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CHALLENGES IN THE DEVELOPMENT OF THE ORBITER ATMOSPHERIC REVITALIZATION SUBSYSTEM

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ABSTRACT

The Orbiter atmospheric revitalization subsystem provides thermal and contaminant control as well as total- and oxygen partial-pressure control of the environment within the Orbiter crew cabin. Challenges that occurred during the development of this subsystem for the Space Shuttle Orbiter are described in this paper. The design of the rotating hardware elements of the system (pumps, fans, etc.) required significant development to meet the requirements of long service life, maintainability, and high cycle-fatigue life. As a result, a stringent development program, particularly in the areas of bearing life and heat dissipation, was required. Another area requiring significant development was cabin humidity control and condensate collection. The requirements for this element of the system include long life, ease of maintenance, and bacteria growth control. These were combined with the requirement to handle a wide range of operating conditions in the zero-g environment. Innovative solutions required to resolve problems that arose during design and qualification of the pressure control system include a vibrating wire and associated electronics to quantify the rate of cabin pressure change; magnets and electronics to accomplish noninvasive valve-position indication; power-saver electronics for hold-open solenoids combined with a failed-closed capability upon loss of power; oxygen-compatible, high-pressure, motor-operated latching valves using pressure-balancing metal bellows; a five-way, two-position manual valve to protect the cabin pressure regulator from ascent-induced vibration; high-accuracy, long-life oxygen partial-pressure sensors; and accurate oxygen/nitrogen flow sensors.

INTRODUCTION

The environmental control systems (ECS's) for Project Mercury and the Gemini and Apollo Programs were all designed for single-mission use. Although high reliability of this hardware was essential, the requirement for multimission use was not a principal design consideration. In contrast, the Orbiter design requirement is for an extended multimission capability, which requires the combination of the high-reliability technology developed during the preceding programs with the capability to withstand the induced and operational environments of the Shuttle Orbiter to produce an ECS with 100-mission life. These requirements resulted in several interesting challenges to be solved during the design, development, certification, and final verification of the various elements of the Orbiter atmospheric revitalization subsystem (ARS).

ORBITER ARS COMPONENT DEVELOPMENT

ROTATING ELEMENTS

The design of the rotating elements contained in the Shuttle Orbiter ARS was considered quite sensitive to this unique concept of multiple mission use. The specific requirements and problem areas that had an impact on the design of the fans, the pumps, and the water separator were as follows.

1. Long-term operating life - 10 000 hours for the bearing system

2. High environmental load levels - as much as ±25g vibration

3. High cycle-fatigue life - approximately 10^6 cycles

4. Minimum weight

5. Thermal environment

6. Maintainability

7. No external liquid leakage

8. Corrosion considerations (galvanic and/or environmental compatibility)

9. Self-generated and system-borne contamination

10. Fluid properties

Motors

The impact of the design requirements affected the design of the electric motors that power the fans, the pumps, and the water separator as applied to the electric motor efficiency and shaft bearing life. Motor efficiency is improved as the gap between the rotor and the stator is reduced. Motor manufacturers try to optimize the combination of shaft size, manufacturing tolerances, and shaft stiffness to achieve best overall efficiency. The unusually high environmental loads (shock and vibration) induced by the Orbiter required close attention to reducing shaft deflection and manufacturing tolerances to meet the minimum motor efficiency target (η = 60 percent).

The long-operating-life requirement coupled with the high-level environmental loads made the bearing selection a very critical design task. To maximize bearing life, choice of the bearing type and the lubricant required close cooperation between the various suppliers and a carefully conceived development program. The bearings as finally selected are precision, deep-groove, angular-contact ball bearings that are sealed and lubricated with Andok C grease. The success of the bearing design is proven by the fact that there have been no flight failures and fans have demonstrated operating lives far in excess of the design requirement. A cabin fan has accumulated in excess of 56 000 hours of operation and an avionics fan in excess of 28 000 hours. The cross section in figure 1 is typical for the various electric motors used in the Shuttle Orbiter ARS.

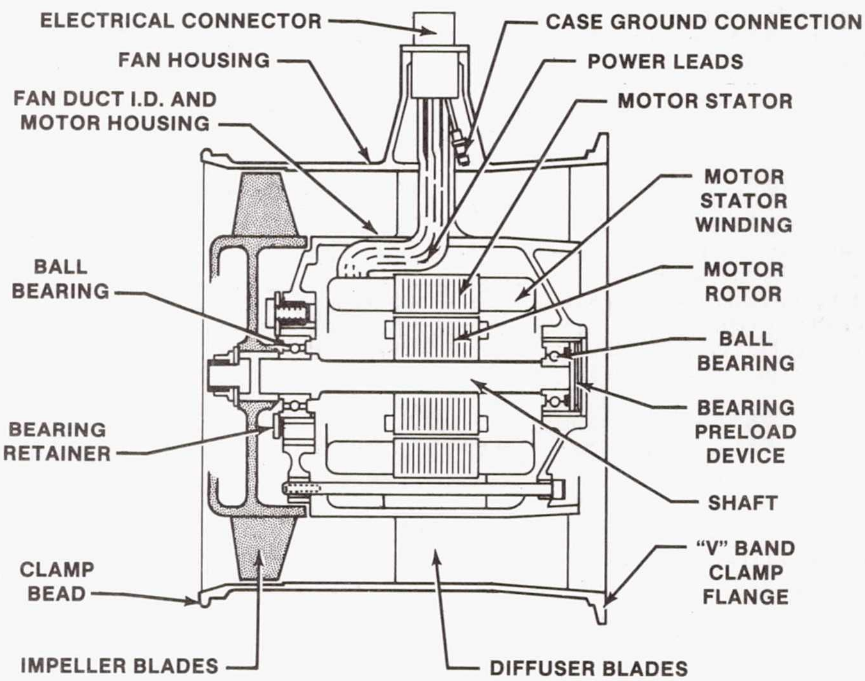

FIGURE 1.- CABIN AIR FAN MOTOR.

