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SPACE SHUTTLE ORBITER AUXILIARY POWER UNIT DEVELOPMENT CHALLENGES

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ABSTRACT

When the flying spacecraft was approved for development, a power unit for the hydraulic system had to be developed. Unlike other systems on the Orbiter, there was no precedent in earlier spacecraft for a hydraulic system nor for the power unit to drive the hydraulic pumps. The only prototypes available were airplane auxiliary power units, which were not required to operate in the severe environments of a spacecraft nor to have the longevity of an Orbiter hydraulic power unit. The challenge was to build a hydraulic power unit which could operate in 0g or 3g, in a vacuum or at sea-level pressure, and at -65° F or 225° F, which would be capable of restarting while hot, and which would be capable of sustaining the hydraulic loads for the life of the Orbiter. This paper describes the challenges of building such a machine and the manner in which they were met.

INTRODUCTION

This paper deals with the problems associated with providing power to aerodynamic control surfaces and other functions, such as steering and braking, for a vehicle intended to function as both a spacecraft and an aircraft. The approach selected to accomplish these tasks for the Space Shuttle Orbiter Program was to use a conventional hydraulic system and thereby to establish conventional aircraft hydraulic system technology as the foundation of the Orbiter system. This approach minimized the technology development requirements except for the power supply unit. Developing a power supply unit to drive the hydraulic pumps thus became one of the major challenges for the Space Shuttle Orbiter Program.

The basic approach to providing hydraulic power for the Orbiter was to use a small, high-speed, monopropellant-fueled turbine power unit to drive a conventional aircraft-type hydraulic pump. Although a misnomer, the power unit was labeled an auxiliary power unit (APU) because of its similarity to conventional aircraft emergency power units, traditionally called APU's. Here, in the name, much of the similarity ends. The stringent requirements imposed on the Orbiter APU quickly made this machine different from existing aircraft APU's.

REQUIREMENTS

Basically, the Orbiter APU's were required to operate in temperature environments of -54° C (-65° F) to 107° C (225° F), in acceleration environments of 0g (on orbit), 3.3g (boost), and 1.5g (landing shock), and in pressure environments of sea level to space vacuum. The units were required to operate for 92 minutes each mission at power levels from 8 to 148 horsepower. A minimum of two restarts was required during each mission. In addition, the APU's were to be used for the 100-mission life of the Orbiter. A breakdown of APU design requirements is shown in table 1. During the ascent, descent, and landing portions of a mission, reliance is placed on the Orbiter hydraulic system (fig. 1) for critical flight control functions. These functions include providing power for the Orbiter control surfaces (rudder/speedbrake, body flap, and elevon actuation systems), main engine gimbaling and propellant control during ascent, landing gear deployment, and steering and braking during landing. Operations occur during launch/ascent, on-orbit checkout, reentry/descent, and landing/rollout.

Operational effectiveness of the APU is predicated on reliable, failure-free operation during each flight, on mission life (reusability), and on serviceability between flights (turnaround). Achieving these elements was the challenge presented to the APU development team consisting of the NASA Lyndon B. Johnson Space Center (JSC), Rockwell International, Sundstrand Corporation, and the Sundstrand subcontractors.

SYSTEM DESCRIPTION

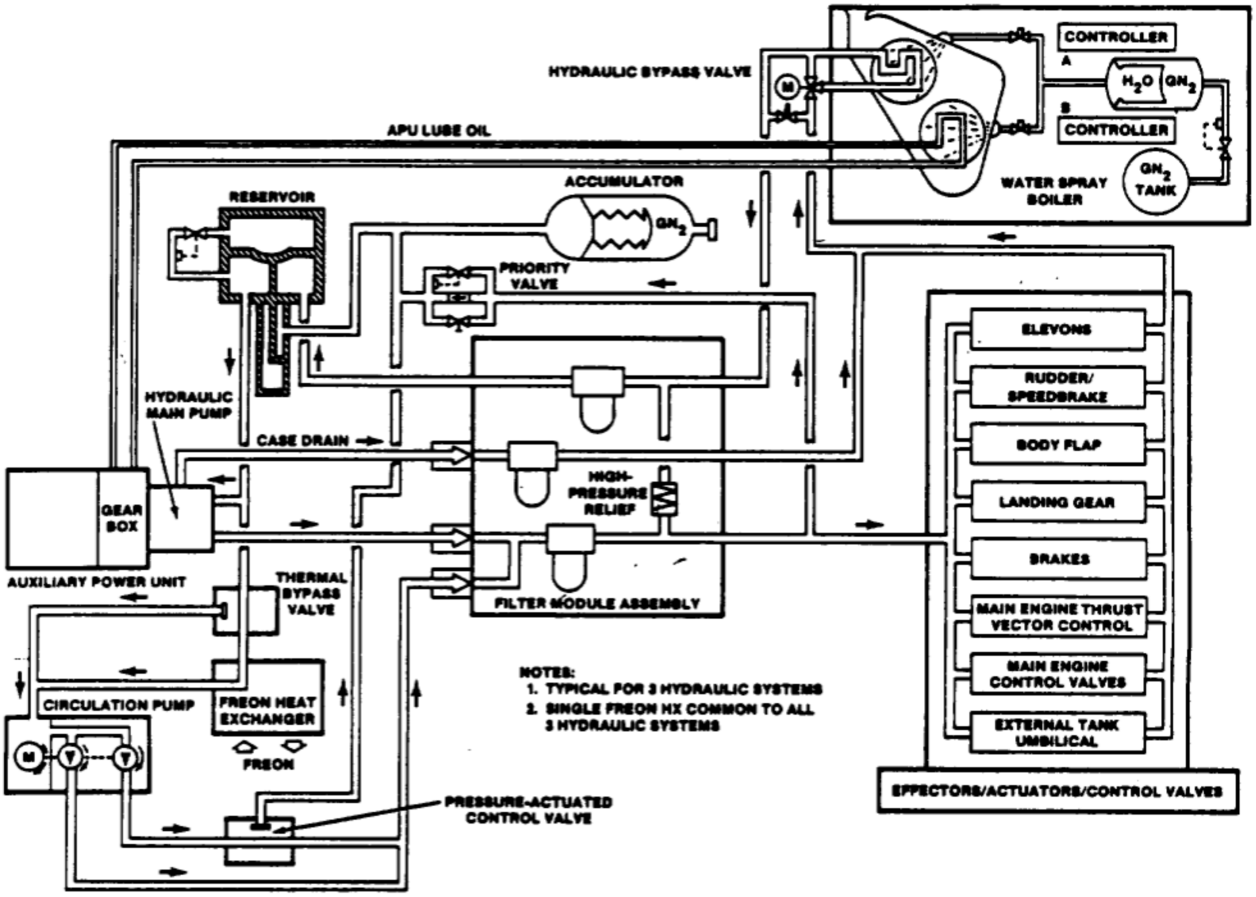
The Orbiter vehicle uses three complete APU subsystems and three hydraulic systems. The APU's, including their fuel systems, are isolated from each other. Pressure-actuated cross-links are provided between the hydraulic systems so that in case of a failure in a single APU or hydraulic system, the remaining two systems can accommodate the total hydraulic load.

TABLE 1.- ORBITER APU DESIGN REQUIREMENTS

Parameter	Requirement
Basic	Provide shaft power for 3 hydraulic pumps to operate aerodynamic control surfaces, main engine thrust vector control, main engine valves, landing gear, brakes, and steering
Design	3 independent APU subsystems; liquid hydrazine fuel supply, filter, valve, APU, controller, lubrication system, thermal management, cooling provisions
Operation	
Power, hp	
Nominal (normal speed)	134
Maximum (high speed)	148
Life between scheduled maintenance, hr	20
Starts	Prelaunch, hold, checkout, contingency checkout, and reentry
Thermal control	Maintain fuel, lubrication oil, and water temperature at 45° to 150° F (7° to 65° C); control fuel system soakback to <200° F (<93° C)
Tank capacity, nominal, lb (kg)	350 (158.8)
Duty cycle, min	
Nominal	92
Abort once around . . .	120
Environmental	
Temperature, °F (°C)	
Min. prelaunch	0 (-18)
Min. on-orbit	-65 (-54)
Min. atmospheric flight	-40 (-40)
Max. reentry soakback	225 (107)
Acceleration, g	
Boost	3.3
Orbit	0
Landing shock	1.5
Vibration, g_{rms}	
Level A	
X-axis	8.2
Y-axis	4.1
Z-axis	4.1
Level B	
X-axis	5.3
Y-axis	2.6
Z-axis	2.6
Pressure	Sea-level to space vacuum

The APU's are hydrazine fueled, turbine driven, and restartable a multiple of times. Power is delivered to the hydraulic pump through a lubricated zero-g, all-attitude gearbox. The units have a thermal control system to prevent both freezing of the fuel during periods of low-temperature environmental exposure and overheating during heat soakback following operation and shutdown. An electronic controller provides all of the functions to check out key APU status parameters before launch, control during operation (startup, speed control, shutdown, redundancy management), and thermal management before and after operation.

