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DESIGN EVOLUTION OF THE ORBITER
REACTION CONTROL SUBSYSTEM

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ABSTRACT

The challenges of Space Shuttle Orbiter reaction control subsystem development began with selection of the propellant for the subsystem. Various concepts were evaluated before the current Earth-storable, bipropellant combination was selected. Once that task was accomplished, additional challenges of designing the system to satisfy the wide range of requirements dictated by operating environments, reusability, and long life were met. Verification of system adequacy was achieved by means of a combination of analysis and test. The studies, the design efforts, and the test and analysis techniques employed in meeting the challenges are described in this paper.

INTRODUCTION

The requirements for the Space Shuttle Orbiter reaction control subsystem (RCS) were replete with challenges; however, four requirements had the greatest impact on system development: (1) a fail-operational/fail-safe design, (2) 10 years of life, (3) a 100-mission reuse capability, and (4) the capability for operation both in orbit and during reentry. The requirement of a fail-operational/fail-safe design not only introduced the complexity of additional hardware but, perhaps more importantly, introduced a complex, critical redundancy management (RM) system. The calendar life and reuse requirements posed problems in material selection and material compatibility and in ground handling and turnaround procedures, as well as classical wearout problems. The requirement for both on-orbit and entry operation complicated propellant-tank acquisition system design.

Because requirements did not identify the need for a specific propellant or propellant combination, an early issue that had to be resolved was that of selecting propellants. The ultimate propellant selection had a significant impact on the four requirements identified previously.

In subsequent sections of this paper, the most significant challenges incurred in development of the Orbiter RCS are identified and the manner in which those challenges were met in the ultimate certification of the system for operational flight is described.

PROPELLANT SELECTION

One of the first major issues to be resolved concerning the Space Shuttle Orbiter RCS was that of selecting the propellant(s) to be used. Early in the program definition phase, oxygen (O_2) and hydrogen (H_2) were baselined as the reactants for all propulsion and power systems. This choice was made for a number of reasons. As a propellant combination, O_2-H_2 provides high specific impulse. Logistics are simplified and less costly with a single propellant combination for all vehicle propulsion systems. The exhaust products are noncorrosive, and the propellants are relatively clean and nontoxic - all attributes desired in a reusable system. As a result of the oxygen/hydrogen baselining, all early technology work addressed improving the technology posture of O_2-H_2 systems. This improvement was necessary because O_2-H_2 systems were far from state of the art when used for reaction control purposes. As the component technology and systems study programs progressed, the weight advantage thought to exist with O_2-H_2 propellant systems gradually diminished. The heavy accumulators (two per system) in combination with redundant turbopumps (six per system) and heat exchangers (six per system) offset the weight advantage afforded by the better performance in the total impulse range being considered. Because system dry weight was high, the O_2-H_2 systems also added to the vehicle landing weight penalty.

A further factor that became more and more apparent as technology work progressed was that the oxygen-hydrogen systems would be very expensive to develop and build as well as extremely complex systems to operate. The complexity generated real concerns with respect to the reliability of the overall system. When it became clear that the weight of the O_2-H_2 system would be no better than that of a monopropellant system (fig. 1), the baseline was changed to a monopropellant hydrazine system to reduce cost and complexity. The monopropellant system baseline was retained through the award of the Orbiter prime contract. As the Orbiter design evolved and the total impulse requirement approached 2 million pound-seconds, performance again became a more important factor and the trade swung in favor of the bipropellant (monomethyl hydrazine (MMH) and nitrogen tetroxide (NTO)) systems, which were still lighter and much cheaper and simpler than O_2-H_2 systems. Another factor being con-
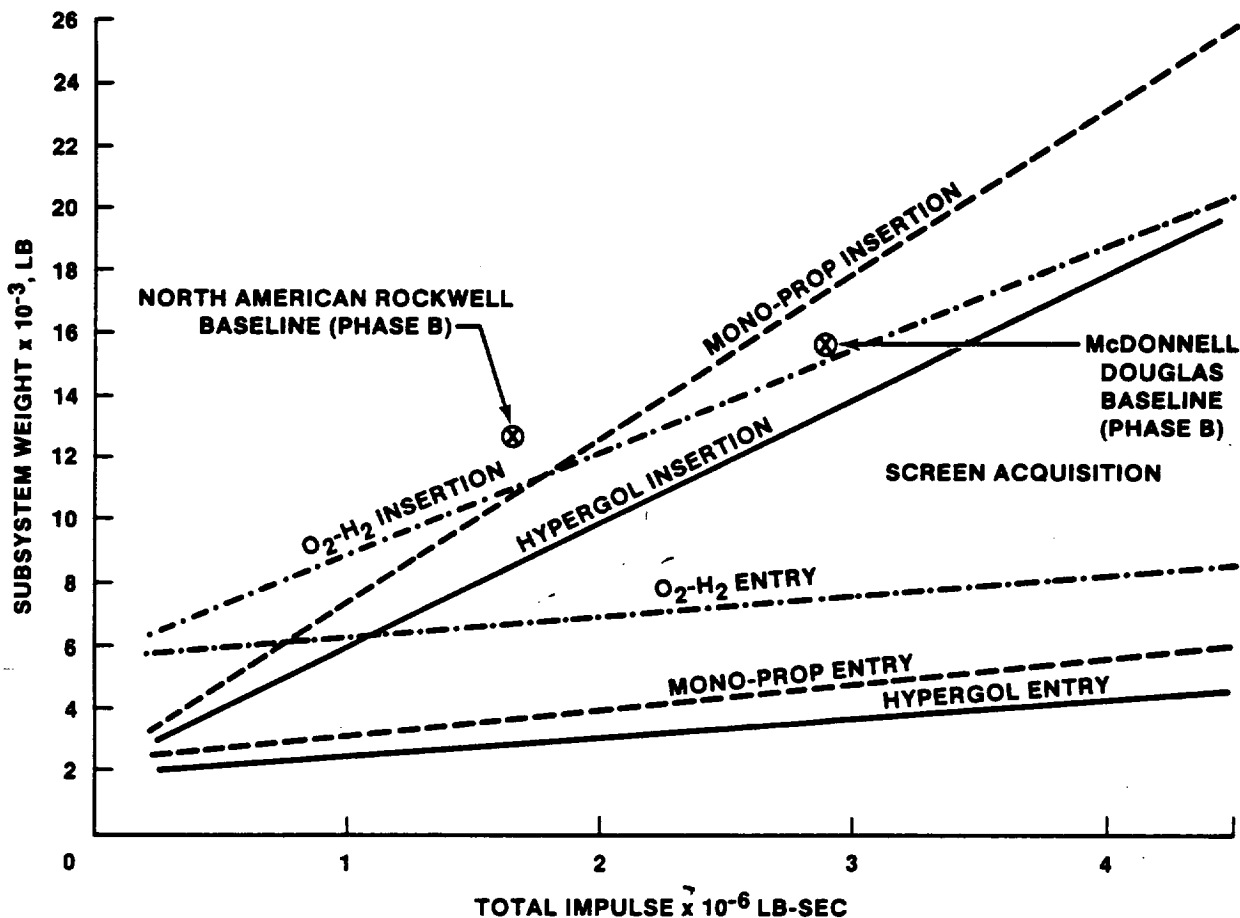
FIGURE 1.- WEIGHT AS A FUNCTION OF TOTAL IMPULSE FOR CANDIDATE PROPELLANTS.

sidered at the time was the potential for integration of the RCS with the orbital maneuvering system (OMS), which also used the MMH/NTO propellant combination. This propellant combination ultimately was selected because of the favorable weight trade-off, the reasonable development cost, and the minimal development risk.

COMPONENT DEVELOPMENT CHALLENGES

During the course of readying each component for flight, a distinct set of development and certification problems arose. Some were the result of well-defined, but rigid requirements. Others were the result of ill-defined or changing requirements; still others were the result of being unable to readily demonstrate satisfaction of requirements. Some of the more significant challenges encountered during the development of the Orbiter RCS components are described next.

SHUTTLE ORBITER RCS PROPELLANT TANKS

For a number of reasons, Orbiter Program management selected a tank concept employing a screen propellant acquisition device (PAD), which is used to acquire and deliver gas-free liquid to the thrusters. In previous spacecraft, a Teflon membrane was used to separate the propellant from the pressurant. However, Teflon membranes rupture after relatively few expulsive cycles and, therefore, would be unsuitable for 100-mission life. No elastomeric membranes that are sufficiently compatible with the RCS propellants to assure a 10-year life have been developed. For these reasons, and because of its weight advantage over the bellows-type tanks, a screen tank was chosen to provide gas-free liquid outflow. See figures 2 and 3 for the forward and aft configuration tanks, respectively. This device works by using the surface tension of the liquid to form a barrier to the pressurant gas. The PAD is made up of channels which are covered with a very finely woven stainless steel mesh, or
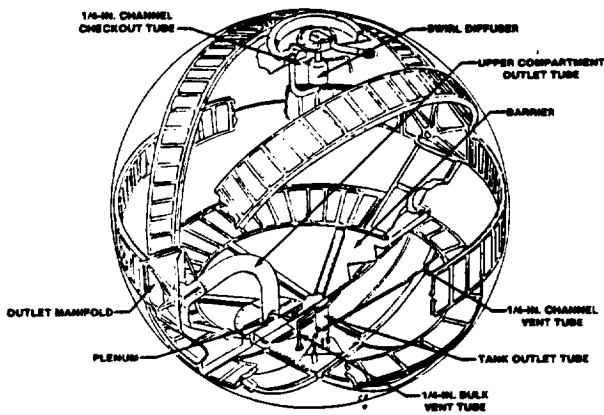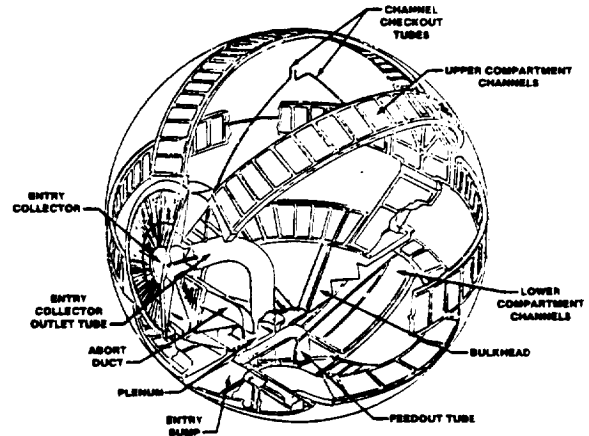
FIGURE 2.- FORWARD TANK.

