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Space Transportation System Solid Rocket Booster Thrust Vector Control System

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The solid rocket booster thrust vector control system was designed in accordance with the following requirements: self-contained power supply, fail-safe operation, 20 flight uses after exposure to seawater landings, optimized cost, and component interchangeability. Trade studies were performed which led to the selection of a recirculating hydraulic system powered by auxiliary power units which drive the hydraulic actuators and gimbal the solid rocket motor nozzle. Other approaches for the system design were studied in arriving at the recirculating hydraulic system powered by an auxiliary power unit. The thrust vector control system has completed the major portion of qualification and verification tests and is prepared to be cleared for the first Shuttle flight (STS-1). Substantiation data will include analytical and test data.

Introduction

THE Space Shuttle flight system is composed of the Orbiter, an external tank (ET) that contains the propellant used by the Orbiter's main engines, and two solid rocket boosters (SRB's). The Orbiter and SRB's are reusable; the ET is expended on each launch.

The SRB's and the Orbiter's main engines will fire in parallel at liftoff. The two SRB's are jettisoned after burnout and are recovered by means of a parachute recovery system. The ET is separated prior to the Orbiter going into orbit. During the boost ascent phase, vehicle steering is provided by a thrust vector control (TVC) system on the Orbiter's main engines and SRB's. Control commands are issued from the guidance, navigation, and control computers in the Orbiter to the TVC system. In both cases, hydraulic servoactuators are employed that move the nozzles.

This paper deals specifically with the TVC system on the SRB's (see Fig. 1).

Trade Studies

In early 1974, trade studies were performed to arrive at the optimum TVC system to gimbal the nozzle on the SRB. Three basic designs were considered. The first was a blowdown system, which would have been relatively simple; however, the weight was approximately 4.5 times more than a recirculating system design. The other two concepts included a solid propellant gas generator (SPGG) to drive a turbine and hydraulic pump and a hydrazine system with a small tank, pump, and gas generator to drive a variable displacement hydraulic pump. The Space Transportation System (STS) vehicle is required to have the capability for one vehicle abort turnaround, i.e., at any phase of a launch, up to SRB ignition, the vehicle must be capable of being recycled for launch in the event of a correctable malfunction. The SRB TVC system ignition start command is issued at SRB ignition minus 20 s. It is apparent that an SPGG would require a backup unit to meet this requirement. In view of the above, the projected program cost of an SPGG supply was not competitive with the more flexible liquid fueled system which was currently under development for the STS Orbiter vehicle. In the fall of 1974, a study was initiated utilizing a hydrazine powered auxiliary power unit (APU) which was currently under development for the STS Orbiter vehicle. Pertinent parameters of the Orbiter system compared to SRB are listed in Table 1.

The primary advantages were the elimination of the majority of design and development costs and the early availability of development hardware. SRB costs were reduced by about 50%.

Resolution of Requirements Peculiar to SRB

Torque: The variation was resolved by the proper sizing of the actuator piston area in relation to the available moment arm and the required slew rate.

Hydraulic Power Unit Horsepower Required: The hydraulic power unit horsepower available (151 hp) vs SRB horsepower required (165 hp) was resolved by a decision to allow a reduced slew rate of 3 deg/s for the case of one hydraulic power supply system failed.

Salt-Water Immersion: The materials associated with exposure to seawater, internal and external, were reviewed in depth to assure a proper conceptual approach. This area was reinforced by appropriate seal changes and flush and purge procedures post-SRB recovery.

Table 1 STS requirements[1]

Parameter	Orbiter	SRB
Torque, $\times 10^6$ in.-lb	1.1; 1.4	4.2
Moment arm, in.	30	66
Gimbal angle, deg	$\pm 10.5; \pm 8.5$	± 5.0
Actuator area, in.^{2}	25; 20	32.3
Slew rate, deg/s/lb	10	5
System pressure, lb/in.^{2}	3000	3200
Hydraulic power unit (HPU), hp	142/155[b]	115/151[a]
System HP (pump), hp	117/129	96/125[a]
HPU		
Mission time, min	74	2.4
Missions	40	20
Salt-water immersion	No	Yes
All-attitude operation	Yes	No
Operating time, h	50	2
Useful life, h	250	10
Pump		
Flow rate maximum, gal/min.	67/75[b]	55/73[a]
Displacement, in.^{3}/rev	4.3	4.3
Rated speed, rpm	3918/4300[b]	3800/4180[a]

[a]110%. [b]113%.

