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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.

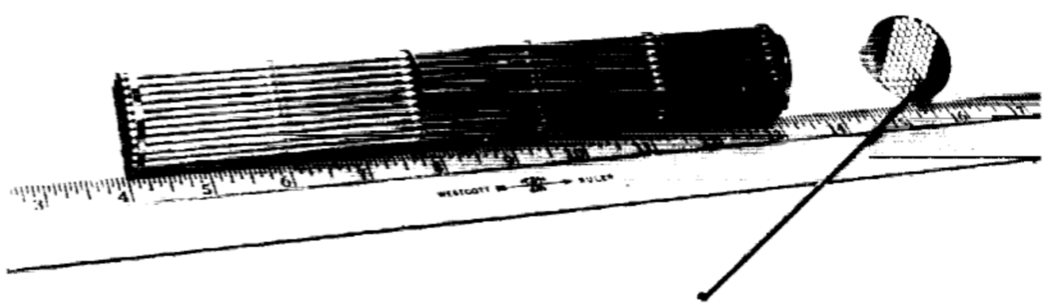

FIGURE 1. HEAT EXCHANGER MODULE TUBE BUNDLE

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.

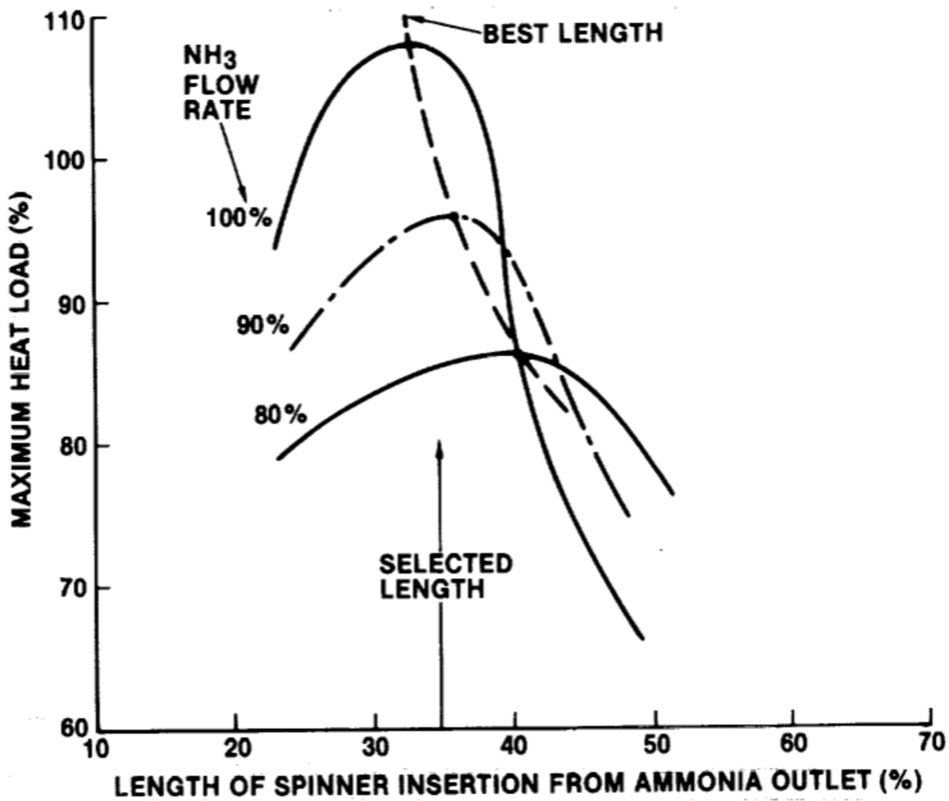

FIGURE 2. EFFECT OF SPINNER LOCATION ON PERFORMANCE

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.

