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OTHER CHALLENGES IN THE DEVELOPMENT OF THE ORBITER ENVIRONMENTAL CONTROL HARDWARE

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ABSTRACT

Development of the Space Shuttle orbiter environmental control and life support system (ECLSS) included the identification and resolution of several interesting problems in several systems. Some of these problems occurred late in the program, including the flight phase. This paper addresses problems and solutions related to the ammonia boiler system (ABS), smoke detector, water/hydrogen separator, and waste collector system (WCS).

ABS problems were concerned with:

- Inducing vortex flow in the heat exchanger to improve heat transfer
- Accumulating contamination from ammonia as a result of evaporation in the heat exchanger
- Excessive carbon content, which developed while redrawing tubes to size resulting in corrosion and leakage
- Slower control system response to changes in temperature as a result of redesign to inhibit moisture entering the outlet temperature sensors

Smoke detector problems and solutions resulted in:

- Changing from a quartz crystal microbalance (QCM) sensing concept to an ionization sensor
- Understanding ion sensor operation during altitude changes
- Changing air pump design
- Revising pump motor design
- Modifying electronics hybrid design

Water/hydrogen separator problems and challenges included:

- Revising flow path lengths to meet pressure drop requirements
- Increasing H_2 removal efficiency by adding flow turbulators
- Techniques of welding tubes into a thin header plate
- Bundling of tubes to withstand shock and vibration environments

Waste collector system problems encountered and resolved during the orbiter flight test program involved:

- Restraint systems
- Last drop of urination removal
- Urine cap evaluation

AMMONIA BOILER SYSTEM

During the Space Shuttle orbiter entry mission phase at altitudes below 120,000 feet, the ammonia boiler system (ABS) provides a means for rejecting waste heat loads into the atmosphere. The ABS also provides cooling on the ground between postlanding but before the ground support cooling equipment is connected. Heat loads generated by Shuttle orbiter systems are transported within the vehicle by two separate and independent Freon 21 loops. When the ABS is operating, heat is transferred from the Freon 21 by evaporation of anhydrous ammonia, which is then vented overboard. The ABS is a completely self-contained system that uses a small amount of electrical power as its only outside supply requirement, and can transfer heat at a rate in excess of 120,000 Btu's per hour.

HEAT EXCHANGER DESCRIPTION

The ABS heat exchanger consists of four separate shell-and-tube modules. Figure 1 shows the tube bundle used in each module, the internal baffles, and the tube sheets. Each bundle contains 77 tubes that have an outside diameter of 0.093 inch and transport the ammonia internally. Each tube expands into each of the baffles to prevent flow bypass and to secure the tubes during vibration. The tubes are brazed into the tube sheets and the tube sheets are brazed into the shell to form a module. The Freon 21 makes five passes through the tube bundle in each module. Each of the tubes in the two ammonia outlet modules contains a spinner, which is a twisted metal ribbon divider that forms two spiral paths to impart a vortex-like flow to the ammonia in order to help increase the rate of heat transfer. The ammonia circuit, which consists of two modules, was sized to bring the superheated ammonia exhaust gas to within 10 °F of the inlet Freon temperature. All of the heat exchanger parts are fabricated from stainless steel and either brazing or welding is used to join parts in order to minimize weight.

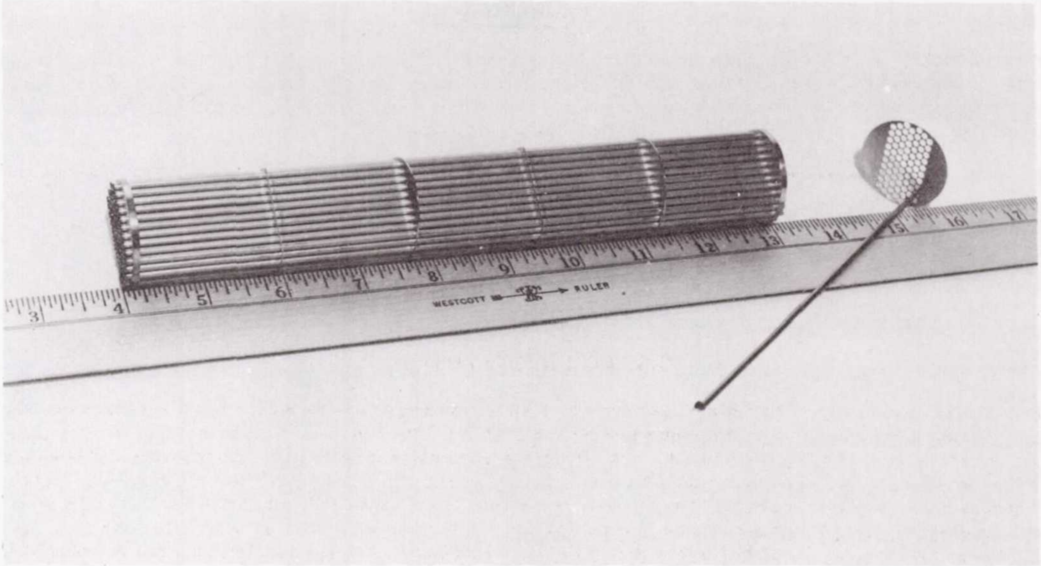

FIGURE 1. HEAT EXCHANGER MODULE TUBE BUNDLE

HEAT EXCHANGER DEVELOPMENT TESTING

In order to confirm the heat transfer and pressure drop characteristics of the heat exchanger, a simplified development unit was built early in the program. The unit consisted of two modules welded together with one counterflow Freon circuit. This configuration would normally be used to cool a single Freon loop. At the ammonia exit there was a long duct containing a bundle of 77 spinners that could be inserted into various positions in the ammonia tubes. The spinner was fabricated by twisting a flat piece of stainless steel to form a helix with about six turns per inch.

During the design phase, it was believed that the spinners would improve the low velocity heat transfer rate at the ammonia inlet end of the tubes by rotating the flow and throwing liquid droplets outward to the warmer tube wall. Initial test results were unusual and it was quickly determined that the best heat exchanger performance was achieved when the spinners were located in the downstream portion of the tubes where the ammonia was being superheated. Figure 2 shows some of the test data and the final spinner placement. When the spinners were inserted further upstream into the mixed (vapor/liquid) region, the liquid droplets probably gathered toward the center of the spinners and traveled down without the normal boiling that would occur when the liquid droplets contact the tube wall. The result was a loss of superheat in the ammonia discharge and a reduction in heat exchanger effectiveness.