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Index categories: LV/M Dynamics and Control; LV/M Propulsion and Propellant Systems.

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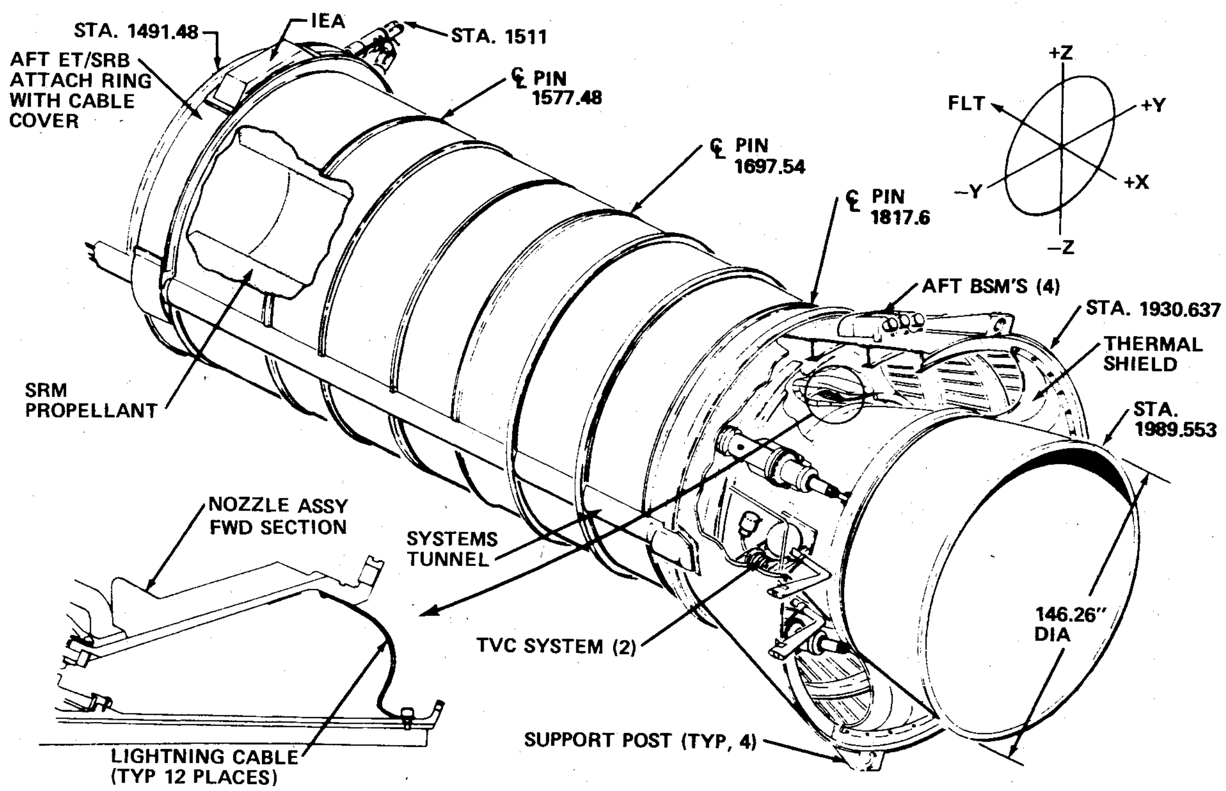

Fig. 1 SRB aft booster assembly (from Ref. 3).

Vibration Landing Shock and Impact Water Pressure: The auxiliary power unit was isolated from the above requirements by the incorporation of metallic vibration isolators and snubbers. The resultant vibration environment was reduced to values below Orbiter design requirements (see Table 2).

