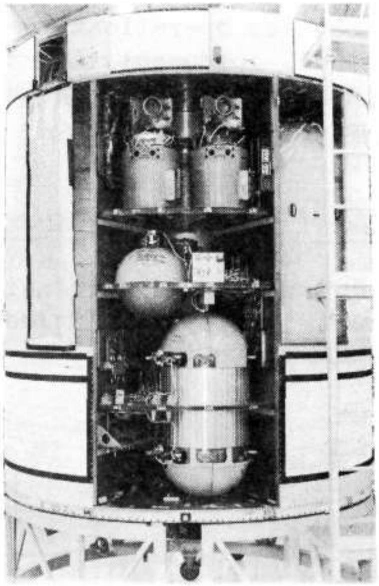

Figure 2

Detailed System Description

Following an oxygen fluid flow path from Tank Number 1, fluid from the tank passes through the system valve module which contains a pressure relief valve, a pressure transducer, a pressure control switch, and a check valve. The pressure control switch operates between a range of 865 to 935 psig. As the pressure in the tank decays due to fluid expulsion, the pressure control switch activates at the low setting, energizing the motor driven electrical transfer switch, which in turn provides electrical energy to the heaters located inside the oxygen tank. The process reverses as the pressure control switch reaches the upper limit setting. The pressure transducer provides pressure readout to the crew and to flight control. The pressure transducer readout is accurate within plus or minus 2.5 percent of full scale within a range of 50 to 1,050 psig. The system relief valve operates within a pressure band of 973 psig cracking pressure with full flow in excess of 100 lbs/hr at 1,010 psig.

Oxygen passing through the system valve module is transported to the fuel cells through check valves, solenoid shutoff valves, and the fuel cell flow meters. Fluid is also transported to the Environmental Control System (ECS) through flow restrictors, check valves and isolation valves. Components within the system are protected from contamination by the use of inline filters ranging from 12 μ absolute to 175 μ absolute.

Pressure and quantity readouts for each tank are displayed on the control and display panels in the command module, and are also provided through telemetry to flight operations. The cryogenic bulk fluid temperatures are also provided to flight operations. The two oxygen systems are completely independent in operation, the systems being interconnected downstream of the fuel cell system check valves and the ECS check valves. The primary purpose of the check valves is to prevent reverse flow from Tank Number 1 to Tank Number 2 and the reverse.

Controls are provided which allow the crew to select ON-OFF or AUTO selection for the O_2 and H_2 tank heaters and fans. Circuit breakers and/or fuses are provided for circuit protection for all electrical components and systems. Installation of the cryogenic system is of a modular concept; all components, including the tanks, are mounted on the equipment shelves which in turn are installed in the service module. Interconnecting lines are brazed, except for the connections to the fuel cells which are mechanical joints.

Apollo 13 Mission Assessment

As a result of the Apollo 13 incident, NR joined with NASA and other contractors in an immediate investigation, including a reassessment of the Command and Service Module (CSM) subsystems, and support equipment. Results of the joint reassessment suggested significant changes in the following two basic areas.

First, the knowledge that emerged from the investigation indicated that new requirements needed to be established for the spacecraft cryogenic system, as well as for the oxygen tank. These requirements resulted in a series of design changes known as the cryogenic system modification.

Second, the experience gained from the safe return of Apollo 13 indicated that, during certain abort-mission conditions, additional power, oxygen, and potable water would enhance the probability of a successful return to earth. This series of changes has come to be known as the return enhancement modification.

The new requirements established revised ground rules for the design of the cryogenic oxygen system as follows:

a) Eliminate or minimize the use of organic materials within tanks and components.

b) Eliminate or reduce blind installations.

c) Eliminate dynamic components exposed to oxygen.

d) Revise instrumentation and caution and warning system to provide for positive indication of system operational parameters.

Changes to the Apollo cryogenic system considered previous flight operational data, which resulted in maintaining changes to a minimum to avoid losing valuable mission experience. The above requirements resulted in the following changes to the spacecraft and components.

1) Redesign the oxygen tank.
2) Add oxygen tank heater instrumentation.
3) Provide for one, two or three oxygen tank heater operation.
4) Install oxygen tank feed line filters.
5) Replace fuel cell reactant shutoff valve.
6) Revise talk-back logic in F/C reactant shutoff valves.
7) Add reactant valve position to caution and warning system.
8) Revise hydrogen tank pressure caution and warning limits.
9) Install third oxygen tank in Apollo 14.
10) Add third oxygen tank isolation valve.
11) Add third oxygen tank check valve.
12) Add oxygen tank 2 and 3 manifold pressure transducer.
13) Install auxiliary battery.