A functional schematic of the APU subsystem is presented in figure 2. Figure 3 shows the APU configuration. The Orbiter installation is shown in figure 4, in which the locations of the fuel feed system, the fuel tankage, the water cooling system, and the water tankage are indicated.



NOTES:
1. TYPICAL FOR 3 HYDRAULIC SYSTEMS
2. SINGLE FREON HX COMMON TO ALL 3 HYDRAULIC SYSTEMS

FIGURE 1.- ORBITER HYDRAULIC SYSTEM SCHEMATIC.

Monopropellant-grade hydrazine fuel is supplied to the inlet of the fuel pump at pressures ranging from 80 psia (5.5 bars) to 370 psia (24.5 bars). The fuel pump increases the pressure to approximately 1500 psia (103 bars). The high-pressure fuel is directed through the gas generator valve module (GGVM) to the gas generator (GG). The GG catalytically decomposes the fuel into gas at a temperature of 1700° F (927° C) and at a nominal pressure of 1260 psia (86.5 bars); the gas is then directed through a two-stage, supersonic reentry turbine. After work is extracted by the turbine, the gas is used to cool the gas generator by flowing over it before exiting the APU.

Once turbine operating speed is achieved, it is controlled within +8 percent by the GGVM, the electronic controller, and speed sensors. Three redundant speed sensors mounted at the turbine shaft provide the electronic controller with pulsed speed signals. The primary nominal turbine operating speed is 75 000 rpm. If the primary speed control mode fails, a secondary speed control mode of 81 000 rpm is activated automatically. This secondary mode may also be selected manually in the event the APU is required to have greater load-carrying capacity. Should the secondary speed control mode fail, a backup (part of the primary circuit) control mode of 83 000 rpm is activated automatically. If both primary and secondary control modes are inoperative, automatic shutdown occurs at 93 000 rpm.

The power from the turbine shaft is transmitted to the hydraulic pump, the fuel pump, and the lubrication pump through the gearbox. The gearbox design features piston accumulators that function as variable-capacity oil reservoirs and gearcase walls that closely conform to the gears. These features enable the lubrication system to function in any attitude and in zero g (ref. 1). Component description and performance may be obtained through references 2 and 3.

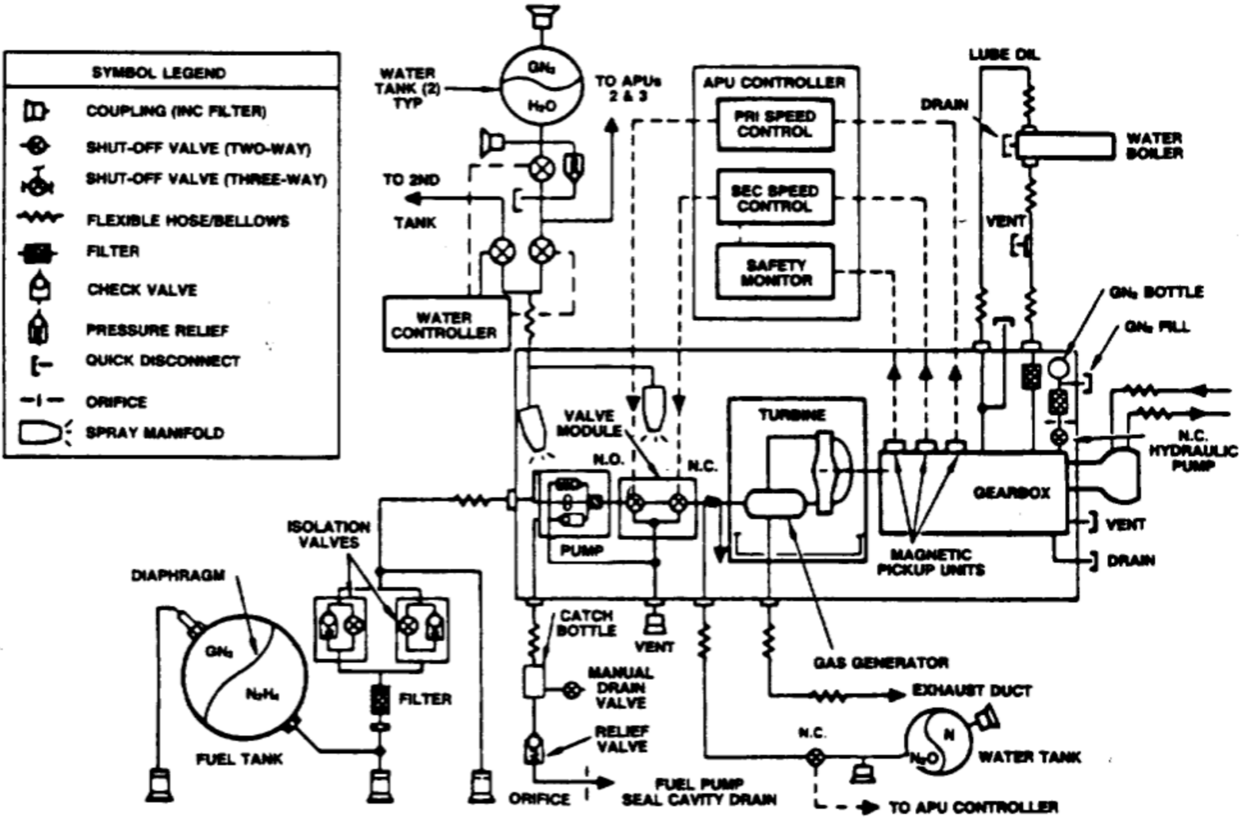


FIGURE 2.- AUXILIARY POWER UNIT SUBSYSTEM SCHEMATIC.

EARLY DESIGN PROBLEMS AND SOLUTIONS

Early in the APU development program, several significant technology issues arose. Key among these were problems with fuel pump life and performance, turbine wheel blade and shroud cracking, gas generator life and hot-restart capability, control valve seat/poppet life and valve performance, gearbox accumulator performance, turbine shaft seal leakage, lubrication oil silting, gearbox performance at low ullage pressures, exhaust turbine containment housing life (cracking), turbine overspeed containment, and controller manufacturing. In the paragraphs to follow, these problem areas are described and the solutions or actions taken discussed.

FUEL PUMP

Because of the very poor lubricity properties of hydrazine, galling of the fuel pump gears was an early problem that significantly limited pump life. The approach taken to resolve this problem was to reduce the pitch velocity, to design the gear teeth to minimize sliding contact between the gears, and to use a gear material less sensitive to galling. This change was accomplished by using a very hard material and many small teeth rather than a few large ones. The resultant design was a 16-pitch, 17-tooth gear made from M2 tool steel. This design is in use today and effectively provides unlimited fuel pump life (fig. 5).

Poor performance (volumetric efficiency) was another problem characteristic of the early fuel pump. This problem was found to be associated with dimensional instability of the graphite sleeve bearings, which permitted internal leakage. The solution was found in the area of clever manufacturing processes rather than in the primary material selection. By partly machining the bearings, then soaking them in hydrazine before final machining, reasonable dimensional stability was achieved. This process was augmented by the use of O-ring seals between the bearing-face ends and the cover plate (body). These changes improved the basic pump performance to such an extent that a controlled