Description of System[2]

The TVC system in conjunction with the solid rocket motor (SRM) provides pitch, roll, and yaw vehicle movements. The system (Fig. 1) located on the aft skirt consists of two separate fluid power modules that supply hydraulic power to the SRB servoactuators to effect mechanical positioning of the nozzle in the tilt plane; the other unit controls nozzle position in the rock plane (see Fig. 2 for rock and tilt). If one module fails, the other increases its hydraulic power output and controls the nozzle position in both planes. The actuators are designed to retain the nozzle in the null position throughout the separation sequence until water entry after SRB/ET separation. The actuators are oriented 45 deg outboard to the vehicle pitch and yaw axes.

Figure 3 is a simple schematic of the TVC system. The system requirements in each SRB include fail-safe operation. It is a self-contained power system that provides for component interchangeability and low cost. In addition, salt water immersion protection had to be provided.

TVC Physical Arrangement

Hydraulic power for each SRB is required. Each actuator is supplied with power by the fluid power modules. Each fluid

Table 2 Environment comparison

	Orbiter	SRB
Vibration		
Liftoff	22.9 g, rms	30.1 g, rms longitudinal and tangential axis
		26.2 g, rms radial axis
Boost	4.5 g, rms	6.5 g, rms longitudinal and tangential axis
		5.3 g, rms radial axis
Landing (water impact)	1.5 g (93 M/s)	40 g (140 M/s) longitudinal
		45 g (100 M/s) lateral
Ascent acceleration	3.3 g	3.3 g
Impact water pressure		110 psia

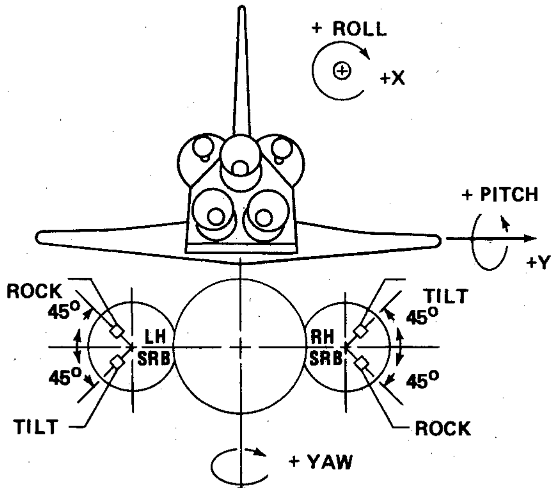

Fig. 2 Space transportation system flight control axes definition.