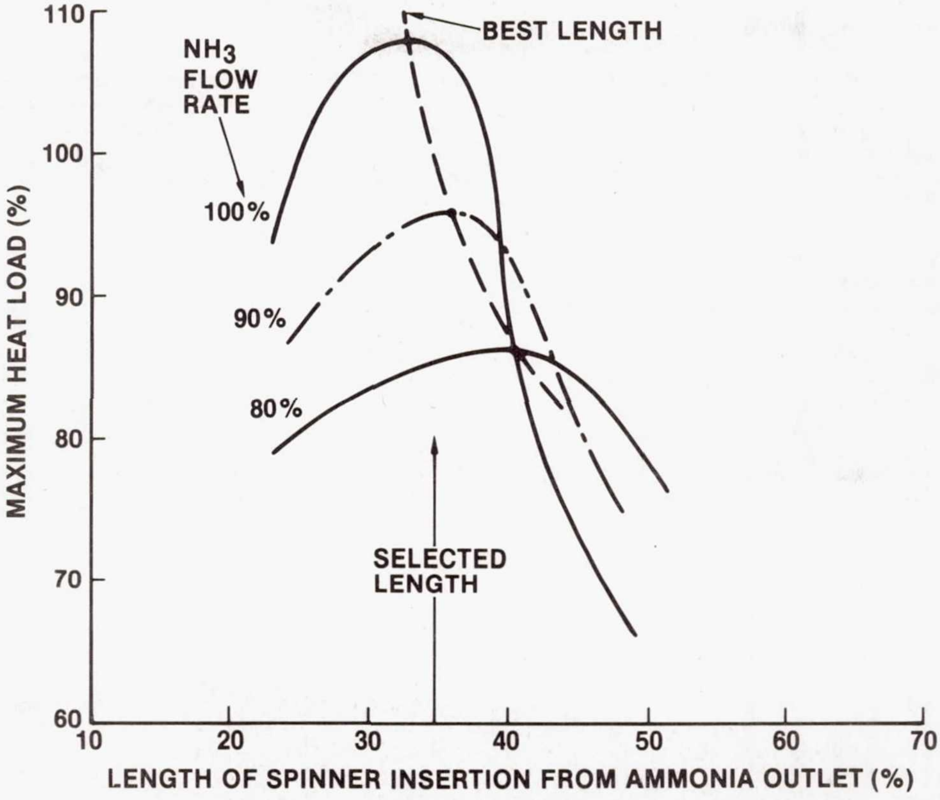

FIGURE 2. EFFECT OF SPINNER LOCATION ON PERFORMANCE

HEAT EXCHANGER CONTAMINATION

During development testing of the full-size heat exchanger with the spinners correctly placed, a loss in superheat was observed with some cold liquid ammonia droplets in the exhaust after considerable operating time. The degradation in performance, which resulted in an increase in ammonia flow rate to absorb the required heat load, was caused by the accumulation of oil in the ammonia tubes. A clean heat exchanger will transfer about 90 percent of the total heat load in the upstream module, but after only about 2 hours of operation, the heat transfer in the upstream module would be about the same as in the downstream module. It was apparent that the transition to dry vapor, which separated the boiling and superheat regions in the heat exchanger, was moving down the ammonia tubes toward the exit with operating time. After about 10 hours of operation, the ammonia side of the heat exchanger was flushed with a solvent. Analysis of the nonvolatile solvent residue disclosed that it contained 4 to 5 cubic centimeters of oil. Subsequent heat exchanger flushing operations that were performed after operating periods in excess of 10 hours indicated that a self-cleaning process limited the amount of oil that could accumulate.

After noticing the accumulation of oil in the heat exchanger, the oil content in the ammonia was monitored. Although the ammonia procurement specification required a 5-ppm maximum oil content and the supplier certified that the ammonia conformed to the specification, actual analysis showed approximately a 30-ppm content. An investigation of ammonia manufacturing, storage, and delivery systems revealed that the 5-ppm oil content limitation is not realistic for ABS operation. A 10-ppm limit appears to be more practical, but it is anticipated that periodic flushing of the heat exchanger will still be necessary for removing oil accumulation and restoring the desired heat transfer effectiveness level; however, instead of specifying a fixed operating time interval between flushing operations, the need for such cleaning on the orbiter will be established by monitoring the ammonia vapor discharge temperature to detect loss of superheat.

CORROSION OF HEAT EXCHANGER TUBING

At the conclusion of the qualification test program, it was determined that there was excessive leakage from the Freon side to the ammonia side of the heat exchanger. The areas were located that were leaking and metallurgical examination with a scanning electron microscope revealed a pitting corrosion attack on the stainless steel 3/32-inch diameter tubing. In the leaking areas, the corrosion had progressed through the 0.008-inch thick tubing wall.

Tubing for the development heat exchanger and for the assembly installed on Orbiter 101 for the approach and landing test program had been specified to be made from 347 CRES material. But delivery schedule problems caused a change to 304L CRES material to meet the manufacturing schedules for the test heat exchanger.

Although the specification for this material allows a maximum carbon content of 0.03 percent, chemical analysis of tubes showed that the actual carbon content was about 0.07 percent. The use of 304 series stainless steel with a carbon content greater than 0.03 percent is not recommended for brazing because of carbide precipitation, which occurs during cooling and results in a loss of corrosion resistance.

Since it was suspected that the tubing vendor had used the wrong material to redraw the tubing to its proper final size, additional tubing was ordered from a different vendor. This time, several samples were chemically analyzed prior to redrawing and found to have a carbon content of about 0.025 percent. After redrawing, chemical analysis of several samples showed a carbon content of about 0.07 percent.

Redrawing of the tubing to the proper final size (3/32-inch outer diameter, 0.008-inch wall thickness) requires multiple draws. Typically, hydrocarbon greases are used to help draw the tube through the dies. After each draw, the tubing is cleaned and annealed to soften the material prior to the next draw. As the tubing diameter becomes smaller, cleaning the grease from the tubing becomes more difficult. Apparently, the small residue of hydrocarbon grease that remained in the tubing after cleaning resulted in carburization of the tubing during the annealing process.

In order to prevent the carburization from recurring, two changes were made. First, after conducting an industry survey to determine practical tube cleaning procedures, a detailed procedure was prepared. Second, the tube material was changed back from 304L CRES to 347 CRES. Although the 347 CRES can also be carburized, substantial amounts of stabilizing elements (columbium and tantalum) make carbide precipitation less likely if a small amount of carburization takes place. Additional tubing was procured from a vendor who followed the recommended cleaning procedure. Samples taken before and after redrawing showed that no carburization had taken place and subsequent usage of this tubing has been successful.

TEMPERATURE SENSOR MOISTURE PROBLEM

Each Freon outlet loop has three surface-mounted platinum resistance temperature sensors to maintain the outlet temperature at a nominal 35 °F, based on a change in sensor resistance with changes in temperature. One sensor controls temperature through the primary control system. The second sensor controls temperature through the secondary control system, which duplicates the primary control system and is used only in the event of a primary control system failure. The third sensor is monitored by circuitry that switches control from the primary to the secondary control system if the Freon outlet temperature is excessively low for an extended period of time. All three sensors are identical in design and each is surface-mounted on the Freon line. The mounting surface of each sensor is coated with a thin film of thermal conducting grease to provide quick response from the sensor to changes in Freon temperature.

After the qualification test program during field operation, there were several temperature sensor failures. These failures were caused by moisture penetration into the porous ceramic insulating material between the platinum element and the metal-mounting baseplate. The ceramic exhibited very high bulk electrical resistivity when dry, but this resistance dropped rapidly when the smallest amount of moisture was absorbed.

The sensor assembly incorporates a fiberglass-reinforced silicone rubber cover to seal the platinum element from the ambient environment. Water immersion testing performed on this design showed a rapid degradation in insulation resistance between the element and the mounting base. Impregnation of the rubber cover with a silicone gel, which was previously used for moisture resistance in similar applications, decreased the rate of moisture penetration through the cover, but the bond between the rubber cover and the silver baseplate was not an adequate moisture seal. Attempts to improve this bond by roughening the silver plate surface and adding room temperature vulcanized (RTV) type silicone rubber were not successful.

In order to provide adequate resistance to moisture penetration, it was decided that the rubber cover should be replaced by a thin metal cover and soldered to the baseplate with multiple rubber seals where the lead wires extend through the cover. Because of the additional mass of the metal cover, it was anticipated that the time response of the sensor to temperature changes might be longer, and, therefore, result in system instability. Water immersion testing of this configuration showed no significant loss in insulation resistance after an extensive length of time; however, the results of system response testing were somewhat surprising. Although the response of the sensor was slower, there was no apparent effect on system stability. Instead, the slower response of the primary control sensor (RT_1) resulted in a longer temperature undershoot during start up. This increased time, monitored by the control transfer (RT_3) sensor, resulted in a transfer of control from the primary to the secondary system.

In order to solve this problem, the length of time required to transfer from primary to secondary control could have been increased, but this would have required an expensive change in the electronic controls. Instead, the thermal conducting grease under the RT_3 sensor was replaced by a silicone grease with a much lower thermal conductivity. The effect was to further slow down the time response of the RT_3 sensor to compensate for the slower time response of the RT_1 and RT_2 sensors.

SMOKE DETECTOR

Brunswick fire detectors are used in the avionics bay enclosures and the crew compartment in conjunction with a Halon suppression system to provide early warning and contain any potential hazards. Figure 3 shows their locations. To better understand the design problems and how they were solved, a brief description of the detector operation follows.

This device is an active instead of a passive ionization detector and continuously samples the surrounding air for detection of submicron pyrolitic matter, which is associated with the early (incipient) stage of fire. Figure 4 shows a sectional view of the unit. The sample air flow drawn into the detector is divided between two paths: one goes through the ionization sensing chamber and the other bypasses the chamber and goes directly to a rotary vane positive displacement pump. The pump is driven by an ac synchronous motor powered by a 28 Vdc dc-to-ac converter motor controller hybrid.

The two-path air flow scheme provides for aerodynamic separation of particles entering the unit and prevents all large particles not associated with a hazard from entering the sensor and creating false alarms. Submicron particles in the air sample combine with charged particles created by a radioactive source of Americium 241, which reduces the ion current produced within the ionization chamber. The resulting change in current is proportional to the concentration of particles. This current is converted to a voltage through a high impedance resistor network, and is processed through a voltage-to-frequency converter hybrid for evaluation by a large-scale integrated circuit (LSI). The LSI measures the frequency and rate of change and triggers an alarm signal when the appropriate threshold values are reached.