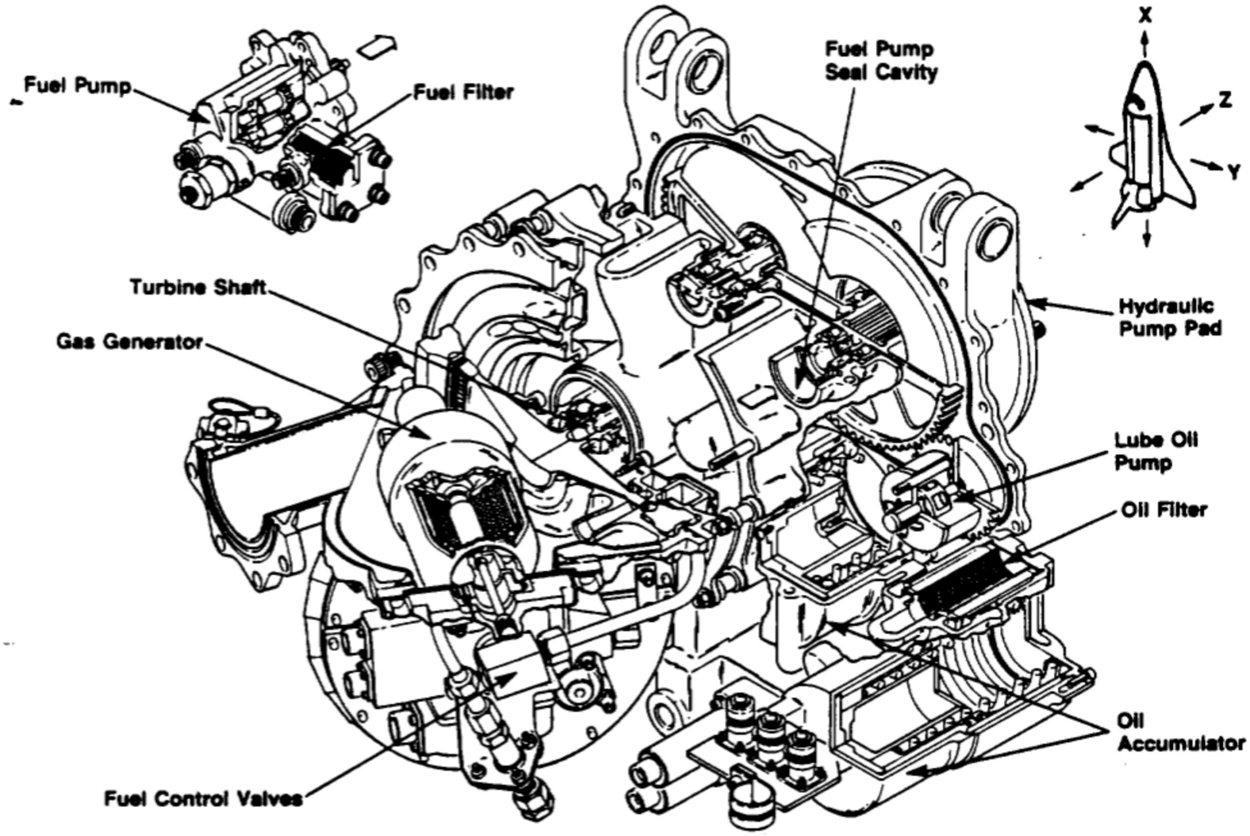


FIGURE 3.- AUXILIARY POWER UNIT ASSEMBLY.

leak (drilled passage from the high-pressure side of the pump to the low-pressure side) is now used to match (lower) the output pressure to levels required by the gas generator design.

During development testing, fuel pump drive-shaft seal leakage problems resulted in several design iterations of the bellows in the seal. These changes were not successful, and after a bellows failure during an Approach and Landing Test (ALT) flight, the bellows-type shaft seal was replaced with a seal that uses an O-ring in place of the bellows to seal between the carbon-face seal holder and the seal case. No further problems with massive fuel leakage due to seal failures have been experienced. A disassembled fuel pump is shown in figure 6.

TURBINE WHEEL

The APU turbine wheel is a 5-1/4-inch-diameter, impulse-type turbine using a blade tip shroud (fig. 7). Early problems with the wheel included blade root cracks (fig. 8), shroud cracks, inadequate welds between the blade tips and the shroud (fig. 9), and blade trailing-edge cracks at the blade tips. The trailing-edge cracks propagated to the point at which pieces of the blades would break off. The combination of blade root cracks and shroud cracks led to at least one instance of loss of a blade and a portion of the shroud during APU operation (fig. 10). The trailing-edge cracking was found to be caused by aerodynamically induced fatigue acting on the very thin (0.005 inch) trailing edge near the tip of the blade. Analysis results indicated that this part of the blade could be removed with a small 45° chamfer at the blade tip without significant effect on performance. Testing later verified this as an acceptable solution for the problem.

The blade root cracking was resolved by carefully controlling the blade root corner radiuses. Stress caused by sharp radiuses was found to cause the cracking. Careful design and dimensional control of the electrochemical-machining (ECM) tooling successfully resolved this problem. The shroud cracking situation was found to be related to both material selection and the welding process.

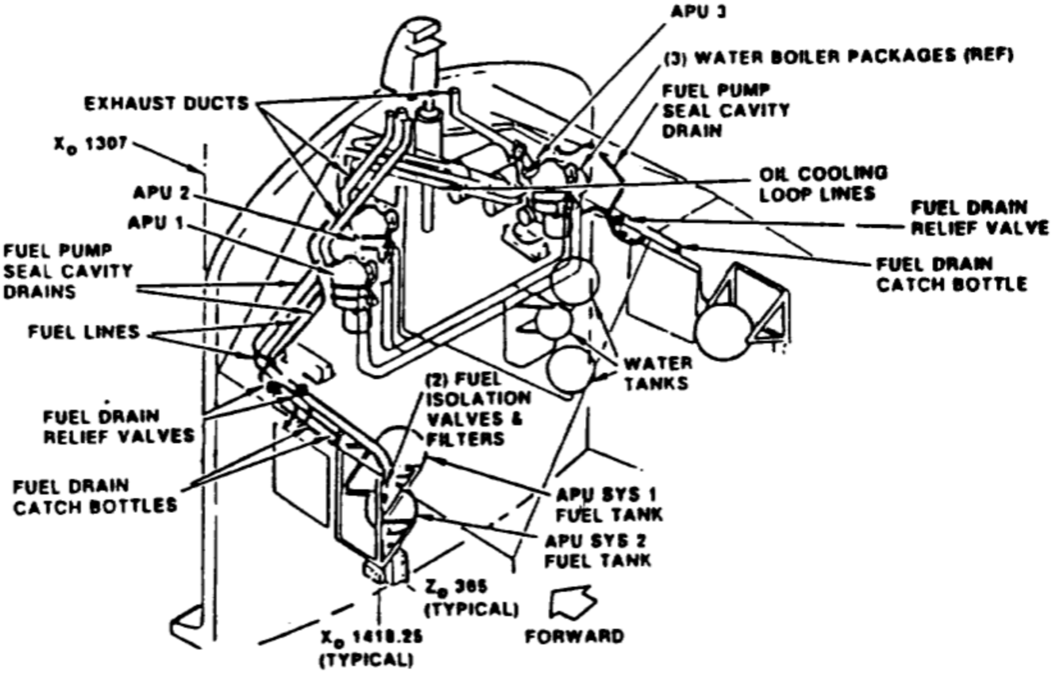


FIGURE 4.- AUXILIARY POWER UNIT SUBSYSTEM INSTALLATION DESCRIPTION.

FIGURE 5.- APU FUEL PUMP GEARS, 17 TOOTH/16 PITCH.

FIGURE 6.- APU FUEL PUMP.

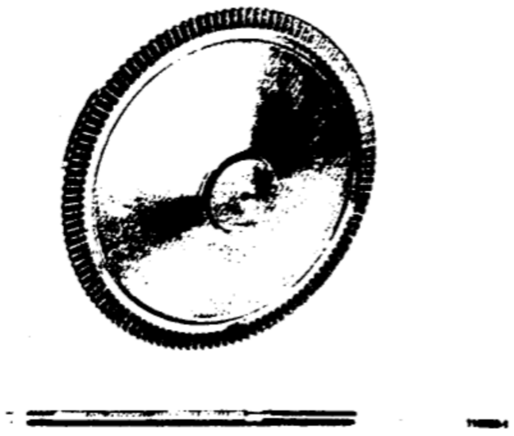


FIGURE 7.- TURBINE WHEEL.

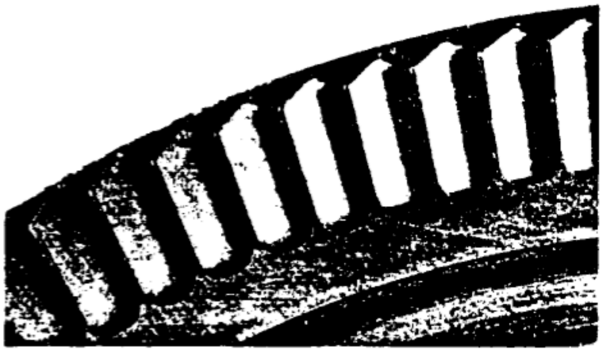


FIGURE 8.- AIRFOIL ROOT CRACKS AFTER 28 HOURS IN APU 102.