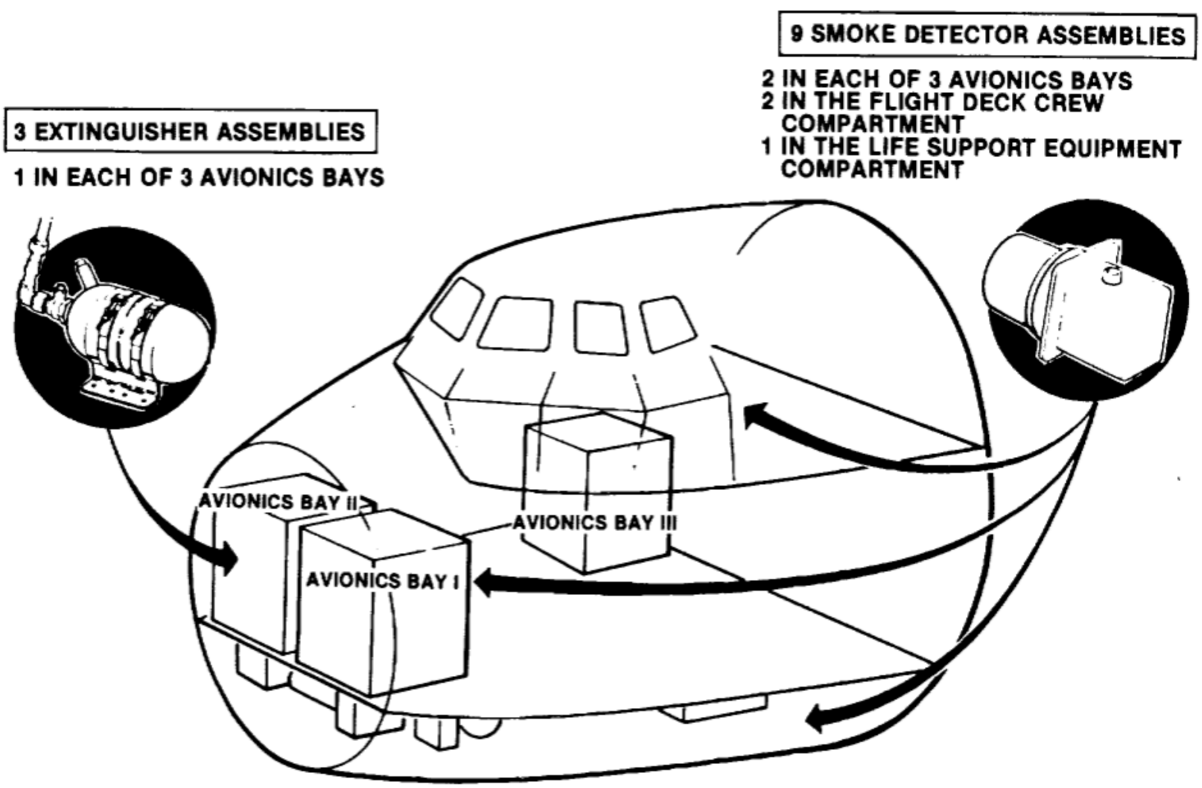

FIGURE 3. SPACE SHUTTLE ORBITER FIRE PROTECTION SYSTEM

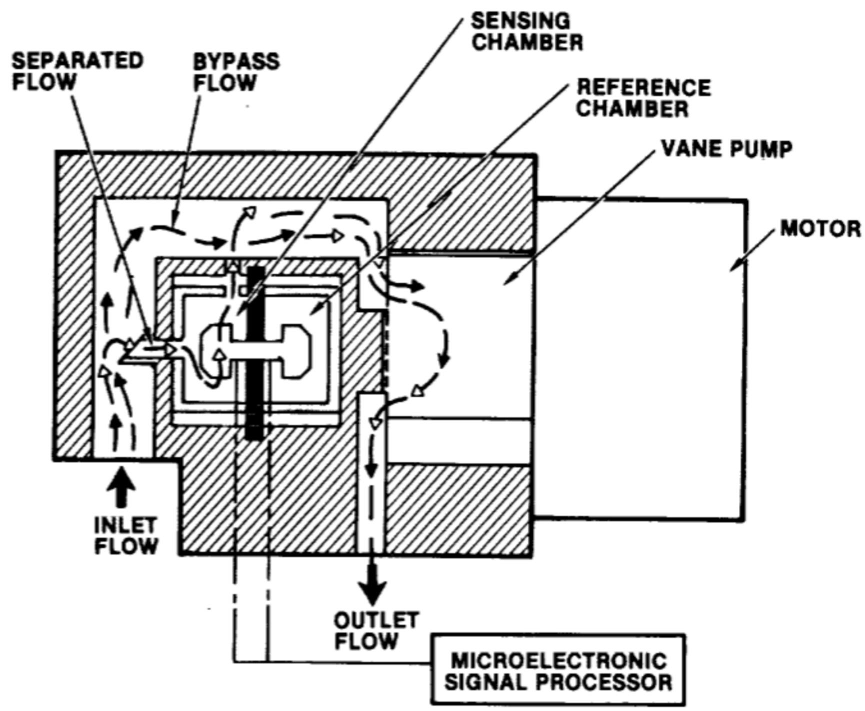

FIGURE 4. SMOKE DETECTOR AIR FLOW DIAGRAM

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.

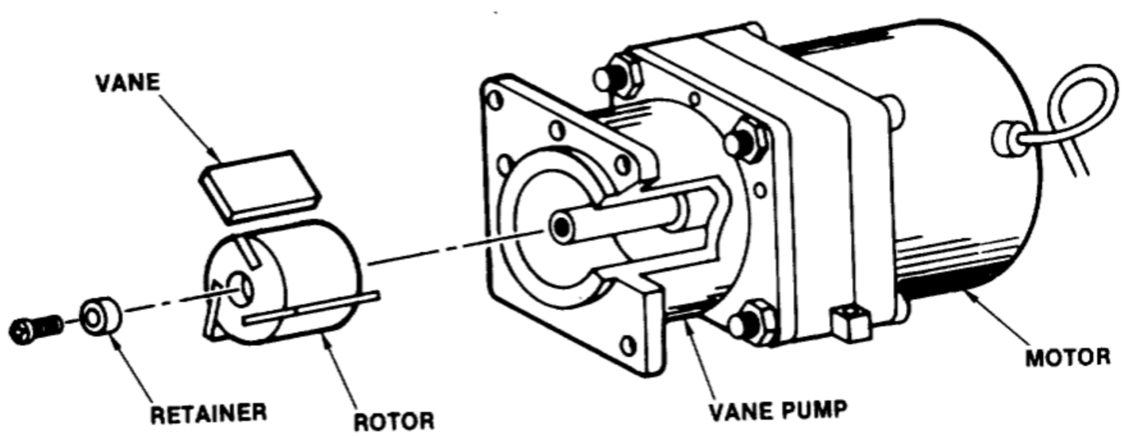

FIGURE 5. PUMP/MOTOR ASSEMBLY