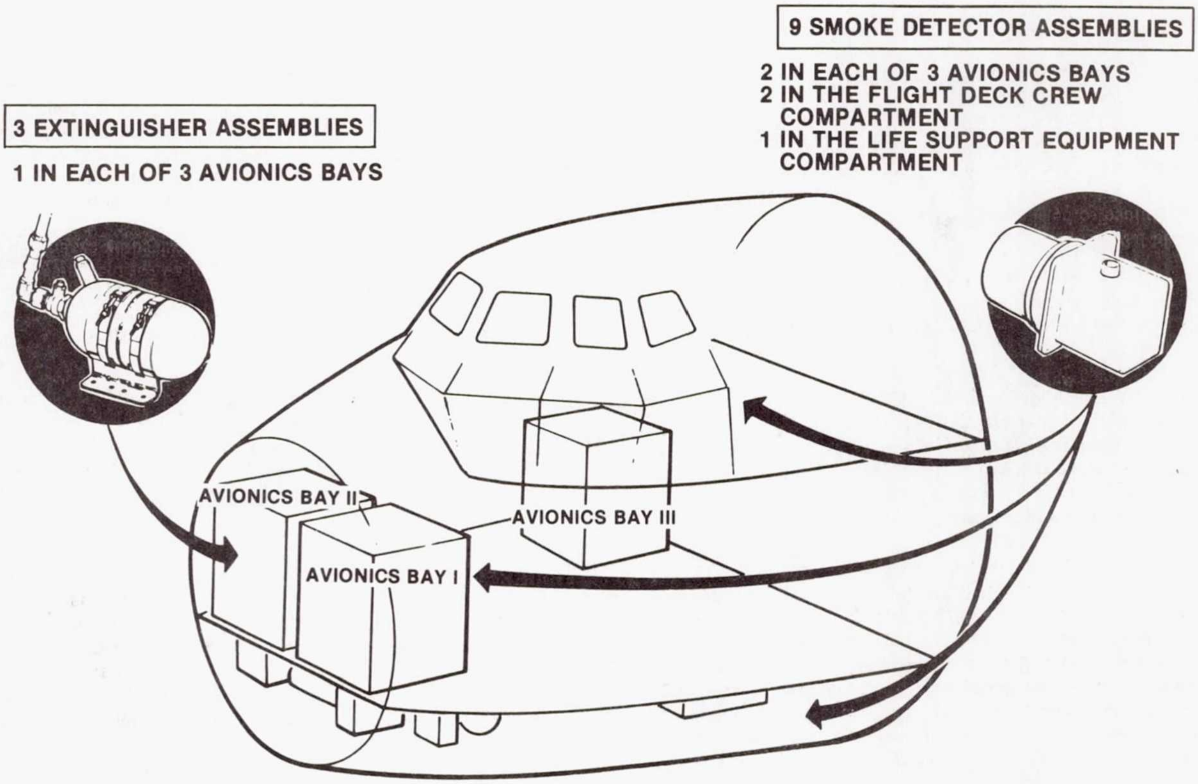

FIGURE 3. SPACE SHUTTLE ORBITER FIRE PROTECTION SYSTEM

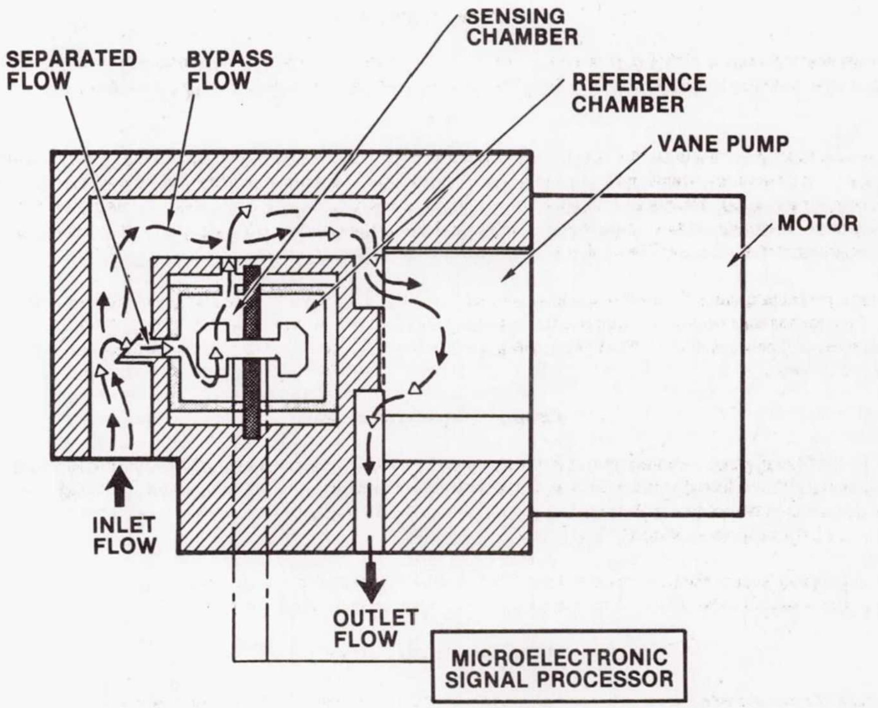

FIGURE 4. SMOKE DETECTOR AIR FLOW DIAGRAM

DESIGN PROBLEMS AND SOLUTIONS

The design problems encountered after the detector basic concept was proven involved meeting the operational life requirements of the orbiter. The problems and their solutions are as follows.

Quartz Crystal Microbalance (QCM) Sensor

The original design used a QCM as the sensing device to measure the rate of mass change that was collected on the crystal, which was the signal generator of an alarm. The problem with this system was in providing adequate crystal life to meet the design goal. Even in a clean environment, constant particle collection was enough to saturate the crystal within a relatively short time. Attempts to regenerate the crystal remotely were cumbersome and required considerable development. At this time, the use of an ionization chamber as a substitute for the QCM was introduced. This chamber's life was a function of the radioactive source's longevity (half life equals 458 years). This substitution did not jeopardize the program objectives and solved the sensor life problem.

Ionization Chamber Altitude Operation

The ionization characteristics of a low-energy alpha source vary with the density of the surrounding air. In order to provide signal compensation for minor changes in the ambient atmosphere, this detector contains two low-energy sources in its sensing and reference chambers, as seen in Figure 4. The orbiter altitude pressure requirement for this system is 8 psia (16,000 feet) and is tested to 7.3 psia to provide margin. During altitude testing of the sensors, a large signal shift in some units and no shift in others (up to 50,000 feet) was observed. It was concluded that there had to be differences in the two ionization sources to create the unbalance in the electrical current that was generated between the two chambers. The two parameters controlling the source characteristics are energy level (mean electron volts [MEV]) and activity (microcuries). If these characteristics are matched, the sensor signal will remain balanced; however, this is not easy to accomplish.

A series of matrix-oriented tests were conducted to pinpoint the characteristic that most affected the signal shift. The most effective results were first obtained by maintaining one source as a constant and varying the second. Through extensive analysis and testing, the upper and lower limit values that produced the desired results were determined for both activity and energy levels. These values were then used to pair the sources before being installed in the sensor. This selection process doubled the number of acceptable sensors; however, manufacturing assembly techniques still create source characteristic changes that prevent 100 percent of acceptable units even after selection.

The importance of this solution is that it determined how to minimize the sensor signal from shifting during changes in ambient air density.

Air Moving Pump Design

Two problems were encountered during the development of the rotary vane air moving pump: one involved the material used to make the vanes and the second involved contact friction between the rotor and the mating end surface during vibration testing. This design is shown in Figure 5.

The original vanes were made from a graphite-impregnated resin material that, by design, deposits a thin layer of resin on the housing wall to improve pump efficiency. Unfortunately, this deposit also increases the friction forces because the graphite does not form a perfect lube surface and, therefore, the motor torque requirements are higher. To overcome this would have meant increasing the motor power to an undesirable value. Various materials were tested that showed high-pressure velocity (PV) characteristics, but only one passed the design criteria. That material is a cadmium oxide impregnated Teflon called Fluoroloy D and it has successfully operated in excess of 12,000 hours without appreciable wear.

The contact friction problem during vibration testing was solved by designing the small diameter rotor retainer such that it always protrudes above the rotor face. This means that only it can contact the mating surface, thus preventing contact with the entire diameter of the rotor face. Also, the retainer was made of heat-treated 17-7 Ph and the mating surface was finished with a Class I anodize so that any contact between them involved two very hard surfaces.