FIGURE 3.- AFT TANK.

screen. Contact with liquid wets the screen, and the surface tension of the liquid prevents the passage of gas. The strength of the liquid barrier is finite, and the pressure differential at which gas will be forced through the wetted screen is called the bubble point. When the bubble point is exceeded, the screen is said to "break down," or to transfer gas. However, if the pressure difference is less than the bubble point, gas cannot penetrate the liquid barrier and only liquid will be pulled through into the channels. Therefore, the goal in designing the tank is to minimize the pressure loss while maximizing the amount of propellant expelled, or expulsion efficiency. The pressure loss is made up of two major components: the flow loss, due to viscous loss, turning loss, entrance loss, etc., and the hydrostatic head loss (fig. 4). The latter is a function of the acceleration to which the tank is subjected. The flow losses depend on the puddle size. As the volume of propellant decreases, the screen surface area in contact with the puddle decreases; thus, to supply the same volume flow rate, the velocity must be greater and, therefore, the pressure differential must be greater.
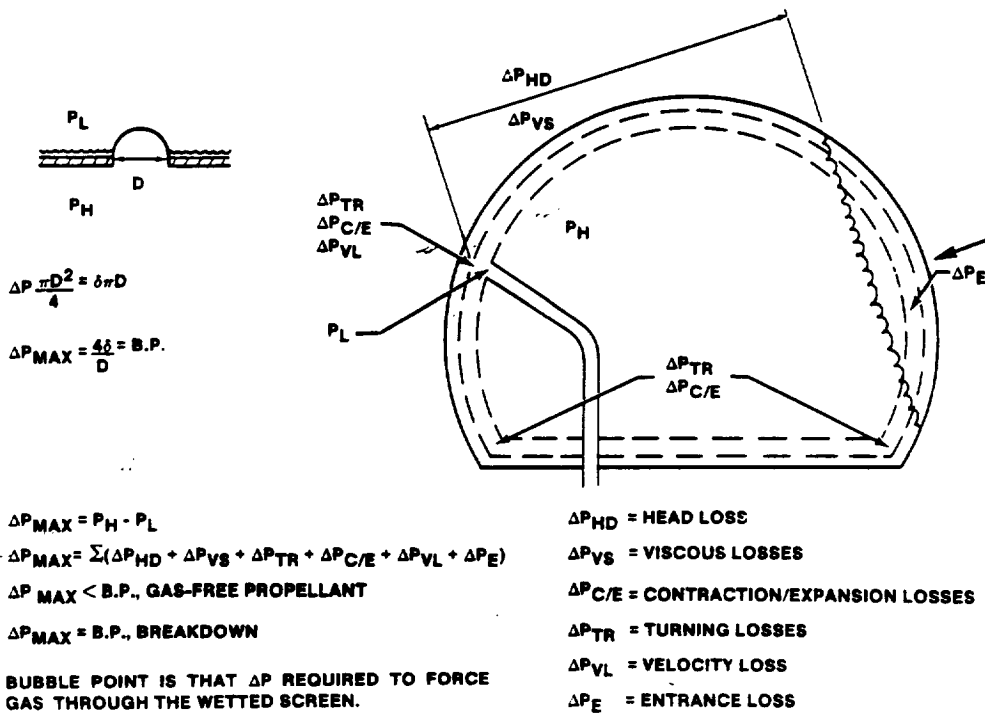

$$\Delta P \frac{\pi D^2}{4} = \delta \pi D$$

$$\Delta P_{MAX} = \frac{4\delta}{D} = B.P.$$

$\Delta P_{MAX} = P_H - P_L$

$\Delta P_{MAX} = \Sigma(\Delta P_{HD} + \Delta P_{VS} + \Delta P_{TR} + \Delta P_{C/E} + \Delta P_{VL} + \Delta P_E)$

$\Delta P_{MAX} < B.P.$, GAS-FREE PROPELLANT

$\Delta P_{MAX} = B.P.$, BREAKDOWN

BUBBLE POINT IS THAT ΔP REQUIRED TO FORCE GAS THROUGH THE WETTED SCREEN.

ΔP_{HD} = HEAD LOSS

ΔP_{VS} = VISCOUS LOSSES

$\Delta P_{C/E}$ = CONTRACTION/EXPANSION LOSSES

ΔP_{TR} = TURNING LOSSES

ΔP_{VL} = VELOCITY LOSS

ΔP_E = ENTRANCE LOSS

**FIGURE 4.- TANK PRESSURE LOSSES.**

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The greatest flow losses occur with the smallest puddle. The expulsion efficiency of a tank is defined as the smallest residual at which the flow and hydrostatic head-pressure losses, combined, are equal to the bubble point of the screen. Because the tank is designed to work primarily in a low-g environment, the hydrostatic head-pressure term is small. However, any ground testing has to be performed in a one-g environment, and the hydrostatic head-pressure loss very quickly becomes the dominant term and, therefore, the tank performance cannot be directly determined or demonstrated in ground tests. This problem was the greatest engineering challenge encountered in the tank development program.

To get around this problem, sophisticated math models were developed to characterize the on-orbit performance of the tank. The math models were developed using ground test of subassemblies in which flow losses of each device in the PAD were measured.

In early 1980, testing at the system level revealed a serious deficiency in the math models. In addition to the steady-state pressure drops, a transient-pressure drop, due to thruster pulsing, was discovered. This loss had not been considered in previous analyses and was unexpected. An additional analysis indicated that when combinations of thrusters were commanded simultaneously, the pressure drop associated with the opening of the thruster valves was being transmitted through the supply lines to the tank. There, the analysis showed, the pressure drops were high enough, with more than three thrusters pulsing, to cause gas ingestion and momentary screen breakdown. Because of the transient problem, gas could be fed out to the thruster and perhaps cause a thruster to misfire and be deselected during a critical mission phase. To avoid this possibility, the number of thrusters which could be simultaneously commanded per system was constrained to three thrusters for all mission phases except entry and return to landing site (RTLS) abort. For entry, the acceleration vector causes the propellant to cover the outlet; therefore, no transient problem is encountered. The RTLS case, however, still required seven thrusters. To satisfy this requirement, it was necessary to "overfill" the aft RCS tanks. Overfill means that the tanks are loaded completely full leaving no ullage volume; therefore, the upper compartment screens are entirely wet and the risk of gas ingestion is almost eliminated. However, overfill entailed a lengthy list of operational problems and procedures and it was viewed as a temporary solution to the transient problem.

Shortly after the problem was discovered, an intensive effort was initiated to quantify the transient problem. Again, because the tank performance could not be defined by direct test in a one-g environment, an advanced transient-pressure math model was developed. It was then correlated with preliminary test data obtained by the contractor from tests on a tank in one g using a test fluid and simulated thruster valves. A more detailed model-validation test plan was then developed using a tank that was specially instrumented with highly sensitive pressure transducers, and a test entitled "OV-102 Aft RCS Tank On-Orbit Performance Test" was run. This test provided pressure transient data from an actual system. The tests were run in the worst case attitude and, because of the large hydrostatic head-pressure loss, with a large residual puddle. The math model predictions for one-g operation agreed fairly closely with the test results, and the model was then used to predict the expulsion efficiency of the tanks for on-orbit conditions. A conservative safety factor was included in the predicted on-orbit performance to account for test uncertainties.