Pumps

Design of the fluid pumps was severely impacted by the Space Shuttle requirements. The restriction on external leakage, the long operating life, and the short turnaround time between launches precluded the use of a dynamic shaft seal between the motor and the pump. The choice was immediately reduced to either a magnetic-coupling pump drive or an immersed motor. The flowthrough (immersed) motor design was selected after a trade-off study revealed the following.

1. The magnetic coupling is more costly.

2. The magnetic-coupling configuration is heavier.

3. The magnetic-coupling drive results in a lower operating efficiency.

4. The immersed motor uses the pumped fluid for its coolant, whereas the magnetic-coupling design effectively insulates the motor and thereby accrues substantial weight penalty in providing a conductive heat path to a thermal ground.

The immersed motor uses hydrodynamic sleeve bearings because antifriction (ball) bearings when running immersed develop excessive friction, which shortens life. A second consideration that reinforced the use of sleeve bearings was the lubrication properties of the operating fluid, water. Water is not a good lubricant. However, carbon-sleeve bearings can even be run dry without galling, chipping, or spalling. The performance of antifriction bearings is degraded by operation in water.

Even though carbon-sleeve bearings have desirable properties, the actual design of the bearings was complicated by the conflicting bearing requirements. The bearings must operate with minimum friction in a zero-g environment and in a very high g-level vibratory environment and must not sustain vibration damage when not operating in the very high g-level environment. The bearings that finally evolved are high-precision parts for which very close control of the bearing/journal clearance (i.e., radial clearance is 0.0004 to 0.0008 inch) is maintained to (1) prevent overloading during high-g operation, (2) prevent the development of the self-destructive half-speed shaft whirl while operating in zero g, (3) prevent impact damage during nonoperating vibration periods, and (4) allow minimum armature/stator clearance for maximum motor efficiency. (The overall pump efficiency is approximately 36 percent.)

Combating the effects of fluid contamination was a very important consideration. The steps taken to reduce the potential wear problems include the following.

1. Precision clean the pump as a detail item.

2. Install "last chance" filters to prevent the ingestion of foreign particles during handling.

3. Adjust operating clearances to minimize pump sensitivity to contamination.

4. Provide a fine-level, high-capacity filter in the pump package on the inlet side of the pump.

The design adequacy of the various pumps and motors was demonstrated by successful performance in passing development and qualification testing, in ground operation, and, ultimately, in actual mission operation. A water pump (fig. 2) has accumulated 42 000 hours of ground test operation, which demonstrates the capability of the fluid pump design.

Water Separator

The water separator is also a Shuttle generation device with little or no previous flight history. It is constructed of two primary components: a fan/separator and a pitot pump. Although a rotary separator and pitot pump assembly was flown on the Apollo lunar module, it was a freewheeling turbine-driven device. The Shuttle separator is driven by an eight-pole, 400-hertz, three-phase synchronous electric motor, which also drives the fan on the same shaft.

The motor-driven system is superior to the turbine separator. Startup is a matter of turning a switch to initiate suction at the slurper, and the humidity control system is ready to function. The turbine separator was dependent on airstream energy to develop adequate power to drive the turbine. This dependence required oversizing the air recirculation fan and motor. If this approach were taken with the Orbiter, the total power consumption would increase significantly since a turbine would impose a significant additional pressure drop. The unique concept of the Shuttle separator is removing condensate with only 2 to 2.5 percent of the airstream flow rate. Figure 3 illustrates the fan/separator.

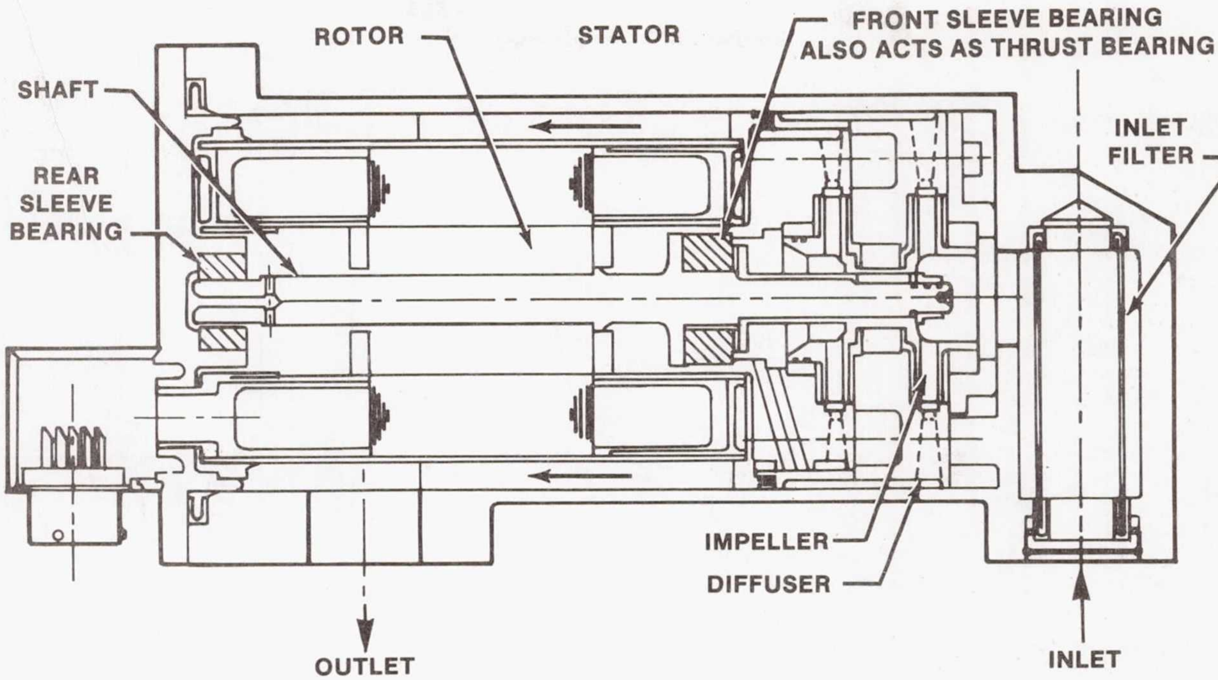

FIGURE 2.- SPACE SHUTTLE PUMP.