Oxygen Tank Redesign and Related CSM Changes

The redesign of the oxygen tank resulted in some additional changes to the spacecraft associated with the electrical system, controls and displays, and instrumentation. The design of the modified tank incorporates three heater elements, versus two on the basic Apollo tank, plus the addition of a heater temperature sensor. The addition of the third heater element provides for additional redundancy, plus the capability of selecting either one, two or three heater element operation. The selection of single or multiple energy input sources becomes important for future missions where higher flow rates, at various fluid density levels are required.

Heater Temperature Sensor

Extensive testing and analysis showed that the bulk fluid temperature sensor installed in the basic Apollo oxygen tank did not reflect the highest temperatures of the fluid or materials within the tank. This was amplified by the removal of the destratification fans, which resulted in a higher degree of stratification of the fluid.

To provide more realistic temperature data, with reference to the highest temperatures within the tank, a heater temperature sensor was added. Comprehensive analysis and test programs have established that the location of the heater temperature sensor is within 30 F relative to the hottest spot on the heater assembly. The addition of the heater temperature sensor required the addition of temperature signal conditioners located on the oxygen shelf assembly as shown on Figure 3.

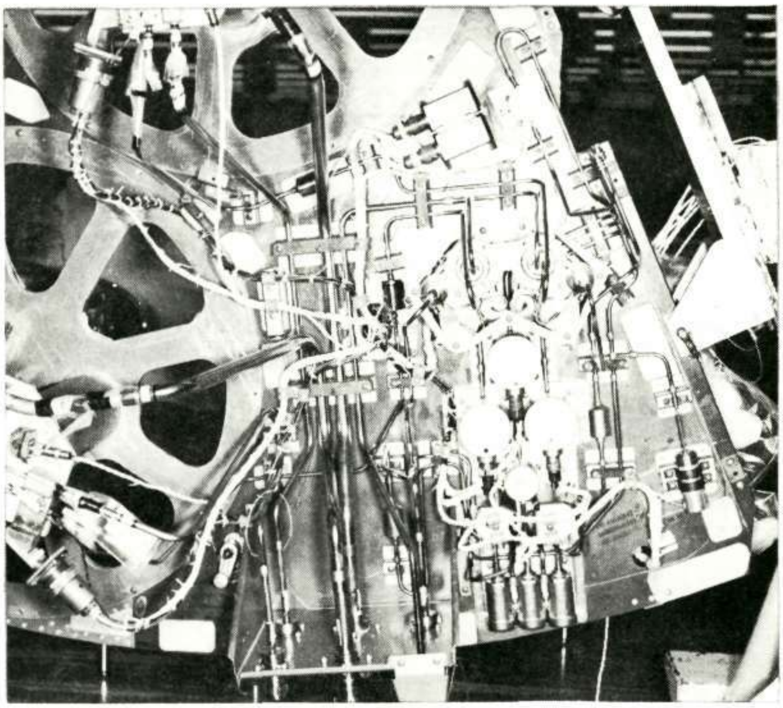

Figure 3

The temperature sensor output range is from -320 F to +600 F. Heater temperature data is available to flight operations for monitoring during the mission. Spacecraft wiring and switch panel modifications have been made to allow for crew selection of varied heater configuration. The establishment of a 350 F heater temperature redline was the result of extensive testing and analysis. The analysis indicated that the heater temperature should not approach the 350 F redline based on currently planned oxygen flow rates for the "H", "J", and Skylab missions. The material test programs have shown that there is no degradation or hazardous operating condition with heater temperatures up to 550 F. The 350 F redline considers the 30° temperature delta between location of the sensor and the hottest spot on the heater, instrumentation error, material limits plus a safety factor.

System Filters

Redesign of the oxygen tank also necessitated the installation of inline filters in the oxygen feed lines. The addition of a heater temperature sensor in the oxygen tank, coupled with relocation of the bulk fluid temperature sensor, resulted in a space limitation within the oxygen tank neck adapter area. This necessitated removing the filters from within the tanks and installing them in the tank feed line.