The "on-orbit" tests, along with the math model, indicated that the abort duct in the aft RCS tank was the device most affected by start transients in the upper compartment and also was the device that determined the entry expulsion efficiency. Because the abort dump for which it was designed had been eliminated, it was decided to remove this abort duct from the OV-099 tank. With this change, the updated math model indicated that the upper compartment would not be sensitive to on-orbit pressure transients after the screens are initially wetted. To test this prediction, and also to test the OV-099 modification tank, a new test concept was proposed. (See fig. 5.) A way had been found to minimize the test uncertainty due to hydrostatic head-pressure loss and to simulate the worst case "terminal" puddle in a one-g environment. By wrapping the screen channels with Teflon tape, leaving a small area uncovered at the bottom of the tank and the aft entry collector uncovered, a simulated low-g expulsion test could be run. With the collector as a high point, and with liquid filled until the level is just below it, thrusters are fired. Because only a small screen area is exposed to propellant flow, the steady-state and transient losses are maximized. Because the height below the collector is small, the hydrostatic head-pressure loss is minimized and thus on-orbit conditions are simulated. The initial results indicated that the tank was performing better than the math model predictions. The math model developed for the forward tanks indicated that the start transients were not as severe as in the aft system. Therefore, no redesign of the forward RCS (FRCS) tank was required. As mentioned earlier, during the first flight, as well as on all subsequent flights, the digital autopilot (DAP) was constrained to firing a maximum of three thrusters simultaneously. A study by the tank contractor, employing the latest model, indicates that a four-thruster capability can be attained on normally filled aft tanks. A five-thruster capability could be achieved on an overfilled aft OV-099 tank; however, because of the problems associated with overfill, this capability will not be pursued. The only major roadblock to deleting overfill is the RTLS, in which the DAP can command as many as seven thrusters simultaneously. Additional analysis performed for RTLS
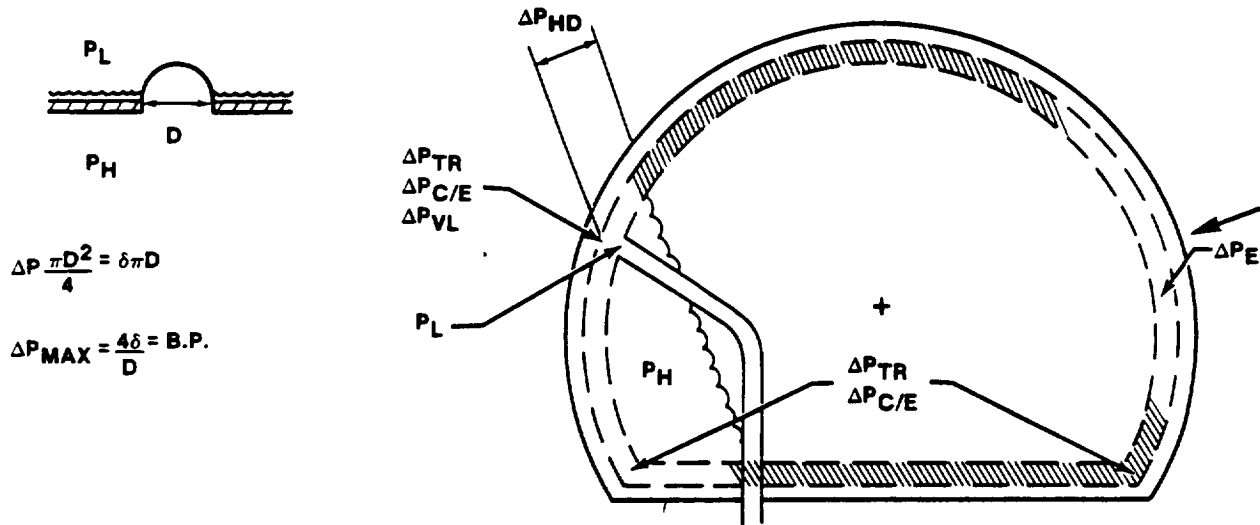
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FIGURE 5.- PRESSURE DROPS WITH MASKED SCREEN.

using avionic simulations has shown that no significant quantities of gas are ingested. Therefore, overfill will be eliminated by STS-8.

With the conclusion of this study, and the OV-099 performance testing, the RCS tank performance certification will be complete.

THRUSTERS

One of the major challenges in the Orbiter RCS development was design of the primary thruster. The thrust size was almost an order of magnitude larger than that used on previous manned spacecraft reaction control systems. The large thrust size coupled with a need for 38 primary thrusters made weight a prime consideration in component design. Because early technology work had shown that a hydraulically operated valve was considerably lighter than a conventional solenoid valve for a Shuttle Orbiter-size engine, that concept was chosen for use on the primary thruster (fig. 6). The new concept introduced new problems. The valve relied on pressure imbalances established by a pilot poppet to provide the necessary opening force. These valve-actuating pressure imbalances could also be created by transient-pressure waves generated by other thruster or isolation valve operation within the system. These inadvertent, momentary valve openings were demonstrated to be safe in flight but unacceptable for ground operation. Furthermore, it was discovered that gas entrapped in recesses of the valve could slow down both opening and closing valve response and also increase the tendency for the valve to "bounce" with pressure transients. To minimize the possibility of valve "bounce" during ground operations, isolation valve operation was procedurally limited to cases in which the pressure differential across the valve was below 25 psid. To accommodate the slowed valve response with the presence of gas in the valve, the minimum thruster firing time was increased from 40 to 80 milliseconds, which was still satisfactory for control purposes.

An ongoing problem that has a potential for considerable downstream program impact is the tendency of some primary thruster valves to leak when subjected to low temperature. The problem was first discovered when liquid was observed to be dripping from the system-level test article engines during a cold environment test. Additional testing at the NASA Lyndon B. Johnson Space Center (JSC)
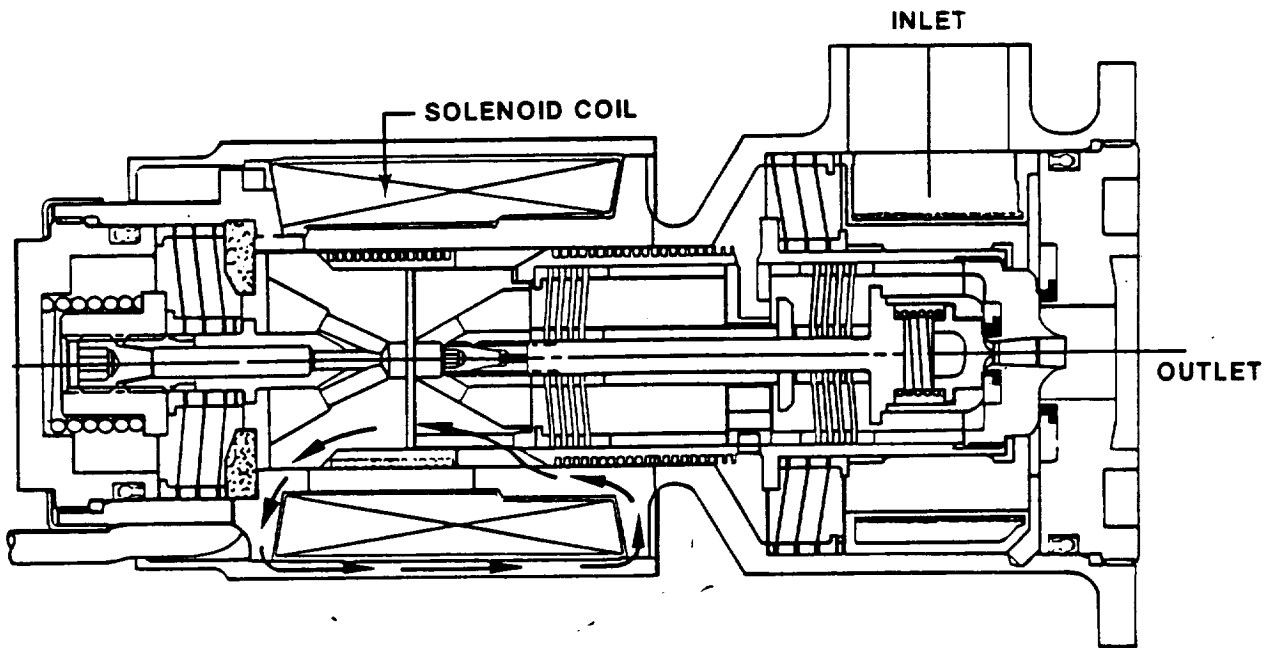
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FIGURE 6.- CROSS SECTION OF PRIMARY THRUSTER VALVE.

revealed that one out of three valves leaked when chilled from ambient temperature to 30° F. Furthermore, the leakage became progressively worse with increased cycling. Preliminary corrective action in the form of a 40°-F screening test was introduced to eliminate "cold leakers." Continued investigation of the problem indicated that the TFE Teflon underwent a marked change in thermal expansion rate in the 65°- to 77°-F temperature range. Because machining, done as a part of seat fabrication, was accomplished in this temperature range, some parts had insufficient seat material exposed at reduced temperature. The flat-seat, non-temperature-compensating design made the unit very sensitive to temperature changes. Therefore, to further reduce susceptibility to cold leakage, two actions, in addition to the screening, were implemented. First, the Teflon is machined at 32° F to ensure uniform dimensions with adequate seat material exposed at reduced temperatures. Second, the thruster heater set points have been raised to maintain valve temperature above 60° F. Even with these actions implemented, there have been instances of cold leakage when heater power had to be turned off during ferry flight operations. Whether the incidence of cold leakage increases as valve seat wear occurs with use still remains to be seen and will determine whether additional work is required.

Another environment-induced development problem involved the requirement for the valve to be capable of withstanding salt fog exposure. Care was exhibited in selecting materials for the valve, and all those selected (Inconel 718, Custom 455, and A-286) were individually compatible with salt fog. However, when all the factors and materials were assembled, a galvanic crevice corrosion on the Custom 455 occurred. The completed series of ingredients that resulted in the corrosion was the stacking of the three valve materials against either of the thruster materials, titanium or columbium, plus the addition of a propellant-soaked crevice around the valve seat, and lastly, the electrolyte, sodium chloride. Severe and rapid pitting occurred on the valve poppet (Custom 455), and leakage ensued. Results of material testing confirmed the four-material problem and suggested a material change as a corrective action. Because the failure occurred late in the production process, the first flight units had already been manufactured and shipped. This situation dictated considering an immediate corrective action for existing hardware and implementing the material change for future replacements. The immediate corrective action was to keep the thrusters sealed against moisture and salt air intrusion by keeping plugs and dessicant protection in place at all times when on the ground. To date, this approach has been satisfactory, and the long-term solution has not been pursued.