After the condensate is centrifugally separated from the return air to the cabin, a pitot pump is employed to pump the fluid into the wastewater tank. At a speed of approximately 5900 rpm, the pitot pump generates 38 to 40 psi at a flow rate of 3.5 to 4.0 lb/hr. The pitot pump has been used extensively in previous programs because it is conducive to these pumping conditions. The pump must overcome the pressure drop of two ball relief check valves and the plumbing to the waste tank. These check valves prevent the backflow of wastewater into the cabin and provide sufficient backpressure on the pitot pump to prevent the pumping of gas into the waste system.

Redundant fan separators are used on the Shuttle; one operates at all times both on the ground and in flight. This continuous operation gives the cabin environment a reliable humidity control system.

HUMIDITY CONTROL SYSTEM

Humidity control for manned spacecraft is a necessary part of the total environmental control and life support system. Proper atmospheric water content is required for crew comfort, for protection of avionic and other electronic equipment, and to prevent the growth of fungi and bacteria. In addition, high humidity levels can result in annoying problems such as condensation on windows, walls, and optical equipment. Compared to dehumidification systems for aircraft, design of a humidity control system for spacecraft is more challenging because of the absence of gravitational force. Condensate removal and storage requires the use of capillary devices and/or rotating machinery to produce artificial gravity.

The advent of the Shuttle Program necessitated longer life and lower maintenance equipment. Rapid turnaround of the Orbiter following each mission was a prerequisite. These requirements prompted the need for an improved humidity control subsystem.

The humidity control system is composed of three essential elements: a condenser, a water collector, and a separator/pump assembly. A plate-fin heat exchanger was selected for the condenser with a four-pass, cross-counterflow coolant loop. The plate-fin design provides excellent performance and lightweight. To improve temperature distribution and provide a free core face for condensate collection, a cross-counterflow approach was necessary. This arrangement also increased coolant velocity, which minimized flow distribution problems and resulted in more uniform core temperatures.

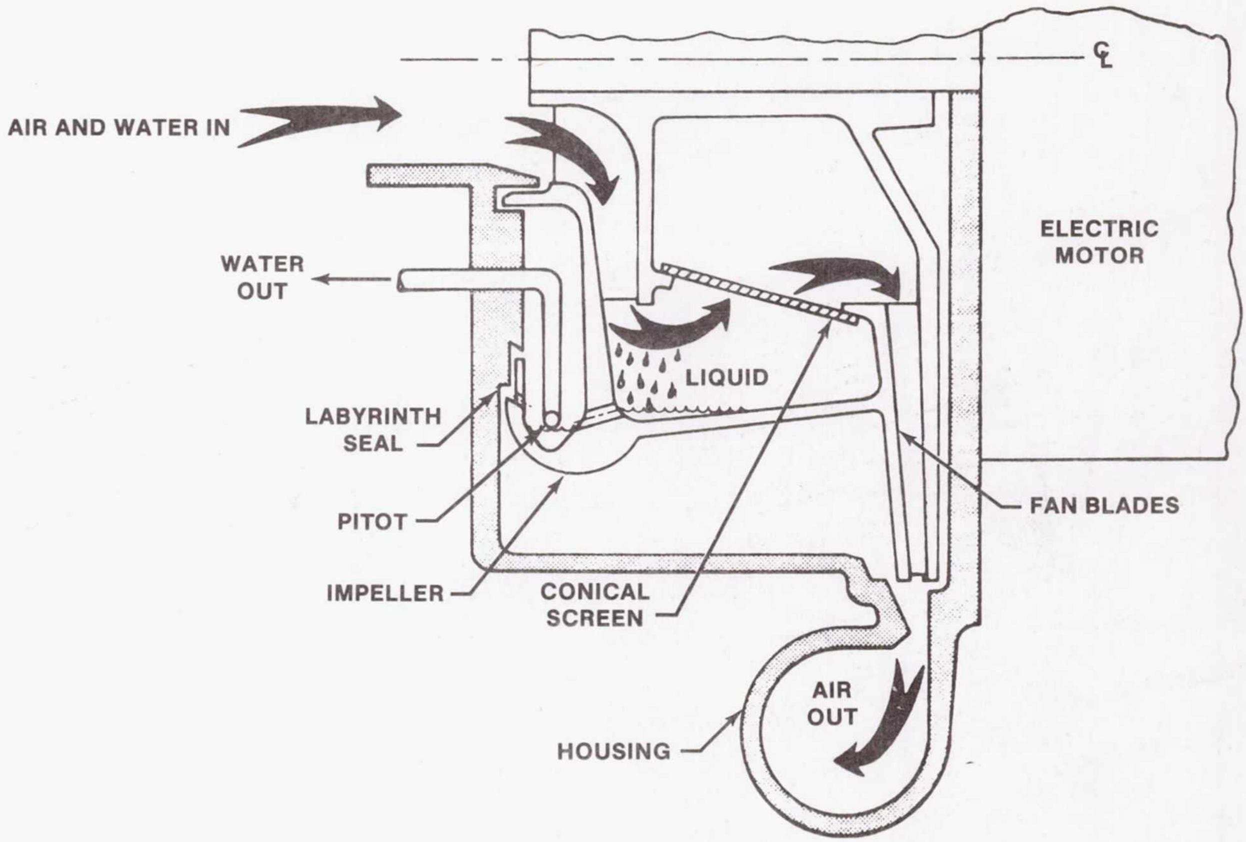

FIGURE 3.- SCHEMATIC OF ROTARY SEPARATOR.

Condensate collection was achieved with the use of a slurper bar (fig. 4). The slurper is the heart of the system, and, although it had never been flown before the Shuttle Program, the slurper concept was selected over two other methods that had been successfully flown previously.

