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Volume I

FINAL REPORT SUMMARY

THRUST VECTOR CONTROL (TVC) SYSTEM STUDY PROGRAM

Thiokol
CHEMICAL CORPORATION
WASATCH DIVISION

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VOLUME I - THRUST VECTOR CONTROL (TVC) SYSTEM STUDY PROGRAM

Thiokol Chemical Corporation

NASA CR-72727
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ADDENDUM 1

FINAL REPORT SUMMARY

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THIOKOL CHEMICAL CORPORATION
WASATCH DIVISION
Brigham City, Utah 84302

Prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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NASA LEWIS RESEARCH CENTER
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Solid Rocket Technology Branch
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FINAL REPORT SUMMARY

THRUST VECTOR CONTROL (TVC) SYSTEM STUDY PROGRAM

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Brigham City, Utah

FOREWORD

The Thrust Vector Control Study Program described herein was conducted by Thiokol Chemical Corporation, Wasatch Division under NASA Contract NAS3-12040 Mr James Pelouch, Solid Rocket Technology Branch, Chemical Rocket Division, NASA Lewis Research Center, was the project manager

ABSTRACT

During the period 3 Jun 1969 to 15 Jun 1970, a program was conducted to study various techniques that could be used for thrust vector control (TVC) on the 260 in (6.6 m) solid rocket booster of a MLV-SAT-1B-5A two stage launch vehicle This study was structured such that three major categories of TVC were considered liquid injection thrust vector control, movable nozzle flexible seal and mechanical exhaust jet interference systems.

Of all the techniques considered, two were selected as the most promising and were subjected to a detailed design and cost analysis with the object of developing a low cost, high reliability system

One of these two systems was a cold gas blowdown nitrogen tetroxide liquid injection TVC system with 16 electromechanical injector valves The other technique selected was a passive cold gas blowdown movable nozzle flexible seal system with hydraulic actuators

On the basis of cost, weight, and relative simplicity, the movable nozzle flexible seal system is the superior approach.

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1. SUMMARY

This document summarizes the final report prepared under NASA Contract NAS3-12040 for Thrust Vector Control (TVC) Study. The program objective was to compare the design of several booster TVC systems for use on the 260 in (6.6 m) solid rocket motor similar to the First Stage of the MLV-SAT-1B-5A two stage vehicle. Techniques considered for thrust vector control included liquid injection, movable nozzle flexible seal, and mechanical exhaust jet interference methods. The technical effort included the following three primary tasks.

1.1 Preliminary Design (Task 1)

Within each of the above mentioned TVC categories, several design variations were screened in order to select the most promising designs for more detailed effort. In the liquid injection TVC (LITVC) category, eight different configurations were selected for additional preliminary design work Of these, a cold gas blowdown, nitrogen tetroxide injectant system with 16 electromechanical injector valves was chosen as the design to be optimized in the detailed design task Similarly, several movable nozzle flexible seal design variations were analyzed in the preliminary design task, and as the result of extensive screening, a cold gas passive blowdown system with hydraulic actuators was selected for design optimization in the detailed design task Mechanical exhaust jet interference designs considered in this task included mechanical probes, jetavators, jet tabs, supersonic splitline, flexible exit cone (Flex-X) and jet vanes. A jet tab design was chosen as the best design in this category, but further detailed design effort was cancelled because of its obvious inferiority to the designs chosen in the other two categories

1.2 Detailed Design (Task 2)

The selected LITVC and movable nozzle designs were subjected to sufficient detail to enable accurate sizing of components. From the detailed layout drawings, planning documents were prepared to define reasonable manufacturing, inspection, and test requirements to develop and produce the designs.

1.3 Cost Analysis (Task 3)

The planning and designs prepared in Task 2 were used to prepare cost estimates for the development and production of the two TVC systems The results of this analysis indicate that the movable nozzle flexible seal system is less expensive on a production unit cost basis and from a long term system development and production standpoint.

Although a complete system tradeoff study was not conducted, it is concluded that the movable nozzle flexible seal TVC system is superior from a cost, weight, and relative simplicity point of view.

2. INTRODUCTION

Large solid propellant booster studies funded by the National Aeronautics and Space Administration have shown that as the size of the solid motor booster increases, the steering requirement generally decreases The magnitude of the thrust vector deflection angle (percent of side thrust required for steering) and its time rate of change required to maintain vehicle control during booster operation could therefore be decreased to reduce cost and complexity and improve reliability of the system.

This program was conducted during the period of June 1969 to June 1970 to study various thrust vector control (TVC) systems using the NASA-furnished reduced steering requirements for the 260 in (6.6 m) motor booster (MLV-SAT-IB-5A two stage vehicle). Emphasis was placed on low cost, simplicity, and increased reliability for optimization of each TVC system.

Three major TVC categories were studied liquid injection, movable nozzle flexible seal, and mechanical exhaust jet interference methods Selection of the two most promising, namely, liquid injection and movable nozzle, were subjected to a detailed design and cost analysis with the objective being development of a low cost, highly reliable system

3. BASELINE NOZZLE DESIGNS

3.1 Baseline Fixed Nozzle

The baseline fixed nozzle design, provided by NASA LeRC, was a fixed, external, convergent-divergent nozzle with an initial expansion ratio of 8 515, an initial throat diameter of 89.1 in (226 31 cm), a half angle of 17.5° (3.27 rad), and an exit diameter of 260 0 in (6 6 m) The basic nozzle weight was 47,901 lb (21,728.45 kg) The nozzle used as a baseline for all liquid injection and mechanical interference TVC designs is shown in Figure 1

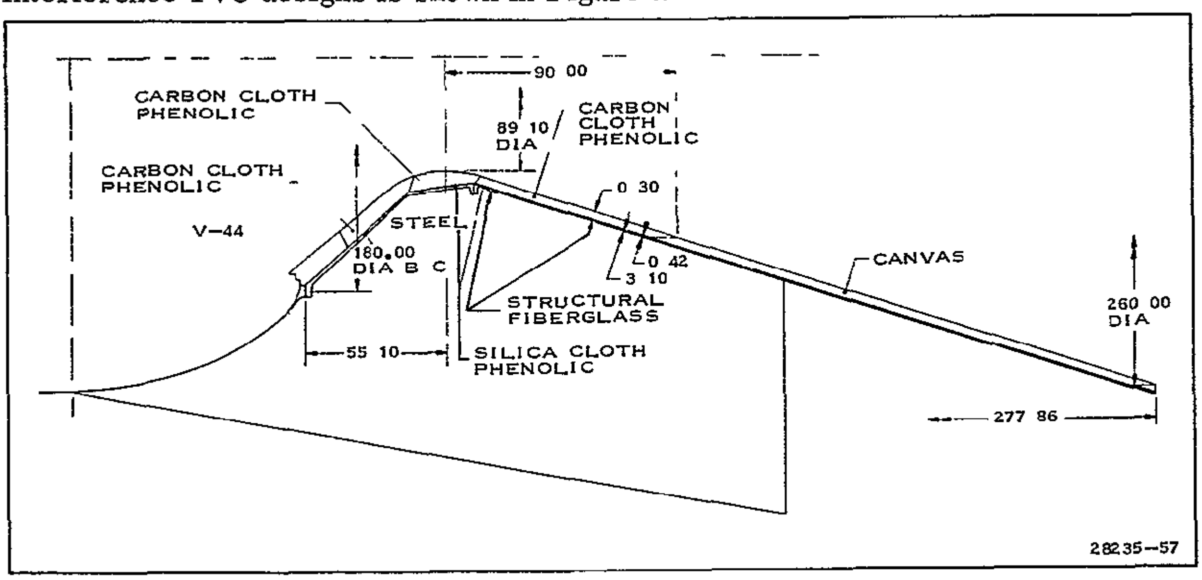

Figure 1. Baseline Fixed Nozzle

3 2 Baseline Flexible Seal Nozzles

3.2 1 Thiokol Baseline Flexible Seal Nozzle--The Thiokol baseline movable nozzles had the same design constraints as the fixed nozzles except that the distance between the aft closure interface and the nozzle throat was 27.00 in (68.58 cm) instead of 55.10 in (139 95 cm). Materials and thicknesses closely approximated those of the Aerojet design to establish a valid basis for comparison. For the movable nozzles this included rubber mastic as the entrance structural shell insulation, 5 70 in (14 478 cm) at the aft closure mounting flange, decreasing to 3 5 in (8 89 cm) thick at the splitline, canvas cloth phenolic as the chamber side insulation of the submerged portion of the nozzle, 3 20 in (8.128 cm) thick, and carbon cloth phenolic, 0 42 in (1.067 cm) thick, was used to back up all insulation except the rubber mastic in the entrance structural shell. The Thiokol movable nozzle incorporated a forward pivoted, near-conical flexible seal with folding protective boot The flex seal consisted of 36 alloy steel spherical shims 0 071 in (0 18 cm) thick and 37 elastomer layers 0 021 in (0.053 cm) thick. The pivot point was located 53.9 in. (136.91 cm) forward of the nozzle throat The flex seal was optimized for minimum system (the combination of nozzle and actuator weights) weight by means of Thiokol's advanced TVC computer program. Nozzle assembly weight was 54,025 lb (25,886 kg) including 37,107 lb (16,847 kg) insulation and 16,918 lb (7,681 kg) structure. The fixed section weighed 8,359 lb (3,795 kg) while the movable section weighed 45,666 lb (20,732 kg). Preliminary actuation system torque requirements were 16.27 million in.-lb (1 86 x 10^5 N-m).

3.2.2 Aerojet Baseline Flexible Seal Nozzle--The Aerojet baseline movable nozzles (Figure 2) had the same design constraints as the fixed nozzles Using the computer program, the Aerojet design was duplicated to obtain weight and torque estimates. The nozzle and seal design (provided by NASA LeRC) incorporated a forward pivoted cylindrical flex seal with folding protective boot. The seal core consists of four alloy steel conical shims, each 0.70 in. (1.78 cm) thick and five layers of elastomer, each 0.30 in. (0.76 cm) thick. The pivot point location was 60 5 in (153.67 cm) forward of the throat. The total Aerojet nozzle assembly weight was calculated to be 56,298 lb (25,559 kg). This weight included 36,262 lb (16,463 kg) insulation and 20,036 lb (9,096 kg) structure. The movable section weighed 47,398 lb (21,519 kg) and the fixed section weighed 8,899 lb (4,040 kg). The total actuation system torque requirements were 17.88 million in.-lb (2.06 x 10^5 N-m).

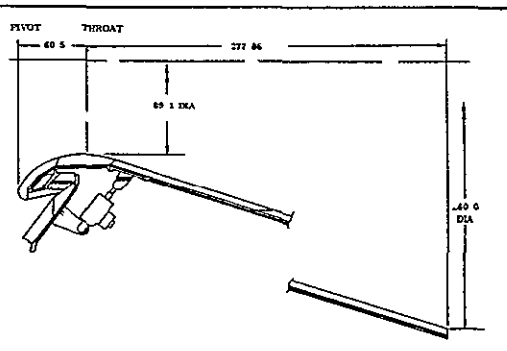

Figure 2. Aerojet Baseline Flexible Seal Nozzle

4. LITVC SYSTEM STUDIES

The objectives of the LITVC system design studies for application to a 260 in solid rocket motor of a MLV-SAT-1B-5A vehicle were to (1) investigate liquid injection parameters and system components, (2) compare potential design approaches, (3) select candidate designs, and (4) select the design approach for a detailed design analysis

The LITVC system design requirements used in this study are presented in Table I.

The following discussions include (1) a summary of the LITVC literature search, (2) design analyses (parametric and component) performed, (3) candidate LITVC system evaluation tradeoff, (4) selection of the best LITVC system design approach, and (5) a description of the final LITVC system design.

4.1 LITVC Literature Search

The literature search revealed that although previous 260 in LITVC studies were conducted with different design requirements (higher vector angle, lower injection impulse), the system designs were comparable to the design finalized in this study program.

The 260 in SRM LITVC system studies conducted by Douglas Missile and Space Systems Division under Contracts NAS8-20242 and NAS8-21051 were reviewed in depth. Table II gives a summary of the Douglas 260 in LITVC system weights

4.2 LITVC System Design Analysis

Numerous investigations have been made in an attempt to arrive at an analytical solution which could accurately predict LITVC performance The results of these works are inconclusive, and to date, a standard LITVC analytical procedure has not been developed. The main approach in establishing LITVC system design parameters has been to acquire experimental data and available information of various injectants, injection parameters, and LITVC system components from previously conducted test and study programs. This procedure was utilized extensively throughout the 260 in. SRM LITVC system tradeoff studies. Other basic ground rules included minimum weight, cost, development effort and simplicity.