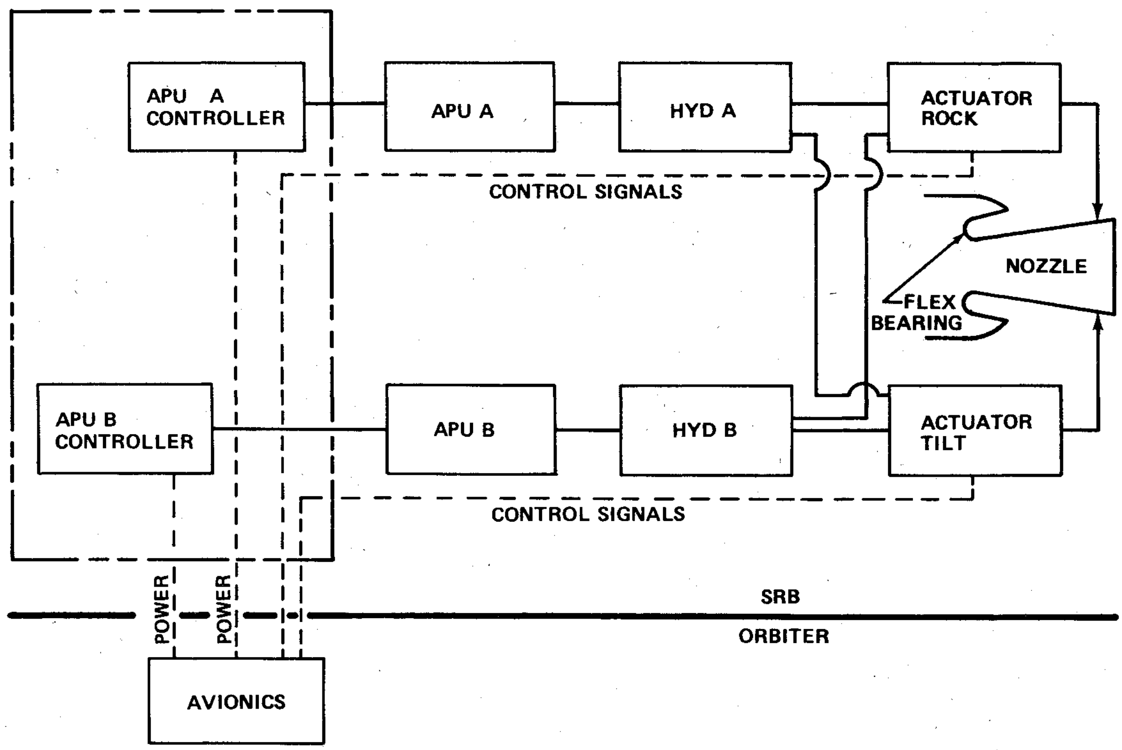

Fig. 3 Solid rocket booster redundancy concept.

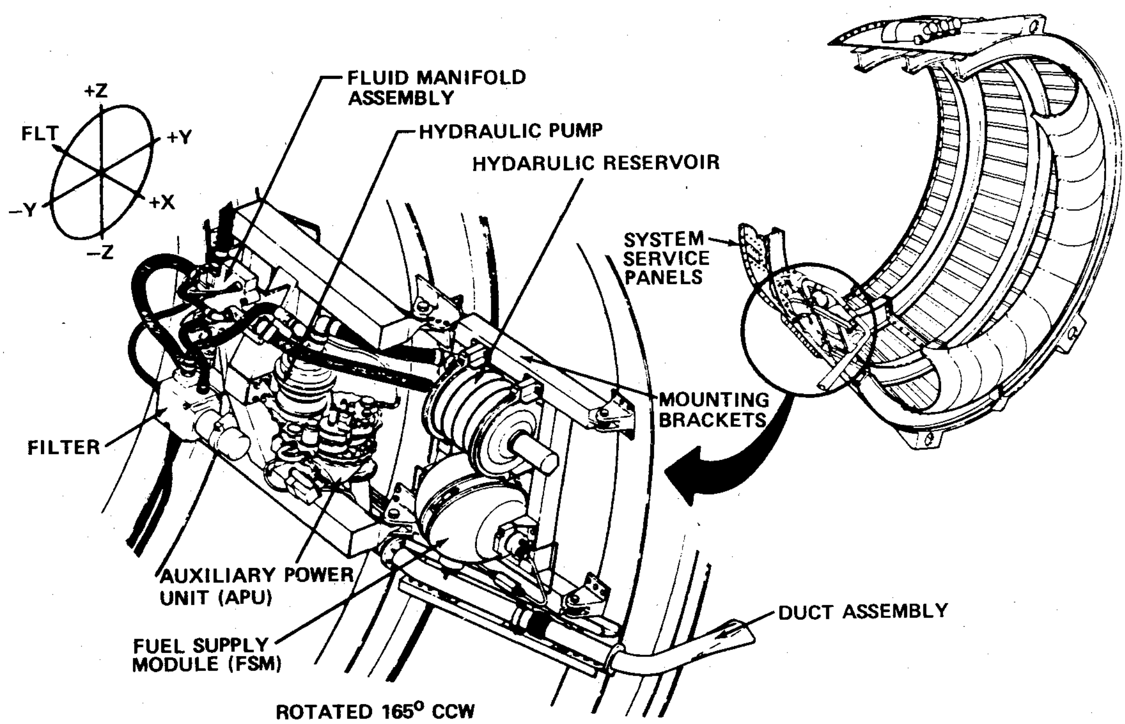

Fig. 4 SRB APU operation (from Ref. 3).

power module consists of an upper panel, lower panel, and overboard exhaust as shown in Fig. 4.

The components mounted to the upper panel are as follows: auxiliary power unit (APU), hydraulic pump (mounted to the APU), fluid manifold assembly, hydraulic fluid check valve and filter assembly, fuel isolation valve, system service panels, instrumentation and wiring, and interconnecting tubing.

The components mounted to the lower panel are as follows: hydraulic bootstrap reservoir, hydrazine (N_2H_4) fuel supply module (FSM), including fuel filter, instrumentation and wiring, and interconnecting tubing.

The overboard exhaust components are as follows: upper duct assembly, lower duct assembly, and mounting brackets.