One of the options available was the "elbow separator and scupper," which collects water downstream of the core in the main airstream outlet duct. The advantages of the elbow and scupper were ease of maintenance, simplicity, and freedom from wicks. Wicks are undesirable for any long-term use since they are susceptible to contamination. Disadvantages of the "elbow/scupper" concept are high pressure drop, which results in increased fan power, and inadequate handling of surges. Surges of condensate are released from the condenser at intervals when sufficient core-pressure drop has developed to overcome the capillary head-pressure rise of the fin passages. As one section of the core is "blown" free, another section is undergoing the condensation process and buildup of water. Deficiency of the scupper in handling surges results in some carryover into the cabin airstream.

A second option is the use of a wick at the face of the condenser to draw away the water from the airstream. The advantages of a wick are low pressure drop and, in the case of an integral wick, lower probability of surge occurrence. A disadvantage of the wick concept is the need for some type of startup procedure by which the wick is prewetted. This requirement is inconsistent with Orbiter operating philosophy.

In view of these considerations, the slurper becomes an attractive device. It incorporates the advantages of the other systems and minimizes or eliminates the disadvantages. With a suction of 2 to 2.5 inches of water provided across the slurper holes by the fan/separator unit, the slurper can separate as much as 3.5 to 4.0 lb/hr of condensate. The slurper has the advantages of a wick in terms of pressure drop and surge protection. A hydrophilic coating on the surface surrounding the 0.020-inch-diameter holes provides a wettable surface, which has "wicking" capability to draw water into the holes. Main airstream pressure drop is not affected, and only 2 to 2.5 percent of the airflow rate is bled from the stream by the fan/separator and is returned to the cabin after condensate

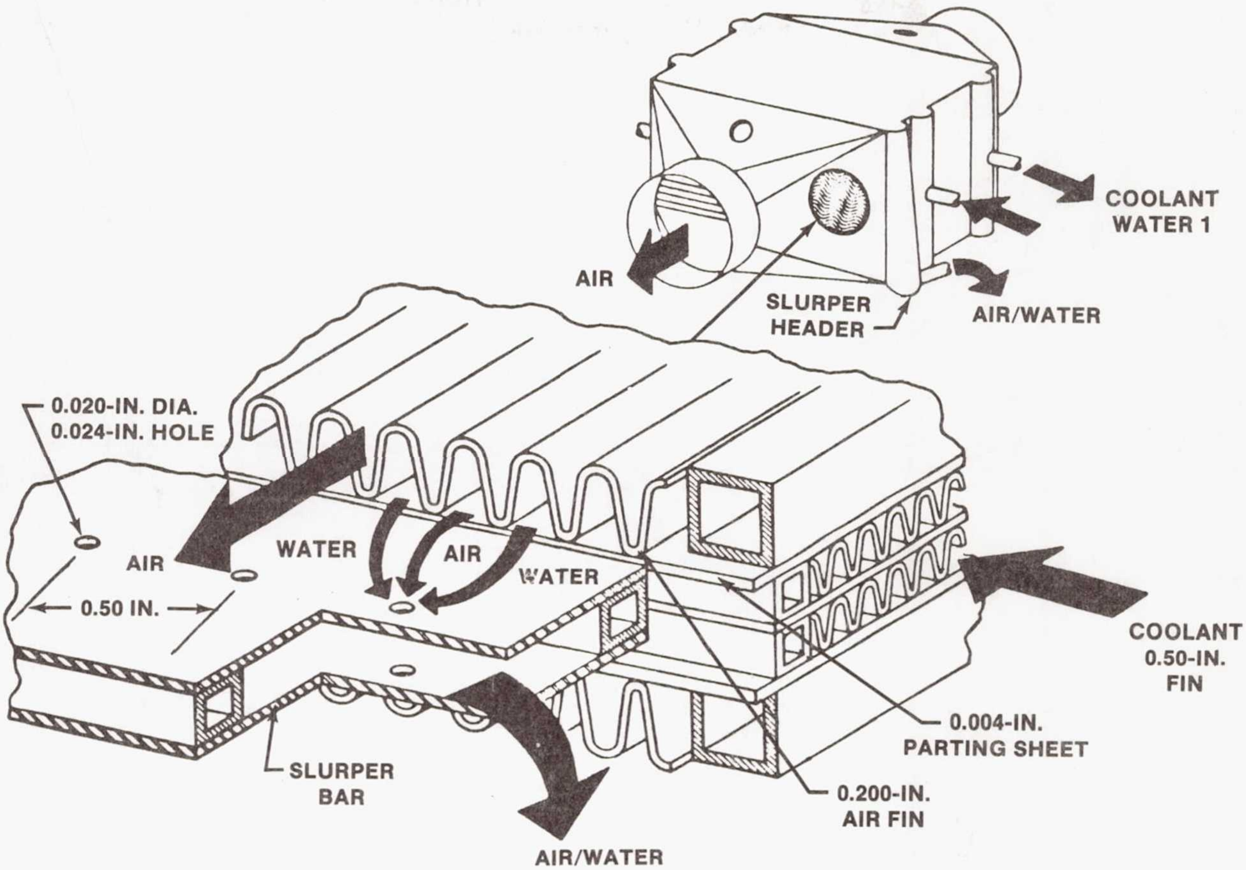

FIGURE 4.- DETAIL VIEW OF SLURPER.

removal. The slurper capability to handle the transient condensation process has been demonstrated in testing and in six Shuttle flights.

Incorporation of the slurper into a heat exchanger is illustrated in figure 4. The slurper is purely an extension of the coolant passage closure bar and, in this location, has the advantages of a face wick. The slurper requires minimum maintenance. It was discovered during the first Shuttle flights that a considerable amount of lint and fibers did plug many of the holes. Backflushing was required to clean the holes and some vacuuming to remove the contamination. If a wick were present, it definitely would be rendered useless since the lint fibers would have penetrated deep into the wick matrix to create a difficult and time-consuming cleaning process.