4.2.1 Liquid Injectant Selection Procedure--Thiokol's IBM Computer Program for Design of a LITVC System was used to establish preliminary design data of the size and weight of LITVC systems using each of the candidate injectants for the established system requirements. The computer program calculated the amount of duty cycle injectant, total amount of onboard injectant required, and the maximum required injectant flow rate. The computer program also was used to calculate the size and weight of actuation and pressurization subsystems, tankage, injector valves, power supply components, liquid and gas lines, plus the weights of hydraulic fluid, disconnects, filters, electrical cabling, brackets, and fittings.

TABLE I

LITVC SYSTEM DESIGN REQUIREMENTS

	English Units	SI Units
Total injection impulse	60 deg-sec	1 047 rad-sec
Pitch and yaw assumes a 25 deg (0 437 rad) thrust misalignment throughout entire flight		
Total injection impulse	6 287 x 10^6 lbf-sec	27,965,000 N-sec
Maximum required equivalent thrust vector angle each, pitch and yaw	1 2 deg	0 021 rad
Maximum required equivalent slew rate	3 deg/sec	0 0524 rad/sec
Average thrust deflection angle of duty cycle, 60 deg-sec/143 sec	0 42 deg	0 0073 rad
Average side force	43,965 lbf	196,000 N
Ratio of control thrust impulse to total vehicle vacuum thrust impulse	0 727%	0 727%

TABLE II

DOUGLAS LITVC SYSTEM WEIGHTS

Component	Phase II		Revised Phase II*		Simplified	
	(lb)	(kg)	(lb)	(kg)	(lb)	(kg)
Injectant tanks	3,280	1,488	2 404	1,090	3,560	1 614
N_2O_4	25,850	11,730	25 850	11,730	28,367	12,867
Helium gas	147	66 7	147	66 7	183	83 0
Tank mounts	202	91 6	202	91 6	202	91 6
Manifold	1,650	748 4	852	386 5	852	386 5
Injectant valves	1,020	462 7	1,020	462 7	876	397 4
Fill and vent modules	15	6 8	15	6 8	15	6 8
Lines and fittings	197	89 4	197	89 4	197	89 4
Contingencies	636	288 5	469	212 7	570	258 6
Electronics	204	92 5	204	92 5	190	86 2
Totals	33,201	15,060	31,360	14,225	35,012	15,922

*Revised weight figures used for performance calculations and in the TVC comparison

For the determination of the amount of duty cycle injectant required, the side specific impulse (Isp_s) for each injectant corresponding to 0.42° (0.0073 rad) thrust vector was utilized (Figure 3) The Isp_s for each injectant corresponding to 1.2° (0.021 rad) thrust vector (Figure 4) was used to calculate the maximum injectant flow rate required per injector port Due to the higher performance (more side force generated per unit of injectant), the maximum injectant flow rate required per injection port and number of ports per quadrant (Figure 5) was considerably less with N_2O_4 than with the other injectants

For this weight study, a representative injectant tankage and pressurization system consisting of two toroidal tanks was selected. One tank contained the injectant, the other contained nitrogen gas initially charged at 3,000 psi (20,684,400 N/m^2) and then regulated to maintain a constant injectant tank pressure of 600 psi (4,136,880 N/m^2) An electrohydraulic actuation system and 20 equally spaced single pintle-type injectors also were selected For these weight tradeoff studies, it was felt that representative LITVC system weight comparisons could be made.

Using the N_2O_4 LITVC system weight (35,180 lbm or 15,958 kg) as a baseline factor, the computer program results of the initial LITVC system launch weights (nozzle excluded) are compared below

LITVC System	Weight Factor
Nitrogen tetroxide, N_2O_4	1.00
Aqueous strontium perchlorate, $Sr(ClO_4)_2 + H_2O$	1.35
Aqueous lead perchlorate, $Pb(ClO_4)_2 + H_2O$	1.55
Freon 114B2	2 01
Freon 113	2 03
Hydrazine, N_2H_4	2.13

Each LITVC system was similar in all respects except for the type of liquid injectant used As a result of the initial LITVC system weight tradeoffs, nitrogen tetroxide (N_2O_4) and aqueous strontium perchlorate [$Sr(ClO_4)_2 + H_2O$] injectants were selected for more detailed LITVC system design work.

4.2.2 Investigation of Injection Parameters--

4.2.2.1 Effective Point of Side Force Reaction--Insufficient nozzle wall pressure data are available to make an accurate analysis of the effective point of side force reaction on an LITVC system. Since the reaction point is somewhere downstream of the injector, probably within a matter of inches, it was felt that a conservative, simplifying, assumption could be made, ie, the reaction point is at the point of injection. The assumption is conservative in that if the point of application of the thrust vector is further aft on the nozzle, greater moments would be applied to the vehicle.

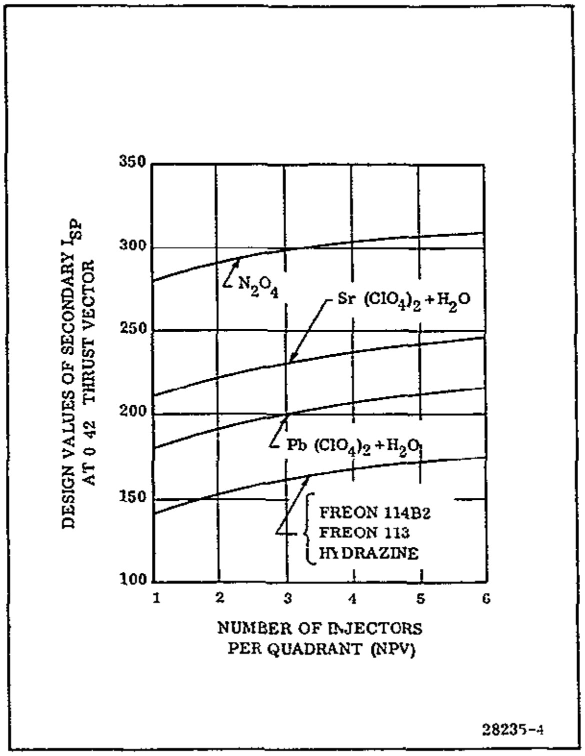

Figure 3. Injectant Performance at Avg Thrust Vector Angle

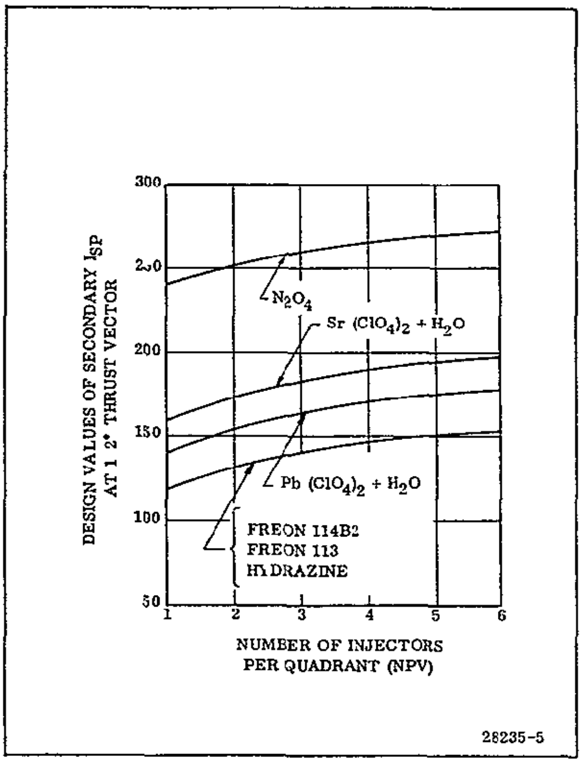

Figure 4. Injectant Performance at Max Thrust Vector Angle

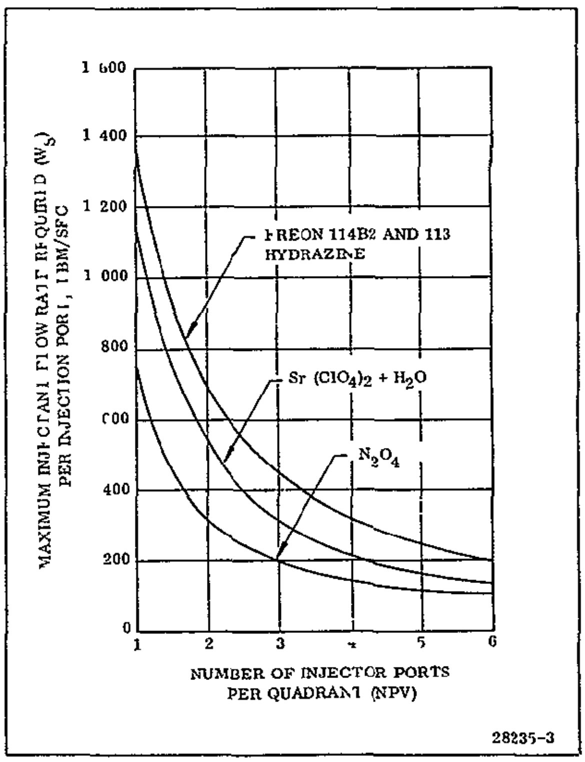

Figure 5 Max Injectant $\dot{W}_S$ per Injector Port vs No. of Ports per Quadrant

The above assumes that the reaction point is at the point of injection for all secondary-to-primary weight flow ratios, ie, for all jet deflection angles

4.2.2 2 Injection Location and Angle--Empirical data indicate that a nominal injection location exists on any nozzle that gives a high level of side force efficiency during liquid injection This optimum injection location seems to be dependent primarily upon the x/L ratio, ie, the axial distance from the nozzle throat to the injection plane (x) divided by the axial distance from the nozzle throat to the nozzle exit plane (L).

Existing data indicate that, as the thrust vector angle increases from 1° to 4° (0.01745 rad to 0 0698 rad), the point of injection for optimum performance moves from approximately an x/L location of 0.35 to 0.45 An x/L ratio of 0.35 and an injection angle of 15° (0.262 rad) were used for the designs in this study.

4.2.3 Evaluation of LITVC Components--

4.2.3.1 Liquid Injector Valves and Actuation Methods--The basic types of liquid injector valves investigated included the constant area injector and the variable area injector. As the result of its demonstrated reliability, the variable area (pintle-type) injector was selected for use in the LITVC system designs. Consideration was given to both electrohydraulic and electromechanical actuation of the injector valves.

4.2.3.2 Pressurization Concepts--Three basic types of pressurization techniques were considered for the 260 in motor LITVC system (1) warm gas using a solid propellant gas generator, (2) cold gas pressure regulated, and (3) cold gas pressure blowdown. A cold gas blowdown system was selected as the most promising concept

Several potential problems were encountered with a warm gas pressurant system, including the compatibility interface between the 2,200°F (1,200°C) gas and the selected injectants (would require design and development of an expulsion bladder), and the requirement of an auxiliary warm gas overboard dump system.

For the cold gas pressurant systems, nitrogen and helium were considered In comparing the two cold gas media, the helium system was lighter than the nitrogen system, but the high diffusibility of helium presented a more demanding problem in the tank design The nitrogen gas (GN_2) pressurization system was selected for the 260 in motor LITVC application as the more conservative approach

A comparison was made between GN_2 pressure regulated and GN_2 pressure blowdown systems The single main advantage of the regulated system, namely, constant injectant fluid pressure, was found to be more than offset by several important advantages of the blowdown system The blowdown system eliminated the need for a regulator, leading to a less complex system of higher intrinsic reliability It also allowed either separate or common tankage for the pressurant and injectant, whereas common tankage is unfeasible in the regulated system. As a result of this comparison, the blowdown system was selected for further analysis.

4.2.3.3 Tank Configurations--A blowdown system using separate tanks for GN_2 and N_2O_4 was compared with a blowdown system consisting of common GN_2 and N_2O_4 tankage. A weight breakdown showed about a 600 lb (272 2 kg) weight increase using the separate tankage system as opposed to the common GN_2 and N_2O_4 tankage.

Several storage tank configurations were evaluated for the pressurant (GN_2) and injectant (N_2O_4). The use of multiple spheres and cylinders yielded a space limitation problem, and was the most complex and heaviest tankage system investigated Also, access for assembly and servicing was poor with a multiple sphere tankage configuration. The double toroidal tank configuration (one tank for gas storage and another for the injectant) was used in the general preliminary LITVC system weight tradeoffs for reasons explained previously. The single common toroidal tank and an arrangement of four common cylindrical tanks were considered for incorporation into more detailed design tradeoffs.