Pump Driving Motor Design

The major problem in the design of the pump motor was the selection of dry lube bearings in order to minimize the power consumption. This type of bearing did not provide the expected motor life. A design change to wet lube bearings required an increase in power to overcome the higher friction load; however, it was possible to reduce the motor speed to increase its driving torque without exceeding the allowable power consumption. This change resulted in a 20,000-hour operational life motor.

Because of the lower motor speed, the lower pump flow had to be compensated for in order to maintain the same sensor performance. This was accomplished by a size change to the orifice that controls the flow split through the sensor.

Electronics Hybrid Design

When the previously discussed motor speed change was made, the motor controller hybrid, which supplies the correct driving frequency to the motor, required a new design. It was a straightforward change to provide the new frequency.

Another function of this hybrid is to supply the self-test signal that verifies the running condition of the motor. The original design measured the running current to determine either a stalled or open-winding condition. The current window available to make this determination was very narrow because of the hysteresis effect on the current, and, consequently, a false not-running condition would occasionally be indicated. A new self-test circuit design was introduced to eliminate this problem.

The new self-test circuit examines the motor current wave-form frequency instead of current level to determine an open winding, thereby making this function independent of normal running current changes. Since this eliminates the aforementioned current window, it allows setting the stall point indicator very close to the actual stall value, which maximizes the most self-test life.

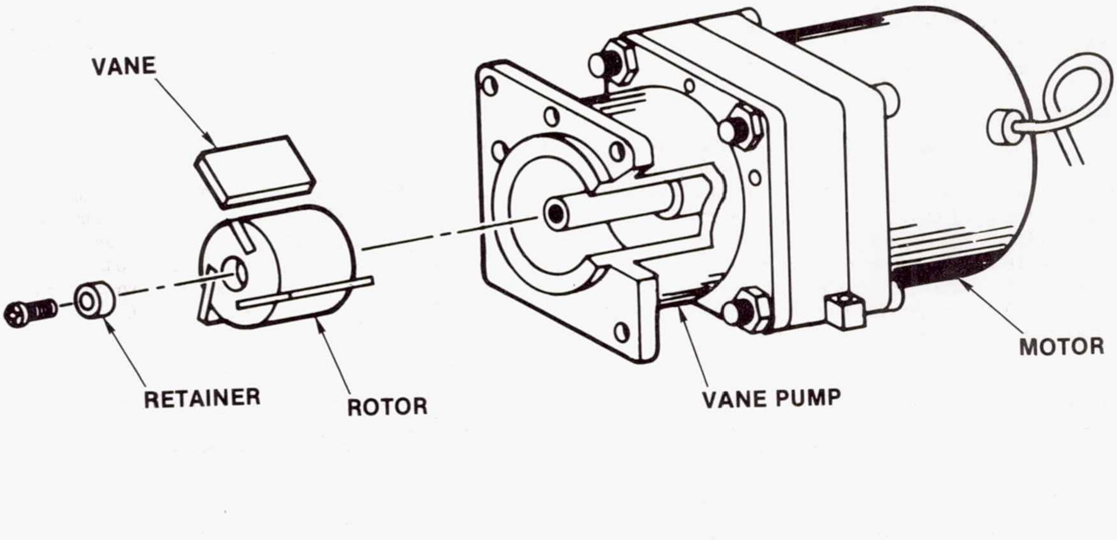

FIGURE 5. PUMP/MOTOR ASSEMBLY

REMOVAL OF HYDROGEN FROM FUEL CELL PRODUCT WATER USING LOW TEMPERATURE CATALYZED METAL TUBES

The water management system (WMS) of the Shuttle orbiter relies upon the water produced by its fuel cells to replenish that water used for either metabolic consumption by the crew or in the Shuttle's flash evaporator. However, the water produced by the fuel cells is saturated with hydrogen (H_2) at the operating conditions of the fuel cell (150°F, 60 psia), which results in 0.066 cubic centimeter of hydrogen being dissolved in every cubic centimeter of water produced. In the process of water storage and consumption, hydrostatic pressure is decreased, which causes the dissolved hydrogen to come out of solution and revert to the gaseous phase unless provisions are made to remove a major portion of it from the water. The technique that has been selected for removal of hydrogen from the fuel cell generated water is based upon the use of catalyzed palladium/silver (Pd/Ag) tubes operating at ambient temperature. Fuel cell product water flows on the inside of the tubes while space vacuum is applied to the outside tube surfaces causing the hydrogen to pass through the solid metal tubes to space vacuum. This hydrogen removal concept was first qualified aboard Apollo spacecrafts; however, to satisfy the removal requirements for the Shuttle orbiter the hydrogen separator was required to demonstrate an absolute hydrogen removal capacity of approximately ten times that of units built for the Apollo spacecraft. In addition, reductions in relative weight and volume were required.

The challenges of developing such a lightweight, high performance hydrogen separator for the Shuttle orbiter were successfully met, but not without development hurdles and problems that required timely and creative solutions. The following discusses the major development challenges and problems encountered and how their solutions were implemented.

PROBLEMS AND CHALLENGES

The major challenge of the hydrogen separator development can be summarized in one statement: reduce size by a factor of three (compared to Apollo hardware) and increase capacity by a factor of ten.

Specifically, the requirements that had to be met were a hydrogen removal rate equal to or greater than 70 percent with product water flowing at 23 pounds per hour at ambient temperature (70°F ± 2), without inducing a pressure drop of greater than 0.7 psid. Maximum allowable hydrogen separator weight was 5 pounds.

PROBLEM RESOLUTIONS

Performance Enhancement

Calculations and experimental data indicated that to remove a minimum of 70 percent of the dissolved and/or free hydrogen from water flowing at a rate of 23 pounds per hour and at ambient conditions would require a total water flow path length in excess of 900 inches. The calculations were based on catalyzed Pd/Ag tubes optimized at a 0.125-inch diameter and a wall thickness of 0.010 inch. Since a single 900-inch path length would exceed the allowable ΔP of 0.7 psid and internal catalyzation of the tube would be impractical, a technique for manifolding the hydrogen-saturated water flow into a combination of shorter series/parallel lengths was devised. This manifold technique permitted the use of 16 Pd/Ag tubes, with each tube having a path length of 57 inches. This series/parallel configuration permitted the fuel cell product water to enter eight inlet tubes simultaneously (Figure 6) and flow through these tubes in parallel; exit from the initial eight tubes and simultaneously enter into a set of four parallel outlet tubes manifolded in series with the initial eight inlet tubes. The water then exited the first four outlet tubes and simultaneously entered a second set of four parallel outlet tubes manifolded in series with the first set of four outlet tubes. The product water passing through the second set of four tubes then exited into a common water outlet port. This series parallel manifolding technique divided the tubing into catalyzable lengths, met the required pressure drop, and still maintained sufficient residence time within the catalytic Pd/Ag tubes to meet the hydrogen removal requirements.

While the calculations predicted satisfactory performance, initial verification testing with the development unit showed less than the calculated 70 percent removal efficiency. Through a series of bench top experiments, the reduced removal rate was traced to the final 10 percent through 15 percent length of each flow path, i.e., where only dissolved (as opposed to free) hydrogen exists with the water. Since flow is laminar in these regions, dissolved hydrogen near the center of the tubes reaches the walls only by diffusion.

The solution to enhancing the removal rate in the diffusion-only regions consisted of developing small turbulators inserted into the last 10 inches of each tube path of the first set of four outlet tubes and into the first and last 10 inches of each tube path of the second set of four outlet tubes (12 turbulators). These thin, spiral-like metal turbulators were designed to break up or turbulate the laminar flow characteristics of the water. This allowed hydrogen trapped at the center of the water column to reach the catalyzed tube surfaces and thereby enhance its removal.

PACKAGING

The use of 16 separate tubes proved feasible from a performance standpoint. The need for creative solutions to the inherent challenge of packaging 16 tubes, each 57 inches long, into a package weighing 5 pounds or less remained to be solved. First, a technique had to be devised for bending the tubes into a double-U configuration with each tube having three 180-degree bends. To achieve a compact configuration, an extremely small bend radius was desired, smaller than standard (0.50 inch) bend radii normally associated with 0.125 inch diameter tubing. Since the Pd/Ag tubes were of such a small diameter and thin-wall construction, bending the tubes in a very tight radius by using conventional techniques resulted in crimping or collapsing the tube. To resolve this, the Pd/Ag tube (in its initial 60 inches of straight length) was sealed at one end (crimped shut) and carefully filled with a nonabrasive, nontoxic water-soluble packing. Once the tube was filled, the open end of the tube was crimped shut. Bending of the tubes to a 0.31-inch radius was then successful and reproducible. Once the tubes were bent, the crimped ends were cut off and water was flushed through the tubes to remove the water soluble packing.