Another subtle material problem occurred in the fabrication of the injectors. During waterflow tests of the injectors for the OV-102 thrusters, water was observed to be externally leaking from the injector adjacent to the acoustic cavities (fig. 7). No confirmed cause for the cracking was determined; however, an ultrasonic screening test was invented to isolate the cracked injectors. The

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20° BLC: 21 HOLES
(0.0200 - 0.0205)

45° BLC: 21 HOLES
(0.0156 - 0.0161)

INBOARD DOUBLETS
69° FUEL: 42 HOLES (0.0225 - 0.0230)
9° OX: 42 HOLES (0.0310 - 0.0315)

OUTBOARD DOUBLETS
24° FUEL: 42 HOLES (0.0225 - 0.0230)
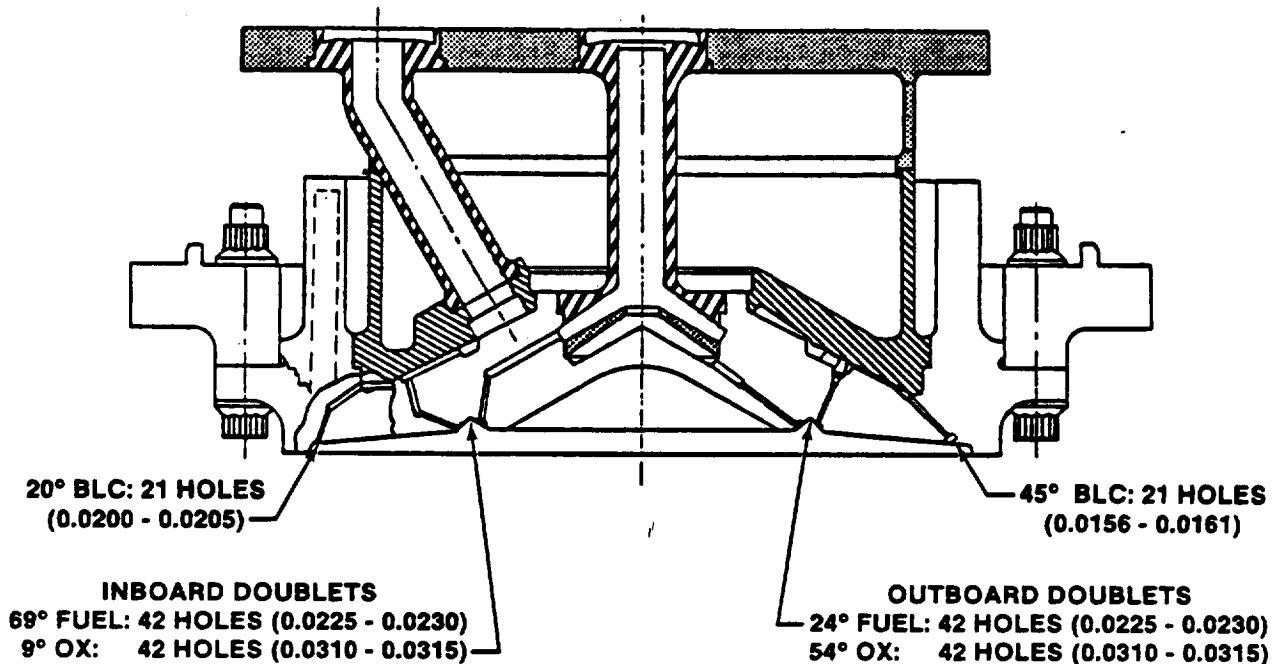54° OX: 42 HOLES (0.0310 - 0.0315)

FIGURE 7.- INJECTOR CROSS SECTION.

screening test was imposed at several stages in the manufacturing process in hopes of determining the cause. During the manufacture of the OV-103 hardware, the problem reoccurred and the screening test paid off. With some good metallurgical investigative efforts, it was determined that the columbium was cracking because of hot salt stress corrosion and that fluoride salt exposure, temperature, and stress all had to be present for cracking to occur. The fluoride salt was a residue from an inadequate rinse of a chemical etch used in preparation for welding. The problem was solved by eliminating the use of the etchant after reaching a certain stage of the injector fabrication process.

One of the latest challenges encountered in the development of the Space Shuttle RCS thrusters was a premature failure of the disilicide coating on the vernier engines (fig. 8). Coating failures were first experienced in the component qualification program and later on the flight hardware. Failures occurred over quite a range of burn times. At first, it was thought to be a single generic problem with the coating itself, but as testing and investigation progressed, it was shown to be a multi-faceted problem. The qualification engine coating spalled after 80 000 seconds of burn time, whereas two of the OV-102 engines developed coating defects at about 10 000 seconds of burn time. Thus, it was theorized that not only burn time but thermal cycling as well was critical. The qualification and flight hardware both had approximately equal thermal cycles. This theory was negated when one engine spalled at 10 thermal cycles and others were spall-free after more than 800 thermal cycles. Evidence pointing to one potential cause was revealed during an inspection of the OV-099 engines performed to document their condition before their first flight. Two of the engines were found to have defects, with nothing more than acceptance-test burn time. Examination of the ground-support throat plugs revealed that metallic fingers on the plug had broken and dislodged pieces from the new engine coating. These throat plugs were abandoned and new ones designed to preclude high loads being put into the coating. It was now obvious that the coating could have been and probably was mechanically damaged in some of the failures, but this mechanism did not explain all of them. Samples tested at the JSC White Sands Test Facility (WSTF) in a special coating test that had never been exposed to any throat plugs developed coating defects. Further investigation determined that poor quality control in manufacture of the combustion chamber was probably contributing to the early wearout. Ridges, undercuts, and smeared material were found in the chamber before coating. Coating over these imperfections was producing weak areas, which, when cycled, were causing coating pinholes or spalling to occur. Combustion chamber machining was subsequently revised to control intersecting cuts, and the finishing cut now is made in one direction in a single pass. Use of this new technique minimizes smearing and ridging. Chemical milling was implemented before coating to further remove any smears and ridges remaining from machining and to remove any contaminants buried in the surface. Testing to verify the improved manufacturing process is underway.
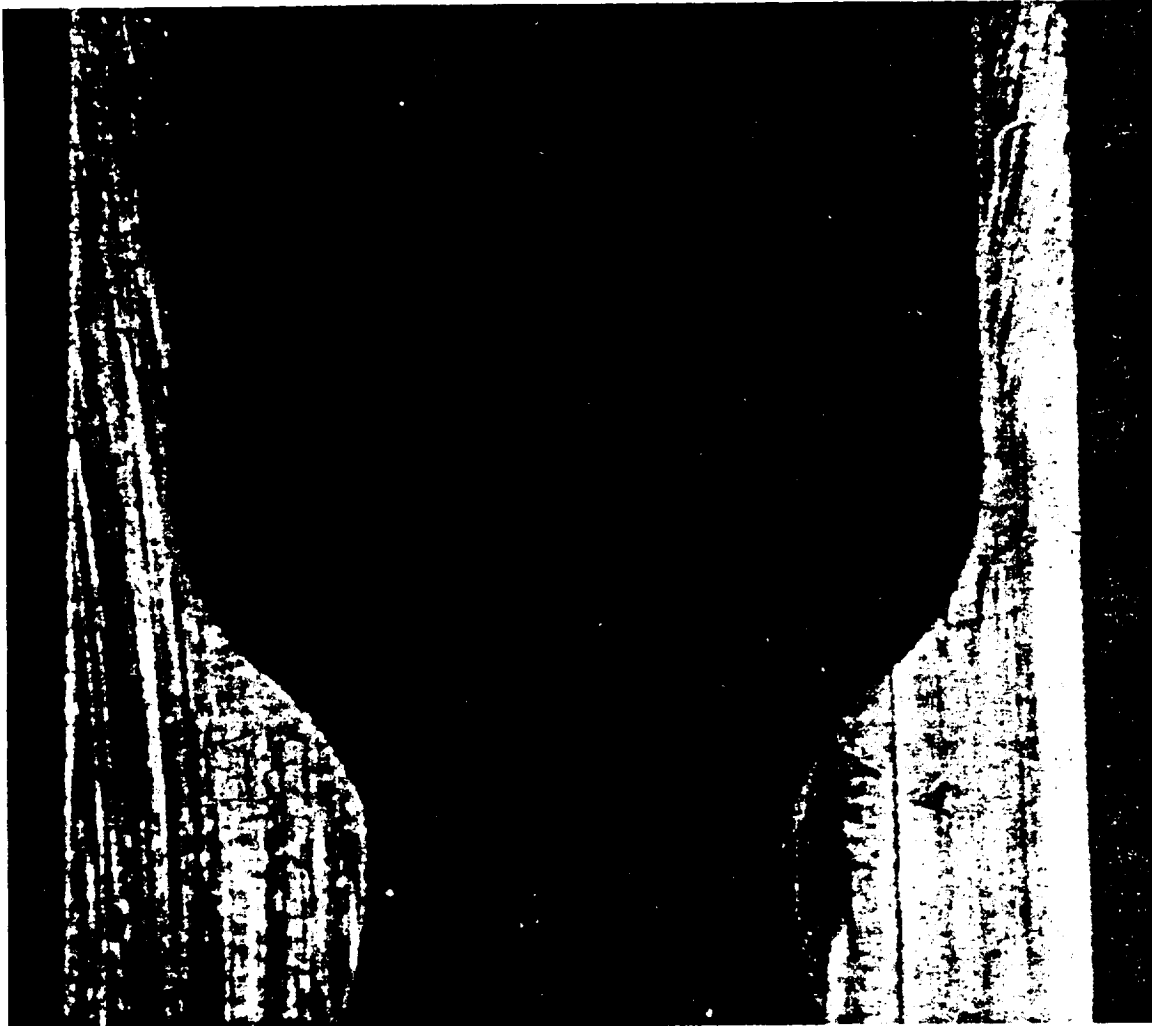
FIGURE 8.- VERNIER THRUSTER COATING FLAW.