4.2.3 4 LITVC Control System Schemes--Several different LITVC control system schemes were investigated during the preliminary design phase. Basically, there are two methods to resolve the guidance system steering commands into injector valve positions. These two methods are pitch-yaw and omniaxis control

In the pitch-yaw control system, the steering commands are used directly to drive the nozzle mounted injector valves within a specified nozzle quadrant Pitch-yaw commands are applied to phase splitters to separate negative and positive commands. For the system shown, injectors are opened equally. Thus, for a 50 percent pitch command, six injectors (1 thru 6) are all opened to 50 percent flow. For an oblique command of 50 percent, 12 injectors (1 thru 12) are opened at 36 percent

In the omniaxis control, the steering commands from the guidance system are resolved in the direction of the required thrust vector to favor a quadrant of injectors.

It was found that a substantial reduction in electronic complexity and cost could be realized if the pitch-yaw control scheme was selected over the omniaxis control scheme. Based upon the primary system design objective (simplicity), the pitch-yaw control scheme was selected for incorporation in the subject LITVC system studies.

4.2.4 Summary of Design Analysis--The selected injection parameters, components and subsystems are summarized in Table III.

4.3 Candidate LITVC System Evaluation Tradeoff

Thiokol and NASA LeRC jointly determined that LITVC system No 3B offered the most design potential and therefore should be pursued further in the detailed LITVC system design task The decision was based on system weight, cost effectiveness, and simplicity.

A comparison of the injectant and pressurant requirements, the estimated total launch and burnout weights (nozzle weight excluded), and estimated cost of each candidate LITVC system design are shown in Table IV.

Referring to the total (wet) launch weights in Table IV, the two aqueous $Sr(ClO_4)_2$ LITVC systems (No. 5A and 5B) exceeded the launch weights of their N_2O_4 counterpart designs (No. 4A and 4B) by 17 percent The heavier aqueous $Sr(ClO_4)_2$ system launch weights resulted primarily from the increase in injectant weight (due to lower Isp_s capabilities than N_2O_4) and the requirement for a minimum of five injectors per quadrant (instead of four per quadrant with N_2O_4).

TABLE III

SELECTED LITVC SYSTEM DESIGN CHARACTERISTICS

Type of injectants	1 N_2O_4 2 Aqueous $Sr\ (ClO_4)_2$ solution
Injector position	35 to 40 percent of nozzle length
Injection angle	+15 (0 26175 rad) upstream of a perpendicular to the nozzle centerline
Type of injection valve	Single pintle-type injectors
No of valves per nozzle quadrant	4 and 5
Type of injector actuation system	1 Electromechanical actuators/battery power source 2 Hydraulic actuators/electric motor pump power source 3 Hydraulic actuators/passive blowdown power source
Type of injectant pressurization	Nitrogen gas (GN_2) blowdown
Type of tank configuration	1 Single common toroidal tank 2 Four common cylindrical tanks
Injection pressure	800 psia (5 516 x 10^6 N/m^2) initially blows down to 400 psia (2 758 x 10^6 N/m^2)
LITVC control system scheme	Pitch-yaw controller

TABLE IV

NASA 260 IN SRM WEIGHT AND COST COMPARISON OF CANDIDATE LITVC SYSTEM DESIGNS

	LITVC No 1	LITVC No 2	LITVC No 3A	LITVC No 3B	LITVC No 4A	LITVC No 4B	LITVC No 5A	LITVC No 5B
Injectant	N_2O_4	N_2O_4	N_2O_4	N_2O_4	N_2O_4	N_2O_4	$Sr\ (ClO_4)_2$	$+ H_2O$
Injectant volume (m^3)	7 85	7 85	7 85	7 97	7 97	7 97	7 37	7 37
(total initial) (in^3)	466 000	466 000	466 000	473 470	473 470	473 470	437 600	437 600
Injectant weight (kg)	11 027	11 027	11 027	11 174	11 174	11 174	13 784	13 784
(total initial) (lbm)	24 309	24 309	24 309	24 634	24 634	24 634	30 387	30 387
Pressurant	GN_2	GN_2	GN_2	GN_2	GN_2	GN_2	GN_2	GN_2
Pressurant volume (m^3)	12 26	12 26	12 26	12 46	12 46	12 46	11 51	11 51
(total initial) (in^3)	728 000	728 000	728 000	739 800	739 800	739 800	683 700	683 700
Pressurant weight (kg)	748	748	748	767	767	767	708	708
(total initial) (lbm)	1 650	1 650	1 650	1 690	1 690	1 690	1 560	1 560
LITVC system								
Estimated total launch (kg)	16 831	15 313	14,941	15 016	15 129	15 123	17 693	17 769
weight* (lbm)	37 105	33 758	32 938	33 104	33 353	33 340	39 006	39 174
Estimated total burnout (kg)	6 089	4 571	4 199	4 131	4 244	4 197	4 266	4 288
weight* (lbm)	13 424	10 077	9 257	9 107	9 356	9 252	9 405	9 454
Estimated LITVC system unit cost**	$452 950	$375 250	$268 950	$245 180	$311,380	$252 980	$327 820	$268 720

*Nozzle weight excluded

**Nozzle cost excluded unit cost based on thirty 260 in motors and LITVC systems

Within the six N_2O_4 LITVC systems evaluated (systems No 1 thru 4B), system No 1, which used four cylindrical N_2O_4-GN_2 tanks, was estimated to be the most costly system, and also the heaviest at launch and burnout. LITVC system No. 3B was the second lightest N_2O_4 design at launch, had the lightest burnout weight, and was the least costly.

4.4 Final LITVC System Design

The LITVC system design developed for application on the 260 in SRM is pictorially illustrated in Figure 6.

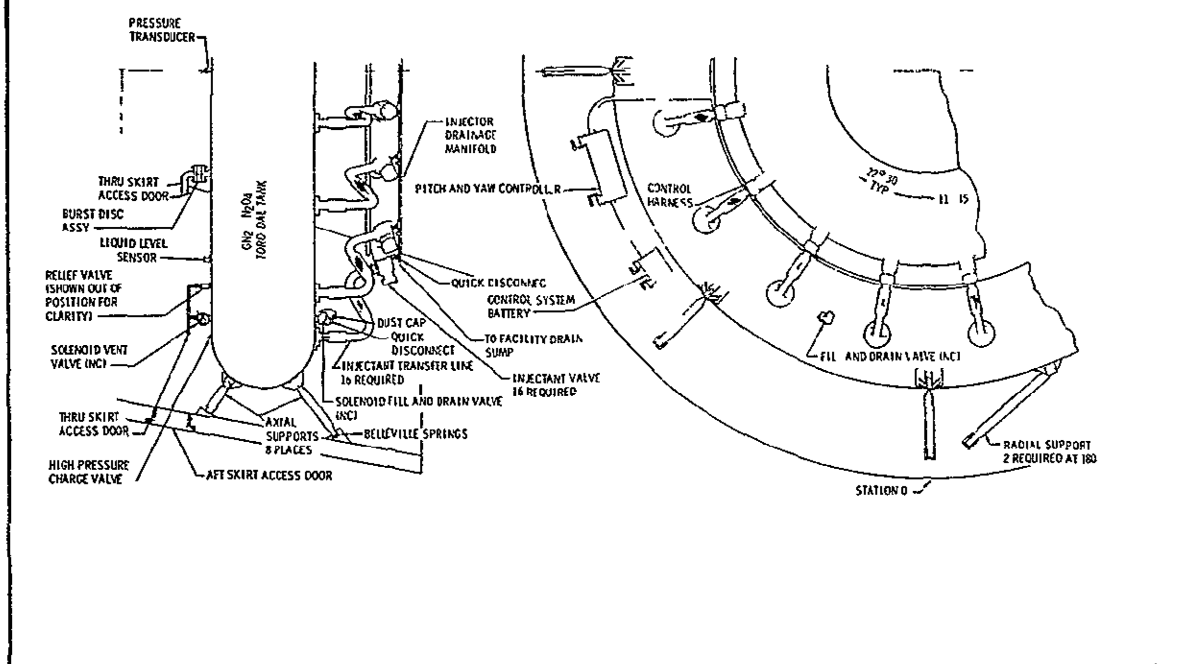

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Figure 6. NASA 260 In SRM Final LITVC System Design

The addition of an aft skirt access door was the only modification required to the basic vehicle design

Discussions of the major selected components for the final LITVC system design follow.

4.4 1 LITVC Fixed Nozzle Design--The LITVC nozzle design consisted of the baseline fixed nozzle design with the following modifications (1) replacing the exit cone fiberglass with steel to support the liquid injectors, (2) mounting the injectors on an integral steel support ring, and (3) inserting silica cloth phenolic ports (one per injector) into the exit cone liner. The initial total weight of the LITVC nozzle, exclusive of any liquid injectant components, was 53,947 lb (24,470 kg)--38,562 lb (17,492 kg) insulation and 15,385 lb (6,979 kg) structure. This total is 6,046 lb

(2,742 kg) greater than the initial weight of the fixed baseline nozzle The total expended LITVC nozzle weight during flight was calculated to be 5,772 lb (2,618 kg).

4.4 2 <u>GN_2-N_2O_4 Tank Assembly</u>--The LITVC tank assembly (Figure 7) is a single toroidal tank (volume, 702 cu ft or 19.88 m^3) which contains both the GN_2 pressurant and the N_2O_4 injectant fluid The tank has provisions for loading and unloading N_2O_4, filling and venting GN_2, emergency venting of N_2O_4 vapors, nonvortex distribution of N_2O_4 to each of 16 injectors, and measurement of unexpended N_2O_4. The GN_2 blowdown system minimum pressure is 800 psia (5 516 x 10^6 N/m^2) at launch and blows down to 400 psia (2 758 x 10^6 N/m^2) at the end of all duty cycle requirements

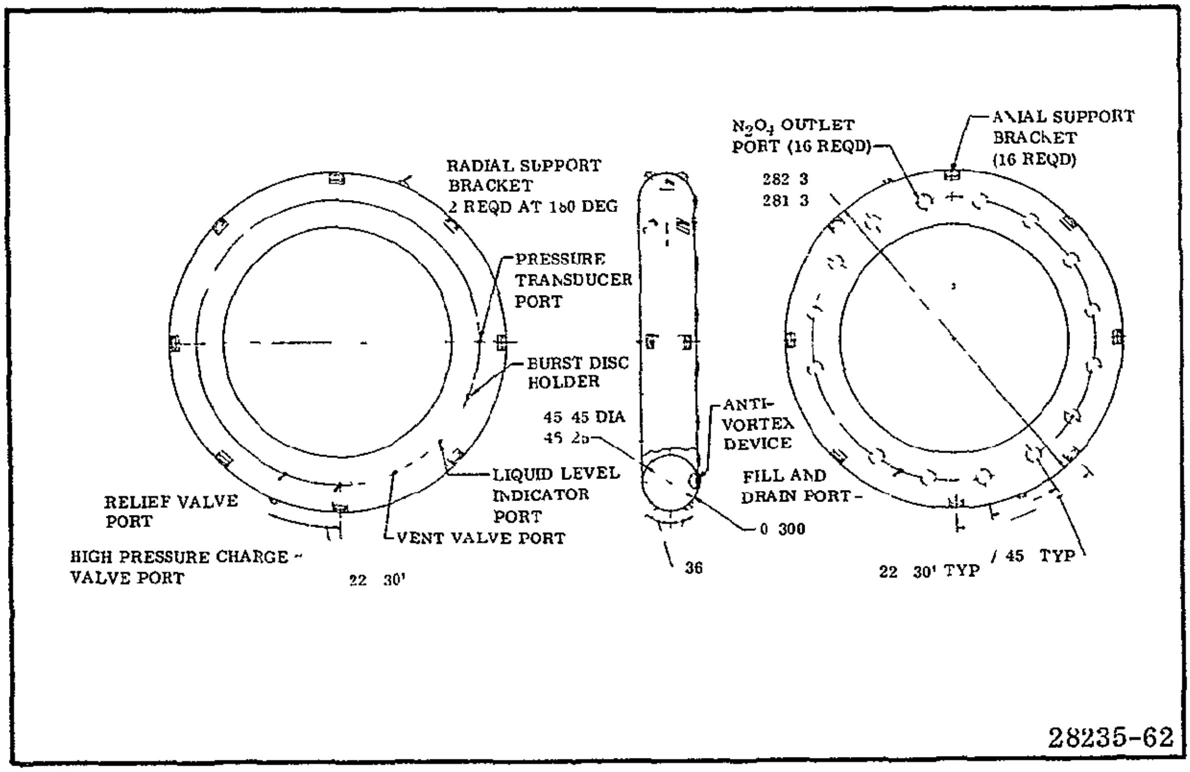


Figure 7 . NASA 260 in. SRM Final LITVC System GN_2-N_2O_4 Tank Design

The GN_2-N_2O_4 tank is supported by a tubular system attached to the internal structural members of the vehicle aft flare The tank support structure design has features to allow for misalignment, asymmetric loads from various sources and possibilities for future support design structure modification and/or growth. The toroidal reservoir will be constructed from four 90° (1.57 rad) stainless steel 17-4 PH CRES (175,000 psi or 1.2066 x 10^9 N/m^2 minimum yield) elbows welded together

The N_2O_4 injectant is distributed from the toroidal tank to each of the 16 injectors through flexible expansion ducts

4.4 3 <u>Electromechanical Injector Valve</u>--The Titan IIIC LTV valve employs a dc "pancake" motor directly driving a ball screw which converts rotary motion into linear motion to actuate the injector pintle. The pancake torque motor and ball screw have the following advantages over other injector systems.