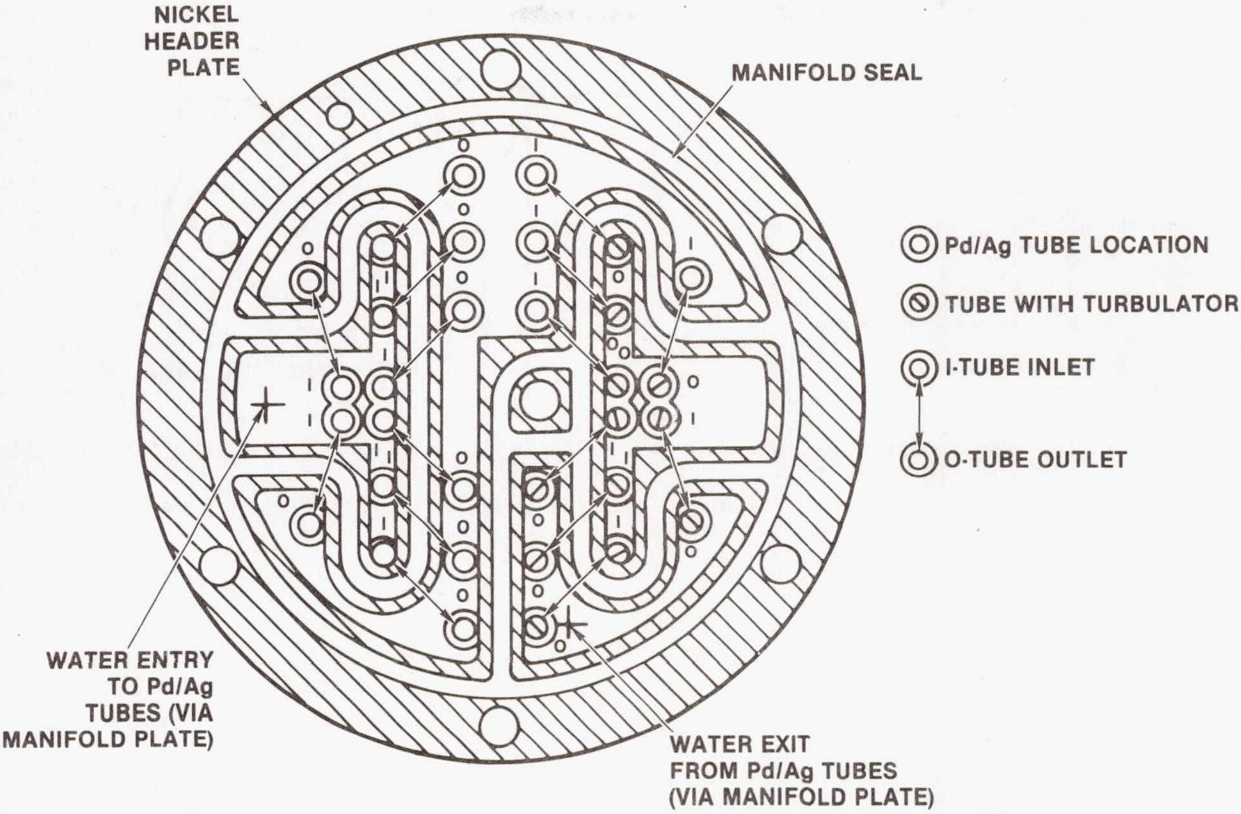

FIGURE 6. HEAD PLATE SHOWING Pd/Ag TUBE LOCATIONS AND MANIFOLD SEAL CONFIGURATION

Locating the tubes into a common header plate posed the problem of performing 32 separate welds (one weld for each end of the 16 Pd/Ag tubes) in a nickel plate designed to be 3.5 inches in diameter and 0.110-inch thick. Heli-arc welding techniques were examined and rejected since the heat generated could warp the thin header plate and the potential for welding error and subsequent increased scrap rates was high. Electron beam (EB) welding was selected as a viable technique to secure the tubes into the header plate. A treepan-type weld (Figure 7) was initially considered but was rejected when calculations showed that stress on the weldment of the treepan-configured joint was too severe. Additionally, reproducibility of an EB weld using a treepan joint was suspect. An EB weld technique using a butt-weld configuration between the Pd/Ag tubes and the header plate (Figure 8) was developed and qualified for weld integrity, structural strength, and reproducibility.

In order for the tube bundle of the welded Pd/Ag tube and header assembly to withstand the shock and vibration conditions experienced aboard the Shuttle orbiter, a technique for forming a tube bundle was devised. The technique allowed for tube growth (about 0.375 inch for the 16-inch lengths) characteristic of Pd/Ag metal exposed to hydrogen. A porous Teflon cord was selected for the tube tie-down and support technique. The Teflon cord was laced through the tubes in a braiding fashion, with the ends of the Teflon cord tied together to form a secure lace through the tube bundle. This Teflon cord braiding at various locations on the tube bundle secured the tubes of the bundle to resist the effects of shock and vibration and at the same time minimize cover up of the catalyzed outside surface of the Pd/Ag tubes, which could result in reduced separator performance and allow adequate tube growth.

Photographs of an assembled hydrogen separator and its components are presented in Figures 9 and 10, respectively. Key features and components are identified.