A/C MOTOR ISOLATION VALVES

An interesting subsystem interface issue that arose on the flight vehicle involves the RCS A/C motor isolation valves and their control circuitry. The RCS isolation valves are ball valves that are driven by high-speed alternating-current motors (fig. 9). The response of the ball is slow, approximately 1 second for full travel in either direction, but the motor is rotating at 8000 rpm. The gear reduction is large, and large inertia force in the gear train is partly removed by a friction brake upon stopping. The valve was built with microswitches for terminating power at the end of valve travel. The original design accommodated the large inertia by removing power from the motor before the mechanism came to rest. By this means, the ball and gear train could "coast down" before impacting the friction energy absorber. The absorber was designed to marginally handle the anticipated inertia load. The valves cycled without problems when operated individually and had in fact completed development testing and part of qualification life testing without mishap. However, when used in the vehicle, the oxidizer and fuel isolation valves were actuated as pairs. Power was left on until the slowest of the two valves completed its cycle. This mode of operation drove the gear train of the fastest valve hard into the energy absorber and left stall torque on the motor until the slower valve completed travel and power was shut off. The added momentum of the gear train as a result of powered impact with the energy absorber caused the absorber to recoil and produce a sudden inelastic reaction load into the gear train. Repeated cycling of the paired valves could cause the nylon teeth of the third-stage planetary gear to strip and, thus, disable the valve. The first in-
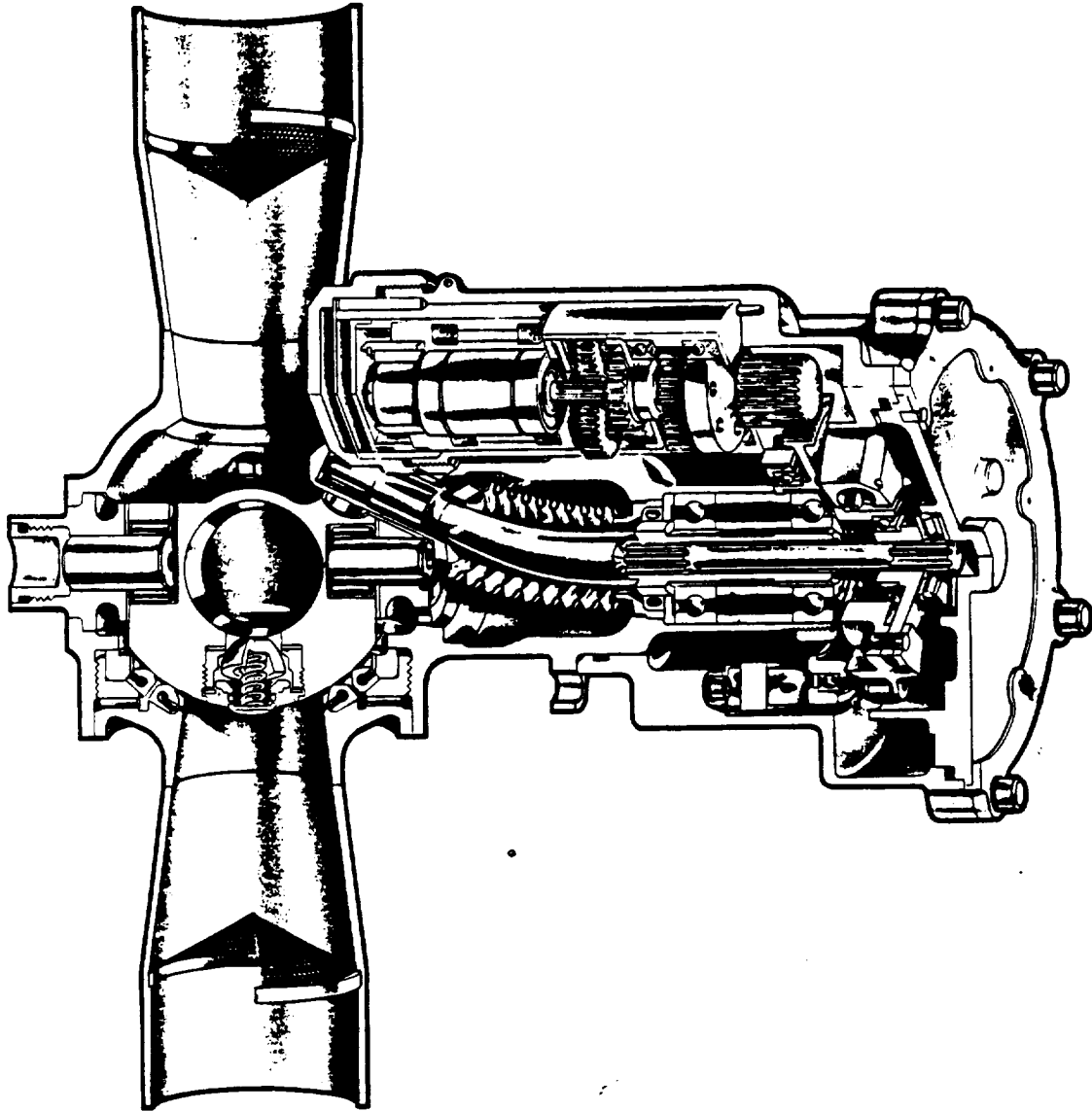
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FIGURE 9.- A/C MOTOR VALVE CROSS SECTION.

dication of this problem occurred when the OV-102 forward module RCS was checked out at the NASA John F. Kennedy Space Center (KSC). The valves were being cycled with a 2-second timing circuit, and it was noticed that the microswitch feedbacks were intermittent. On closer investigation, it was discovered that power in excess of 1.15 seconds could cause intermittent open/close indications because the gear train would backlash enough to cause an open circuit to occur on the microswitch. Further investigation indicated that the vehicle wiring would leave power on for greater than 1.15 seconds and, therefore, could cause intermittent indications. Driving a valve beyond the microswitch turnoff signal was known as a "hard cycle." Testing on the A/C motor valve was begun to pursue the effects of "hard cycling" on "paired" valves. It was discovered that the reliable life of the valve was no more than several cycles. Work was initiated on redesigning the gear train to accommodate the larger loads. The resultant product was a new, all-metal gear train incorporating a magnetic brake in the motor and a different, and significantly better, energy absorber for the inertia load, designed to sustain the full inertia load plus motor stall torque driving into the stop. Certification testing of the new valve verified that the new configuration could achieve the required full 100-mission life in the hard-cycle mode.

RCS SYSTEM-LEVEL DEVELOPMENT AND CERTIFICATION

A major challenge with any liquid propulsion system such as the Space Shuttle RCS is to verify that all the components combined as a system operate as a unit during all expected operating modes and that the interaction between components will not cause problems. A second significant activity required on a system-level test article is the development and verification of all ground checkout and servicing procedures necessary for a multiuse vehicle. To ensure that these goals were met and also to verify system structural integrity, a major ground test program was performed on the RCS (fig. 10). This ground test program included the following major elements.

1. FRCS and ARCS Breadboard Development Test

2. FRCS and ARCS Development Tests

3. FRCS and ARCS Qualification Tests

4. FRCS Thruster Installation Tests

5. ARCS Pressure Panel Tests

6. FRCS and ARCS Vibroacoustic Tests

The major objectives of these test programs were as follows.