1 Rugged components.

2. Fully reversible for fail-safe closure.

3 Motor specially adapted for quasi-static positioning.

4 Ball screw 90 percent efficient in converting rotary to linear motion.

5 High coupling stiffness and torque-to-inertia ratio

6 Compact, frameless design.

This electromechanically actuated pintle type valve varies the flow rate by changing the effective flow area. The servocontrolled assemblies are capable of modulating N_2O_4 flow from 0 to 169 lbm/sec (76.7 kg/sec) at 800 psi (5.516 x 10^6 N/m^2) and from 0 to 120 lbm/sec (54.4 kg/sec) at 400 psi (2.758 x 10^6 N/m^2). The injector valves use developed servocomponents to provide valve opening and closing time capabilities for achieving the required slew rates

4 4.4 LITVC Control System--Most flights will not require the use of all the N_2O_4 injectant. Therefore, after evaluating several alternate dump schemes, a continuous injectant dump system incorporating a liquid level transducer (Kavlico Electronics, Inc) was selected to minimize the performance penalty of carrying all N_2O_4 injectant to first stage burnout The system continuously compares the residual injectant quantity (sensed by the liquid level transducer in the injectant storage tank) with a preprogramed residual quantity which varies as a function of flight time. An error signal, proportional to the excess of injectant over the preprogramed quantity, is added with the guidance commands to each control servo, resulting in superposition of control and symmetrical dump commands.

4.4.5 LITVC System Weights--A component weight breakdown (nozzle excluded) of the 260 in. LITVC system is presented in Table V. The initial weight is 38,801 lb (17,600 kg), the burnout weight is 14,804 lb (6,715 kg). The total initial, expended, and burnout weights of the nozzle and LITVC system are shown in Table V. The total initial nozzle and LITVC system weight is 92,748 lb (42,070 kg), the total burnout weight is 63,553 lb (28,847 kg)

A correlation of Titan III N_2O_4 injection data of axial thrust augmentation as a function of side force generated was used to determine the thrust augmentation possible from this system The calculated increase in axial impulse was 0.233% or 2,018,600 lb-sec (8.98 x 10^6 N/sec).

4.4 6 Major LITVC System Characteristics--The NASA 260 in. SRM final design characteristics are summarized in Table VI.

4.5 Detailed Cost Analysis of LITVC System

Prior to developing the detailed cost estimates for the LITVC system, a system development and qualification program plan, which described the recommended individual system and component testing for developing the TVC system was prepared.

Table VII is an overall summary for the expected costs to be incurred in developing and producing the LITVC system chosen for the detailed design A tabulation of the individual TVC system components on a unit cost basis is indicated in Table VIII.

The unit cost of the basic fixed nozzle, after allowing for structural modifications, was priced at $623, 200 for materials and 35, 200 hours for labor.

TABLE V

LITVC SYSTEM COMPONENT WEIGHTS
(Nozzle Excluded)

Component	Weight (lbm)	Weight (kg)
Injectant pressurant tank assembly	10 470	4 74[illegible]
Injectant nitrogen tetroxide (N_2O_4)	[illegible]4 634	11 1[illegible]4
Pressurant nitrogen gas (GN_2)	1 690	76[illegible]
Burst disc assembly	3	1 3[illegible]
Operational pressure transducer	1	0 [illegible]
Liquid level indicator	5	[illegible]
Relief valve	3	1 3[illegible]
Solenoid vent valve		
GN_2 pressure charge valve	2	0 [illegible]
Solenoid fill and drain valve		
Quick disconnect and dust cap	2	0 [illegible]
Injector valves (16 at 20 lbm) (with electronics)	[illegible]0	14[illegible]
Injector housings (16 at 12 lbm)	19[illegible]	[illegible]
Tank to injector N_2O_4 transfer lines (16)	40	10
Axial supports (16)	392	1[illegible]
Radial supports (?)	103	46 7
Aft skirt support mounting brackets (18)	4	[illegible]
Pitch and yaw controller	30	[illegible]
Control system battery	40	[illegible]
Power transfer switch	9	[illegible]
Electrical harness assembly	160	[illegible]
Injector valve drain manifold assembly	19	[illegible]
Relief and solenoid vent valve tubing assembly	16	[illegible]
Burst disc assembly tubing assembly	4	1 [illegible]
Total initial weight (lbm)	38 [illegible]01	1[illegible]00
Total burnout weight (lbm)	14 804	[illegible]

Initial N_2O_4 = 24 634 lb (11 1[illegible]4 kg)
Expended N_2O_4 = 23 997 lb (10 [illegible] kg)

5. MOVABLE NOZZLE - FLEXIBLE SEAL

5 1 Literature Search

The systems studied all had one common design feature, they all used hydraulics as the means of transmitting power to the load and used linear servoactuators A solid propellant gas generator was consistently used as the primary power source except for the Sundstrand design and Stage II design of the Douglas study Sundstrand proposed a hydrazine gas generator to drive a turbine-pump system while the Stage II 260 in vehicle used by Douglas in the comparative study of TVC systems used two electric motors to drive the hydraulic pumps. In the latter case, a large accumulator was used to supplement pump flow during peak periods.

5 2 Design Requirements

The vector angle of $\pm 1.5°$ (0. 026 rad) in any plane was changed to ± 1 61° (0. 028 rad) due to the change in pivot point location in the Aerojet bearing design The design slew rate was 3 0°/sec and 8°/sec^2 (0. 052 rad/sec and 0. 139 rad/sec^2) maximum slew acceleration The duty cycle in the RFP was modified by NASA and is shown in Figure 8 The duty cycle is identical for both planes except for the pitchover event at 10 sec. At this point the yaw actuator maintains its steady state position

TABLE VI

MAJOR LITVC SYSTEM CHARACTERISTICS

1 GENERAL

Injectant fluid	N_2O_4
Pressurant gas	Nitrogen (GN_2)
Nozzle-LITVC system reliability prediction	0 9886
Initial CG to aft equator Y_{Go} (in)	661 (1 679 cm)
Aft equator to nozzle throat station (in)	121 (307 cm)
Nozzle throat station to nozzle injection station x (in)	98 (249 cm)
Equivalent point of side force insertion (in)	880 (2 235 cm)
L* = 661 + 121 in (in)	782 (1 986 cm)
Vacuum specific impulse (lbf-sec/lbm)	254 34 (2 494 N-sec/kg)
Total vacuum axial impulse (lbf-sec)	864 776 960 (3 84653 x 10^9 N-sec)
Control impulse capabilities (lbf-sec)	6 289 000 (27 965 x 10^6 N-sec)
Control impulse capabilities (-sec)	60 (1 047 rad-sec)
Control impulse-to-total vacuum axial impulse (%)	0 727
Axial impulse gained by thrust augmentation (lbf-sec)	2 018 600 (8 979 x 10^6 N-sec)
Thrust augmentation-to-total vacuum axial impulse (%)	0 233

2 N_2O_4 AND GN_2 RESERVOIR

Shape	Toroid
Number required	1
Total tank assembly weight (dry) (lbm)	10 470 (4 749 kg)
Total storage volume (cu ft)	702 (19 88 m^3)
Initial N_2O_4 volume (cu ft)	274 (7 76 m^3)
Initial N_2O_4 weight (lbm)	24 634 (11 174 kg)
Initial GN_2 volume (cu ft)	428 (12 12 m^3)
Initial GN_2 weight (lbm)	1 690 (767 kg)
Operating pressure of GN_2 blowdown system	
Initial (psi)	800 (5 516 x 10^6 N/m^2)
Burnout (psi)	400 (2 758 x 10^6 N/m^2)
Proof pressure (psi)	1 200 (8 274 x 10^6 N/m^2)
Burst pressure (psi)	2 000 (13 79 x 10^6 N/m^2)
Material	17-4 PH CRES (175 000 psi min yield) (1 2066 x 10^9 N/m^2)
Major diameter of torus (nominal) (in)	236 (599 cm)
Minor ID of torus (nominal) (in)	45 3 (115 cm)
Wall thickness (in)	0 300 (0 762 cm)
Envelope diameter of toroidal tank assembly (in)	281 8 ± 0 5 (715 8 ± 1 3 cm)

3 LITVC FIXED NOZZLE

Insulation (initial) (lbm)	38 562 (17 492 kg)
Silica and asbestos filled Buna rubber	
Carbon cloth phenolic	
Silica cloth phenolic	
Canvas	
Structure (initial) (lbm)	15 385 (6 979 kg)
Alloy steel (4130)	
Fiberglass	
Total initial nozzle weight (lbm)	53 947 (24 470 kg)
Total expended nozzle weight (lbm)	5 198 (2 358 kg)
Total burnout nozzle weight (lbm)	48 749 (22 113 kg)
Nozzle axial length from throat to exit L (in)	277 86 (706 cm)
Nozzle axial length from throat to injection station x (in)	98 (249 cm)
Injection station x/L	0 353
Initial nozzle expansion ratio at injection station	2 69 1

4 INJECTION SUBSYSTEM

Type of injector valve	Single pintle-type injectors (LTV design)
Type of injector actuation system	Electromechanical actuators/battery power source
Number of valves per nozzle quadrant	4
Angle between adjacent injector port centerlines (°)	22 5 (0 393 rad)
Injector location	
x/L	0 353
Area ratio	2 69 1
Injection angle	+15 upstream of a perpendicular to the nozzle centerline (0 26715 rad)
Injection system slew rate capabilities (/sec)	3 (0 0524 rad/sec)
LITVC control system scheme	Pitch-yaw + dump controller
Maximum required equivalent thrust vector angle (each-pitch and yaw) (°)	1 2 (0 02094 rad)
Maximum required equivalent side force (lbf)	114 000 (489 280 N)
Maximum required N_2O_4 flow rate per quadrant (NPV = 4) (lbm/sec)	440 (199 6 kg/sec)
Maximum required N_2O_4 flow rate per injector port for NPV = 4 (lbm/sec)	110 (49 9 kg/sec
Maximum N_2O_4 flow rate capabilities per injector port	
P_i = 800 psi (lbm/sec)	169 (76 7 kg/sec)
P_i = 400 psi (lbm/sec)	120 (54 4 kg/sec)
Maximum N_2O_4 flow rate capabilities per quadrant (NPV = 4)	
P_i = 800 psi (lbm/sec)	676 (306 6 kg/sec)
P_i = 400 psi (lbm/sec)	480 (217 7 kg/sec)