In addition to the above, two electrohydraulic servoactuators are hydraulically connected to the fluid power modules and mechanically linked to the nozzle.

An overview of the design and performance characteristics for each major component of the TVC system is presented in the following paragraphs.

APU: The APU (shown in Fig. 5) provides mechanical shaft power to the hydraulic pump. The principal parts of the APU are as follows: integral fuel pump, gas generator, dual pass, reentry turbine, gearbox, control system, primary

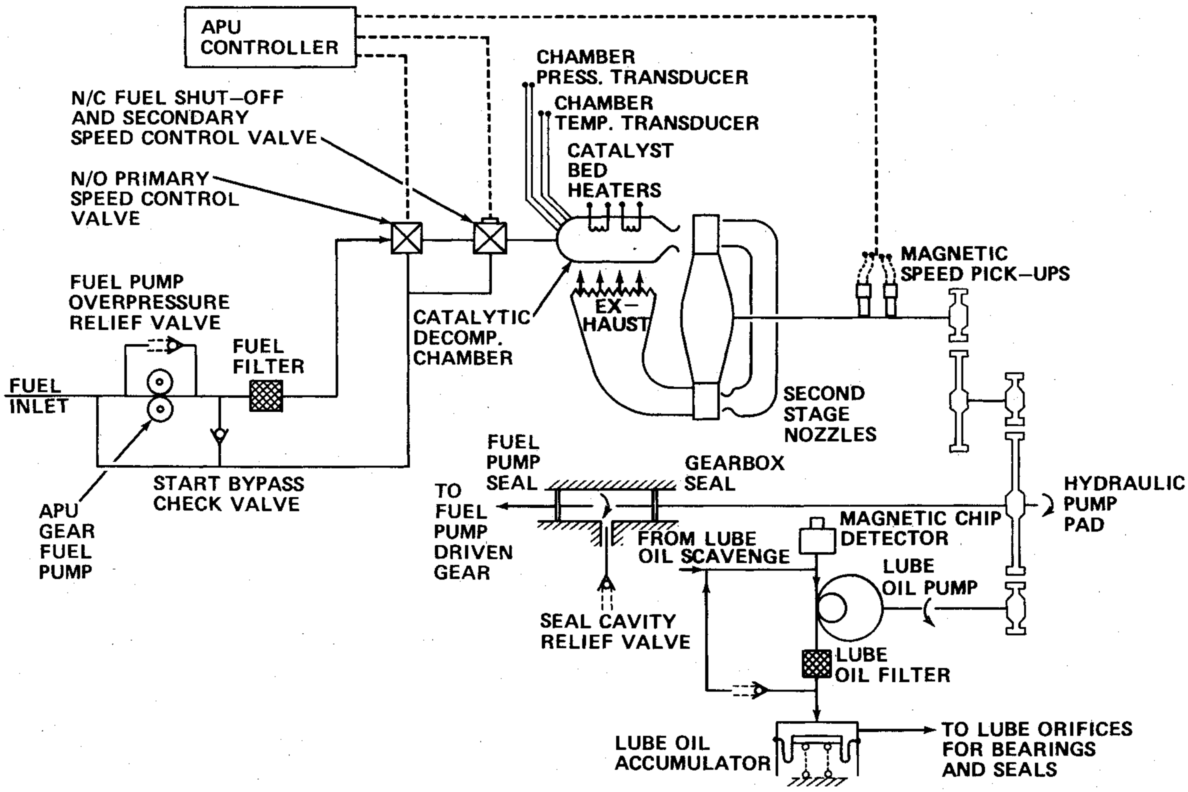

Fig. 5 SRB APU system schematic.

control valve (normally open), secondary control valve (normally closed), and lubrication system.

APU operation is as follows. To start the APU, two electrical power signals are applied. The first power signal energizes the normally closed fuel isolation valve (FIV) to the open position allowing hydrazine (N_2H_4) to be introduced into the APU. The FIV remains energized in the open position throughout APU operation. The second power signal energizes both the primary and secondary control valves and the APU controller. With the second power signal, the normally closed secondary control valve is energized open and remains open unless control by the normally open primary control valve is interrupted. After this sequence, the N_2H_4 flow path from the fuel supply module (FSM) to the APU gas generator is open.