1. FRCS and ARCS Breadboard Development Test - Provide early system data to support the analysis and design efforts and to evaluate servicing and checkout procedures. Simulated propellants were used in this test.
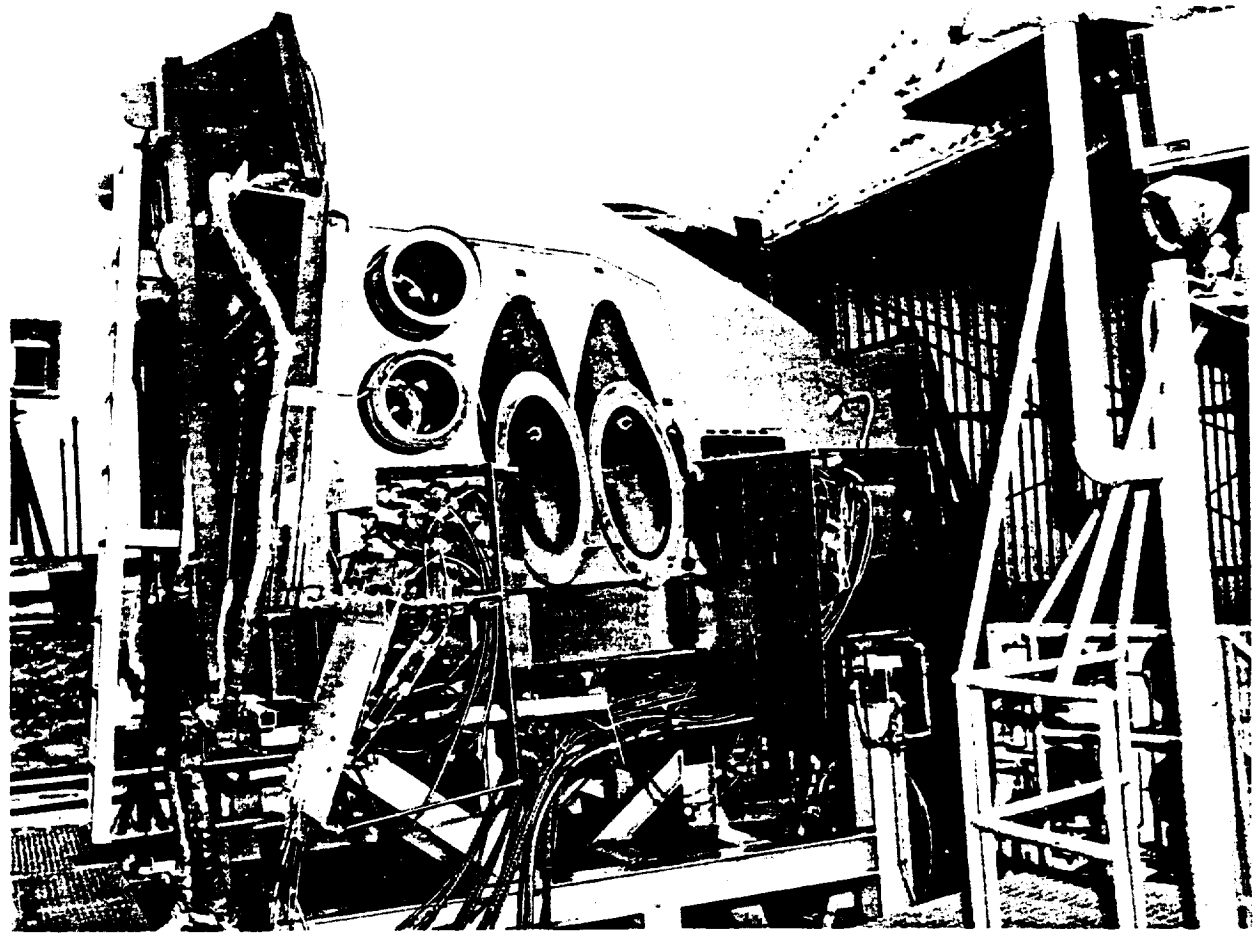

FIGURE 10.- TYPICAL SYSTEM TEST ARTICLE (FRCS).

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2. FRCS and ARCS Development Tests - Conduct 12 test series on the FRCS and 11 test series on the ARCS at WSTF to verify RCS design, including evaluation of steady-state and transient performance under all operating conditions, and develop and evaluate servicing and checkout procedures. This was the first actual system hot-fire testing on complete FRCS and ARCS test articles.

3. FRCS and ARCS Qualification Tests - Conduct sufficient test series on the FRCS and ARCS to certify the system for development and operational flights. These tests were divided into Qual I (STS-1), Qual II (operational flights), and Qual III (OV-099 and subsequent modifications). Thirteen test series were performed on the FRCS and 15 on the ARCS with each series approximately equivalent to one mission.

4. FRCS Thruster Installation Tests - Provide data for thermal and structural certification of the complex RCS thruster installation. The firing tests were performed at simulated altitude at WSTF, and the vibroacoustic tests were performed at Rockwell International (RI).

5. ARCS Pressure Panel Tests - Certify the RCS helium pressurization system for simulated series regulator failures including relief system limit testing.

6. FRCS and ARCS Vibroacoustic Tests - Provide data to certify FRCS and ARCS primary and secondary structure, components, and tubing for the acoustic environments experienced during ascent. The FRCS test was conducted at RI and the ARCS at JSC.

Numerous challenges resulted from the problems discovered during the ground test programs listed. Some of the major challenges and the eventual technical solutions are discussed next.

The breadboard test program revealed two major problems requiring resolution.

1. Servicing procedures resulted in propellant residual entrapment in the helium pressurization lines. Subsequent activation of the system by opening the fast-response helium isolation valves produced pressure surges that would sometimes rupture the burst disk in the helium relief system. This problem was solved procedurally for the OV-102 vehicle by implementing a series of pressure cycles called "breathing cycles" which cleared the liquid from the helium lines. For OV-099 and subsequent vehicles, the problem was solved by a change in the helium system plumbing to add a separate, dedicated propellant vent line.

2. The ARCS breadboard test revealed that certain combinations of engine firings produced pressure transients in the propellant feed system in excess of the design limits. The pulse characteristics were also erratic under these conditions. As a result of this finding and parallel findings from the development testing at WSTF, the minimum pulse on/off duration and frequency were changed from an initial value of 0.040 second on/0.040 second off with a maximum frequency of 12.5 hertz to 0.080 second on/0.080 second off with a maximum frequency of 6.25 hertz. This change resulted in more propellant usage in some cases but eliminated the pressure transient concern and resulted in much more repeatable pulse performance with the corresponding reduced risk of engine pressure spikes and erroneous deselections by the Shuttle RM system. This change was a major step in improving the reliability of the RCS.

Challenges resulting from RCS system-level development and qualification testing were numerous. Some of the major challenges involved engine valve problems, servicing and activation problems, propellant-tank checkout, propellant-tank surge-flow evaluation, and subsystem life certification. The first major challenge occurred very early in development testing and involved engine/system incompatibilities. The initial plan was to fill the RCS tanks with propellant and the manifolds with low-pressure gas. During system activation, the propellant isolation valves were opened and the gas was compressed; these actions left large gas bubbles in the RCS feed system and engine valves. As discussed in another section of this report, the primary engine valve operation is adversely affected by gas entrapment. During initial FRCS system-level testing, major problems occurred including missed pulses, failure of valves to close between pulses, long ignition delays, cold flows of one propellant due to oxidizer and fuel valve mismatch, and valve bounce due to system pressure transients. This inefficient operation also caused concern for potential hard-start (spike) problems resulting from residue accumulation in the combustion chambers. The following plan was implemented to solve these problems.

1. Change the loading procedure to a vacuum-fill process to eliminate gas bubbles.

2. Perform bench tests on the thruster valves to map performance characteristics as a function of gas entrapment/flow, static and dynamic pressure, propellant saturation, etc.

3. Install linear variable differential transformers on some thruster valves on the FRCS and ARCS test articles to determine effects of gas bubbles, saturated propellants, and system pressure transients.

4. Change minimum pulse on and off times from 0.040 second to 0.080 second.

5. Run system-level tests with vacuum-filled manifolds and saturated propellants to verify adequacy of modification.

6. Perform single engine pulse tests at altitude simulating conditions seen in step 5 to determine whether oxidizer and fuel residuals cause problems at altitude.

This program was successful in characterizing the valve and valve/system interactions. The test program also revealed that the corrective actions of vacuum filling and changing the minimum pulse time were adequate to allow the thruster valve to be used for flight without major valve or system design changes.

Problems of engine valve leakage at cold temperatures and low pressure and engine valve bounce caused by upstream isolation valve or quick-disconnect cycles were also discovered in system-level testing. These problems were solved by procedural controls and are discussed more fully in the section entitled "Thrusters."

Checkout of the RCS propellant-tank surface-tension acquisition screens proved to be another major challenge. For the screens to perform properly in flight, there must not be any holes in the screen that will cause a reduction of the bubble-point pressure. It is desirable to have a technique that allows contingency and periodic checkout of the screens during operations without removing the propellant tanks or using fluids other than the propellants. The basic process proposed for this checkout involves filling the tanks with propellants, draining them without drying the propellant from the screens, and then determining the bubble point (pressure at which gas penetrates the wet screen surface) through the special checkout ports provided for this purpose. This process proved to be fairly easy to implement for the fuel tank because of the low vapor pressure of MMH. Implementing the process for the oxidizer tank, however, proved to be a very difficult task because of the high vapor pressure of NTO. All initial attempts to check out screens on the system level with oxidizer proved to be unsuccessful because the screens dried out. This challenge was met by implementing a special test program on the tank alone with simulated system-level checkout access plumbing and valves. This approach allowed for experimentation with thermal control, tank orientation, and propellant saturation level of the nitrogen gas introduced into the tank. This approach finally revealed the key controls that must be used to allow checkout with oxidizer. The most important parameter requiring control is the saturation level of the gas. The incoming pressurant gas (nitrogen) must be saturated with propellant. Second, the incoming gas must be at the same temperature as, or warmer than, the tank, and third, the tank pressure should be in the 60- to 70-psi range. The concept was then proven on system-level tests, and current plans are to implement it for the operational phase of the program at KSC.

Test effort on the system level caused the development of some very effective techniques for evaluating the complex surface-tension acquisition devices. The use of X-rays was found to be very effective in determining the locations of propellants in the tank for evaluating performance, loading and drain procedures, and potential acquisition device gross damage. Elaborate instrumentation concepts were also developed to evaluate surge-flow pressure differentials in the tank. These were used to evaluate pressure differentials for high flow rates into and out of the tank associated with crossfeed/interconnect operations and propellant manifold repressurization. High-response piezoelectric instrumentation was also used to determine differential pressures across the screens to evaluate engine start transient effects in the tank.