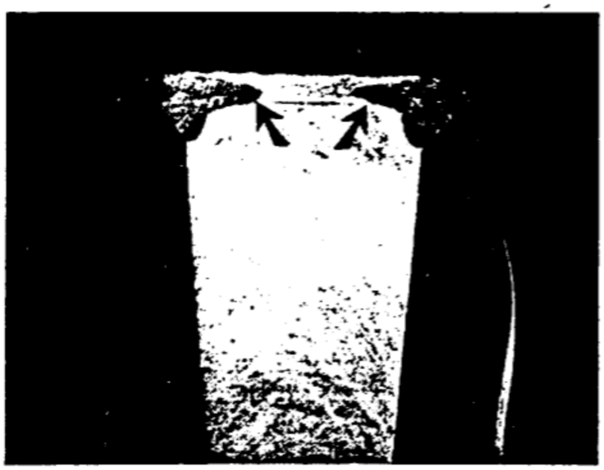


FIGURE 9.- METALLOGRAPHIC SAMPLE OF EB-WELDED JOINT RANDOMLY SELECTED. ARROWS DENOTE UNWELDED AREA IN CENTER OF JOINT (14X).

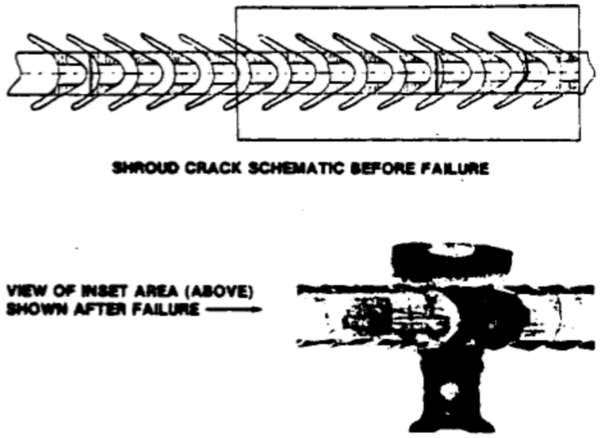


FIGURE 10.- SHROUD CRACK. TOP: SCHEMATIC BEFORE FAILURE. BOTTOM: VIEW OF INSET AREA (ABOVE) SHOWN AFTER FAILURE.

Increased strength and weldability characteristics were achieved by changing the shroud material from Hasteloy X to Inconel 625. Then, a very precisely controlled electron-beam (EB) weld procedure was developed to ensure full penetration weld across the chord of the blades without overheating the shroud. These actions eliminated the shroud crack problem.

GAS GENERATOR VALVE MODULE

Development of a reliable valve (fig. 11) to control the fuel flow into the APU gas generator proved to be one of the most challenging tasks of the APU program. The valve is required to "pulse" fuel into the GG at frequencies of 1 to 3 hertz. Leakage requirements were stringent for both safety and efficiency reasons. In addition, the valve is exposed to significant pressure fluctuations (80 to 1500 psia per cycle) and must provide high response, yet have high reverse-cracking capability to seal against the GG pressure at valve closing.

The primary problems with the valve centered around leakage and limited life due to wear and failure (breakage) of the tungsten carbide valve seat. Considerable effort was invested in redesign

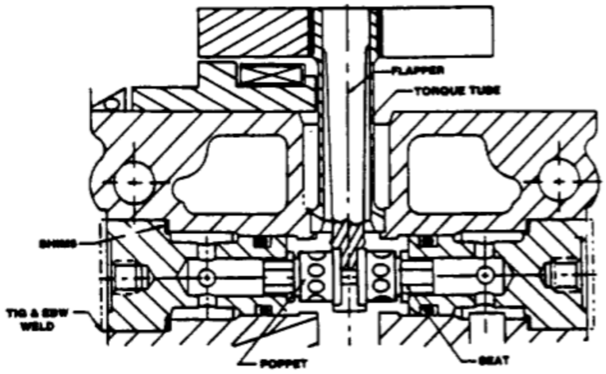


FIGURE 11.- CURRENT VALVE CONFIGURATION.

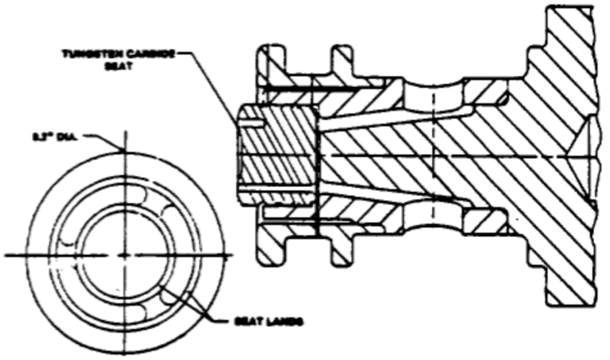


FIGURE 12.- APU SUBSYSTEM GGVM REDESIGNED SEAT AND MANIFOLD.

of the seat, in stress analysis, and in developing manufacturing processes. This effort resulted in an intricate seat design with concentric, dual-sealing surfaces and redesigned internal flow passages (fig. 12). The seat was diamond slurry honed as part of the manufacturing process to remove the recast layer left by the electrodischarge machining (EDM). This recast layer is a source of stress risers (cracks) and was considered one of the primary factors causing seat failure. The machining and manufacturing process turned out to be almost an art, and all seats and poppet assemblies were manufactured in a small, one-man shop.

Key lessons learned during the development of the GGVM include the following.

1. The tungsten carbide seat material is sensitive to many solvents and other fluids. Leaching of the binder material can significantly reduce strength and initiate intergranular cracking.

2. The seat configuration (internal corners, interfaces, etc.) caused residual internal stress that greatly affected the cracking characteristics.

3. The condition of the seat material surface significantly affected the cracking characteristics. The irregular, porous, cracked recast layer left after the EDM process was directly related to seat cracking.

4. Seat wear characteristics (life) were directly related to concentricity between the seat and the poppet, to seat-land width, to seat-poppet impact velocity, to closing spring force (reverse-cracking pressure), to poppet self-alinement design features, and to overall seat-poppet alinement established during the valve assembly process.

5. The use of damping oil in the valve armature area reduced rebound and was effective in reducing seat wear and seat-land edge chipping problems.

GAS GENERATOR

A key component of the APU is the gas generator. The GG receives hydrazine from the GGVM in short controlled pulses. The fuel is injected (flows) radially into a Shell 405 catalyst bed, where it is decomposed into hydrogen, nitrogen, and ammonia. The resultant gas mixture leaves the bed at approximately 1200 psia and 1700° F. The performance and the useful life of the GG are measured by the stability of the decomposition process. Pressure fluctuations (roughness) of greater than ±10 percent of the steady-state level, pressure spikes (pulse spiking) of 2000 psia, or three consecutive pulses greater than 1900 psia indicate that the GG is no longer serviceable.

Key design features developed to extend useful GG life centered around the fuel injector and the catalyst bed. The size, the shape, the distribution, and the retention scheme for the catalyst granules were factors receiving significant development effort. The final design used had concentric, cylindrical beds separated by a cylindrical divider (figs. 13 and 14). The inner bed was packed with 14- to 18-mesh catalyst retained within a unique metal foam. The outer bed did not contain the metal foam. The technique used to pack the bed was found to be critical to good performance. This is an art-like operation consisting of pouring, shaking, tapping, and, in general, handworking the proper amount of catalyst into the bed. Because of the subjective nature of the operation, it has been, and still is, a basic concern in the manufacturing process.

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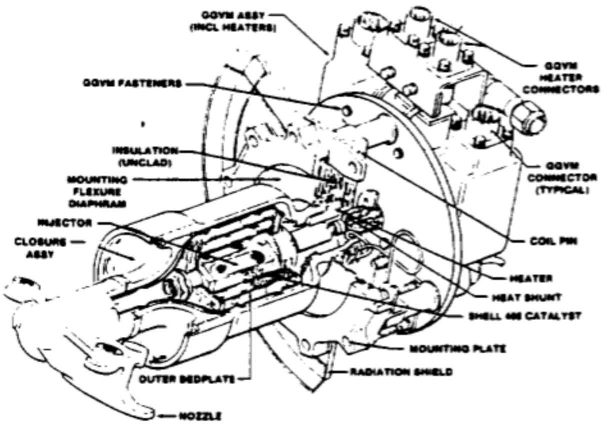

FIGURE 13.- MIN-MOD GAS GENERATOR - BASELINE.