Replacement of Fuel Cell Reactant Shutoff Valves

The reactant shutoff valve assembly is composed of three solenoid valves and two check valves as shown on Figure 4.

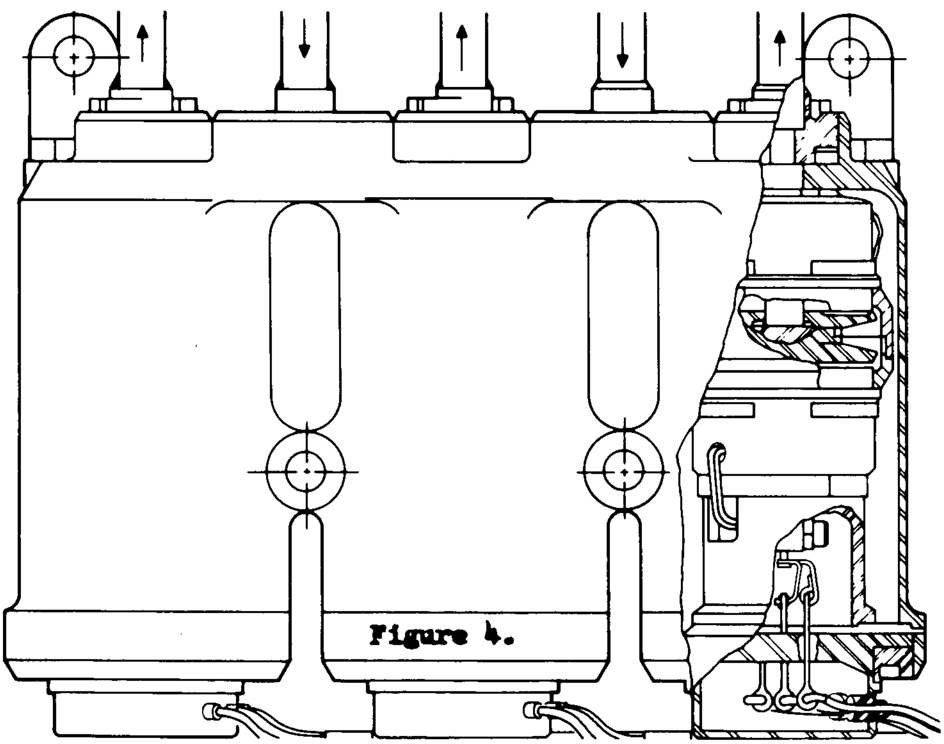

Figure 4.

The oxygen enters from each oxygen tank through the check valves into a plenum. The plenum allows for oxygen to flow from either tank to the fuel cells. Three latching solenoid shutoff valves are used to close off reactant flow to the fuel cells. A talk-back is displayed to the crew to indicate the open or closed valve position.

The replacement of the oxygen reactant shutoff valve was the result of the flammability analysis conducted on all components in the oxygen loop. The O_2 reactant shutoff valve was identified as having teflon coated electrical wiring, teflon material, and open terminals exposed to high pressure oxygen. Rework of the valve to provide an oxygen barrier was considered too extensive, requiring a complete redesign of the valve; therefore, the valve was modified by removing the solenoid shutoff valves from the housing. This maintained the manifold for fluid distribution to the fuel cells and the check valves. The replacement valve as shown on figure 5 was installed between the manifold and the fuel cell flow meters.

