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SPACE TRANSPORTATION SYSTEM SOLID ROCKET BOOSTER THRUST VECTOR CONTROL SYSTEM

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16. ABSTRACT

The Solid Rocket Booster, Thrust Vector Control (TVC) 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 (APU) 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 APU. These systems must withstand the imposed environment and be usable for a minimum of 20 Space Transportation System flights with a minimum of refurbishment. The TVC system has completed the required qualification and verification tests and is certified for the intended application. Substantiation data will include analytical and test data.

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TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

TECHNICAL MEMORANDUM

SPACE TRANSPORTATION SYSTEM SOLID ROCKET BOOSTER THRUST VECTOR CONTROL SYSTEM

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 engine will fire in parallel at lift off. 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 Thrust Vector Control (TVC) 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 report deals specifically with the TVC system on the SRB's (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 latter system was baselined.

In the fall of 1974 timeframe, another study was initiated utilizing a hydrazine powered APU that Rockwell International had under development for the Space Shuttle Orbiter. Pertinent parameters of the Orbiter system compared to SRB were as follows:

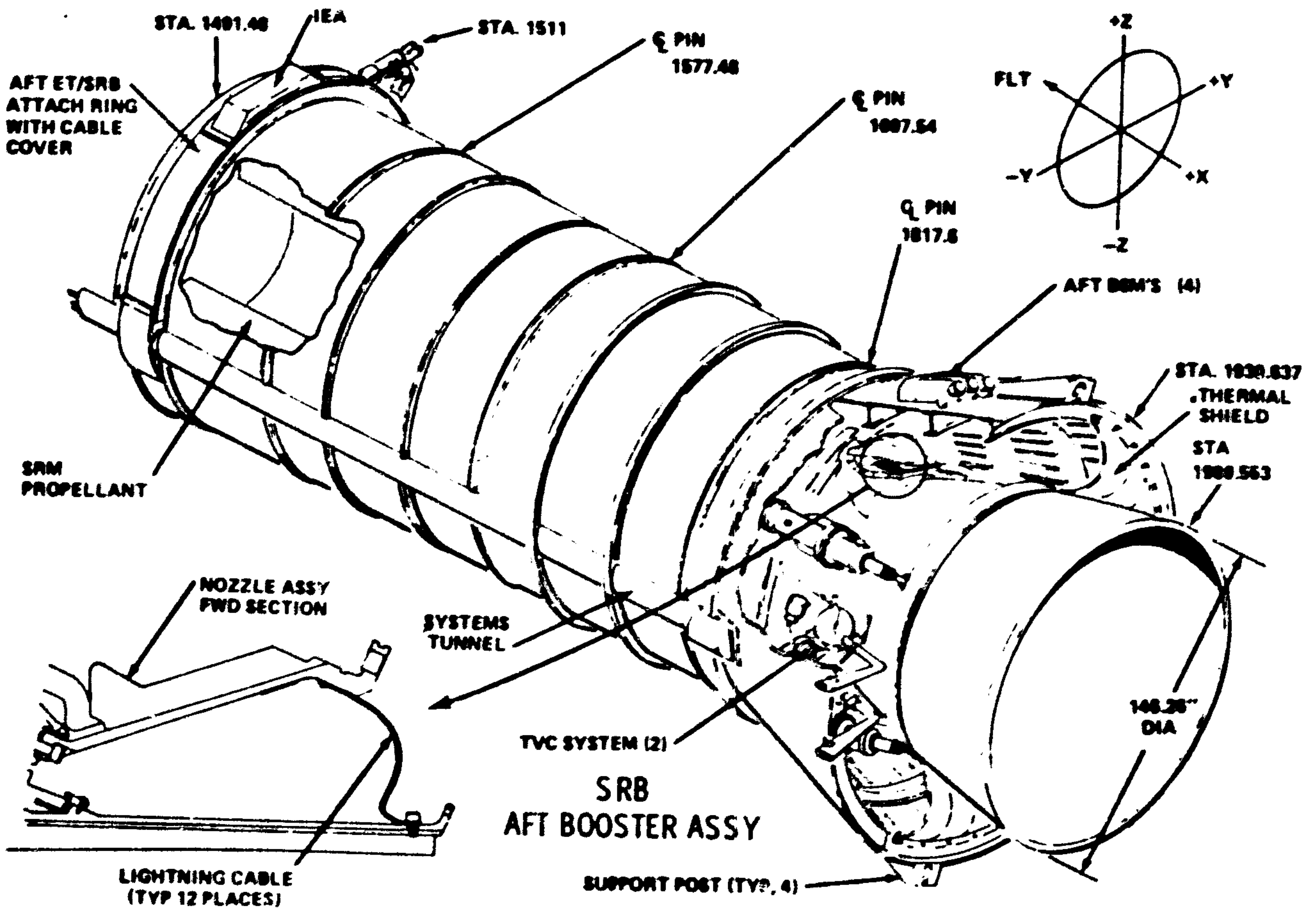

Figure 1. TVC system on the SRB.