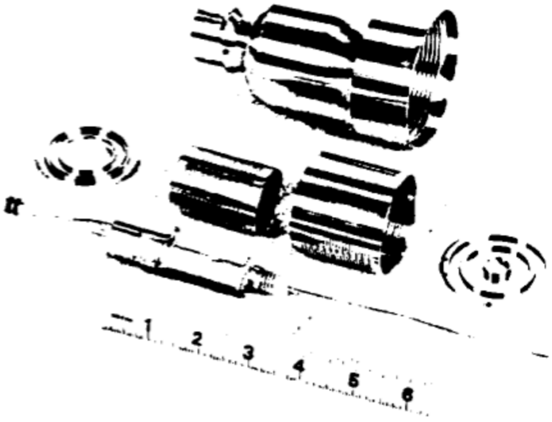

FIGURE 14.- APU GAS GENERATOR.

Injector design was also a critical element of GG performance. The current design consists of a core body with shaped fuel distribution channels feeding four injector panels. The injector panels are made from a sintered metal mesh material called Rigimesh (fig. 14). These panels produce uniform radial and axial distribution of fuel being fed radially into the catalyst bed. Design of the injector to produce uniform fuel distribution was a key element in extending GG life.

Another primary driver relative to GG bed life was vibration. Each piece of the GG was carefully analyzed and designed to minimize vibration within the GG. Specifically, the unit and its components were designed such that their natural frequencies did not tune with the APU or the hydraulic pump characteristic frequency. In some early configurations, resonances discerned at the 600-hertz pump frequency and at the 1250-hertz turbine frequency resulted in very early GG performance deterioration (roughness) due to mechanical breakup of the catalyst. The catalyst breakup caused bed voids, which allowed small accumulations of fuel to decompose violently and cause pressure roughness.

Thermal control within the GG was another area of significant concern. Overheating of the injector assembly during soakback after APU shutdown caused damage to the GG, damage to GGVM seals, decomposition of residual fuel in the injector upstream of the injector Rigimesh panels, and damage to the panels themselves (fig. 15). Early corrective actions included using a copper heat shunt between the injector and the GGVM mounting plate to dissipate some of the heat in the injector, and decreasing the thermal mass of the injector such that the incoming fuel could better cool the injector.

Even though these changes resolved the thermal concerns about the operating APU, it was found that if the APU restarted before the injector cooled to less than 400° to 450° F, the fuel would thermally decompose behind the injector panels and cause damage to the injector and would even feed back upstream to damage the GGVM. Limited hot-restart capability was finally achieved by adding an active water cooling system to the GG to be used only for hot restarts. This system injects water into a cavity within the injector. The steam thus generated is vented overboard (fig. 16). Use of this system enables restarts at any time after the cooling process, which requires a 210-second delay, is completed.

HYDRAZINE

In addition to the hot-restart problems discussed previously, the thermal instability of hydrazine also caused major problems with the APU fuel feed system (GGVM and fuel pump). After APU shutdown, soakback temperatures of 275° F and higher were causing excessive fuel decomposition within the GGVM and the fuel pump. Although the process was low order and did not damage the hardware, it did produce gas bubbles in the fuel system. After an "explosion" severely damaged a GGVM during an APU test (fig. 17), subsequent testing and analysis revealed the potential for adiabatically compressing hot gas bubbles within the GGVM and thereby increasing the temperature of the fuel vapor in the bubble to the point at which detonations occurred. This situation was controlled by limiting the maximum soakback temperatures in the fuel feed system (200° F) to minimize bubble formation and, by the same action, eliminating any APU starts when fuel feed system temperatures were higher than 200° F.

FIGURE 15.- APU GG INJECTOR FAILURE.

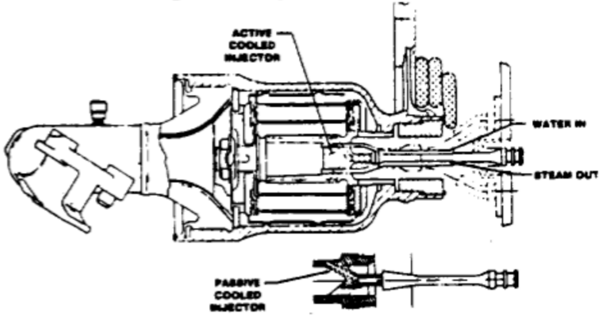

FIGURE 16.- GAS GENERATOR.

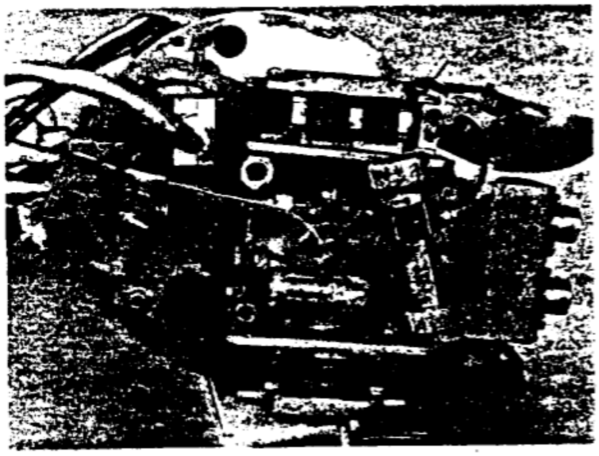

FIGURE 17.- GGVM DETONATION DAMAGE.

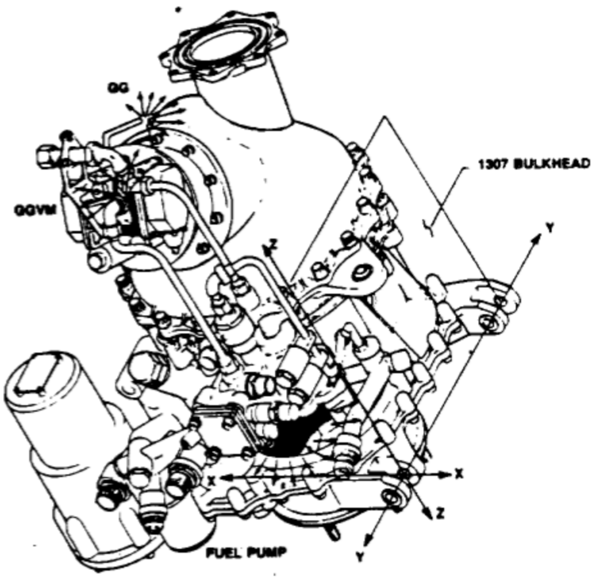

FIGURE 18.- ORBITER APU COOLING REGIONS.

The fuel pump and GGVM temperatures were controlled by use of an active water cooling system that sprays water externally onto the components (fig. 18).

During the course of the APU development, the sensitivity of hydrazine to decomposition has been a continual concern. Critical elements involved are temperature, materials in contact with the fuel, and purity of the fuel. High-purity hydrazine in contact with certain materials decomposes at significant rates at fairly low temperatures. Contamination within the feed system is always a concern and has the potential of causing detonations. Rust in any form is a catalyst and causes great concern.

A series of tests at the JSC White Sands Test Facility (WSTF) is being performed to define the compatibility of hydrazine with various materials and to define the sensitivity of hydrazine to the adiabatic-compression phenomenon. In addition, the effects of shock-wave propagation through the fuel and its vapor are being investigated. This work is being done to gain a better understanding of hydrazine in its application as a fuel and to ensure that, for use in the APU's, there are adequate safety margins relative to temperature limitations, to material compatibility, to shock and compression phenomena, and to the composition and chemical control of the fuel.

GEARBOX

The APU gearbox is required to reduce the 75 000-rpm turbine shaft speed to the hydraulic pump speed of 3700 rpm. It also drives the fuel pump and the lubrication oil pump. Development challenges were associated with the oil accumulators (required to control the oil-gas ratio in the gearbox), operation at low gearbox pressure, shaft sealing, and lubrication oil contamination. The oil accumulators in the gearbox control the quantity of oil in the lubrication circuit. To maintain proper lubrication oil flow and pressure, the ratio between oil and gas (void volume) must be controlled. Excessive oil causes churning and oil overheating, whereas insufficient oil causes inadequate oil flow. The original accumulators were pistons, sealed with an elastomeric diaphragm (Belofram, fig. 19). Failures of the diaphragm were common because of wear, scuffing, and folding as the pistons moved. The end results were contamination of the lubrication oil, leaks between the oil and gas side of the accumulators, and occasionally oil flow restrictions when a damaged diaphragm blocked the accumulator oil outlet passage. This problem was resolved by replacing the diaphragm with piston-ring-type seals made of Teflon.