PRESSURE CONTROL SYSTEM

Rapidly increasing or decreasing pressure within the atmosphere of the Space Shuttle Orbiter is often indicative of a malfunction that may endanger the crewmembers or the mission. A ruptured pneumatic line (pressure increase) within the flightcrew compartment or a puncture in the compartment's pressure barrier (pressure decrease) are extreme examples of such malfunctions. The need for a device capable of providing a warning, in "real time," as contrasted to a graph that provides historical data of events that have previously transpired is obvious. Such a device should also relieve crewmembers of constant visual monitoring and interpretation of graphs.

Pressure Decay Sensor

The pressure decay sensor produces an electrical signal that accurately represents the actual instantaneous pressure change in the cabin. The electrical signal produced by the pressure decay sensor is visually displayed and is interfaced with caution and warning devices that alert crewmembers to the necessity of immediate corrective measures. This same electrical signal is telemetered to Earth monitoring stations.

The natural resonant frequency of a fine wire varies with the tension on the wire. The wire is driven by an oscillating current in the wire acting in a permanent magnetic field. The wire is part of the electrical driving circuit; therefore, the circuit oscillates at the resonant frequency of the wire. The cabin atmospheric pressure acting upon a metal bellows aneroid varies the wire tension and thus the frequency becomes a function of the atmospheric pressure. The cabin pressure rate of change is continuously calculated from the frequency and expressed as an output voltage.

The electronic circuit boards that comprise the rate electronics portion of the decay sensor must withstand exposure to the cabin environmental conditions of relative humidity as great as 100 percent, salinity of 1 percent by weight, temperatures of -12° to 120° F, and pressure from 4.8 psia to 15 psig. These circuit boards are therefore mounted in a sealed, anodized aluminum enclosure that is vented through a water-shedding surfactant filter. Additionally, each circuit board is protected by a coating of approved silicone rubber. Unit interfacing is accomplished through two hermetically sealed electronic receptacles. The pressure transducer portion of the decay sensor, except for the pressure port, is hermetically sealed. The pressure port is open to the vibrating wire through a surfactant filter that protects against moisture and contamination. Unit venting through surfactant filters coupled with the hermetic seals incorporated in the design of the decay sensor also protect the unit from sand and dust.

Specified g-levels corresponding to specific phases of Shuttle operation were 3.3g in the longitudinal axis and 2.8g in the vertical axis. Through testing, it was determined that the pressure transducer anvil transmits the force of the aneroid to the vibrating wire. The mass of the anvil was reduced and thereby the effects of the specified g-loadings were minimized. Additionally, the least sensitive axis of the pressure transducer was oriented in the atmospheric revitalization pressure control system (ARPCS) control panel to aline with the Shuttle axis subject to the greatest g-level. Each circuit board in the rate electronics portion of the decay sensor is fully supported; thus, flexing at the g-levels specified is eliminated.

The suspended (free) portions of the pressure transducer (aneroid, vibration wire, and anvil) have been designed for high strength-to-mass ratio to maximize resistance to the rectangular pulses of various g-levels, in the minus-Z direction, experienced during landing. The initial design change called for tapered ends on the vibrating wire, appropriate configuration of the anvil, and minimal aneroid size without affecting sensitivity. During testing, however, it was discovered that the tapered ends of the vibrating wire tended to fracture. The new configuration calls for a chemically machined, square wire with wide ends and narrow center section. Testing has proven this configuration to be the best suited to rectangular pulses.

Required operating life is a minimum of 20 000 hours over a 10-year period. Early decay sensor designs encountered problem areas. Small fractures in the vibrating wire were observed at the vibration nodes, and cracks were observed at the welded seam joining the two formed disks of the sealed bellows. The new chemically machined, square-cross-section vibrating wire with wider ends eliminated fractures in the vibrating wire. Brazing replaced welding of the two formed disks of the sealed aneroid bellows. This change resulted in lower residual stress and reduced contamination in the axis of attachment. The insulator at the electrically insulated end of the vibrating wire was also changed from fired lava to machined alumina, which resulted in improved resistance to fatigue stress, enhanced dimensional stability, and relief from low-rate, continuous drop in resonant frequency. In addition, the anvil mass was redesigned to the absolute minimum and the assembly technique incorporated an adjustment to establish "zero" inherent twist in the vibrating wire. These measures eliminated all extraneous modes of vibration except for the desired mode.

Pressure-Balanced Latching Valve

The pressure-balanced latching valve is used to control the combined flow of oxygen (O_2) and nitrogen (N_2) at a pressure of 3300 psi. During the Skylab Program, a solenoid valve that weighed 4.35 pounds was used for a similar requirement. Weight limitations imposed in the Space Shuttle Program required a much lighter valve. The Skylab valve solenoid coils accounted for a majority of this weight. The Shuttle version, which has an overall weight of 1.5 pounds, incorporates an electric motor drive and screw arrangement.

The latching function of the pressure-balanced latching valve is provided by a bistable Belleville spring. The electric motor drives the valve stem and the Belleville spring in the same direction. After actuation from either stable region (open or closed), the spring "snaps through" and retains the valve in the selected position. The Belleville spring provides a positive mechanical latch that is unaffected by vibration and shock conditions.

As its name indicates, the latching valve is pressure balanced. Simply stated, the force required to either actuate or deactuate the valve is not affected by the level of inlet or outlet pressures controlled by the valve. This pressure balancing is accomplished by making the effective areas of both the bellows and the orifice identical. Valve reliability has been greatly increased by the employment of a triple-wall, electrodeposited nickel bellows. This bellows configuration eliminates the necessity of dynamic seals. The O-ring seals used on the pressure-balanced latching valve are secondary seals only.

Power Saver

Two large nonlatching, normally closed, solenoid-operated valves are used in the N_2/O_2 control panel. Design parameters dictate that these two valves "fail safe" in the closed position in the event of power failure. Hence, mechanical or magnetic latching is not feasible. These valves require two distinct operating power levels: the "actuating" level and the "holding" level. The actuating level requires high power to overcome friction and move the armature or valve stem to the operated position; the holding level requires 10 to 25 percent of the power needed in the actuating level to maintain the valve in the operated position. Although the holding power level is greatly reduced from the actuating level, the power drain is still significant. The holding power must be applied on a continuous basis because the valves do not have mechanical or magnetic latching devices.