Requirements

	Orbiter	SRB
Torque (10^6 in.-lb)	1.1, 1.4	4.5
Moment Arm (in.)	30	64
Gimbal Angle (deg)	±10.5 ±8.5	±5.0
Actuator Area (in.^{2})	25, 20	36.4
Slew Rate (deg/sec)	10	5
System Pressure (lb/in.^{2})	3,000	3,000
HPU Pad HP	135/150*	118/165
System HP (Pump)	112/124*	97/139
HPU		
Mission Time (min)	74	2.4
Missions	40	20
Salt Water Immersion	No	Yes
All Attitude Operation	Yes	No
Operating Time (hr)	50	2
Useful Life (hr)	250	10
Pump		
Flow Rate Maximum (gpm)	63/71*	55/79
Displacement (in^3/rev)	4.3	4.3
Rated Speed (rpm)	3,600/4,000*	4,000

Environment Comparison

	Orbiter	SRB
Vibration		
Lift-Off	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
Shock		
Landing	1.5 g (260 sec)	Water Impact 40 g's (140M/sec) Longitudinal 45 g's (100M/sec) Lateral
Acceleration		
Ascent	3.3 g's	3.3 g's
Impact Water Pressure		110 psia

*110%

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 percent.

DESCRIPTION OF SYSTEM

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. Figure 2 shows 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° outboard to the vehicle pitch and yaw axes.

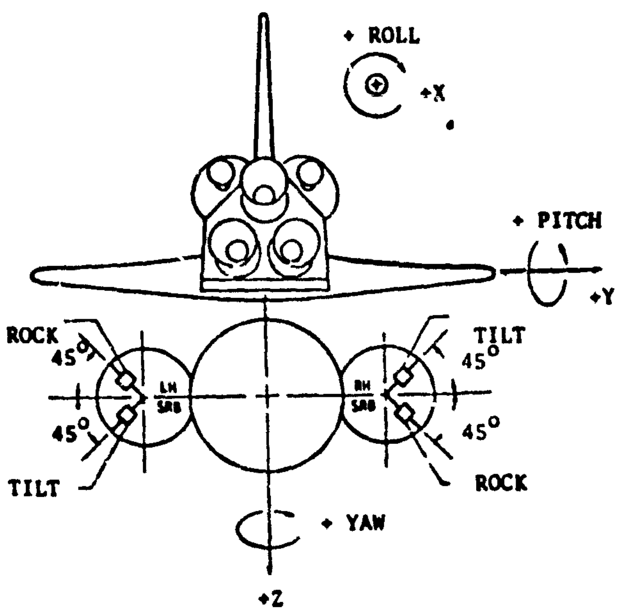

Figure 2. Rock and tilt.

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. Other requirements are shown below.