During the development test program, it was determined that if the pressure within the gearbox was less than approximately 1 psia, the oil pump was incapable of functioning in a satisfactory manner (i.e., low pressure could develop on orbit because of seal leakage). The problem was primarily due to low net positive suction head (NPSH) pressure at the pump, but because the system is a closed loop which is not completely filled, voids could also form at the pump inlet. It, therefore, became necessary to provide a fluid (gas or oil) for the pump to displace to assure presence of oil at the inlet. This problem was resolved by adding a gaseous nitrogen pressurization system which guarantees a minimum of 4 to 7 psia in the gearbox at startup and during operation (fig. 20).

Shaft seal design was also one of the significant technical development challenges, especially the turbine shaft seal. When operating at high speeds and high temperatures, leakage was a continuing problem. Acceptable performance was finally achieved by using a hand-lapped, carbon-face seal with special provisions to ensure high face loading and stable rotational dynamics. Special lubrication oil cooling was also required for satisfactory performance.

Leakage of the turbine exhaust products through the turbine shaft seal caused another unusual secondary problem. The ammonia in the exhaust gases reacted with a particular additive in the lubrication oil to produce a silt that was plugging the oil filter and adversely affecting lubrication system performance. Once the additive was identified, a new oil was selected and the silting problem resolved.

The gearbox shaft seal at the fuel pump interface (bellows-type carbon-face seal) coupled with the shaft seal on the fuel pump posed problems that have not been solved (fig. 21). Slight leaks through these seals result in contamination of the lubrication oil with hydrazine. The reaction of the hydrazine with the lubrication oil produces contamination in the gearbox composed of a waxy, long-chain polymer (hydrazide) and a salt (pentaerythritol). The search for a hydrazine-tolerant oil is still in progress. Because free hydrazine in 270° F oil is dangerous because of the poten-

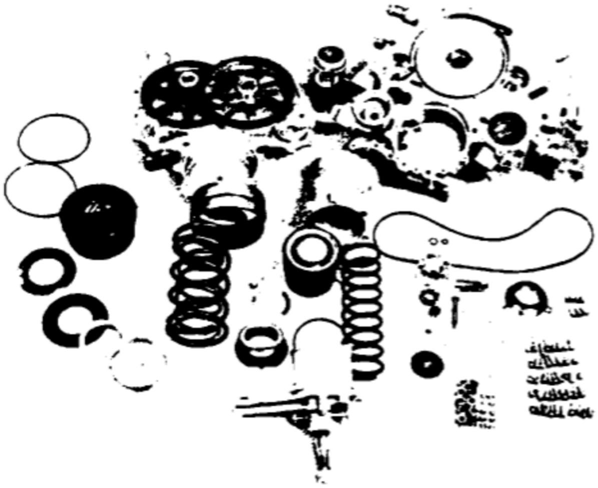

FIGURE 19.- GEARBOX.

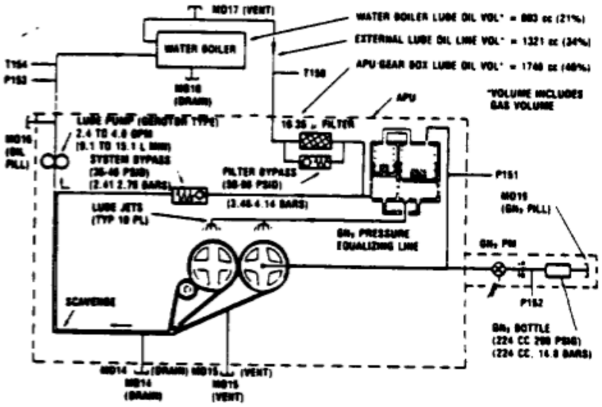

FIGURE 20.- APU LUBRICATION SYSTEM.

tial for detonation of the hydrazine, the most promising approach has been to add scavenging agents to the oil. However, this method has tended to cause some incompatibility problems between the oils and certain metals within the APU. Efforts in this area continue.

TURBINE HOUSINGS

Early in the development test program, it was discovered that the Stellite turbine containment housings and exhaust housings were cracking because of thermal cycling stresses (figs. 22 to 24).

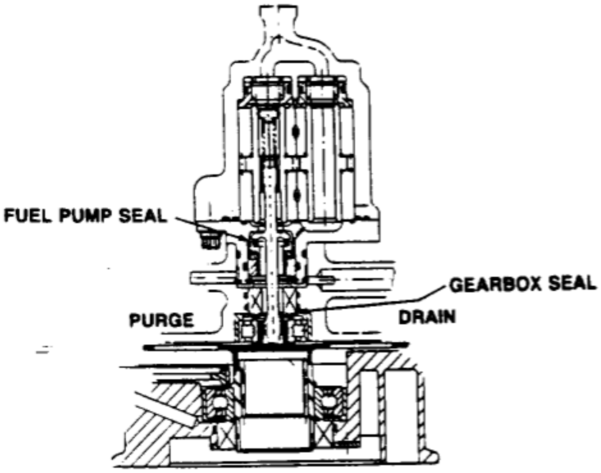

FIGURE 21.- APU FUEL PUMP.

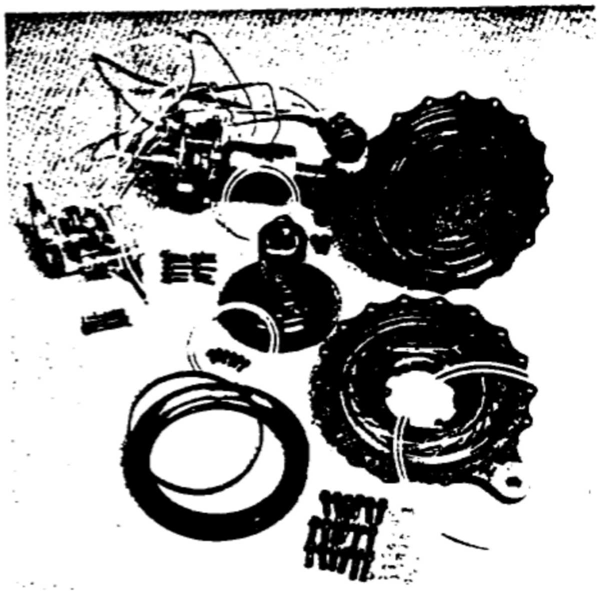

FIGURE 22.- GAS TURBINE MODULE.

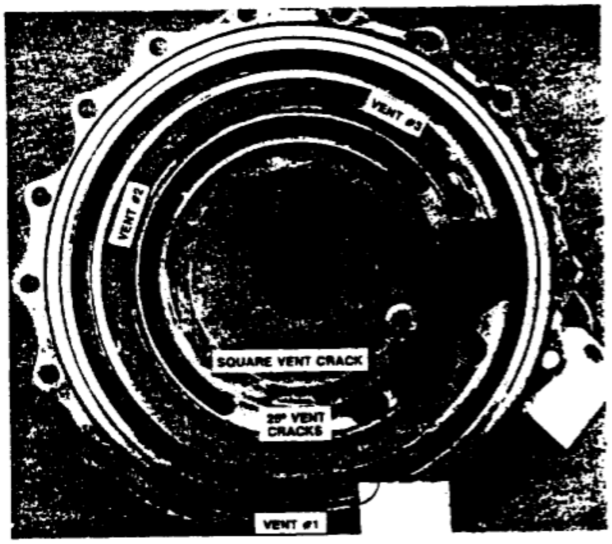

FIGURE 23.- TYPICAL EXHAUST HOUSING CRACKS.

FIGURE 24.- CRACK AT 25° VENT, APU EXHAUST HOUSING.

Analysis results showed that the normal thermal cycles associated with starting and stopping the APU were causing stresses that exceeded the elastic limits of the Stellite. These cracks would develop within as little as 5 hours of APU operation. However, they were in noncritical areas and never adversely affected APU operation. The housings were qualified for 20 hours of operation with cracks. Part of the rationale used to support qualification with the cracks was that several cracked housings were used for more than 40 hours and two for more than 70 hours without any problems. The cracks were a concern, however; if the cracks were to continue to grow, housing failure would be theoretically possible. For this reason, a housing material change has always been high on the list of potential APU product improvement items. Sundstrand has fabricated housings using Udimet LX. Early development testing indicates that this material change could eliminate the cracking problem.