NPV = No of Single Pintle Injectors per Quadrant

TABLE VII

LITVC SYSTEM DEVELOPMENT AND PRODUCTION SUMMARY

	1971		1972		1973		1974		1975		1976		1977		
	First	Second	First	Second	First	Second	First	Second	First	Second	First	Second	First	Second	Total
1 Design															
Labor	140 800	146 960	27 120	14 140	—	—	—	—	—	—	—	—	—	—	329 020
2 Component development and system testing															
Labor	12 219	69,312	—	—	—	—	—	—	—	—	—	—	—	—	81 531
Material	340 667	583 859	—	—	—	—	—	—	—	—	—	—	—	—	924 526
3 Qualification (3 R & D systems)															
Labor	—	2 542	925 146	—	—	—	—	—	—	—	—	—	—	—	927 688
Material	—	265 000	2 583 861	—	—	—	—	—	—	—	—	—	—	—	2 848 861
4 PFRT (7 PFRT systems)															
Labor	—	—	301 516	1 833 888	—	—	—	—	—	—	—	—	—	—	2 135 404
Material	—	—	1,622 574	4 056 435	—	—	—	—	—	—	—	—	—	—	5 679 009
5 Production (20 systems)															
Labor	—	—	—	—	538 737	561 304	569,607	593 003	601 366	626 421	635,552	662 235	671 473	699 688	6 159,326
Material	—	—	—	—	1 622 574	1 622,574	1 622 574	1 622 574	1 622 574	1 622 574	1 622 574	1,622 574	1 622 574	1,622 574	16 225 740
6 Administration and support															
Labor	84 261	87 923	89 110	92 927	94 266	98 327	99 777	104 018	105 525	110 038	111,633	116 409	118 078	123 149	1 435 341
Other direct	12,969	15,860	58,682	81,970	26,373	27,438	27,828	28,933	29,326	30,511	30,940	32,138	32,635	33,958	469,029
Total direct cost	590,916	1 171 356	5 607 409	6 079,360	2 281 950	2 309 643	2 319,786	2 348,528	2 358,731	2 389 544	2 400 699	2 433 416	2 444 760	2 479 377	37 215,476
Estimated overhead	421,530	648,052	2,974,601	3,848,479	2,281,950	1,355,878	1,370,522	1,411,973	1,426,682	1,471,135	1,487,222	1,534,360	1,550,739	1,600,594	22,417,688
Total cost	1 012 446	1 819 408	8 582 010	9 927 839	3,597 872	3 665 521	3,690 308	3,760 501	3 785 413	3 860 679	3 887 921	3 967 776	3 995 499	4 079 971	59 633,164

TABLE VIII

260 IN LITVC SYSTEM COMPONENTS
(ROM Cost Summary)

Item No	Component	Vendor Tooling and Devel Costs	Per Unit Costs
1	Injectant - pressurant tank assembly	$150,000	$ 75,000
2	Injectant - nitrogen tetroxide (N_2O_4)	--	1,600
3	Pressurant - nitrogen gas (GN_2)	--	280
4	Burst disc assembly	--	20
5	Operational pressure transducer	--	1,250
6	Liquid level sensor	--	1,800
7	Relief valve	--	350
8	Solenoid vent valve	--	385
9	GN_2 pressure charge valve	--	75
10	Solenoid fill and drain valve	--	385
11	Quick disconnect and dust cap	--	80
12	Injector valves (with electronics) - (16 at $3,800 each)	--	60,800
13	Injector housings - (16 at $200 each)	--	3,200
14	N_2O_4 - transfer lines (16 at $755 each)	2,600	12,080
15	Supports and brackets		
	Axial supports (16)	--	--
	Radial supports (2)	--	--
	Aft skirt support mounting brackets - (18)	--	--
	36 units = 950 lb at $ 47/lb	--	447
16	Pitch and yaw controller	--	16,000
17	Control system battery	--	4,200
18	Power transfer switch	--	1,700
19	Electrical harness assembly	--	8,000
20	Injector valve drain manifold assembly	--	270
21	Relief and solenoid vent valve tubing assembly	--	100
22	Burst disc assembly, tubing assembly	--	45
		$152,600	$188,067

NOTES

Unit cost based on 30 system buy

All prices are based on inhouse engineering estimates or catalog prices, except items (1) injectant - pressurant tank assembly, (6) liquid level sensor, (8) solenoid vent valve, (10) solenoid fill and drain valve and (14) tank to injector transfer line, which are vendor quotes

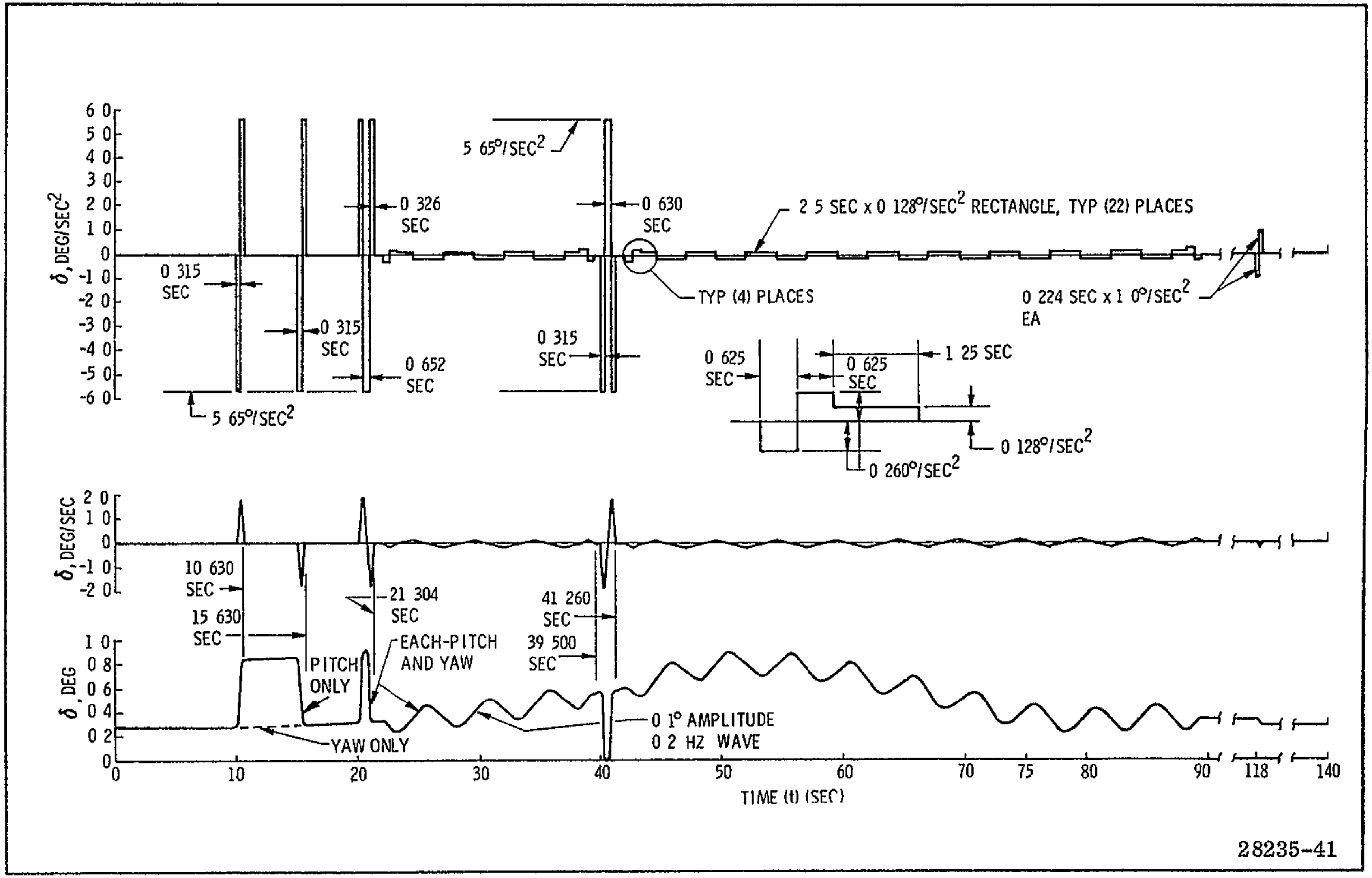


Figure 8. Movable Nozzle Power Duty Cycle

All components used in the actuation system were to be flight-type and flightweight. Development of components was to be kept to a minimum and use of existing items and techniques were to be employed wherever possible to minimize cost and increase reliability

5.3 Nozzle Torque

5 3 1 Seal Spring Torque--Seal spring torque results from the shear stress produced by the seal's elastomer layers upon nozzle vectoring

For $0 < t \leq 60$ sec, the torque component was 4 063 million in.-lb (0 46 x 10^6 N-m) for the Thiokol nozzle, and 4.05 million in.-lb (0 457 x 10^6 N-m) for the AGC nozzle. After 60 sec into the firing, the vector angle requirement drops from 1 61° to 1 18° (0 028 rad to 0.0206 rad) and the seal torque drops to 2 97 million in -lb (0.336 x 10^6 N-m) for the AGC nozzle

No attempt was made to calculate any torque component as a function of time for the Thiokol design due to the decision to eliminate it from further consideration The torque vs time curves appearing in this subsection, as well as the following subsections, apply to the AGC nozzle only.

5.3 2 Internal Aerodynamic Torque--Internal aerodynamic torque is the result of flow asymmetry in the deflected nozzle, producing a pressure differential in the plane of actuation. The maximum value for this component was computed to be 2 30 million in -lb (2 6 x 10^5 N-m).

5.3 3 Offset Torque--This torque component is defined as the null position internal aerodynamic torque resulting from asymmetrical gas flow in the unvectored nozzle. Factors contributing to asymmetrical flow are the fabrication tolerance buildup, uneven ablative erosion, and uneven propellant burn The maximum value for this component was 2.523 million in.-lb (0 286 x 10^6 N-m) and it occurred at 108 sec into the motor firing.

5 3 4 Boot Spring Torque--Boot spring torque was calculated from a previous bench test on a similar boot. The decrease in elastomer thickness of the AGC was compensated for in the calculation The AGC 260 in boot is approximately the same thickness and same cross sectional area as was the 156 in. motor boot In the 156-9 flexible seal bench test, boot torque was 4 percent of the seal torque. However, the total elastomer height in the 156-9 seal was 2.075 in. (5.268 cm), whereas, the elastomer height in the AGC 260 flexible seal is only 1.50 in. (3 81 cm) This decrease in elastomer thickness (height) results in a stiffer seal and changes the ratio of boot torque to flexible seal torque in inverse proportion

Therefore, maximum AGC boot torque was calculated as

at $0 \leq t \leq 60$ $$T_{boot} = (T_{seal})\,(0\ 04)\left(\frac{2.075}{1.500}\right) = 0\ 224 \text{ million in -lb } (2\ 53 \times 10^4 \text{ N-m})$$

at $t > 60$ $$T_{boot} = (T_{seal})\,(0.04)\left(\frac{2\ 075}{1.500}\right) = 0.164 \text{ million in -lb } (1\ 85 \times 10^4 \text{ N-m})$$

Maximum boot torque for the Thiokol nozzle was 0.160 million in -lb (1.809 x 10^4 N-m) or 4 percent of Thiokol seal torque

5.4 Preliminary Screening

The ground rules applied to the program required that state-of-the-art components be selected. Low cost, low development risk, and simplicity of operation were stressed in the design Linear electrohydraulic servoactuators were selected to drive the nozzle. The primary task in the preliminary screening was to select a power source to drive the actuators Staying within the guidelines established, the following power sources were investigated in some detail (1) warm gas solid propellant generator (blowdown and turbine pump), (2) warm gas liquid propellant generator, and (3) cold gas blowdown Under each category listed, several different configurations were studied. During the screening process, the same torque values were used for all configurations studied. The servoactuators were sized at the beginning of the study and used for all power sources. The torque was later reduced at the preliminary design review, however, the auxiliary power supply studied during the preliminary design used the initial torque values.

5.4.1 Warm Gas Solid Propellant Gas Generator Turbine Pump Systems With Accumulator--The most conventional system investigated was a warm gas solid propellant warm gas generator driving a turbine-gearbox-hydraulic pump combination The warm gas drives a partial admission axial flow turbine which is coupled directly through a gear box to a variable displacement hydraulic pump. The gear box reduces the speed by a factor of 10 or 15 to 1 and is provided with a self contained lubrication system. Various size hydraulic pumps were used in the following designs but all are of the positive-displacement, axial piston type which have found application throughout the aerospace industry The flow of the pumps is controlled by the speed of rotation of the pump and the piston displacement Pump rotational speed can be set by the turbine-gearbox arrangement, however, piston stroke is regulated by the pump itself During periods of low flow demand, the yoke angle is reduced to shorten piston stroke System pressure is maintained, however, the flow is reduced to that sufficient to supply internal leakage

A bootstrap reservoir is used on all systems requiring a hydraulic pump. The reservoir is sized to contain sufficient hydraulic fluid to allow for thermal expansion, leakage, and the filling of the blowdown accumulator when used. In addition, the reservoir supplies inlet pressurization to the pump in the range of 50 to 100 psi (344×10^3 to 689×10^3 N/m^2).