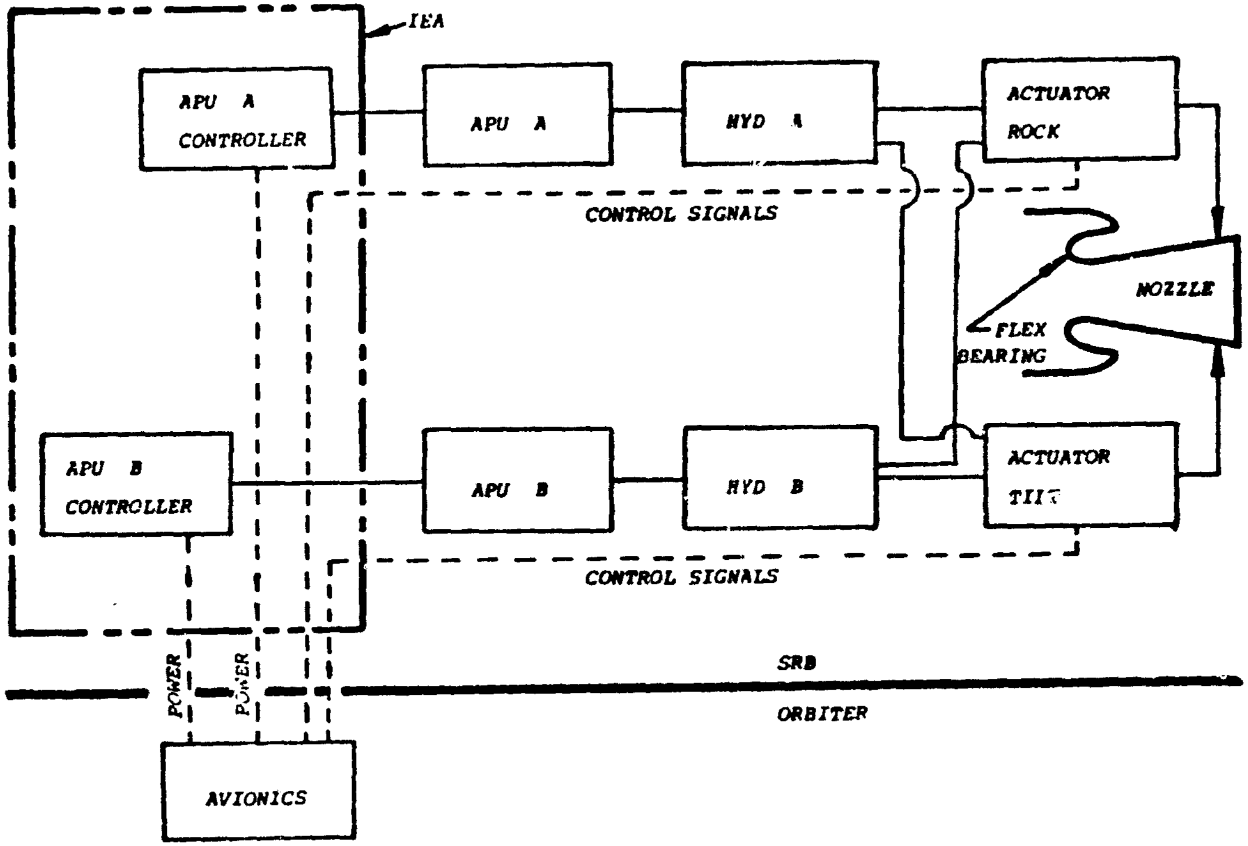

Figure 3. TVC system schematic.

DESIGN REQUIREMENTS

SRB TVC System

1) Torque - 4.2×10^6 in./lb
2) Motor Gimbal Rate - 5.0 deg/sec/axis
3) Redundancy - Fail-Safe
4) Motor Gimbal Rate (Fail-Safe) - 3.0 deg/sec/axis
5) Reusable (withstand water impact loads)

SRB Hydraulic Power Unit

1) APU Speed - 100/110 percent
2) APU HP - 114/148
3) System Pressure (HYD) - 3,000 psig
4) Hydraulic Fluid Flow Rate (max) - 55/71 gpm
5) Mission Time - 166 sec (including one 20-sec recycle)
6) Missions (uses) - 20

TVC PHYSICAL ARRANGEMENT

Hydraulic power for each SRB is required. Each actuator is supplied with power by the fluid power modules. Each fluid power module consists of an upper panel, lower panel, and overboard exhaust as shown in Figure 4. The components mounted to the upper panel are as follows:

1) Auxiliary Power Unit (APU)

2) Hydraulic Pump (mounted to the APU)

3) Fluid Manifold Assembly

4) Hydraulic Fluid Check Valve and Filter Assembly

5) Fuel Isolation Valve

6) System Service Panels

7) Instrumentation and Wiring

8) Interconnecting Tubing

The components mounted to the lower panel are as follows:

1) Hydraulic Bootstrap Reservoir

2) N_2H_4 Fuel Supply Module (FSM), including fuel filter

3) Instrumentation and Wiring

4) Interconnecting Tubing

The overboard exhaust components are as follows:

1) Upper Duct Assembly

2) Lower Duct Assembly

3) 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 TVC system's major component is presented in the following paragraphs.

APU - The APU (Fig. 4) provides mechanical shaft power to the hydraulic pump. The principal parts of the APU are:

1) Integral Fuel Pump

2) Gas Generator

3) Dual Pass, Reentry Turbine

4) Gearbox

5) Control System

6) Primary Control Valve (normally open)

7) Secondary Control Valve (normally closed)

8) 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.