For start, N_2H_4 is initially introduced to the APU at the fuel pump inlet. There it bypasses the static fuel pump through the fuel pump start bypass. The N_2H_4 then passes through the fuel pump outlet filter and the primary and secondary control valves and into the gas generator. Hydrazine is decomposed in the gas generator by exposure to a catalyst comprised of iridium coated alumina pellets. The hydrazine (N_2H_4) is disassociated into ammonia and nitrogen and subsequently into hydrogen and nitrogen. This gas is utilized to drive the turbine assembly. As turbine speed increases, the fuel pump output pressure increases, causing the start bypass to close. When this occurs, N_2H_4 is delivered only through the fuel pump. During startup operation, the turbine speed continues to increase until the speed reaches the control speed of the APU. At control speed, the primary control valve is energized closed on a signal generated through the APU controller. This stops N_2H_4 flow. With the N_2H_4 flow shut off, the turbine slows until control speed is again reached. At this control speed, a signal is generated through the controller to open the primary control valve. This restores N_2H_4 flow and the turbine speed increases until the sequence repeats. Control in this manner continues as long as power is applied to the APU.

Under normal operation, the APU turbine operated at 100% speed (72,000 rpm $\pm$8%) to meet hydraulic pump demands from 9 to 135 hp. Control under operation is provided by the primary control valve.

Under backup operation, the APU operates at 110% speed (79,200 rpm $\pm$8%) to meet hydraulic pump demands up to 151 hp. Backup operation is used if one APU is required to supply the hydraulic power for both actuators. Control under backup operation is provided by the primary control valve. The command to switch to backup operation is automatic within the controller.

If during either normal or backup operation the APU fails to control properly, the controller automatically switches from the primary control valve to the secondary control valve. Speed is then controlled at 112% speed (80,640 rpm $\pm$8%).

Hydraulic Pump: The TVC system hydraulic pump is a variable-delivery, pressure-compensated type that delivers hydraulic fluid to operate TVC system components. The hydraulic pump is attached to the APU gearbox mounting pad with the hydraulic pump shaft spline directly coupled to the gearbox spline. The APU drives the hydraulic pump at 3800 rpm $\pm$8% nominal speed to produce a full-flow pump output of 3050$\pm$50 psig at a rated flow of 55 gal/min. Hydraulic fluid from the hydraulic bootstrap reservoir is supplied to the hydraulic pump inlet at 55 to 65 psig (rated). During TVC system operation, the hydraulic pump runs continuously and provides a rated discharge pressure of 3200 $\pm$50 psig under low-flow conditions. When electrohydraulic gimballing is required, the hydraulic pump discharge pressure decreases to 3050 $\pm$50 psig and the variable delivery control positions the hydraulic pump hanger assembly to produce a flow of 55 gal/min within 80 ms. When hydraulic demand ceases, the discharge pressure rises to 3200 $\pm$50 psig, and the hanger assembly is repositioned to the low-flow condition. For the first 5 s of start, the depressurization solenoid valve is energized to allow the APU turbine to start up under minimum hydraulic pump pressure conditions (600-1000 psig).

Fluid Manifold Assembly: The fluid manifold assembly collects and distributes hydraulic fluid to the TVC system. The fluid manifold assembly permits filling and bleeding of the system and initial pressurization of the hydraulic bootstrap reservoir. The connecting lines vary in size from ¼ to 1½ in in diameter. The ¼ in. lines are 304L stainless steel. The remaining lines are titanium. Bulkhead fittings are utilized to interface with the manifold. The line fittings incorporate a metal-to-metal seal.

Electrohydraulic Servoactuator: The electrohydraulic servoactuator is dual acting and converts TVC system hydraulic fluid power into a linear motion for positioning the SRB nozzle in response to the Orbiter vehicle attitude control commands. The electrohydraulic servoactuator is hydraulically interconnected to each TVC fluid power module for operating redundancy if a failure occurs in either module. The electrohydraulic servoactuator is connected to the aft skirt attach point and the nozzle by spherical rod end bearings. The major parts of the electrohydraulic servoactuator consist of the following: power valve assembly, main actuator piston assembly, and negative piston position feedback mechanism.