Two basic methods are commonly employed to maintain a non-latching-type solenoid valve in the operated position. The first method is the continuous application of power at the actuating level. This method tends to cause serious overheating and power requirement problems. An alternate method is the use of an additional switch and resistor circuit. The overheating of the solenoid coil is eliminated; however, the heating problem is now switched to the resistor.

The power saver is an alternative to the two previously applied methods. The power saver is connected between the solenoid valve and the power source, and automatically sequences power to the solenoid without the use of resistors. Hence, excessive overheating and excessive power loss due to increased line resistance is eliminated. Upon solenoid circuit initiation, power from the power source passes through the power saver and is applied to the solenoid valve at the actuating level. After actuation (usually 1/2 second or less), the power saver automatically reduces applied power to the holding level.

Initially, the power saver provides full actuating power to the solenoid coil from the power source. This full power is supplied until the power saver senses some preset current level in the solenoid coil; application of power is then discontinued. Discontinuation of power allows the current in the solenoid coil to decay through a "freewheeling" diode. When the current in the solenoid coil has decayed to some preset level, as sensed by the power saver, full power is once again applied to the solenoid coil. The averaging of these two preset current levels produces the holding power level.

The power saver is completely solid-state; thus, the unit is compact, dependable, and durable. All switching operations occur without inducing line voltage spikes from coil induction and without introducing electromagnetic interference (EMI) from the changing current rates. The switching points for actuation and holding levels are absolute values and are not affected by changes in line voltage, ambient temperature, or coil warmup temperatures. The power saver has met all operating parameters imposed and has a rated minimum useful life of 20 000 hours.

Valve-Position Indicator

Several inherent shortcomings of standard mechanical switches has led to the development of the solid-state valve-position indicator. This position indicator employs two samarium-cobalt magnets attached to the valve stem and a Hall-effect transducer to accurately indicate the relative position (on/off) of a given valve within a sealed housing. This valve-position sensing technique is accomplished without penetration of the valve pressure wall. Mechanical switches require a portion of the valve stem to extend through the pressure wall. Valve stem penetration of the pressure wall necessitates additional dynamic seals at the point of penetration and thus increases friction and potential leakage points. In the case of the valve-position indicator, a magnetic flux, developed by the samarium-cobalt magnets, passes directly through the pressure wall to operate the Hall-effect transducer (fig. 5).

The new valve-position indicator technique results in a reduced hysteresis (differential travel) distance. Mechanical switches require a minimum of 0.010 inch of travel between the on and off switching positions. The magnet and Hall-type transducer combination is capable of discerning movements as small as 0.003 inch. This value is less than one-third previously required travels; thus, lower valve flow settings are obtainable.

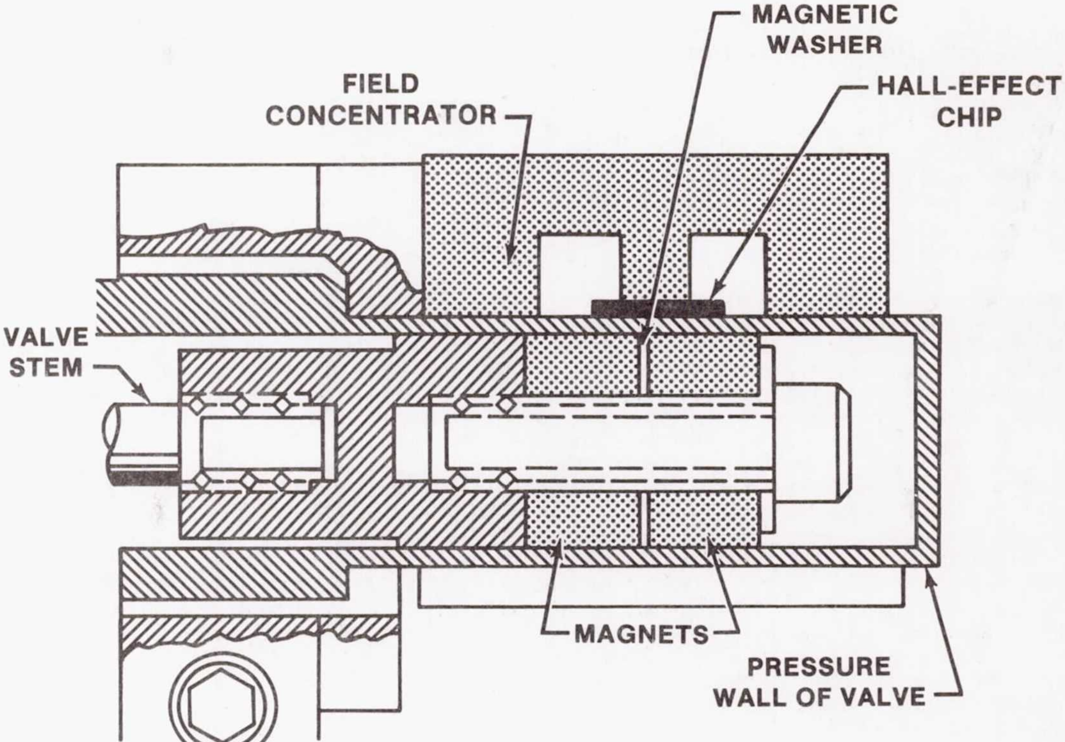

FIGURE 5.- SOLID-STATE VALVE-POSITION INDICATOR.

The absence of moving parts completely eliminates wear-related failures and ensures infinite cycle life. Mechanical switches are subject to breakdown due to excessive flexing, which results in deterioration of hermetic seals. Mechanical switches are also subject to contact erosion with resulting increases in circuit resistance; additionally, contact-point bounce produces unwanted EMI. The output signal of mechanical switches is of poor quality and may result in a sensitive indicator or recorder producing erroneous data. This valve-position indicator is free of these mechanical impairments and consistently produces "clean" signals in less than 0.5 millisecond.

Vibration has no effect on the valve-position indicator. The sensing element (Hall-type transducer) is rigid with no moving parts, and the magnets are rigidly attached to the valve stem.