A nitrogen precharged accumulator is used in many applications to supplement hydraulic flow during peak demand periods. For systems studied in this program which required accumulators, a piston type accumulator precharged to 2,200 psi ($15,105 \times 10^3$ N/m^2) was used During startup time, the pumping unit pumped fluid from the reservoir into the accumulator compressing the nitrogen to system pressure. System pressure for all designs was 4,000 psi ($27,600 \times 10^3$ N/m^2).

5.4.2 Servoactuator Sizing--The servoactuator effective area was sized during preliminary screening assuming a stall torque of 17.726×10^6 in.-lb (1.95×10^6 N-m), a lever arm of 96.5 in. (245 cm) and a hydraulic system pressure of 4,000 psi The torque figure used was obtained at the 1 61° (0 028 rad) vector angle. A slew rate of

3.0°/sec (0.052 rad/sec) in an oblique plane requires a rate of 2.12°/sec (0.037 rad/sec) in both the yaw and pitch planes. The flow necessary to meet this rate is 87 or 43.5 gpm (5.48 l/sec or 2.74 l/sec) per actuator. For preliminary design it was decided to use a 50 gpm (3.15 l/sec) servovalve (standard production model) to meet this requirement. The servovalve is a two stage, four-way electrohydraulic unit. The actuator stroke required to give a vector angle of 1.61° (0.028 rad) is 2.71 in. (6.88 cm). The maximum vector angle on the duty cycle presented by NASA was 0.948° (0.165 rad) at approximately 20 sec. The slew rate at that time was 1.84°/sec (0.032 rad/sec)and the torque is 14.8×10^6 in.-lb (1.67×10^6 N-m). The flow rate required to meet this slew rate is 38 gpm (2.39 l/sec). At 20 sec, the pressure drop across the actuator is 3,250 psi ($22{,}400 \times 10^3$ N/m^2) and the resulting valve flow is 40.3 gpm (2.54 l/sec) which is adequate to meet the 1.84°/sec (0.032 rad/sec) slew rate. These values were used for the first phase of the preliminary design.

5.4.3 <u>Accumulator Sizing</u>--The accumulator was sized using the hydraulic flow response obtained from an analog computer study.

The precharged accumulator is used to supplement hydraulic flow during peak demand periods where the demand exceeds the output capability of the pump. In Figure 9, $\dot{\delta}$ (nozzle vector rate) is depicted as a triangular wave and the resulting flow is shown directly below. Pump capacity, Q_p, is indicated by the horizontal line. The required accumulator flow is shown by the shaded area. During the time between accumulator flow demands, the pump recharges the accumulator. It is obvious that the accumulator cannot supply more than half the flow if recharging between demands is required. Figure 10 shows a typical flow curve obtained from the computer. For preliminary design it was assumed that the response would be independent of power supply design. By varying Q_p and integrating the area above the line, the flow from the accumulator could be determined. This method was used to size all accumulators for the preliminary design.

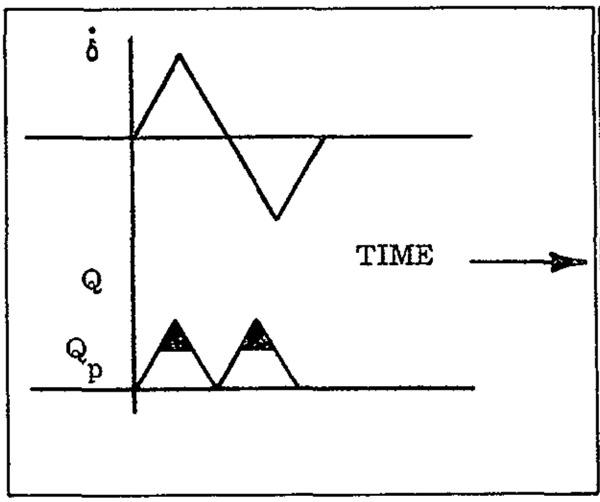


Figure 9. Vector Rate and Flow Diagram

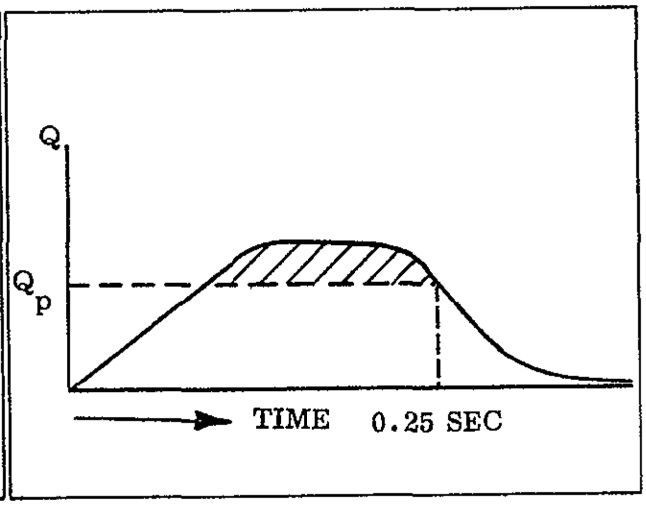


Figure 10. Typical Computer Flow Curve

5.5 Preliminary Designs

5.5 1 Warm Gas Solid Propellant Gas Generator Turbine Pump With and Without Accumulator--

5.5.1.1 With Accumulator--The pump selected for this design is a variable displacement type capable of flowing 60 gpm (3.78 l/sec) at 7,100 rpm Turning at a higher rpm requires a larger gas generator but a smaller accumulator The efficiency used for the pump was 0 8 and an efficiency of 0.5 was assumed for the turbine-gearbox which is higher than normally used, however, in recent contacts with a turbine manufacturer, they have stated that this value is within state-of-the-art A pressure control valve and sonic orifice act as a regulator and relief valve for the gas generator Use of a variable displacement pump requires a turbine speed control to prevent excess turbine speed during time of no flow requirement The accumulators were sized as described in para 5 4.3 The pressure was allowed to decay from 4,000 to 3,800 psi (27.6 x 10^6 to 26.2 x 10^6 N/m^2) during the blowdown cycle This allowed sufficient supply pressure to meet duty cycle requirements. Total system weight was estimated at 210 5 lb (95.48 kg).

5 5.1 2 Without Accumulator--The maximum flow was determined to be 87 gpm (5.48 l/sec). The pump selected for this design was the B70 pump developed by Vickers. The pump will flow 100 gpm (6.3 l/sec) at 4,000 psi (27.6 x 10^6 N/m^2). This is more than sufficient to meet the requirements for this particular program The weight of the major components was estimated at 310.5 lb (139 9 kg). This weight penalty plus the additional cost for the pump and turbine-gearbox eliminated this design from further consideration.

5.5.2 Warm Gas Solid Propellant Gas Generator Turbine Pump System With Dual Pump (No Accumulator)--To overcome the difficulties encountered by a single large pump, consideration was given to dual pumps each capable of delivering 48 gpm (3.02 l/sec) at 4,000 psi (27 6 x 10^6 N/m^2) driven by a common turbine-gearbox arrangement. Weight difference is insignificant but the additional pump adds complexity which may decrease reliability Total system weight was estimated at 227.6 lb (103 kg)

5.5 3 Warm Gas Solid Propellant Gas Generator Turbine Pump With Small Dual Pumps (Precharged Accumulator)--The same two pumps described in para 5 5 2 were used with a small accumulator to reduce horsepower requirements The two pumps were run at a reduced speed of 3,750 rpm at which the total hydraulic flow is 64 gpm (4 03 l/sec). Using the value of 87 gpm (5.48 l/sec) as the required flow to meet the design slew rate, the accumulator will be required to flow 23 gpm (1.45 l/sec) which is approximately one-fourth of the total flow Although some advantages are realized (e g , lower output horsepower required, better pump efficiency), the system is complex System weight was estimated at 220 6 lb (100 kg).

5.5 4 Warm Gas Solid Propellant Gas Generator With Small Pump and Large Accumulator--Thiokol compared the system specified in para 5.5.3 with one having the smallest pump size capable of meeting the duty cycle requirements with the aid of a large precharged accumulator This design is similar to that described in para 5.5.1 Use of a smaller hydraulic pump flow reduces the size of the solid propellant gas generator required. However, the accumulator and reservoir increase in size so that the net weight difference is slightly in favor of the larger pumping unit. The pump used was the same size but was turned at 5,650 rpm instead of 7,100 rpm. The pressure was allowed to decay to only 3,800 psi (26.2 x 10^6 N/m^2) which resulted in the large volume. This pressure value was used to compare all systems on the same basis. Total system weight was estimated at 224 lb (101.5 kg).

5.5 5 Warm Gas Solid Propellant Gas Generator with Precharged Accumulator--One of the primary disadvantages of a precharged accumulator is that during peak flow demands, system pressure decays as the accumulator discharges fluid. To overcome this difficulty a design was considered which charged the accumulator from the warm gas generator instead of using nitrogen.

By using a warm gas generator, the system pressure can be maintained at essentially 4,000 psi (27 6 x 10^6 N/m^2) during the time accumulator is discharging fluid. A switching arrangement can be provided so that between cycles, the pump will fill the accumulator with hydraulic fluid making it ready for the next demand. There are several disadvantages with this type of system. In order to use a 4,000 psi (27 6 x 10^6 N/m^2) supply pressure it would require either a gas generator operating at this pressure or a differential area type accumulator

The added complexity of the valving plus the heavier gas generator and accumulator eliminated this concept

5 5.6 Warm Gas Liquid Propellant (Turbine Pump)--This system uses the same components as previous designs except for the gas generator and accessories necessary for the liquid propellant gas generator The system was sized using two different hydraulic pump speeds (7,100 and 5,600 rpm) with a precharged accumulator to supply additional flow for peak demands. Lack of experience and heavy development effort eliminated this design. System weights were estimated at 198 and 218 8 lb (89.8 and 99.2 kg)

5.5 7 Warm Gas Blowdown--A warm gas blowdown system is one of the least complex of the systems studied. It utilizes a solid propellant warm gas generator to pressurize an accumulator which contains sufficient hydraulic fluid to meet duty cycle requirements. Because this system requires additional weight and is duty cycle limited, it was considered inferior to the more conventional turbine pump system. Total system weight was estimated at 463.5 lb (210.2 kg).

5.6 Preliminary Design Review

The design presented to NASA as the candidate for detail design was the one described in para 5.5.1 (with accumulator). This actuation system was used on both the Thiokol and Aerojet nozzles. Since the torques for the two seal designs were within 10 percent of each other, both have the same actuation system

This system uses solid propellant gas generator driving a turbine-gearbox, a single hydraulic pump turning at 7,100 rpm and the Thiokol flex bearing. A weight breakdown of the individual actuation system components is shown in Table IX. Actual weight of components supplied by vendors were used wherever possible If such data were not available, the Thiokol-TVC Preliminary Design Computer Program was used to estimate weight. This system was selected because it is the most conventional system involving the least development risk There would be little component development, although the system as a whole will require extensive checkout and bench test to insure adequate performance and response characteristics

TABLE IX

WEIGHT BREAKDOWN OF SELECTED SYSTEM

Component	Weight English Units (lb)	SI Units (kg)
Gas generator	82 5	37 4
Pump	19 8	8 98
Accumulator	37 0	16 75
Hydraulic fluid	40 0	18 1
Reservoir	15 5	7 02
Turbine-gearbox	42 5	19 25
Tubing and fittings	50 0	22 6
Filter and disconnect	14 0	6 35
Actuator (2)	480 0	217
Servovalves (2)	40 0	18 1
	821 3	372
+10% for brackets and contingencies	82 0	37 1
Total	902 3	408

5.6.1 Major Component Cost--Preliminary cost figures for all major components were obtained from vendors The quotes were based on quantities required for a total of 30 complete motors using a new, complete actuation system on each motor. Itemized costs are shown in Table X.

TABLE X

MAJOR COMPONENT COST BREAKDOWN OF CANDIDATE SYSTEM (TURBINE PUMP)

Item	Recurring Cost/Unit ($)	No of Units	Cost ($)	Nonrecurring ($)	Total ($)
Gas generator	500	32	16,000	--	16,000
Actuator*	20,000	64	1,280,000	150,000	1,430,000
Turbine gearbox	20,000	32	640,000	200,000	840,000
Hydraulic pump	1,450	32	46,400	--	46,400
Accumulator	950	32	30,400	--	30,400
Servovalve*	1,472	64	94,208	--	94,208
Total	65,844			350,000	2,457,008

*Two required per system

5.6 2 Preliminary Design Review Meeting for Candidate TVC System Selection (Movable Nozzles)--Because of motor orientation during static test and the zero gravity conditions during flight, gravity torque would not be a component of the total required torque. The maximum torque value used for the design was 8.86 x 10^6 in.-lb (0 1 x 10^6 N-m). Total torque and torque component vs time are shown in Figure 11.