Other vehicle attitude commands are transmitted to the electrohydraulic servoactuator as four electrical signals proportional to the desired main actuator piston displacement. Each signal positions a separate servovalve in the power valve assembly. Each servovalve controls a hydraulic control channel in the power valve assembly. The outputs of the four channels are force-summed to position the power valve to direct high pressure hydraulic fluid from the TVC hydraulic pump to the extend (or the retract) cylinder of the main actuator piston assembly and simultaneously to force hydraulic fluid from the opposing cylinder to the low pressure chamber of the fluid manifold assembly. The piston position feedback mechanism provides electrohydraulic servoactuator displacement output to each of the four servovalves to close the electrohydraulic servoactuator position control loop when the piston displacement corresponds to the desired position.

The electrohydraulic servoactuator extends or retracts 6.40 ± 0.03 in. from the null position at a piston rod velocity of approximately 6.4 in/s under rated load (63,348 lb). At maximum electrohydraulic servoactuator command under rated load, the minimum nozzle gimbal acceleration rate is 2 rad/s^2.

Fuel Isolation Valve: The normally closed fuel isolation valve insures positive isolation of the fuel in the FSM from the APU during nonoperational periods. The fuel isolation valve which remains closed during system ground operation and checkout, is electrically energized to the open position at system startup initiation, and returns to the normally closed position upon SRB separation from the Orbiter vehicle.

System Service Panels: Three service panels for each fluid power module facilitate TVC system ground servicing, checkout, and testing. These panels are accessible through cutouts in the aft skirt skin. Quick disconnects, manual valves, and bulkhead fittings, as appropriate, are installed on the service panels for performing the following TVC system operations: N_2H_4 fill and drain, gaseous nitrogen (GN_2) pressurization and purge, APU ground checkout with GN_2, hydraulics ground checkout with GSE, low-pressure relief valve venting, and postoperation servicing.

Hydraulic Bootstrap Reservoir: In each system, the hydraulic bootstrap reservoir stores a launch load of 2.1 gal of the total 7.3 gal of hydraulic fluid contained within the TVC system. During system operation, the hydraulic bootstrap reservoir supplies pressurized hydraulic fluid at 60 ± 5 psig to the inlet port of the hydraulic pump.

N_2H_4 Fuel Supply Module (FSM): The FSM is a stainless steel spherical pressure vessel that stores approximately 31.5 lb of liquid N_2H_4 fuel for the APU in each system. Approximately 1.1 lb of GN_2 at 400 psi is used to deliver the N_2H_4 to the APU fuel pump inlet. The FSM contains appropriate sumps, N_2H_4 feed and drain lines, GN_2 pressurization and purge lines, a 25-μ absolute fuel filter, pressure and temperature sensors, and antivortex motion control devices to inhibit GN_2 flow.

The FSM supplies pressurized N_2H_4 to the APU fuel pump at an initial, nominal working pressure of 400 psig at APU startup. The pressure decreases to approximately 300 psig during 160 s of operation.

Miscellaneous: In addition to the TVC system active components described in the preceding paragraphs, various passive components essential to subsystem operation are required: 1) tubing network for routing hydraulic fluid and N_2H_4 fuel between active components; 2) instrumentation for monitoring or controlling critical operating parameters; 3) wiring to provide SRB power or instrumentation signals to appropriate active components; and 4) ground service connections to facilitate performance of fill, bleed, drain, and purge operations and permit subsystem checkout with GSE.

Testing Status

The development of flight qualified hardware requires that a highly disciplined sequence be followed. In the early phases, development hardware is utilized to define conceptual problems. As the program matures, flight-type hardware is introduced and firm test requirements are imposed to insure upon test completion that flight-type hardware is comprehensively tested to flight requirements.

A summary of testing to date can be seen in Table 3. D-1 and D-2 are development tests. The remainder of the tests are part of the verification program. The V-3 TVC hardware was installed in the aft skirt and tested before being shipped. It was used to gimbal the motor in two SRM development test firings—DM-3 and DM-4 and qualification motor tests QM-1 and QM-2. The final test, QM-3, is scheduled for Feb. 1980. The V-2 test program consists of flight hardware mounted on a simulated skirt and connected to a mass simulator with a spring constant of 500,000 lb/in.