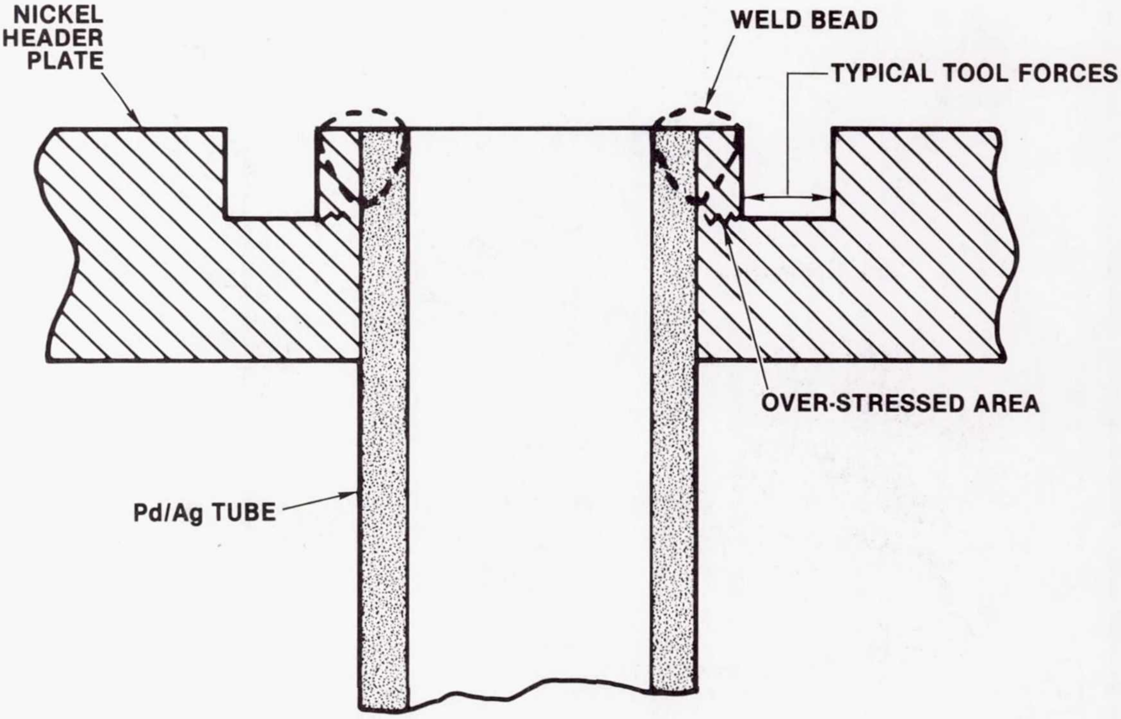

FIGURE 7. CROSS SECTION OF A TREEPAN WELD

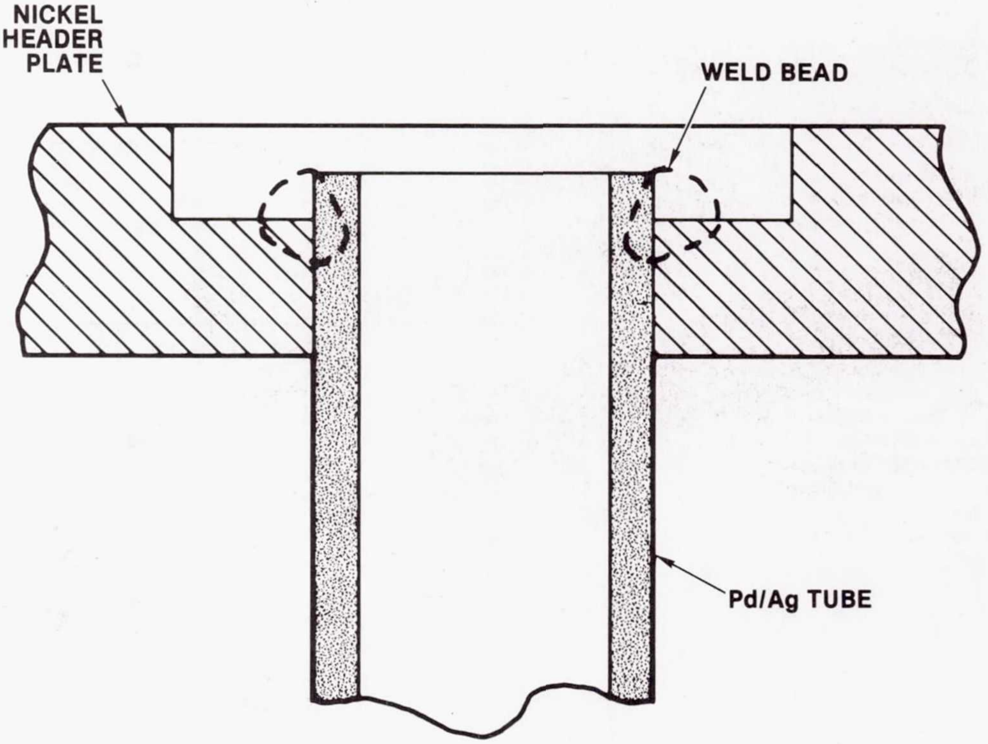

FIGURE 8. CROSS SECTION OF PRESENT WELD JOINT

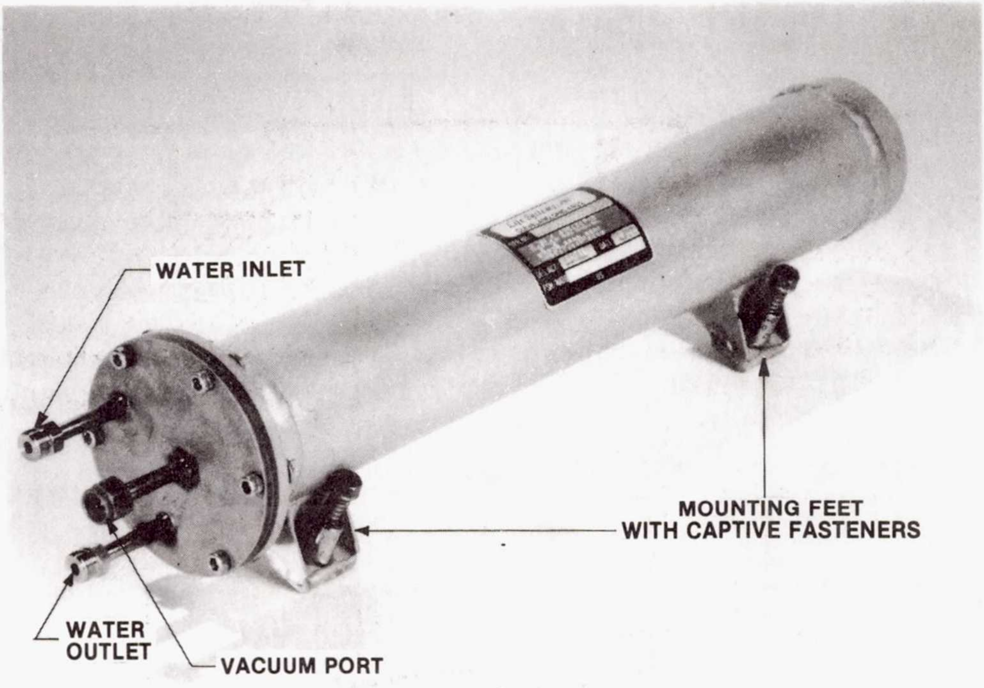

FIGURE 9. ASSEMBLED H_2 SEPARATOR

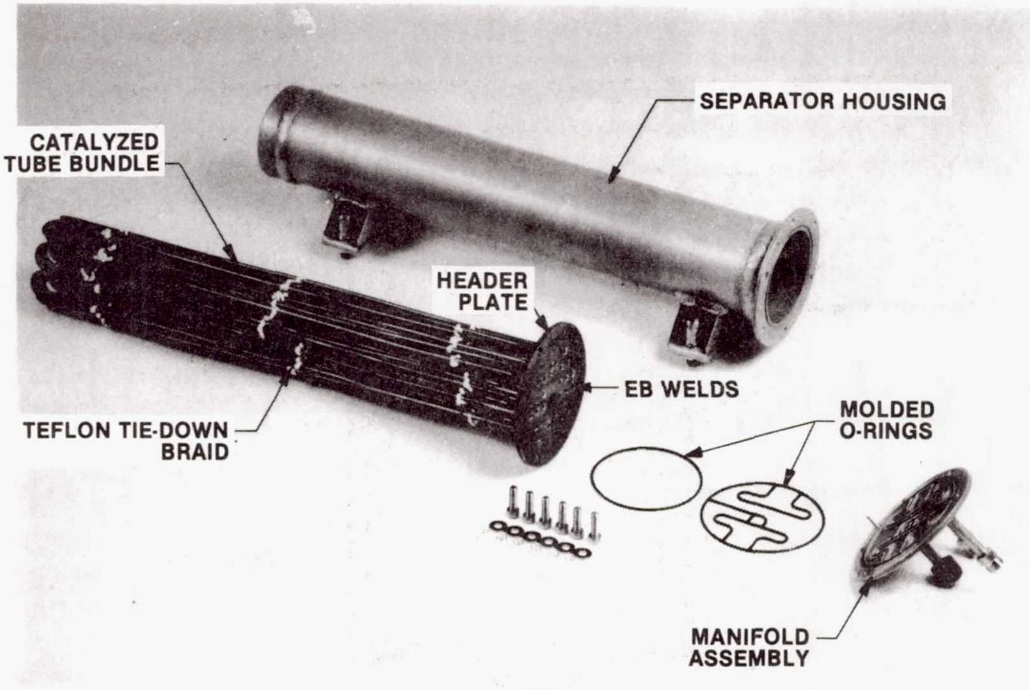

FIGURE 10. H_2 SEPARATOR COMPONENTS

FLIGHT EXPERIENCE

Shortly after STS-2 was launched, a high PH alarm occurred, which indicated potassium hydroxide (KOH) in the fuel cell produced water. The supply water system was configured to isolate the contaminated water from the drinking supply. The problem fuel cell was shut down and the mission was successfully completed. After this problem, the crew reported gas in the drinking water. It was suspected that the KOH had poisoned the separator catalyst. The following actions were undertaken:

- Hydrogen separator performance was tested at Life Systems, Inc.
- Water dispenser servicing techniques were reviewed.
- Drink bags were tested for residual gas.

Tests on the separator showed that the KOH had not affected its performance; however, servicing procedures used for the water dispenser could have trapped air in it, which was later displaced during the mission. Also, the water drink bags, which were serviced by evacuation were determined to be slightly permeable to air. It was concluded that the last two conditions were the cause of the problem.

To minimize recurrance on future flights, water dispenser procedures have been changed to preclude air entrapment. Water bags are evacuated as late as possible to minimize air permeation. No change was necessary for the separator.

CONCLUSIONS

Solution to key challenges in performance and packaging resulted in the successful development of a hydrogen separator that was capable of removing greater than 70 percent of the dissolved hydrogen from the fuel cell product water at ambient temperatures and at a flow rate of 23 pounds per hour within the specified pressure drop of 0.7 psid. The compact unit had a total length of 16.8 inches, an outside diameter of 3.5 inches, and not only met the 5-pound weight goal but beat it by 34 percent, weighing only 3.3 pounds.