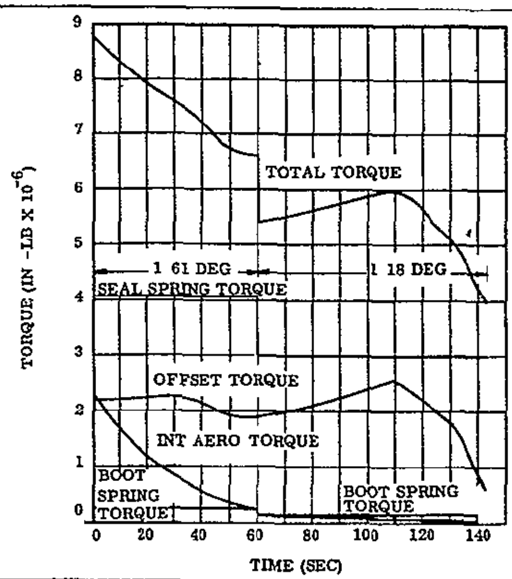


Figure 11 Nozzle Torque vs Time

The duty cycle was multiplied by $\sqrt{2}$ and a 1 61° (0.028 rad) event was added at 60 sec. This occurred on both the pitch and yaw axis. The slew rate was defined as 3°/sec (0 0524 rad/sec) average velocities when taken from hardover in one direction to 90 percent of full travel The Aerojet bearing was selected by NASA LeRC for the detail design phase of the program. NASA LeRC elected to extend the preliminary design phase so that a passive, cold gas blowdown system could be investigated A turbine-pump system was redesigned using the new torque and slew rate values.

5.6 3 Cold Gas (Passive Blowdown)--The passive blowdown system consists primarily of a single tank containing both the pressurant and hydraulic fluid The system considered did not use either a piston or bladder to separate the pressurant from the fluid

The two most critical items in the design of a passive blowdown system are to insure adequate fluid and pressure to meet the design duty cycle. Initial pressure of time equal zero was set at 4,000 psi (27 6 x 10^6 N/m^2) As pressure decays there will be less vector angle capability.

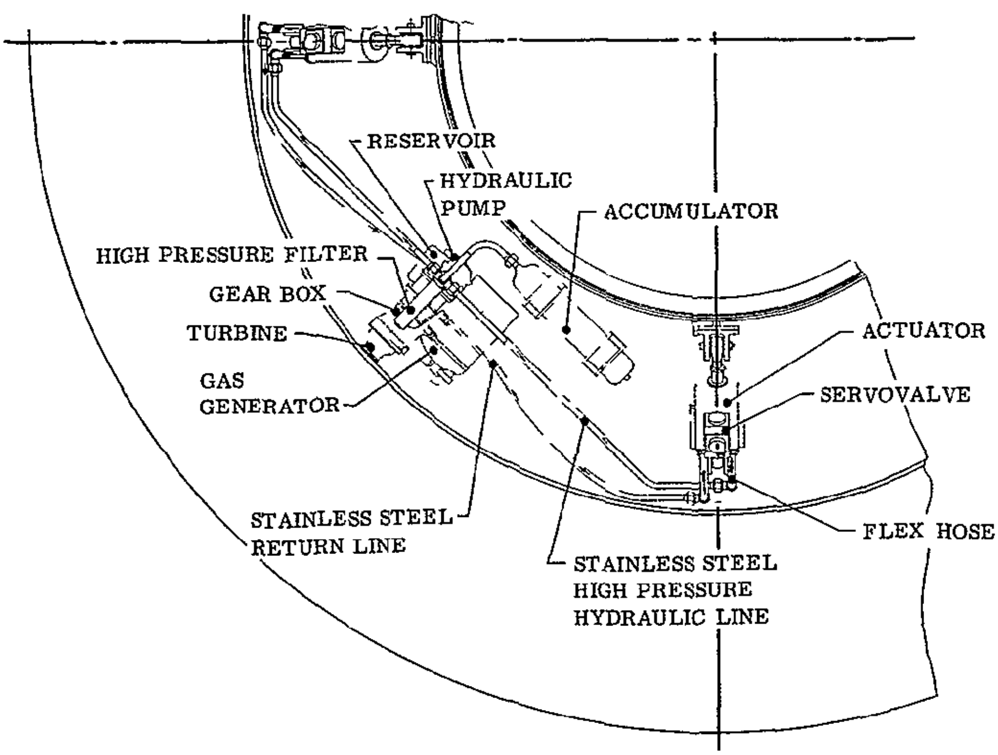
For the passive blowdown system, the initial pressure was set at 4,000 psi The actuator area was sized by assuming a supply pressure of 3,000 psi (20 7 x 10^6 N/m^2) at 110 sec and a torque of 8 8 x 10^6 in -lb (0.995 x 10^6 N-m). This resulted in an area of 30 4 sq in (196 cm^2)

The response rate used was an average of 3.0°/sec (0.524 rad/sec) where the system was stepped from ±1.61° (0.028 rad) to 90 percent of full travel It was assumed that this time was approximately 1 sec. To determine the maximum rate during that interval a second order system with a damping ratio of 0.8 was used to simulate the actuation system. Using nondimensional charts of second order systems, the time (nondimensional) to reach 90 percent of the final output is 2.95.

The passive blowdown system selected in the preliminary design phase has a solenoid valve which will be closed until just prior to launch is mounted on the outlet of the pressure vessel. The purpose of the valve is to prevent hydraulic fluid leakage through the servovalves during the hold period on the launch pad This valve could be replaced by a squib valve. Quick disconnects are located on the pressure and return lines for ground checkout after assembly. The system weight was estimated at 949 lb (430 kg).

5.6.4 Redesigned Warm Gas Solid Propellant Gas Generator Turbine Pump--This system is similar to that shown in the sketch below. Three different systems were redesigned differing only in the hydraulic pump output capability in order to assess the impact of the revised design requirements.

System I used a large pump without an accumulator The required flow, using the 30.4 sq in. (196 cm^2) actuator area, is 68 gpm at 4,000 psi (27 6 x 10^6 N/m^2) outlet pressure.



Sketch of Candidate System, Movable Nozzle - Flexible Seal

The pump selected for System I is capable of 70 gpm (4.41 l/sec) at a speed of 5,400 rpm

Systems II and III used a pump turning at 5,650 and 4,500 rpm, respectively The output flow is 48 gpm (3 02 l/sec) for the former and 40 gpm (3 52 l/sec) for the latter. Accumulators were included with these systems to make up for the additional flow requirement

Component weights for these three systems were estimated at 774 lb (352 kg), 750.5 lb (340 kg), and 745 lb (338 kg).

5.7 Selection for Detail Design

The passive blowdown system was chosen for further consideration in the detailed design task

From a weight standpoint, the turbine pump system offers a slight advantage It is also more flexible from a growth or demand viewpoint. The blowdown system is much more simple with less components and moving parts The development risk with such a system is almost nonexistent

The primary disadvantage with any blowdown system is the duty cycle limitation The system presented here has a 25 percent pad which could be increased by increasing the size of the accumulator.

The blowdown system seems to have the advantage over the turbine system in every category except weight and the above mentioned limitation

5.8 Detailed Cold Gas Passive Blowdown Design

A layout of the actuation system is shown in Figures 12 and 13. The fixed end of the actuators are mounted to brackets which are bolted to the nozzle aft mounting flange. The reservoir, made of 4340 steel, is mounted on the aft skirt with the reservoir centerline parallel to the longitudinal axis of the motor. The tank contains no barrier between the pressurant and hydraulic fluid. For static test, the tank is reversed and the plumbing to the filter bracket rerouted.

Hydraulic power is supplied to the two servoactuators through flexible hose attached to hard tubing at the actuator mounting bracket The tubing follows the nozzle aft mounting flange to the filter bracket.

Stainless steel tubing is used for all high pressure lines except for flexible hose which connect both pressure and return tubing to the actuators. Aluminum return lines, which are designed for low operating pressure, reduce system weight. The high pressure supply line has an outside diameter of 1.25 in. (3 18 cm) and a wall thickness of 0 089 in (0.226 cm). This gives a safety factor of 3 8 or a burst pressure of 15,200 psi (0 105 x 10^9 N/m^2). One inch (2.54 cm) lines branch off the main supply line at the 180 in (456 cm) bolt circle and follow the bolt circle to the actuator bracket where they are connected to flexible hose with swivel connectors. The 1 in. line has a wall thickness of 0.065 in. (0 165 cm) yielding a safety factor of 3.5 Burst pressure for the 1.25 and 1.0 in. aluminum return lines are 1,440 and 1,800 psi (9 92 and 12 4 x 10^6 N/m^2) respectively. The high pressure flex hose has a burst pressure of