Another challenge associated with system-level testing involved life certification for 10 years and 100 missions. Obviously, a 10-year/100-mission life test would be very expensive. Therefore, the concept used was to certify the individual components in bench-type environments for 100 missions of cycle life and vibration exposure and to run short, 90-day screening tests for propellant compatibility. The components and the system were then tested in a development program representing 11 to 13 missions over an approximately 9-month period. This test was followed by a qualification test program representing 13 to 15 missions spread over a 3-year period. Including other special tests, the qualification hardware was exposed to 4 to 5 years of operation. All operations on the systems were designed to be representative of actual Space Shuttle servicing, flight, and repair procedures. The acoustic test articles were exposed to a full 100-mission or more equivalent exposure in a short time period except for the FRCS module, which was exposed for only 10 missions and analyzed for the remaining 90 missions. All failures or problems were analyzed for any life-limiting indications, and, if a life limit was indicated, it was so noted and identified as limited-life hardware. The described approach was then used for 10-year/100-mission certification with any exceptions being noted.

The ARCS vibroacoustic test revealed a problem very late in the certification program that required extensive effort to solve. Initial testing on an ARCS pod structure revealed that vibration levels on individual components and zones in the pod were higher than had been previously predicted

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and were higher than the levels used for component certification. This pod was originally equipped with "mass simulated," nonfunctional components with the idea that the levels would be equal to or less than the levels used in component tests. Therefore, component tests could be used for certification. Since the levels were higher, a decision was made to use the vibroacoustic pod for component certification. This decision required a last minute change to install functional components in the pod and complete the component and system certification in this manner. Since the levels were higher in the ARCS, test results could also be used to certify the FRCS components for 100 missions. The FRCS had only been tested for 10 missions as a system.

RCS INTERFACES

The Orbiter RCS is the most complex RCS ever designed. To use it effectively requires major RCS interfaces with avionics/software, wiring, instrumentation, thermal control, and structures subsystems. A major challenge in the RCS design was to ensure that compatible interfaces exist within these areas. Although difficult interface challenges existed in each of the areas, perhaps the most difficult was the RCS/avionics/software interface. Only this interface will be discussed here. Principal functions performed in the Shuttle avionics/software for the RCS are redundancy management, quantity monitoring, RCS crossfeed sequencing, OMS-to-RCS interconnect sequencing and gaging, FRCS propellant dump, trickle-current testing, and system monitoring and annunciation functions. All these functions required extensive exchange of information between subsystems to ensure that the software and the avionics hardware were compatible with the RCS hardware in terms of timing, sequencing, limit sensing, redundancy requirements, etc. The most complex avionics/software interface is the area of redundancy management. The purpose of the RM system is to monitor the 44 RCS engines, annunciate and isolate failures, and reconfigure the system to maintain vehicle control during all mission phases. This function is necessary to effectively maintain the RCS fail-operational/fail-safe redundancy. The major elements of the final system design are as follows.

1. Fail-off detection - compares computer fire command with engine chamber pressure feedback to determine whether engine has fired. If no response occurs in an appropriate time, the engine is declared failed-off, annunciated to the crew, and taken out of the available jet table in the computers.

2. Fail-on detection - compares jet driver output with computer fire command to determine whether an engine is firing with no command. If a failed-on engine is detected, it is annunciated to the crew so that the appropriate manifold may be isolated to prevent excessive propellant loss.

3. Valve leak detection - monitors engine fuel and oxidizer injector temperatures to determine whether engine valve leakage is occurring. If the temperature of the oxidizer injector tube is below 30° F or of the fuel is below 20° F because of rapid propellant evaporation, a leak is indicated. For a leak indication, the problem is annunciated to the crew and the engine is taken out of the available jet table. The crew may then manually close the appropriate isolation valves if propellant loss is excessive.

4. Manifold status monitor - monitors RCS manifold isolation valve positions to determine whether valves are open or closed. If the valves are closed, the engines on that manifold are removed from the available jet table.

5. Jet fault limit monitor - limits number of jets which may be automatically removed from the available jet table in response to failure indications. This function is designed to ensure that the RM system will not automatically remove engines to levels at which insufficient control authority exists.

All RM functions may be overridden by the crew in all phases except for ascent, for which only limited override capability is available. To date, this system has been very effective in detecting RCS engine problems and managing RCS redundancy in flight.

The other major avionics/software interfaces are now briefly described. Quantity monitoring uses RCS helium and propellant-tank pressure and temperature measurements to calculate and display the RCS propellant status at all times using the pressure/volume/temperature relationship to determine the quantity of helium gas that has been transferred from the helium tank to the propellant tank. The RCS crossfeed sequence provides automatic sequencing of 28 RCS/OMS valves to feed RCS engines in both aft pods from the RCS propellant tanks in a single pod. The sequence will also reconfigure to normal feed and is operational only in ascent and entry phases. The OMS-to-RCS interconnect sequencing and gaging performs the OMS/RCS valve sequencing required to feed OMS propellants to RCS engines during abort dumps and to reconfigure to normal feed after the dump is completed. During on-orbit operations of normal missions, the OMS-to-RCS interconnect sequence initiates OMS-to-RCS gaging and automatically pressurizes the OMS tanks as required. The on-orbit valve sequencing is a manual operation. The FRCS propellant dump sequence provides capability for the crew to dump the FRCS propellant through opposing Y-axis engines for center-of-gravity control. The trickle-current

test is used to check the electrical circuits that provide voltage to fire the RCS engines. Various RCS pressures and temperatures are limit sensed, displayed, and annunciated by the avionic/software interface to alert the crew of potential RCS problems.

OPERATIONS

Operations challenges for the RCS can be divided into two major categories: ground operations and flight operations. More emphasis is placed on ground operations because most major operations challenges have occurred in that area. As an introduction to ground operations, the basic operational concept for the RCS and the OMS is described.

The basic design concept for the hypergolic systems with their toxic, flammable propellants is to include the systems in modules or pods that can be removed from the Shuttle Orbiter and taken to a dedicated maintenance facility for hazardous repair or checkout operations. This facility is called the Hypergolic Maintenance Facility (HMF). By performing hazardous operations in the HMF, the work can be done in parallel with other Orbiter work and, thus, valuable turnaround time between flights can be saved. The HMF is also used to perform lengthy checkout operations, whether hazardous or not, to save serial turnaround time. The modules or pods are also provided with access panels and numerous plumbing access connections to enable performance of most checkout functions in the Orbiter Processing Facility (OPF) without removal from the vehicle. The decision on whether to perform repair or checkout in the OPF or the HMF is usually based on access and turnaround time considerations.

Development of ground checkout philosophy has been a major challenge for a reusable system that contains highly corrosive propellants, is used on a continuous basis in flight, and has considerable redundancy. The general philosophy that has been developed is as follows. A complete electrical and mechanical checkout on the FRCS module and the ARCS pods is performed by the manufacturer before the units are delivered to be installed on the Orbiter. The interfacing Orbiter electrical and instrumentation wiring is also checked out using module and pod simulators before the actual hardware is installed. The most critical components and the system plumbing integrity are checked again in the HMF before final installation on the Orbiter. After the module and pods are installed for the first Orbiter flight, the electrical components are checked for proper end-to-end channelization where possible by actual physical response, e.g., flow, pressure, or temperature response. The system is then loaded with propellants and helium on the launch pad. During the actual flight, the system pressures, temperatures, quantities, and valve positions are monitored closely for any indication of malfunction. Special procedures are also used to get as much component functional data as is reasonably possible by changing from one operational component to a redundant component during each mission; this is done with regulator paths, heaters, and engines. Special hot-fire tests are also performed to check out engines that might not normally be used. Use of this technique verifies the functional capability of as many components as possible to reduce ground checkout requirements. After the Orbiter lands, component checkout is performed on a very limited number of components every flight based on their criticality and whether they can be checked out in flight. Most components are only checked out on a 5- or 10-mission basis to screen for unexpected deterioration. The system plumbing is leak checked by monitoring for pressure decay at normal turnaround pressures after every flight. The engine chamber and nozzle coating is also inspected for defects after every flight. By using the described approach, the turnaround time is minimized without excessive sacrifice in reliability.