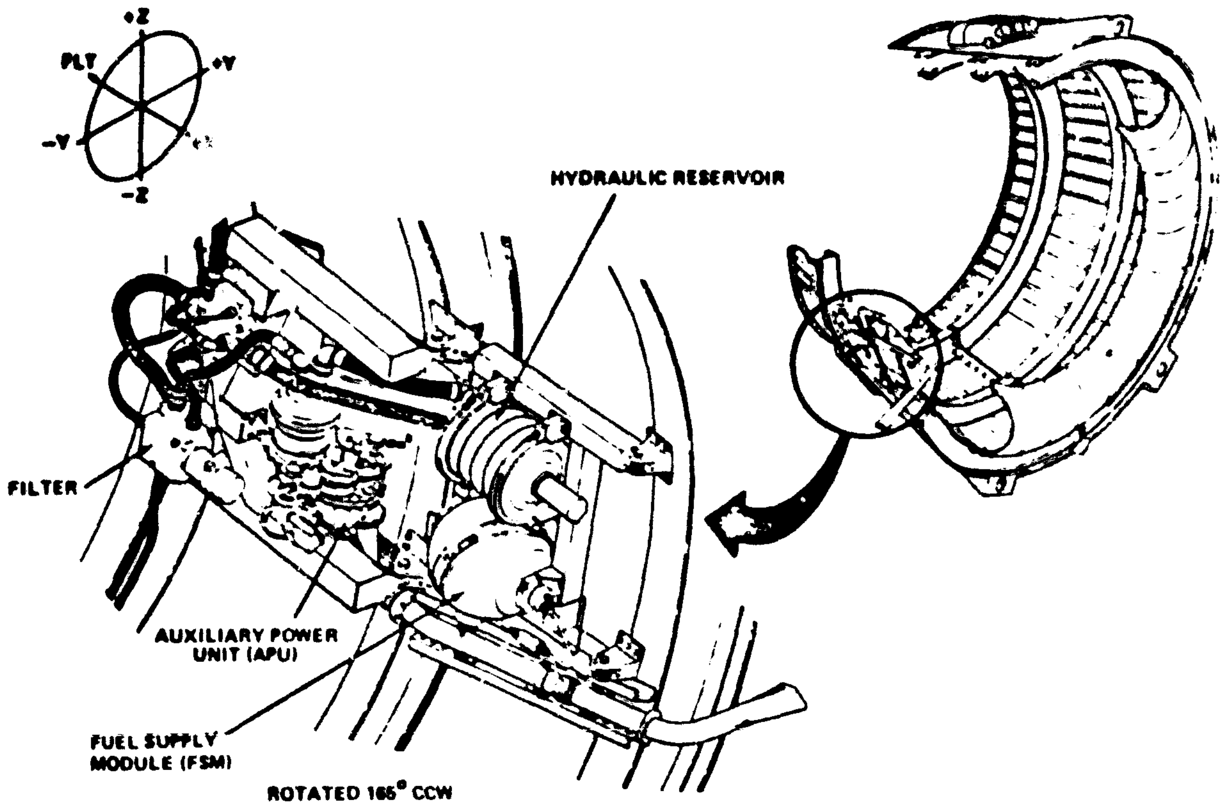

Figure 4. SRB TVC in aft skirt.

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. 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 the 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 above sequence repeats. Control in this manner continues as long as power is applied to the APU.

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

Under backup operation, the APU operates to 110 percent speed (79,200 rpm ± 8 percent) to meet hydraulic pump demands up to 148 hp. Backup operation is used if one HPU 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 percent speed (80,640 rpm ± 8 percent).

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 3,800 rpm ± 5 percent nominal speed to produce a full flow pump output of 3,050 ± 50 psig at a rated flow of 55 gpm. 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 3,200 ± 50 psig under no flow conditions. When electro-hydraulic gimballing is required, the hydraulic pump discharge pressure decreases to 3,050 ± 50 psig and the variable delivery control positions the hydraulic pump hanger assembly to produce a flow of 55 gpm within 80 msec. When hydraulic demand ceases, the discharge pressure rises to 3,200 ± 50 psig, and the hanger assembly is repositioned to the no flow condition. For the first 4 seconds of start, the depressurization solenoid valve is energized to allow the APU turbine to start up under minimum hydraulic pump pressure conditions (600 to 1,000 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.

Electro-Hydraulic Servoactuator - The electrohydraulic actuator 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 electro-hydraulic servoactuator is hydraulically interconnected to each TVC fluid power module for operating redundancy if a failure occurs in either module. The electro-hydraulic servoactuator is connected to the aft skirt attach point and the nozzle by spherical rod end bearings.

The major parts of the electro-hydraulic servoactuator consist of:

1) Power Valve Assembly

2) Main Actuator Piston Assembly

3) Negative Piston Position Feedback Mechanism

Orbiter vehicle attitude commands are transmitted to the electro-hydraulic 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 (HP) 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 (LP) chamber of the fluid manifold assembly. The piston position feedback mechanism provides electro-hydraulic servo-actuator displacement output to each of the four servovalves to close the electro-hydraulic servoactuator position control loop when the piston displacement corresponds to the desired position.