TURBINE FAILURE CONTAINMENT

The basic APU was designed with a turbine wheel radial containment ring and a blade tip seal and rub ring to safely control failures of the high-speed assembly (fig. 25). The honeycomb seal and rub ring was designed to dissipate rotational energy of a failing turbine wheel. The containment ring was intended to then keep any fragments of a wheel that was breaking up from leaving the APU envelope. Overspeed failure tests showed that speeds of greater than 155 percent (of 72 000 rpm) were required to destroy the turbine wheel. At these speeds, the containment features of the APU were incapable of totally containing wheel fragments. Typical overspeed tests resulted in damaged APU fuel lines, damaged housings, broken containment rings, and the escape of several wheel fragments with sufficient energy to dent test cell facility lines and equipment (figs. 26 and 27).

Attempts to improve the APU containment capability were made by redesigning the rub-ring features and strengthening the containment ring. Both size and material changes were considered in attempts to redesign the containment ring. Within reasonable design practices, these attempts were not successful. Containment rings capable of containing 155-percent speed ruptures were not practical because of size, weight, and configuration considerations. In the end, no physical changes were made to the APU relative to containment.

The approach finally taken to address this issue was to provide safety features that would allow operation within the existing degree of containment. An overspeed safety circuit is used to automatically shut down an APU at 93 000 rpm (129 ± 1 percent). Additionally, this overspeed signal is used to close the fuel tank isolation valve to minimize any potential loss of fuel because of line damage on the APU. To provide further insurance against wheel failure, stringent flaw-detection inspections were imposed. With these controls, results of fracture-mechanics analysis showed the theoretical life to be many (approximately 10) times the 100-mission requirement.

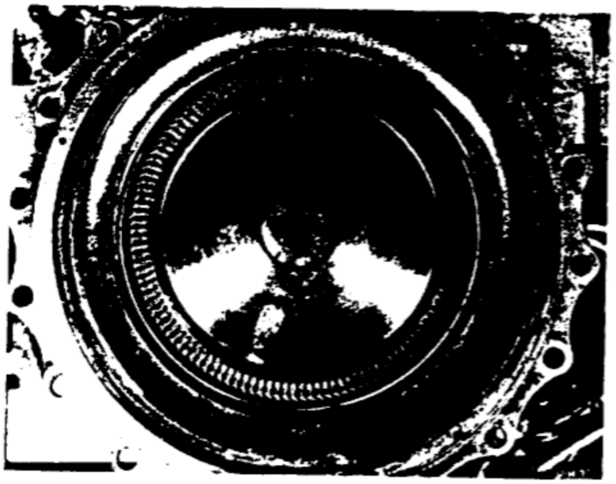

FIGURE 25.- CONTAINMENT RING.

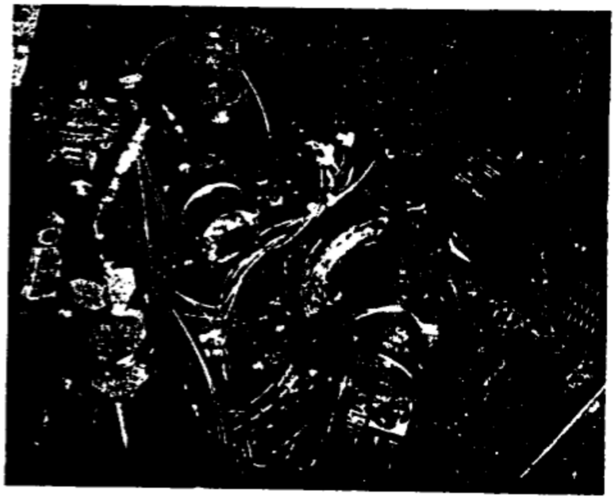

FIGURE 26.- TURBINE OVERSPEED TEST.

CONTROLLER

The critical problem areas associated with the development of the APU electronic controller (fig. 28) were basically not in design. There were some design iterations associated with reducing the complexity of the unit, primarily in the built-in test equipment (BITE) circuits, and some changes were made to provide redundancy for the higher stressed components. However, the significant challenges were associated with manufacturing. Basic deficiencies in manufacturing procedures, equipment, specifications, and technician skill caused problems in being able to repeatedly build high-quality hardware. Development of proper wave soldering techniques and procedures was also required. Once adequate specifications, manufacturing procedures, and quality control procedures were written, and the technicians were properly trained, the controller became a very reliable and trouble-free component.

The only problem encountered in qualification was stress corrosion on the rivets in the controller frame. This problem was resolved by installing the rivets with a wet coat of Super Korpon paint.

Although not an integral part of the controller, there was a manufacturing problem with the magnetic pickup units (MPU's) that feed the APU-speed signal to the controller. During assembly, it was necessary to braze a 0.002-inch lead wire from the MPU coil to a 20-gage output wire. This operation went through several iterations. At one point, a special holding fixture was used to position the wires during brazing. In the end, however, the most reliable joints were those done by hand by a skilled technician.

TEST FACILITIES

Specialized facilities were required to test the APU in all attitudes and environments that the APU would encounter during flight. The Integrated Test Article (ITA) built to simulate the entire APU subsystem included proper line lengths and routing and all the components in the APU subsystem. Capabilities of the ITA included turning the subsystem from launch to landing attitudes, temperature variations from -18° C (0° F) to 52° C (125° F), and exhaust pressures from sea level to 100 mmHg (50 000 feet). The ITA did not include a vacuum environment around the APU. This test facility was used to prove the APU subsystem could operate in various attitudes and prelaunch temperatures, to size the heaters for prelaunch environments, and to exercise the vehicle-servicing ground-support equipment.

FIGURE 27.- TURBINE WHEEL FRAGMENTS.

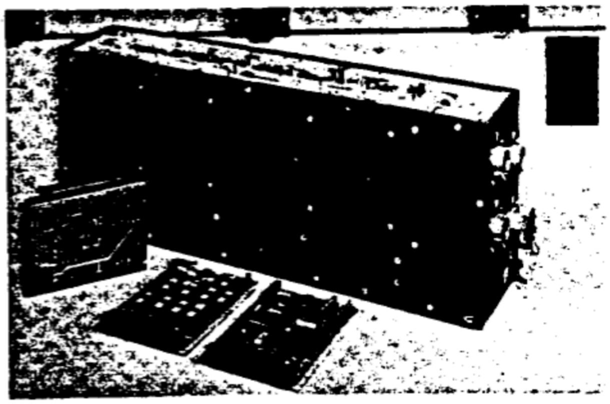

FIGURE 28.- ORBITER APU CONTROLLER.

ORIGINAL PAGE IS OF POOR QUALITY

To test the APU in a vacuum environment, a vacuum chamber at the JSC Thermochemical Test Area (TTA) (fig. 29) was used. The TTA vacuum chamber was capable of pressure conditioning from ambient pressure to 0.365 mmHg (180 000 feet) with a nonoperating APU or 2.49 mmHg (130 000 feet) with an operating APU and of temperature conditioning from -54° C (-65° F) to 107° C (225° F). This facility was used to prove that the APU could operate in a vacuum environment at the temperatures expected in space and, also, that the design of the heaters was adequate for on-orbit conditions. Testing in this chamber defined the cooldown rate of the APU and showed that the APU could not be shut down and restarted for an abort once around without performing an actively cooled hot restart. Testing in this chamber also revealed the problem of adiabatic compression of bubbles at high temperature by which an APU was destroyed after an attempted hot start.

To test the capability of the gearbox to function in zero g, a KC-135 aircraft was used to fly Keplerian parabolas while the onboard gearbox was operating.

None of the testing facilities used was a perfect simulation of the operating environments of the APU, but the facilities were sufficient to isolate and correct problems in the design of the APU. The full test of the APU with the vehicle hydraulic system and correct environments was performed during the Approach and Landing Test and the Orbital Flight Test (OFT) Programs.

FLIGHT EXPERIENCE

The APU was tested in flight for the first time during ALT for three captive/active flights and five free flights. In all flights, the APU was proved capable of handling flight loads (ref. 4).