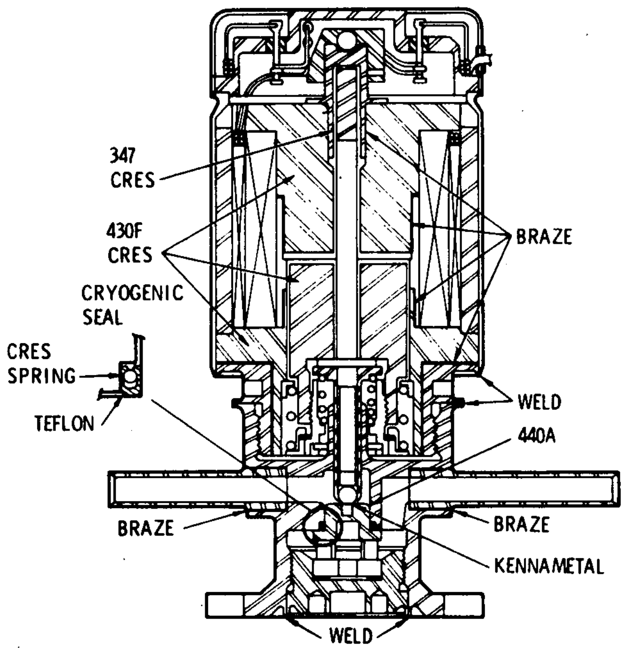

Figure 5

This valve was developed and is currently used on the Apollo reaction control system. All electrical components are shielded from high pressure oxygen. The only change to the valve was to replace a body seal to eliminate leakage at cryogenic temperatures. The valve was successfully subjected to an extensive test program, which included cryogenic operation, life cycling, thermal shock and magnetic latch holding capability. This valve was flown on Apollo 14. The installation of the valve is shown in figure 3.

Reactant Valve Talk-Back Logic

The talk-back logic on basic Apollo was such that both the H_2 and O_2 reactant shut-off valves were required to be closed to provide talk-back display. This was to ensure that for ground operation and checkout both valves were either closed or open. With the O_2 and H_2 system pressurized, closure of either the O_2 or H_2 valve places a high, damaging, pressure differential across the fuel cell. The Apollo 13 assessment indicated the requirement to provide inflight information of any reactant valve closure. This change was accomplished by wiring the H_2 and O_2 reactant switches in parallel. The talk-back logic was also added to the caution and warning system for early indication of valve closures. (Figure 6)

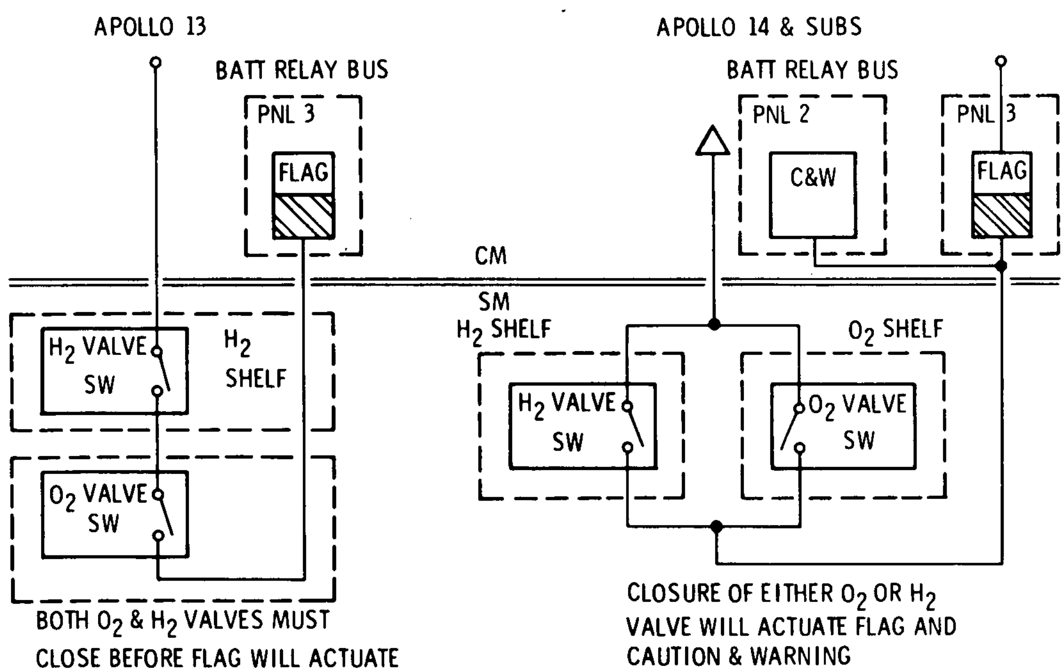

Figure 6

Hydrogen Tank Pressure Caution and Warning Limits

The low pressure caution and warning signal for the hydrogen tanks on basic Apollo was set at approximately 1.0 psi below the lower trip point pressure on the hydrogen tank pressure control switch. Due to a pressure imbalance between tanks, or a shift in pressure control switch setting, the alarm can be triggered when, in fact, system operation is normal. To delete the possibility of nuisance alarms, and the potential screening effect of the C&W system as related to the H_2 system pressure switch setting, the system was revised to lower the C&W low pressure actuation point to effectively reduce the chance of pressure switch and C&W interference.