One of the first major challenges encountered in actual operations was the need to provide rain protection for some of the Orbiter engines after the protective structure was moved away and the protective ground covers were removed from the RCS engines. The requirement was to protect the three upward-facing engines and eight of the left side engines from rainwater accumulation on the launch pad. The upfiring engine covers had to prevent water accumulation that could freeze in the injector passages during ascent. The side-firing engine covers had to prevent water from accumulating in the bottom of the chamber and to protect the chamber pressure-sensing ports. Freezing of accumulated water during ascent could block the sensing port and cause the engine to be declared "failed off" when it was first used. The original design concept was to install Teflon plugs in the engine throats (side-firing) and a combination Teflon plug tied to a Teflon plate that covered the nozzle exit (upfiring). This concept added vehicle weight, required special procedures to eject the plugs in flight, and had the risk of accidental ejection in ascent that could damage tiles. The second concept evaluated involved Teflon sheets that were glued to the nozzle exits and pulled off by lanyards when the crew access structure was retracted. This concept was considered to be unnecessarily complex and did not provide protection all the way to launch or for all the engines. The final solution was a novel approach of using ordinary plastic-coated freezer paper cut to fit the exit plane of the nozzle and glued in place (fig. 11). Tests proved this concept would provide a reliable seal under all expected rain and wind conditions. Wind-tunnel tests revealed that the covers could blow off in ascent before Mach 1. The covers were, therefore, very low cost, simple, and added no significant weight.
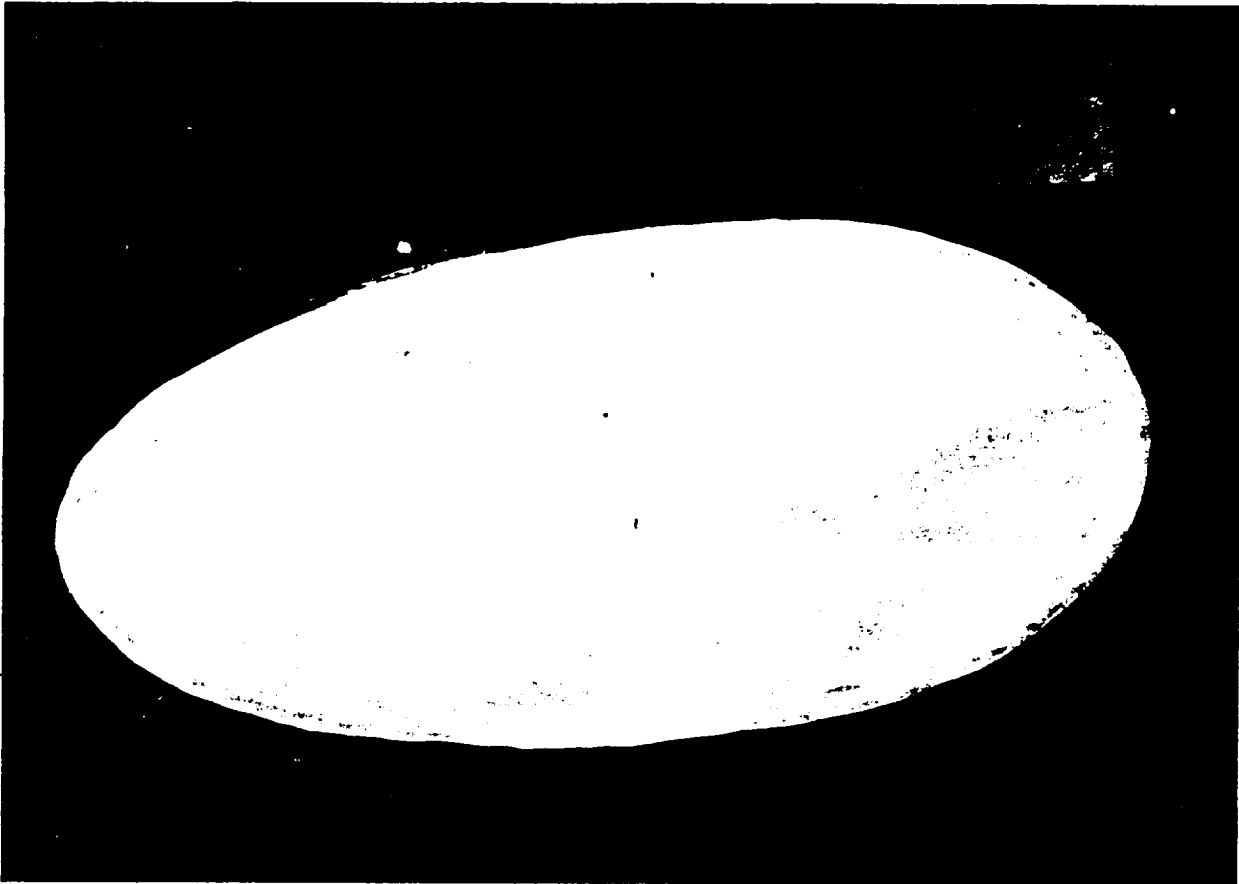
FIGURE 11.- PAPER ENGINE COVER.

The next major operational challenge involved RCS engine valve leakage problems during ground turnaround. Following the first orbital flight of the Shuttle, the FRCS module and the ARCS pods were removed for inspection and checkout. A test was performed to evaluate the capability to evacuate the manifolds after they had been drained of propellant but not completely dried. Following this test, four RCS engine oxidizer valves developed high gas-leak rates. This leakage caused great concern because the leak rate was high enough to indicate that the valves might leak liquid. To understand the problem, one of the engines was removed for failure analysis. This failure analysis, in combination with the analysis performed on another engine removed for a different reason, revealed the causes for the leakages. The valves had low Teflon seal height and some nitrate deposits in the seal area. The drying of the oxidizer system by evacuation caused Teflon shrinkage, which, in combination with the nitrates, caused leakage. It was expected that rewetting the seal with liquid oxidizer would swell the seal and dissolve the nitrates and, therefore, prevent liquid leakage. Experience has shown that this does happen. The KSC turnaround procedures were changed to preclude drying the RCS manifolds by evacuation unless they are to be refilled immediately with liquid. The problem of oxidizer valve gas leakage during turnaround has not recurred.

Prevention of iron nitrate contamination in the RCS oxidizer proved to be another operational challenge. Storage of oxidizer in tanks and plumbing that contain iron has been found to cause iron contamination in the propellant. This contamination can form a nitrate that can precipitate and cause valve leakage, filter blockage, interference in sliding fits, etc. Several RCS component failures were related to this problem; the most prominent one was the failure of a ground-half quick disconnect to close resulting in an oxidizer spill on the launch pad just before STS-2. A program was implemented at WSTF to determine the parameters that cause iron nitrate formation and then to implement procedures to prevent their formation in Shuttle propellants. This program resulted in understanding the relationship between iron, water, and nitric oxide content and nitrate formation. Also, production and storage controls and filtration techniques to remove the iron were developed. With the implementation of these controls, the iron nitrate problem appears to have been solved.

Another major operational challenge was development of the best procedures for ferry flight of the Orbiter RCS after a mission. Because of the initial concern for engine valve leakage at cold temperatures and propellant slosh effects on tank screens, the RCS propellants were drained at the landing site before ferry flight. Following STS-2, the drain operation had two valve sequencing errors that subjected the RCS propellant tanks to potentially damaging surge flows. These errors were attributed to the remote location of the drain site and the difficulty of communications between the drain site and KSC, where the systems data were available. Consequently, the operations site (KSC) recommended that the propellant not be drained before ferry flight. This recommendation was accomplished after STS-3 by turning the RCS thruster heaters and FRCS area heaters on through a special hookup to the carrier airplane. The carrier airplane was also instrumented with a special accelerometer to monitor for excessive slosh loads on the RCS tanks. A recognized risk was taken that 15 to 25 percent of the RCS thruster valves might leak as much as 10 cm^3/hr of liquid propellant during ferry flight even with the heaters on. This approach has been successful on all ferry flights from STS-3 to the present with only minor leakage occurring in a few engines. Damaging slosh loads have never been encountered.

The incidents that occurred during draining at the landing site created another major operations challenge. There was concern that the RCS tank screens and/or internal bulkhead structure might have been damaged by the surge flow into the tanks. Since the RCS tank checkout procedures by bubble-point technique had not been fully developed at that time and no ground-support equipment (GSE) was available to perform in-place tank checkout, the only way to check the tanks was to remove them and send them to the manufacturer for checkout. This action would have been a major impact to the program schedule and to hardware deliveries for subsequent vehicles. To avoid this impact, a decision was made to attempt to duplicate the surge incidents on the ARCS test system at WSTF and then to check out the test tanks to determine whether damage occurred. This resulting test program required a meticulous duplication of all the procedures that had been performed on the systems at the landing site. This duplication was particularly challenging since data were not available during some periods at the landing site and the crossfeed plumbing and the GSE were different at WSTF than on the Orbiter. The test program was successfully completed, and results indicated that the tanks on the vehicle were not damaged. This testing resulted in saving about 2 months on the Shuttle schedule, since the tests at WSTF were run in parallel with the other Orbiter operations and no checkout times were required for the tanks.

The next major operations challenge occurred after STS-3, when the Shuttle Orbiter landed at White Sands, New Mexico. Just after landing, high winds blew gypsum sand into the RCS engines before they could be covered. This event caused concern that the injector orifices could be blocked and thus cause unstable combustion and/or improper cooling of the combustion chamber walls. Results of bench tests revealed that the gypsum would migrate into the passages of the injector, particularly on the upfiring engines, where the gypsum accumulated on the injector face. Results of bench tests also revealed that the gypsum would harden and cake when exposed to propellants or water such as seen in ferry flight (cold leakage and moisture from the air). To solve this problem, a plan was implemented to remove and replace all nine of the upfiring engines and to remove three horizontal-firing engines. The three horizontal-firing engines were inspected and test fired to ensure that no detrimental effects were seen. Data from these three engines were then used to clear the other horizontal engines for flight.

A general program goal during the operational phase has been to improve/reduce turnaround time and operations. The RCS program has been very successful in this area to date, and additional reductions are expected in the near future. Major turnaround improvements to date include the following.

1. Deleted screen drying requirement - 16 hours.

2. Developed computer program to track nitric oxide content in oxidizer and thus deleted requirement for postflight oxidizer samples - 8 hours.

3. Deleted requirement to drain and refill tanks and manifolds between flights - 2 to 3 days.

Turnaround improvements in work include the following.

1. Delete overfill requirement on the ARCS propellant tanks - 1 to 2 days.

2. Improve loading procedures - 8 hours.

These improvements have been achieved primarily by implementing special programs on the test articles at WSTF to ensure that the changes are acceptable. The testing has also been supplemented by analysis efforts in some cases.

Numerous problems or challenges and their solutions have been identified in this paper. The solutions to the problems have produced satisfactory operational hardware. The real achievement in completing the development program, however, was not in the final hardware itself but in what was learned to make that hardware possible. Those real achievements on this program must become the routine working tools for the next major effort so that the creative engineers of tomorrow may spend their time constructively in dealing with tomorrow's challenges.