WASTE COLLECTOR SYSTEM (WCS)

The major achievement of the WCS was to focus the problems of waste management into one integrated multifunction assembly (Figure 11). The WCS collects and processes human wastes, wash and extravehicular mobility unit (EMU) dump water, and trash vent gases in a sanitary and odor-free manner. Specific challenges were to simplify user procedures while minimizing weight, power, and volume requirements. There were significant achievements in several areas, including:

- Zero gravity operation
- Valve design
- Liquid/gas separation
- Corrosion protection

ZERO GRAVITY OPERATION

Simplified operational mechanisms and procedures for crew accommodation and restraint systems were developed through the use of past history, neutral buoyancy tests, and aircraft tests of many concepts. Final proof was obtained during STS flights where sufficient zero gravity time was available for full evaluation.

RESTRAINT SYSTEM

Prior to STS-5, the WCS restraints relied on a seat belt and a fixed-foot support. STS-1 through STS-4 data indicated that these methods were inadequate for reliable user positioning and restraint. A number of options were evaluated on STS-5 and several became operational.

Spring-loaded thigh bar restraints are self-stowing, easily positioned for use, permit a no-hands required retention of the user, and offer the user additional handholds for zero-gravity locomotion in the stowed position. No actions are necessary for stowage for launch and entry.

Foot restraints, consisting of a heel cup and toe straps, were added to an adjustable foot support for additional user restraint and height adjustment, if desired.

A user-adjustable toe bar was also added to provide a restraint means for standing micturations in the zero-gravity environment. The toe bar is used with the footrest in the stowed position. Restraint systems are shown in Figure 12.

URINAL CAPS

Prior to STS-5, a common urinal cap was utilized for both males and females. The STS-4 crew reported urine migration under the cap in the unsealed area between the urinal and the cap. This open area had been provided for proper air flow when the cap was used by a female. In addition, the crew also reported the last-drop problem.

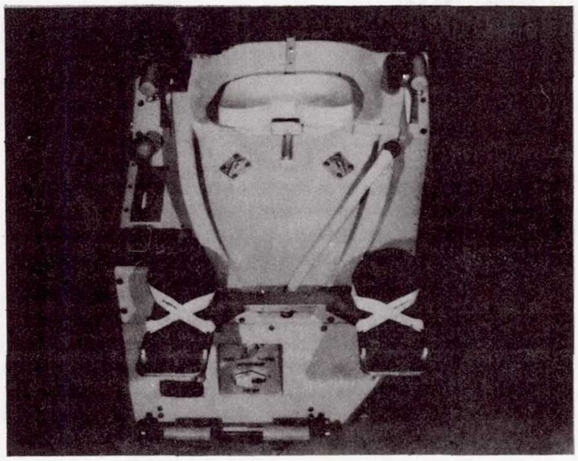

FIGURE 11. WCS ASSEMBLY

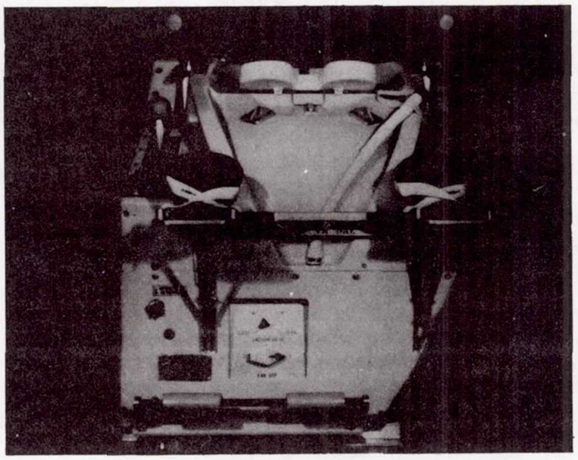

FIGURE 12. THIGH BAR AND FOOT SUPPORT WITH HEEL CUP, TOE STRAPS, AND TOE BAR

Several revisions were made to the caps for a male-only design. The mating area between the urinal and the cap was sealed by addition of a rubber gasket. This directed all air through the top opening only, which increased the effective air velocity and eliminated a leakage path.

There were several options for the cap opening to support in-orbit testing. The cap variations included the large rectangular opening (the common male-female cap with rubber gasket added), a centered hole opening, and an off-set hole opening, as shown in Figure 13. The smaller opening area of the latter two versions increased the air velocity at the collection point to aid in last-drop removal.

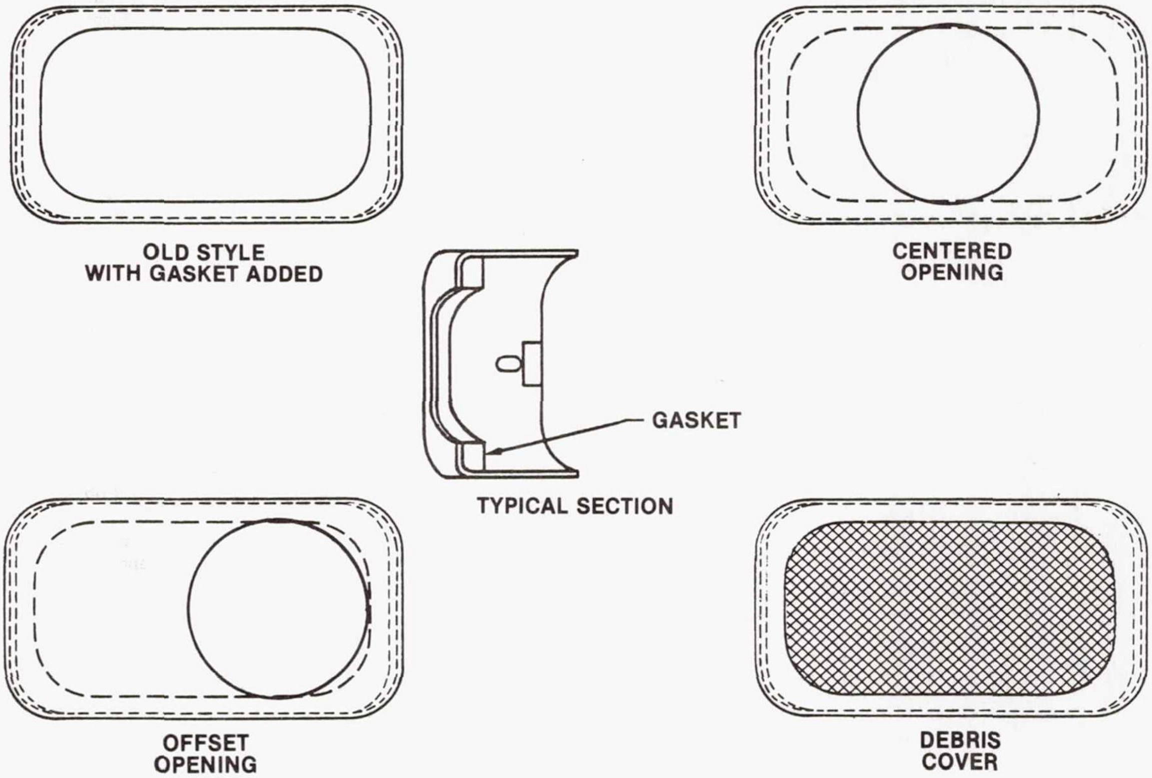

FIGURE 13. URINAL CAPS

In-flight testing of these three male-only caps was limited to the off-set hole version by the STS-5 crew, as it was very effective. No reports of liquid migration were received with the new cap. In addition, when combined with the pinch valve urinal, collection of the last drop ceased to be a problem.

In order to limit debris accumulation in the urinal, a cap with a debris screen was provided to cover the urinal when not in use. This was effective in preventing ingestion of cabin debris.

URINAL DEBRIS PROBLEM

STS-1 revealed problems related to unexpected amounts of cabin debris. During operation of the WCS, cabin air (8 scfm) is drawn into the urinal for liquid transport. After the STS-1 flight, when tested in a dry condition, the urinal screen was found to be nearly blocked with lint and debris. When wetted with liquid in zero gravity, the urinal air flow was further impaired such that the clogged screen acted as a liquid/gas separator.

Because of the suction of the fan-separator, the liquid thus tended to collect downstream of the screen in large liquid slugs with small pockets of air. This is compared to normal operation where only small slugs of liquid are separated by relatively large pockets of air. The result was an excessive instantaneous urine flow to the fan separator, which overwhelmed the centrifugal phase separator and carried over to the fan, which forced the urine with the air to the odor filter.

The problem was solved by adding a single filter, called a prefilter, to the urinal, as shown in Figure 14. The prefilter is easily changed on a daily basis to prevent debris buildup. Subsequently, the WCS operated successfully to confirm the postulated cause of the problem. Because of excessive debris collection in the urinal, the urinal prefilter will continue to require periodic replacement in flight.