Installation of Third Oxygen Tank in Apollo 14

The decision to install the oxygen tank in Apollo 14 was based on three factors.

First, to provide added confidence in mission success with redesigned tanks.

Second, to provide a return enhancement capability in the event anomalies would prevent making oxygen available from tanks 1 and 2.

Third, system performance in the low density regime, without destratification fans to provide forced convection, was not understood.

The "J" configuration Apollo vehicles are designed to provide for more extensive lunar exploration, which includes the Scientific Instrumentation Module. The extended operation required additional reactants for the fuel cells, plus oxygen for the command module. As a result, the "J" mission vehicles have been modified to accept one each additional hydrogen and oxygen tank and related controls as shown on figure 7.

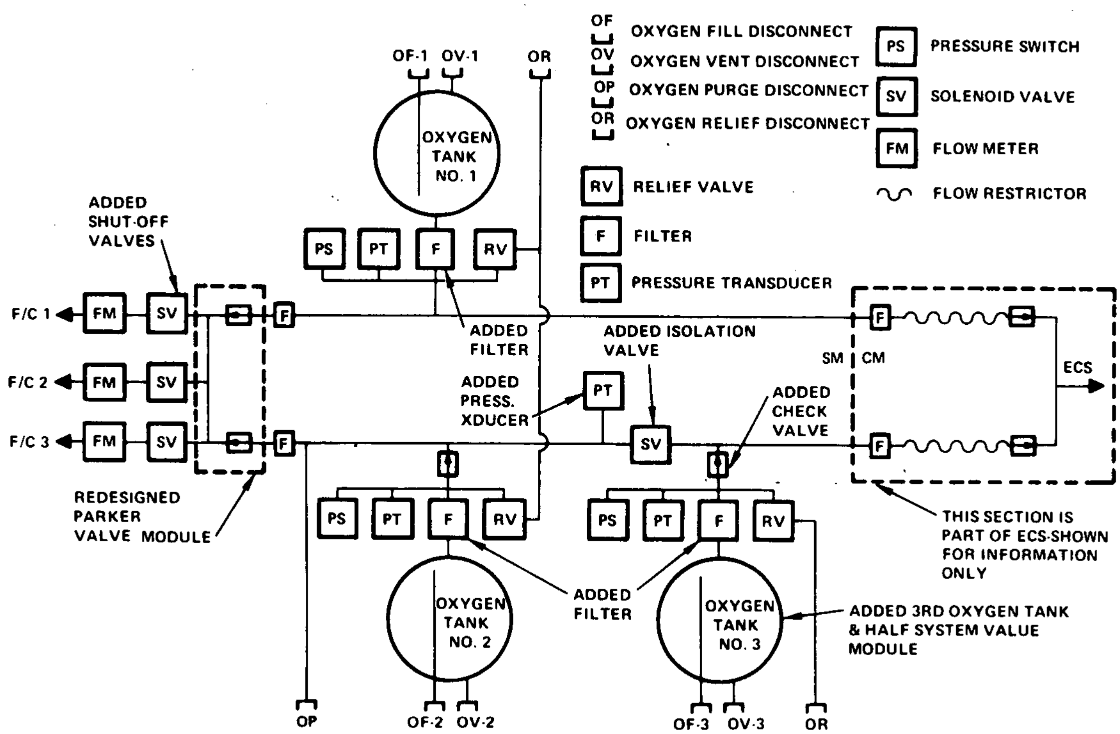

Figure 7

Because of additional crew activities, including external vehicle activity (EVA), operation of oxygen tanks in lower fluid density ranges is anticipated. In order to provide advance information on system response at low fluid density operation; and to provide added confidence in mission success, a decision was made in July 1970, to install a third oxygen tank on the Apollo 14 spacecraft. The third oxygen tank was installed as shown on figure 8 and is plumbed in parallel with oxygen tank number 2. A pressure switch, relief valve, and pressure transducer package is provided which is identical to the basic system components.