Several problems were encountered during ALT. First, during a ground test, an APU gearbox was improperly serviced with an excessive quantity of oil causing an overtemperature of the gearbox. That problem was solved by a more accurate tool for measuring ullage volume in the gearcase. During

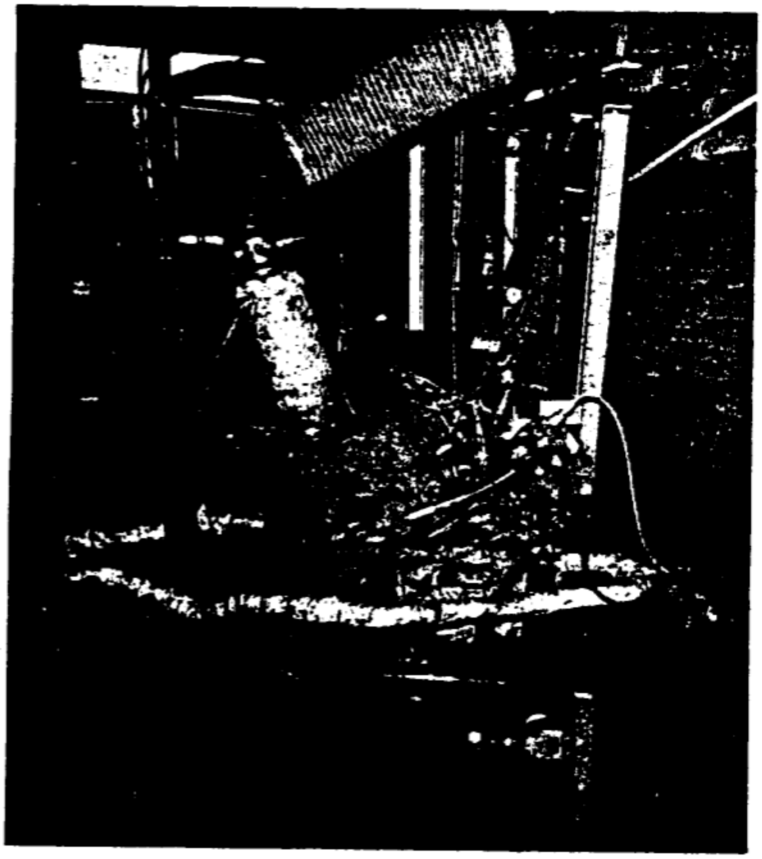

FIGURE 29.- JSC THERMAL VACUUM TEST.

captive/active flight 1, APU 1 developed a fuel leak which was large enough to be observed by a chase plane. Subsequent investigation showed that the bellows of the fuel pump seal was highly stressed in that it was exposed to dynamic pressures from tank pressure to 68 atmospheres (1000 psi). Because of the high stresses, the bellows design was abandoned and replaced with an elastomeric seal. No failures have occurred with the elastomeric seal design.

The exhaust-gas temperature (EGT) transducer was troublesome throughout the ALT flights and did not perform well in the extreme temperatures of the exhaust-gas environment. The crew was trained to shut down the APU upon indication of an exhaust-gas overtemperature. During captiv-/active flight 3, APU 1 was shut down because of the EGT transducer failure and erroneous indication of an overtemperature. After that incident, the crews were instructed to confirm the exhaust-gas overtemperature on a backup EGT instrument before taking action to shut down the APU. The EGT transducer was tackwelded to the exhaust duct, where the delicate leads were not adequately protected from vibration, and breakage of the leads caused the overtemperature indication. Following ALT, the EGT was changed to a probe which screwed into the exhaust duct and the leads were better protected.

The first Space Transportation System orbital flights (STS-1 to STS-4) proved the design concept of the APU for performance in zero g, vacuum, and extreme temperatures. These flights proved that the APU was well capable of handling the hydraulic loads in the extreme environments of space (ref. 4).

During STS-1, both APU 2 gas generator heaters failed. The heaters shared a common case, in which argon gas acted as a heat-transfer medium. A crack in a weld allowed the argon gas to escape. Long-term operation of the heaters caused overheating of the wire and subsequent failure of both heaters. During the qualification tests, the heaters passed an evacuated test. It was not a long-term, steady-state test, but consisted of many heater actuations, which was believed to be the worst case. After the flight, an inspection procedure was developed for all heater cases in which the heater was placed in a vacuum chamber and the resistance measured during the heatup cycle. If there was a leak in the case, the heater wire would get hotter and consequently have a higher resistance. For long-term redesign, as part of the improved APU program, the heater will be redesigned to have separate cases for each of the redundant heaters and the watt density will be lowered.

Also during STS-1, there was an indication of bubbles trapped in the fuel feedline as revealed by the gas generator pressures. This condition introduces the potential for the adiabatic compression of hydrazine discussed earlier. As a result of ground testing, a water system had been added to cool the GGVM and the pump after shutdown to prevent the decomposition of hydrazine. Also, care had been taken to service the flight system so as to prevent the trapping of bubbles in the feedline. Therefore, the appearance of bubbles on STS-1 was surprising. Tests run on the ITA indicated that bubbles could still be in the feedline from servicing; therefore, for STS-2, even more care was taken with servicing. During STS-2, bubbles were again evident in the APU 1 gas generator trace, and, after that mission, the APU was removed for investigation. The results of that investigation showed that significant decomposition of the fuel could take place at lower temperatures during a long exposure period. Servicing on the vehicle occurred several months before the actual flight. Also, it was determined that the fuel pump filter could act as a surface-tension device in trapping bubbles for some time before being flushed through the gas generator. These two results were convincing that the APU would have to operate with bubbles. A requirement was instituted that the APU should not be started unless the fuel feed system temperature was less than 200° F. This limit was backed up with APU and adiabatic-compression testing. Work is continuing on a filter that will not trap a bubble but allow it to be purged through the gas generator during startup before the first high compression occurs.

During the STS-2 prelaunch period, APU's 1 and 3 had high lubrication oil outlet pressure, an indication that the lubrication oil filter was plugged and that the gearbox was operating on the relief valve around the filter. The filter was determined to be contaminated with pentaerythritol, a compound formed when hydrazine fuel penetrates the gearbox. The gearboxes were flushed, and elaborate turnaround procedures were developed for keeping hydrazine out of the gearbox. Between every mission, the gearbox is flushed with lubrication oil and the filter replaced. The seal cavity drain (the common drain between the fuel pump and the gearbox) is flushed with alcohol to prevent a buildup of the waxy contaminant. The seal cavity drain pressure is maintained below the gearbox pressure to keep the driving force away from the gearbox. All of these procedures are time consuming, and none is totally successful. The APU 3 filter plugged again on STS-4. Work is continuing on redesigning the seal cavity drain and developing a compatible lubrication oil. Other minor problems on the APU during OFT included drain relief-valve leaks, "fuzz" leaks of the servicing quick-disconnect fittings, and a misthreaded fitting in the APU 1 GGVM/fuel pump water cooling line.

IMPROVED APU

The APU was developed under schedule constraints; consequently, as problems arose, modifications were made that were not necessarily optimum. The goal of the improved APU program is to optimally de-

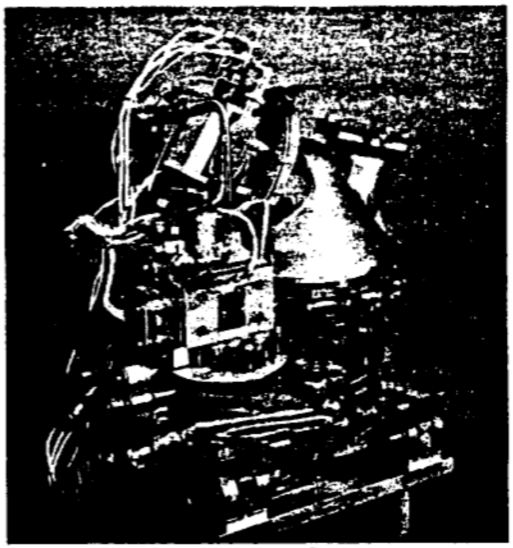

FIGURE 30.- IMPROVED APU.

sign the APU for durability and for performance, and to solve the flight and development problems. The design goal is for a 75-hour life, a passively cooled valve and pump, exhaust and containment housings that do not crack, a fuel pump filter that does not trap bubbles, and a redesigned seal cavity that prevents hydrazine from penetrating the gearbox (fig. 30). Development tests are already underway, and if implementation is approved by Orbiter management, the redesigned APU could be on the Orbiter by early 1987.

SUMMARY

The APU suitability for orbital flight, durability, and reusability have been demonstrated during OFT flights. More than 862 hours of APU operation (29.3 hours in OFT vehicle) and 1574 starts (72 starts in vehicle) have been accumulated with 100 percent success.

Enhancements have been identified to extend life to 75 hours (50 missions), to reduce weight (150 pounds (68 kilograms) per vehicle), to improve the lubrication system, and to reduce turnaround time. These enhancements are directed toward significantly reduced life-cycle cost, turnaround, and weight, and increased reliability, maintainability, and operational effectiveness.

The performance of the APU system has both proved the effectiveness of the APU development program and revealed the areas in which additional efforts could be effective. The necessity for a thorough development program with adequate test hardware, test programs, and design support and analysis has been emphatically shown. Where shortcuts have been taken, problems have often developed late in the program with significant adverse impacts. Timely and thorough development effort has been invaluable in guaranteeing safe, reliable, operationally effective systems.

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