The first D-1 test was run July 15, 1976, with an Orbiter APU and most other components were off-the-shelf. This series of tests was very successful. The fuel pump had a small amount of degradation after each test. Lightning failed a pressure transducer on the gas generator. Both of these items gave insight to allow for early correction of the deficiencies.

The D-2 testing was performed on the TVC system between May and Aug. 1977. During this program, development

Table 3 TVC test summary

	Hot firing, s (starts)	GN_2 spins, s (starts)
	System A[a]	
Development		
D-1	2971 (30)	2046 (16)
D-2	1883 (18)	629 (3)
Verification		
V-2	15,696 (114)	14,733 (80)
V-3	1377 (11)	1065 (9)
DM-3 & 4, QM-1 & 2	630 (4)	480 (4)
	System B[b]	
Development		
D-2	3292 (32)	1255 (9)
Verification		
V-2	15,613 (114)	14,111 (66)
V-3	1397 (10)	929 (9)
DM-3 & 4, QM-1 & 2	630 (4)	480 (4)

Total hot firing = 43,489 s
Starts = 337
GN_2 spin = 35,728 s

[a] System A is designated the Rock System.
[b] System B is designated the Tilt System.

hardware of flight configuration was employed for the first time. During these tests, a load bank was used and later a Space Shuttle main engine (SSME) actuator (free stroking with no mass on the end) was used. This hardware performed in accordance with the design criteria.

The important objectives that were confirmed from this test series are summarized as follows: 1) demonstration of maximum APU horsepower at 100 and 110% speed; 2) demonstration of vehicle gimbal system requirements using unloaded actuator; 3) verification of pump to actuator pressure drops at various flow rates; 4) demonstration of contaminant holding capability of the TVC system filters for multimission operation; 5) demonstration of off-nominal operation of the system with considerable success (low voltage, low reservoir level, and internal fluid leak); 6) acquisition of fuel consumption data that verifies the FSM propellant load and pressure setting; and 7) the hydraulic and hydrazine servicing procedures were demonstrated and improved during this program. Lube oil level sensitivity was noted. Procedures for spinning the APU with GN_2 were demonstrated. The D-2 testing gave confidence for building the flight hardware.

The V-2 and V-3 testing comprise the formal qualification program. These tests were started in Nov. 1977, and were completed Sept. 1979. Thus far in the test series, Systems A and B have over 35,000 s of hot firings and 257 starts. The important objectives that were confirmed from this test series are summarized as follows: 1) systems performance with loaded actuators, 2) system redundancy, 3) servicing procedures, 4) specific fuel consumption, 5) structural adequacy, and 6) off-nominal conditions.

The testing, including the DM-3 and DM-4 and three qualification motors, is the best test representation relative to the flight configuration.

Conclusions

The solid rocket booster thrust vector control system has been designed, developed, and qualified for Space Shuttle flight. Initial guidelines regarding simplicity, low cost per flight, reusability and high reliability have been proven. Common Shuttle-hardware was successfully modified for the solid rocket boosters. The system for the first Shuttle flight has been assembled, hot-fired, and prepared for flight.

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TURBULENT COMBUSTION—v. 58

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Practical combustion systems are almost all based on turbulent combustion, as distinct from the more elementary processes (more academically appealing) of laminar or even stationary combustion. A practical combustor, whether employed in a power generating plant, in an automobile engine, in an aircraft jet engine, or whatever, requires a large and fast mass flow or throughput in order to meet useful specifications. The impetus for the study of turbulent combustion is therefore strong.

In spite of this, our understanding of turbulent combustion processes, that is, more specifically the interplay of fast oxidative chemical reactions, strong transport fluxes of heat and mass, and intense fluid-mechanical turbulence, is still incomplete. In the last few years, two strong forces have emerged that now compel research scientists to attack the subject of turbulent combustion anew. One is the development of novel instrumental techniques that permit rather precise nonintrusive measurement of reactant concentrations, turbulent velocity fluctuations, temperatures, etc., generally by optical means using laser beams. The other is the compelling demand to solve hitherto bypassed problems such as identifying the mechanisms responsible for the production of the minor compounds labeled pollutants and discovering ways to reduce such emissions.

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