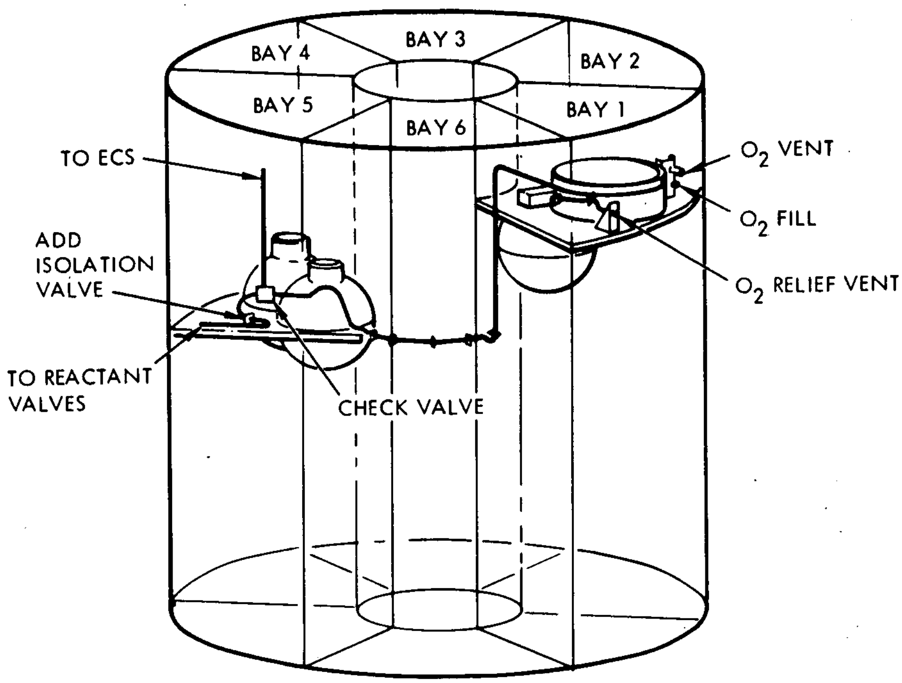

Figure 8

Isolation Valve

As part of the return enhancement capability, an isolation valve was installed which provides a means to isolate tank number 3 from the rest of the system, providing oxygen only to the command module. The isolation valve is identical to the new fuel cell reactant shut-off valves and carries the same part number. The isolation valve is wired to the battery bus to assure operation in the event of the loss of primary spacecraft electrical power.

Tank Number 3 Check Valve

The installation of the tank number 3 check valves is identical to tanks number 1 and 2 and serves the same purpose, i.e., preventing reverse flow between tanks during normal system operation and in the event of the loss of a system.

Return Enhancement Provisions

In addition to the third oxygen tank installed in Apollo 14, provisions were made to install a battery in the service module to provide emergency return electrical power in the event of total loss of the spacecraft primary electrical power system. The battery is rated at 400 amp hours and is identical to the LEM descent battery. The emergency return power profile, assuming total loss of the Apollo primary electrical power system, is such, that the spacecraft capability of a safe return from worst case condition is enhanced.

Testing

The redesigned components and the system were subjected to an extensive test program which considered all phases of environmental and operation conditions, including off-limits testing. The three tank system was subjected to two mission life cycle tests at the Beech Aircraft test facility in Boulder, Colorado. The system was also operated in parallel with the Apollo 14 mission, simulating actual mission oxygen flows, at established density ranges. The successful completion of the test program provided added confidence in the redesign of the components and the system.

The installation of the third oxygen tank in Apollo 14 allowed for performing a specific series of tests at fluid densities below 20% during the mission. Data from the test showed good temperature correlation with the zero "G" heat transfer models. The test demonstrated that with two heater element operation, flows up to 7.0 lb/hr can be provided while maintaining heater temperatures below 350 F.

The Apollo 14 flight test program also demonstrated that within the proposed flow regime for the Apollo 15 mission, pressurization of the system can be maintained without the use of destratification fans or external pumping loops to increase convective heat transfer. The test, and total system operation, verified that pressure drops associated with sudden mixing of stratified fluids is negligible.

<u>Conclusion</u>

The new requirements, test programs and attendent changes as implemented on the follow-on spacecraft have:

1) Extended the capability of the cryogenic system by providing a high degree of confidence and great flexibility in system operation.

2) Provided an extremely high confidence in a successful return to earth from worst case abort conditions.

3) Supplied data from the Apollo 14 mission which is directly applicable to future, more advanced Apollo missions; established analyses/flight correlation techniques applicable to future programs and systems.

4) Provided increased knowledge regarding ignition characteristics and burn rates of materials exposed to high pressure oxygen.

5) Established new design requirements for cryogenic systems relative to future programs and systems.