A minimum of 5 ounces of actuation force is required to operate the most sensitive mechanical switches; many switches require 10 to 20 ounces actuation force. The valve-position indicator requires only 4 ounces of force to operate. Additionally, no preloading of the valve stem and no retention force is required to maintain the Hall-type transducer in the actuated position. Since no mechanical linkage is made with the switching portion arrangement in the valve-position indicator, overtravel problems are nonexistent.

Flow Sensor

Two flow sensors are used in each of two redundant systems in the cabin pressure control panel: one for oxygen at 900 psi and the other for nitrogen at 200 psi. Each flow sensor is calibrated to read mass flow rates between 0 and 5.0 lb/hr using the appropriate gas and pressure. Flow-rate displays are provided for the crew, and data are telemetered to monitoring stations on Earth. Caution and warning signals alert the crew if flow rates exceed 4.9 lb/hr.

The flow sensor consists of a relatively large, straight-through, cylindrical passage with several thicknesses of woven stainless steel wire filter mesh located approximately midway across the passage. A parallel flow path bypasses the filter by way of a capillary tube the ends of which are just upstream and downstream of the filter. The purpose of the filter is to produce a pressure drop across the ends of the capillary tube and thereby to induce a small flow through the capillary tube.

The flow sensed is flow that bypasses the main stream by way of this small-diameter tube. A layer of thermally conductive, electrically insulating material is deposited on the outside of the capillary tube. Two separate coils of very-small-diameter resistance wire are closely wrapped, one after the other, around the capillary tube. Each of these resistance coils is one leg of an electrical bridge.

The determination of flow rate is based on the difference in temperature of these adjacent resistors as a result of flow. The resistance of the wire varies with the wire temperature so that the bridge bias that exists at zero flow is upset. The degree of upset is sensed, amplified, temperature compensated, and linearized to compensate for nonlinear pressure differential across the aforementioned layers of filter screen. The result is an analog voltage output that varies from 0 to 5 volts direct current as the mass flow rate varies from 0 to 5 lb/hr.

The basic design approach remained the same during development and qualification. However, satisfactory implementation of the design proved troublesome. In retrospect, the solutions seem obvious. At the time, each anomaly seemed mysterious and required careful investigative work. One frustrating example was originally thought to be a matter of test equipment and test procedure differences between the manufacturer and the receiving inspection. Identical test masters for both stations were calibrated at the same time. The same gage facility and test equipment was duplicated; test procedures were standardized to no avail. Test results still differed. It was finally discovered that the manufacturer, to assure an optimum degree of cleanliness, was flushing the unit with cleaning fluid after his acceptance tests. Unfortunately, the cleaning fluid used was badly contaminated. This in turn partly clogged the internal filters, used to create a controlled pressure differential, and altered the heat-transfer characteristic of the flow-sensing capillary tube. The solution was clean fluid and the addition of a finer convoluted wire mesh filter at the unit inlet.

The need for additional diodes was revealed by EMI tests. Finding space for the diodes and providing mechanical support to withstand launch vibration required additional time to work out and prove.

Another problem was that some flow sensor elements could not be trimmed and adjusted within the range of the electrical elements designed to accomplish this function. The defect was traced to a partial breakdown of electrical insulation between the capillary tube and the wrap of resistance wire around the tube. Triple electrical insulation coatings are now used. This modification resulted in a reduction of flow sensor sensitivity due to the thermal insulating effects of the electrical insulation layers. To compensate, the electronics components were changed to supply more power so that the necessary degree of sensitivity could be returned.

One final undesirable characteristic of the flow sensor remains. Flow rates greater than 5.0 lb/hr are not displayed; caution and warning signals occur at 4.9 lb/hr. As the flow rate increases, the two adjacent legs of the resistance bridge, wrapped around the flow-sensing capillary tube, move closer to each other in temperature and resistance because the limited power available to the bridge is overcome by the increased heat dissipation of the higher flow rate. At some flow rate, the display starts to reverse with additional flow-rate increases until an indication approaching zero may be shown.

Oxygen Partial-Pressure Sensor

The oxygen partial-pressure (pO_2) sensor (refs. 1 and 2) has an impressive operational record including thousands of hours of flight time accumulated during the NASA Skylab and Apollo-Soyuz missions. In the Shuttle, the sensor performs the same function as in the Skylab application - providing the control signal to maintain proper oxygen levels in the two-gas (O_2/N_2) cabin atmosphere. The oxygen sensor has evolved into a device suitable wherever continuous, real-time monitoring of oxygen is critical and has been successfully adapted to a wide range of man-rated environmental control systems in addition to that of the spacecraft cabin oxygen monitor described previously.

The sensor is a self-contained, self-powered electrochemical cell, which generates a millivolt signal as a function of the O_2 partial pressure in the environment being monitored. The millivolt signal generated automatically compensates for temperature and is compatible with end-item telemetry and instrumentation systems. The sensor uses the controlled conversion of chemical energy to electrical energy to provide a direct measure of oxygen partial pressure. This function is accomplished by immersing a pair of electrodes, as shown in figure 6, in an electrolyte retained within a bladder and a gas-permeable membrane.

Oxygen contained in the atmosphere to which the sensor is exposed permeates the membrane to the gold sensing electrode serving as a catalyst to ionize the oxygen molecule. The electrolyte, an alkaline solution, provides a conductive path for ionized O_2 to the metal counter electrode to form a

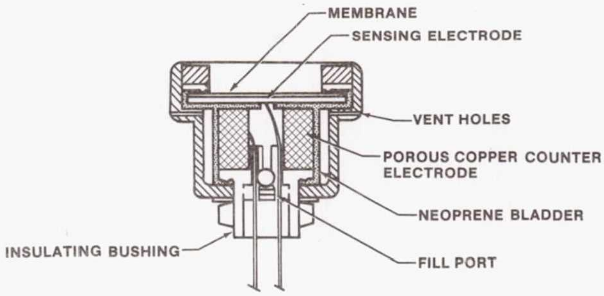

FIGURE 6.- CUTAWAY VIEW OF THE OXYGEN PRESSURE SENSOR.