The electro-hydraulic servoactuator extends or retracts 6.40 ± 0.03 in. from the null position at a piston rod velocity of approximately 5.95 in./sec under rated load (63,348 lb). At maximum electro-hydraulic servoactuator command under rated load, the minimum nozzle gimbal acceleration rate is 2 rad/sec^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 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:

1) N_2H_4 Fill and Drain

2) Gaseous Nitrogen (GH_2) Pressurization and Purge

3) APU Ground Checkout with GN_2

4) Hydraulics Ground Checkout with GSE

5) LP Relief Valve Venting

6) Post-Operation Servicing.

Hydraulic Bootstrap Reservoir - In each system, the hydraulic bootstrap reservoir stores a launch load of 2.1 gallons of the total 5.3 gallons 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 - The FSM is a spherical pressure vessel that stores approximately 31.5 lbs 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 micron absolute fuel filter, pressure and temperature sensors, and anti vortex 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 260 psig during 160 sec 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.

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 adhered to, 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 the following table. D-1 and D-2 are development tests. The remainder of the tests is part of the verification program. The V-3 TVC hardware was installed in the aft skirt and tested at MSFC before being shipped to Thiokol to be used to gimbal the motor in two SRM development test firings -- DM-3 and DM-4 and will be used in qualification motor tests QM-1 through QM-3. The V-2 testing is the program at MSFC consisting of the flight hardware mounted on a simulated skirt and connected to a mass simulator with a spring constant of 500,000 lb/in.

TABLE 1. TVC TEST SUMMARY

	Hot Firing Secs (Starts)	GN_2 Spins Secs (Starts)
System A		
Development		
D-1	2,971 (30)	2,046 (17)
D-2	1,883 (18)	629 (3)
Verification		
V-2	15,696 (114)	14,733 (80)
V-3	1,687 (13)	1,305 (11)
DM-3 & 4	790 (5)	600 (5)
	23,027 (180)	19,313 (116)
System B		
Development		
D-1		
D-2	3,292 (32)	1,255 (9)
Verification		
V-2	15,613 (114)	14,111 (66)
V-3	1,707 (12)	1,169 (11)
DM-3 & 4	790 (5)	600 (5)
	21,402 (134)	17,135 (91)

Total Hot Firing (secs) - 44,429
Starts - 314
GN_2 Spin (secs) - 36,448

The first D-1 test was run July 15, 1976, with an Orbiter APU, and all other components were off-the-shelf or manufactured at MSFC. This series of tests was very successful. The fuel pump had a small amount of degradation, 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 August 1977. During this program, development hardware of flight configuration was employed for the first time. During these tests, a load bank was used and later an SSME actuator (free stroking with no mass on the end) was used. This hardware performed in accordance with the design criteria.

The important objectives t[illegible] ere confirmed from this test series are summarized below:

1) Demonstration of maximum APU hp at 100 percent and 110 percent speed.

2) Demonstration of Level II gimbal system requirements using unloaded actuator.

3) Verification of pump to actuator pressure drops at various flow rates.

4) Demonstrated contaminant holding capability of the TVC system filters for multimission operation.

5) Demonstrated off-nominal operation of the system with considerable success (low voltage, low reservoir level, and internal fluid leak).

6) Obtaining fuel consumption data that verifies the present FSM propellant load and pressure setting.

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, comprised the formal qualification program. These tests were started in November 1977, and will be completed June 1979. Thus far in the test series, systems A and B have over 9,000 seconds of hot firings and 68 starts. The important objectives that were confirmed from this test series are summarized below:

1) Systems performance with loaded actuators

2) System redundancy

3) Servicing procedures

4) Specific fuel consumption

5) Structural adequacy

6) Off-nominal conditions.

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

SUMMARY

The Solid Rocket Booster, Thrust Vector Control System evolved from detailed trade studies with firm guidelines regarding simplicity, low cost per flight, reusability, and high reliability. Common Space Shuttle hardware was utilized where practical, and the remaining components were developed specifically for the Solid Rocket Booster.

The program progressed through design, development, and qualification with a minimum of problems because a significant amount of personal attention was focused on sensitive areas from the beginning.

The system has completed all required testing and is certified for flight.

The first flight system for STS-1 is currently being assembled at Kennedy Space Center.

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APPROVAL

SPACE TRANSPORTATION SYSTEM SOLID ROCKET BOOSTER THRUST VECTOR CONTROL SYSTEM

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The information in this report has been reviewed for technical content. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

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