VALVE DESIGN

Manual operation of control valves was dictated by the weight and power limitations and the complexity of the interlocking and sequencing of functions. As a consequence, the valves typically required low operating forces for the required large orifices. The large 4-inch sliding gate valve that opens the commode for defecation is also a vacuum seal. The pressure differential on the gate is relieved prior to opening to minimize operating force and structural weight.

Conversely, the pressure differential on the floating gate is used to achieve sealing pressure against a simple O ring when the commode is closed for vacuum drying of the solid wastes.

Similarly, a three-way 1-1/2 inch ball valve used for air flow control and vacuum sealing utilizes a floating seal design to achieve sufficient pressure for sealing while operating at a low torque of less than 25 inch-pounds.

A third unique valve design developed for the WCS was a simple pinch valve for air flow control in the urinal, as shown in Figure 14. An air flow of 8 scfm is used to entrap the urine and convey it through a funnel to a liquid/gas separator. The last drop of urination is often as large as a tablespoon of liquid, which has always been a disposal problem in zero gravity. For the WCS, this is collected by diverting the suction air flow to a port at the top of the collection funnel, which is achieved by squeezing a rubber tube at the base of the funnel, stopping the main flow air, and causing a small amount of suction flow at the top port. The user merely touches the drop to the port and the liquid is drawn into the system.

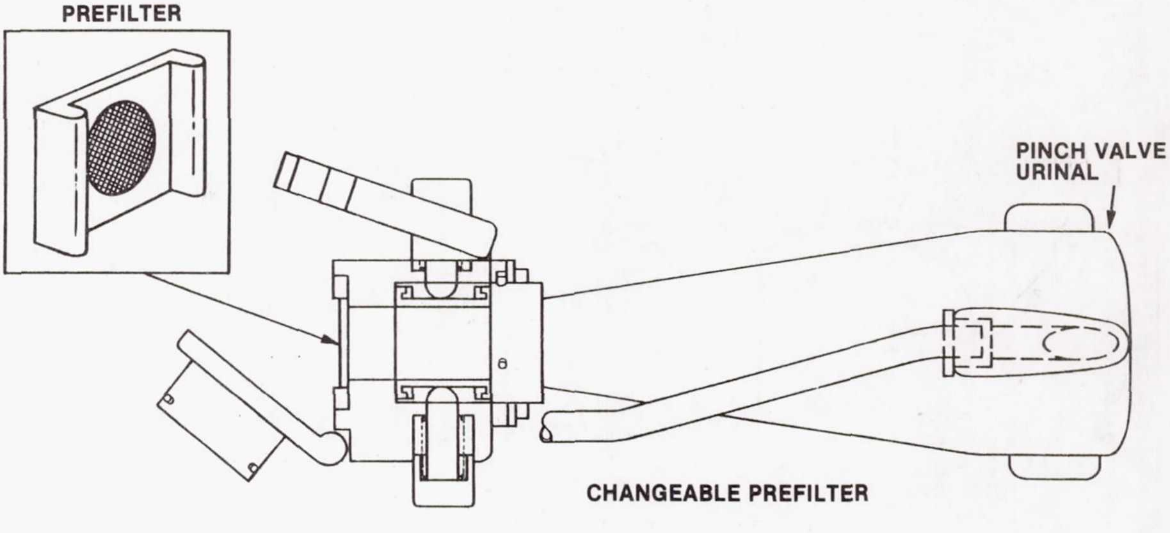

FIGURE 14. URINAL/PINCH VALVE ASSEMBLY

LIQUID/GAS SEPARATION

Separation of urine and other waste liquids from the transport air presented a number of design challenges. Foremost was the need to achieve reliable phase separation at minimal weight and power consumption. One method used to accomplish this goal was the integration of three functions into the fan separator (Figure 15): liquid/gas phase separation, liquid pumping, and air flow pressurization. Power requirements were further reduced by eliminating high friction dynamic seals and maintaining proper pressure differentials at required seal locations. By properly designing the flow paths for the commode and urinal air flows, it was possible to maintain a lower internal pressure in the rotating bowl than that between the bowl and the external housing. This condition prevents any liquid leakage out of the bowl and eliminates the need of a seal, which would add a significant cost in power, complexity, and reliability.

When the liquid/air mixture reaches the fan separator, the liquid is centrifugally separated from the air and pumped out of the unit through a stationary pitot tube in the separator. The fan separator is designed to produce sufficient air flow for the operation of the urinal and the commode. Since the commode is not necessarily used during micturition, a ballast air flow of approximately 30 cfm enters the system via a particulate filter, a calibrated orifice, and valve. The air mixes with the urine transport air flow in the fan separator to assure that moisture in the warm urine transport air does not condense in the cooler outlet line.

CREW TRAINING

Crew comments during flight debriefing indicated that considerable difficulties were being experienced in obtaining the proper position. As a result, a special training aid was designed, utilizing a television camera to assist the crew in obtaining proper positioning. In addition, the WCS development was utilized during flight simulations by the flight crew. Comments from crew personnel who have utilized the training aid indicate that it is very effective.

CONCLUSIONS

The greatest challenge in developing the WCS was integrating multiple waste management functions into a single flight assembly. In addition to the typical flight constraints of minimal power, weight, and volume, other requirements imposed on the WCS included ease of operation, user acceptance, liquid/gas separation performance, and satisfactory materials protection against the various waste products.

Flight experience has confirmed the basic design integrity of the WCS and that the principles of operation in zero gravity were correct. Modifications that have been incorporated have improved positioning and restraint methods utilizing user-accepted systems.

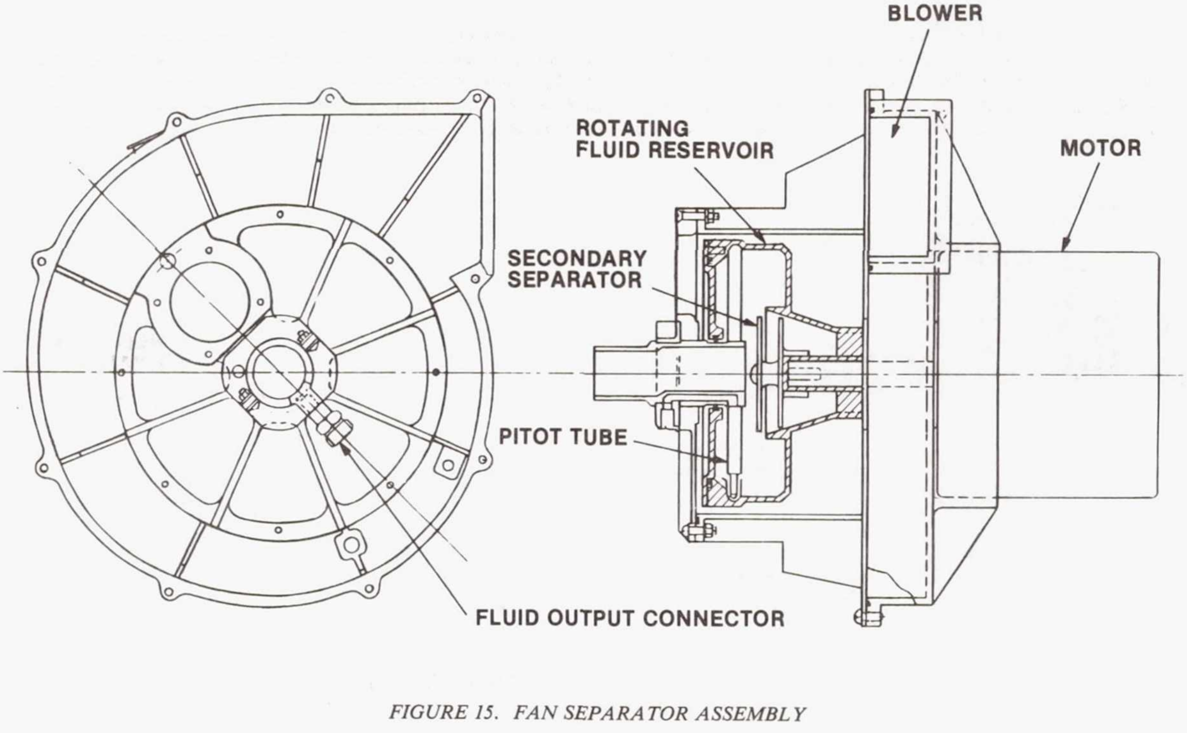

FIGURE 15. FAN SEPARATOR ASSEMBLY