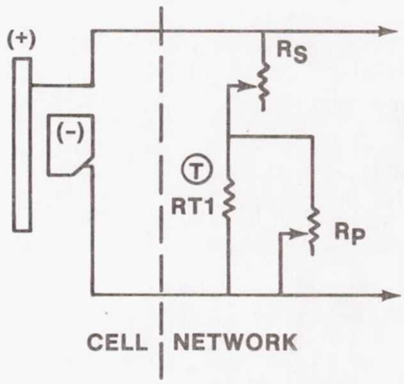

FIGURE 7.- SENSOR SCHEMATIC.

metal oxide. This oxidization involves a release of electrons, which flow through an external resistance (fig. 7) to provide the sensor output signal.

The current/partial-pressure relationship is constant for a specific electrode configuration and constant temperature. For changes in temperature, the absolute permeability of the membrane varies and thus produces a change in the output current. The change in permeability (hence current) is a first-order change increasing logarithmically with increasing temperature. Dependence on temperature is essentially eliminated from the sensor output signal by matching the cell to a resistive load including a temperature-sensitive component (fig. 7). The component, a thermistor, is trimmed with series and parallel resistances to provide a network temperature coefficient which is equal in magnitude but negative with respect to the temperature component of the membrane permeability.

The theoretical sensor life is readily determined by electrochemical relationships. The copper counter electrode is the consumable and is depleted at a rate which is related directly to the electrical current generated by the sensor. Actual life of a specific sensor will vary with average operating temperature and oxygen partial pressure as well as with thickness of the diffusion barrier (membrane).

Required calibration frequency is a function of system accuracy constraints and sensor drift. Initial calibration upon installation will hold for the life of the sensor. Results of recently completed tests indicate average sensor drift during operation to be -0.23 mmHg pO_2 per month. When compared to the Shuttle oxygen monitor accuracy requirement of ±7.75 mmHg pO_2, it is clear that an initial calibration should hold. Required operating life is 6236 hours at 297 K and 165 mmHg pO_2.

The sensor is not affected by background gases normally found in a habitable atmosphere. A shift in calibration with total pressure would therefore be attributed to a physical change within the sensor, specifically to a change between the diffusion barrier and the sensing electrode. A shift of this nature is prevented by (1) the flexible bladder referenced to sample pressure and (2) the front-end design for which a unique process has been developed to integrate the membrane and sensing electrode into a stable one-piece assembly.

Sensor response rate is a function of temperature, film thickness, and thickness of the goldplate applied to the sensing electrode. Film and goldplate thickness have evolved to satisfy the maximum number of applications and to idealize overall performance. Rate of output response for the standard sensor at 298 K is to within 90 percent of a step change in pO_2 in 30 seconds or less.

Early sensor configurations employed a stainless steel rigimesh substrate sensing electrode. A gold-plated, sintered nickel sensing electrode was substituted to enhance performance, through greater active surface area, and to eliminate sensitivity drift during storage. Additionally, the sintered nickel disk provides a more uniform sealing surface and an increased film support area and permits spotwelding of leads. Newer sensor configurations also employ a gain adjustment within the amplifier portion of the transducer to facilitate field adjustment. This gain adjustment replaces the previous method of individually adjusting the potentiometers within the sensor and eliminates the possibility of unbalancing the sensor temperature compensation circuit.

Cabin Pressure Regulator

The cabin pressure regulators and the oxygen partial-pressure sensors together maintain the crew compartment atmosphere at 14.7 ± 0.2 psia total pressure and 3.20 ± 0.25 psia oxygen partial pressure (ref. 3). The function and accuracy of the oxygen partial-pressure sensors are unaffected by vibration, acceleration, and shock once their elements are adequately supported to withstand the resultant dynamically induced stresses. However, cabin pressure regulators depend on the positional interaction of internal mechanical elements. Close-tolerance pressure regulation required, ±1.36 percent, necessitates a design sensitive both to the crew compartment pressure feedback control and to the externally imposed dynamic environment.

Qualification testing showed the 14.7-psia pressure regulators to be sensitive to the random vibration spectrum of the Shuttle launch environment. The level of regulation exceeded Shuttle specification limits during launch vibration. Since their operation during launch is unnecessary, this deviation might have been countered by closing the unit's manual on-off valves before launch and opening them when in orbit. However, two other problems occurred as a result of 100-mission random vibration testing: (1) after vibration, the pressure regulation level decreased as much as 0.25 psi and (2) internal leakage increased greatly. Short vibration time qualified the ARPCS N_2/O_2 control panel for use on the first Shuttle development flights. Nevertheless, extending the vibration duration to encompass 100-mission-life simulation showed that the cabin pressure regulator performance degraded sufficiently to require further corrective action.

The control pressure sensed by the cabin pressure regulators during launch is only a little higher than the 14.7 psia that they are set to control. This means that the springs and the pressure-sensing device are practically in balance so that any disturbing force, such as imposed vibration, causes these internal elements to react rather violently. The movement thus induced causes accelerated wear. Damage to the pressure regulator seats caused excessive internal leakage and pressure regulation shifts. The most effective and uncomplicated way to immobilize the unit internally was to close the port where the regulator senses the crew compartment pressure and, at the same time, raise the pressure that the regulator sensing element sensed internally. This raised pressure must be high enough to force the metal bellows pressure-sensing element back against its internal parts to achieve the desired results. The source selected to backpressurize the cabin regulators was the nitrogen regulator normally used to pressurize the water tanks.

The cabin pressure regulators already had manual toggle-operated on-off valves. The cabin pressure regulators were redesigned in such a way that a single action of the toggle could accomplish the required functions simultaneously. The resultant multifunction toggle valve is a two-position, five-way valve. Two poppet/seat combinations have been added to accomplish the desired backpressure function. Nitrogen from the 16-psig water pressurization regulator is fed to the appropriate port of the designed valve to act as the backpressure source. Reversing the toggle position closes the poppets that were open and opens those that were closed so that normal crew compartment pressure control can resume.

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