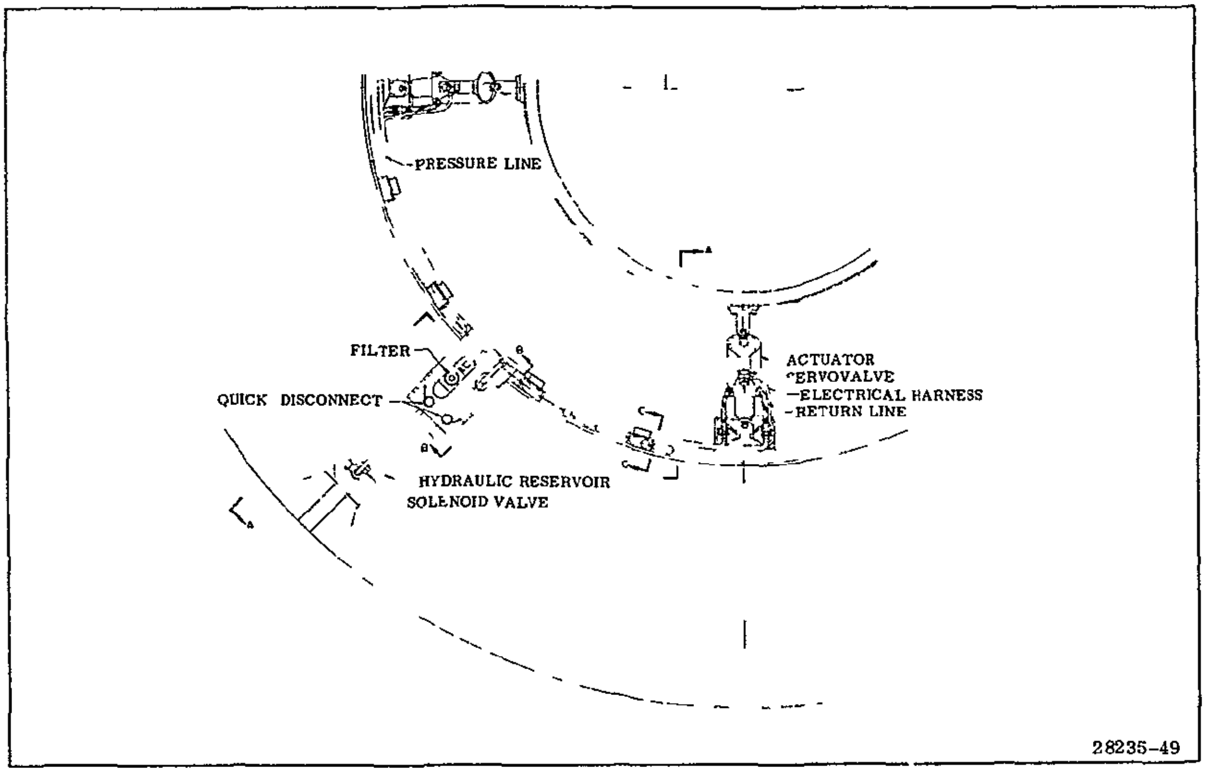


Figure 12 Actuation System for Movable Nozzle, End View

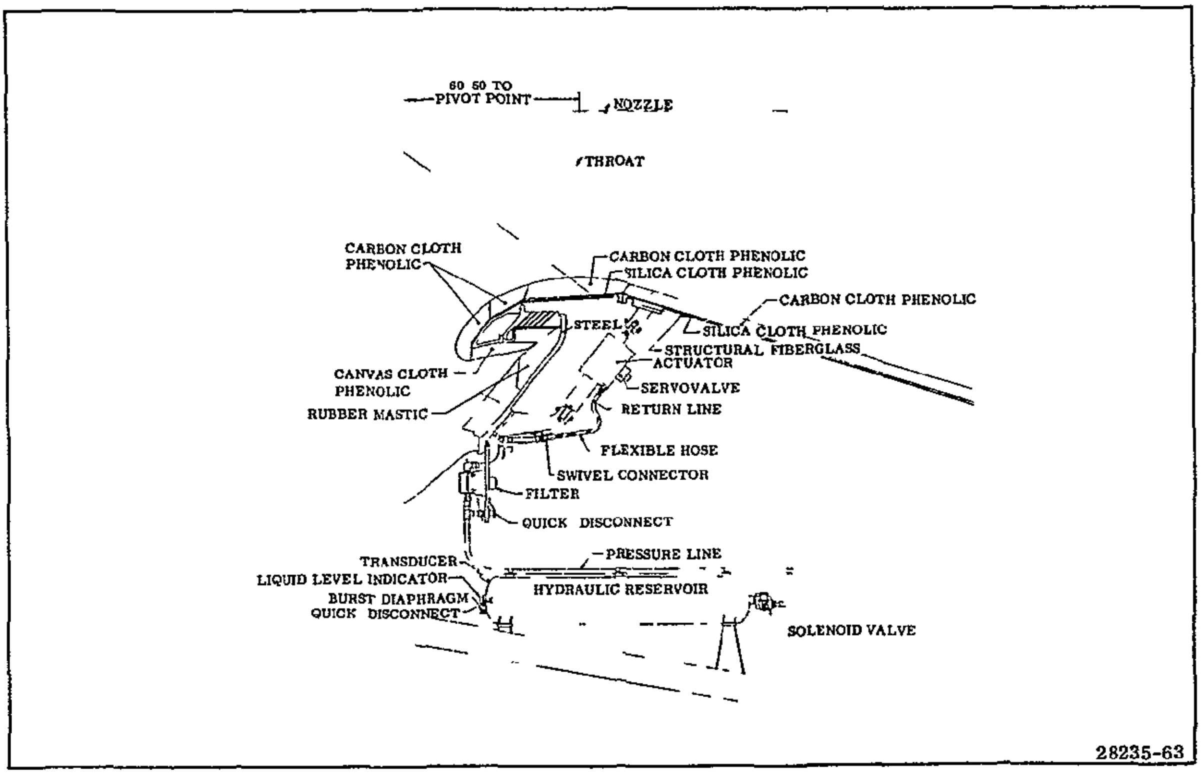


Figure 13. Actuation System for Movable Nozzle, Side View

12,000 psi (8.274×10^7 N/m^2) while the low pressure hose has a burst pressure of 4,200 psi (29×10^6 N/m^2)

A normally open solenoid valve located at the pressurization tank outlet is closed after filling the tank to the required level with hydraulic fluid. This valve remains closed during the prefiring checkout to prevent loss of fluid and pressure through servovalve leakage. This leakage is estimated at 1.0 gpm (0 063 l/sec) for both valves. At a predetermined time before firing, the valve is opened to pressurize the system. A solenoid valve was used rather than an explosive operated valve so that it could be reclosed if a hold occurred during the final stages of the countdown

A filter located in the hydraulic supply line has a rating of 10 micron nominal/ 25 micron absolute. The filter is secured to a bracket which mounts to the 180 in bolt circle. Two quick disconnects also are mounted on the filter bracket and used to supply ground hydraulic power for prelaunch checkout of the actuation system The high pressure quick disconnect is also used to fill the system with hydraulic fluid A check valve designed to open at 50 psi ($0\ 344 \times 10^6$ N/m^2) differential pressure is the return line near the filter bracket

Four brackets mounted on the 180 in (456 cm) bolt circle secure the pressure and return tubing in a fixed position Details of the brackets as well as the actuator mounting brackets, flexible boss brackets, and the filter bracket are shown in Thiokol Drawing TUL 13113.

5.8.1 Analog Computer Simulation--The analog computer program used in this study has been in use at Thiokol for several years The primary purpose of the program is to study the stability and response characteristics of TVC system The results obtained with this program have agreed well with test data from static tests A high degree of confidence has been attained in the ability of the program to predict performance of TVC actuation systems.

Step inputs were applied to the program and the gains were varied in order to insure stability and the required response. System pressure was held constant for these steps since they were of short duration Response and stability characteristics were studied at a pressure of 4,000 and 3,000 psi (27 6 and 20.7×10^6 N/m^2) When system pressure was 4,000 psi, the torque at zero sec was used For the 3,000 psi case, the torque at a time of 60 sec was used Figures 14 and 15 show the response to a step input of hardover to hardover for the 4,000 and 3,000 psi cases, respectively For the step from -1.61° to +1 61° (-0 028 rad to +0 028 rad), note that the angular velocity peaks at approximately 4.5°/sec (0.0785 rad/sec) at 3,000 psi system supply pressure. The velocity is lower in this direction due to the manner in which offset torque is input.

A step hardover to hardover implies a step of 3.22° (0 0562 rad) Ninety percent of this value is 2.898° (0 0505 rad) or approximately 1 3° (0 0227 rad) in the positive direction To average 3°/sec (0 0524 rad/sec) over 2.898° (0 0505 rad) requires a time of 2,898/3 which is 0.966 sec From the trace in Figure 14 it can be seen that it takes approximately 0 9 sec to reach +1.3° (0.0227 rad) for an average of 3.22°/sec (0 0562 rad/sec)

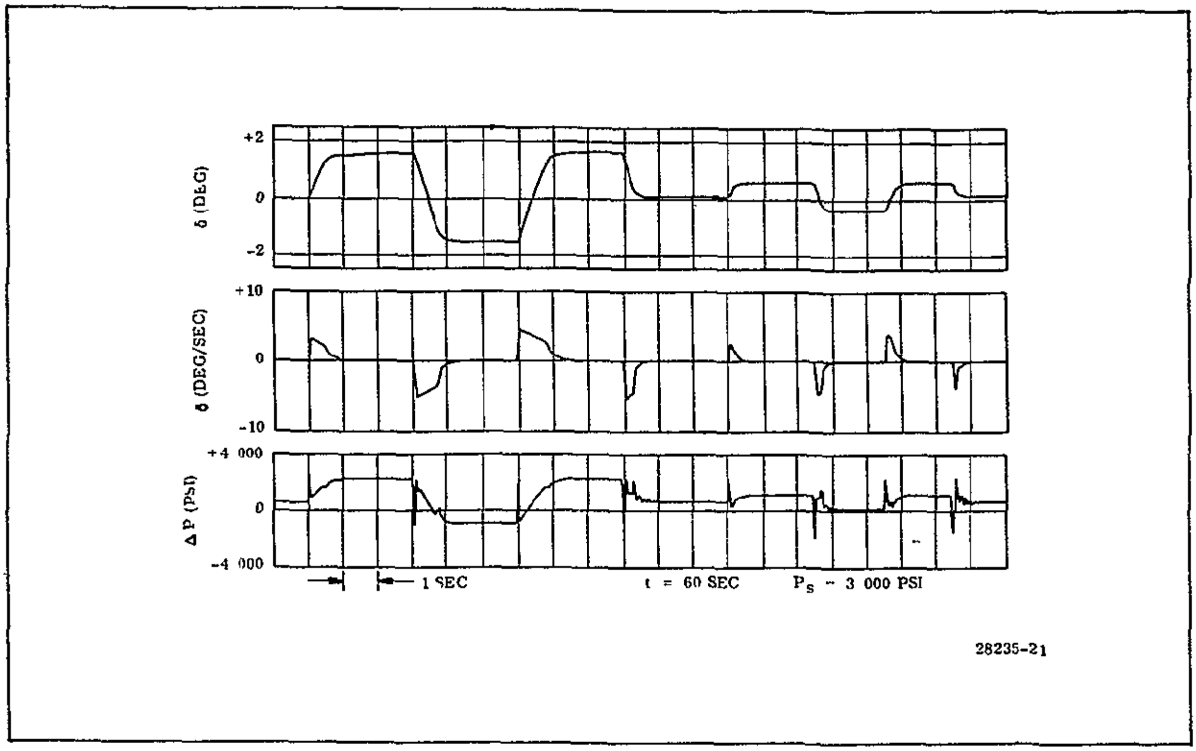


Figure 14. Response to Step Inputs

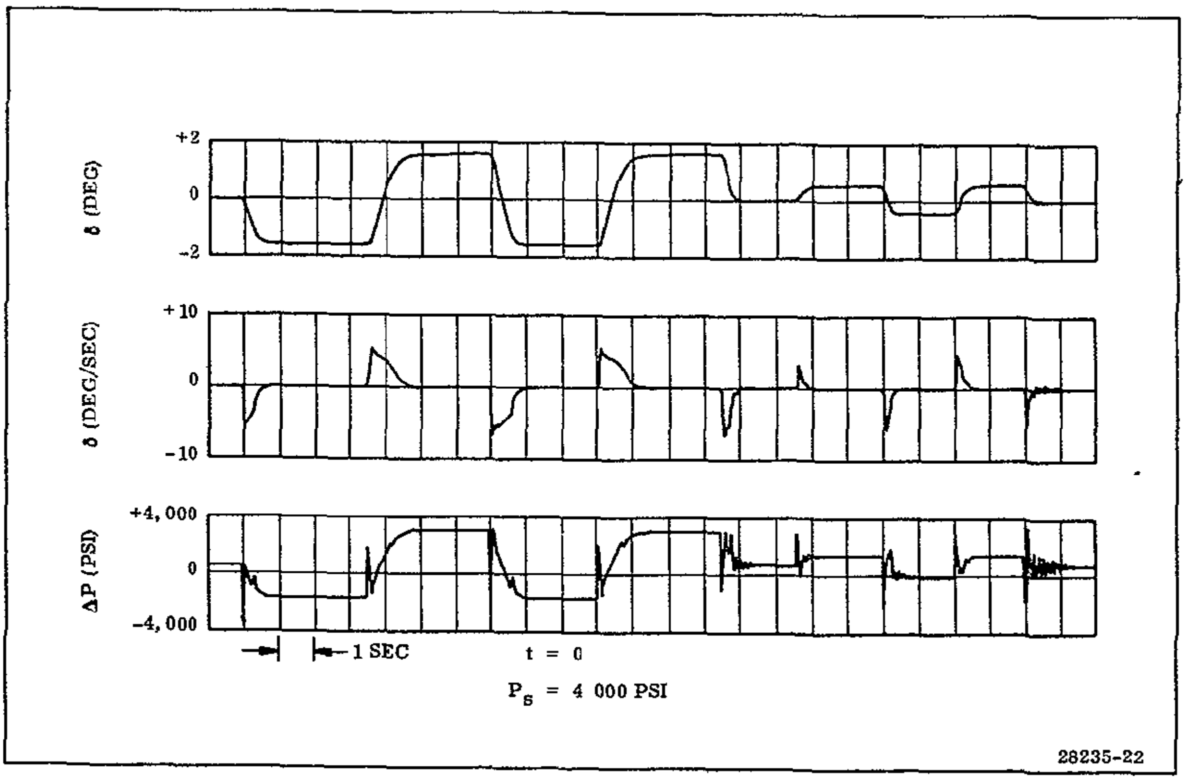


Figure 15. Analog Analysis

Figures 14 and 15 also show the response of the system to small step changes This was done to insure stability for small disturbance about the null position.

The duty cycle was put on magnetic tape and used as an input to the analog computer. The results are shown in Figures 16 and 17. The results of the step inputs described above prove the stability and response of the system, hence, the purpose of the duty cycle input is primarily to demonstrate the ability of the blowdown reservoir to supply sufficient pressure to allow compliance with the duty cycle over the total motor burning time. Note that at the initiation of the 1.61° (0 028 rad) event, supply pressure had decayed to approximately 3,100 psi (2.14 x 10^7 N/m^2) and dropped to 3,000 psi (20.7 x 10^6 N/m^2) at the conclusion of the event (Figure 17). System pressure at the end of firing was 2,680 psi (1 85 x 10^7 N/m^2). The volume of oil expended over the duration of motor firing was 1,660 cu in. (27 2 l) as shown in trace 6 of Figure 17 and the resultant gas volume at this time is 6,720 cu in. (110 l)

Trace 3 of Figure 17 is essentially the pressure margin which exists at anytime. The pressure P_r is that which is required to meet the vector angle at that particular time.

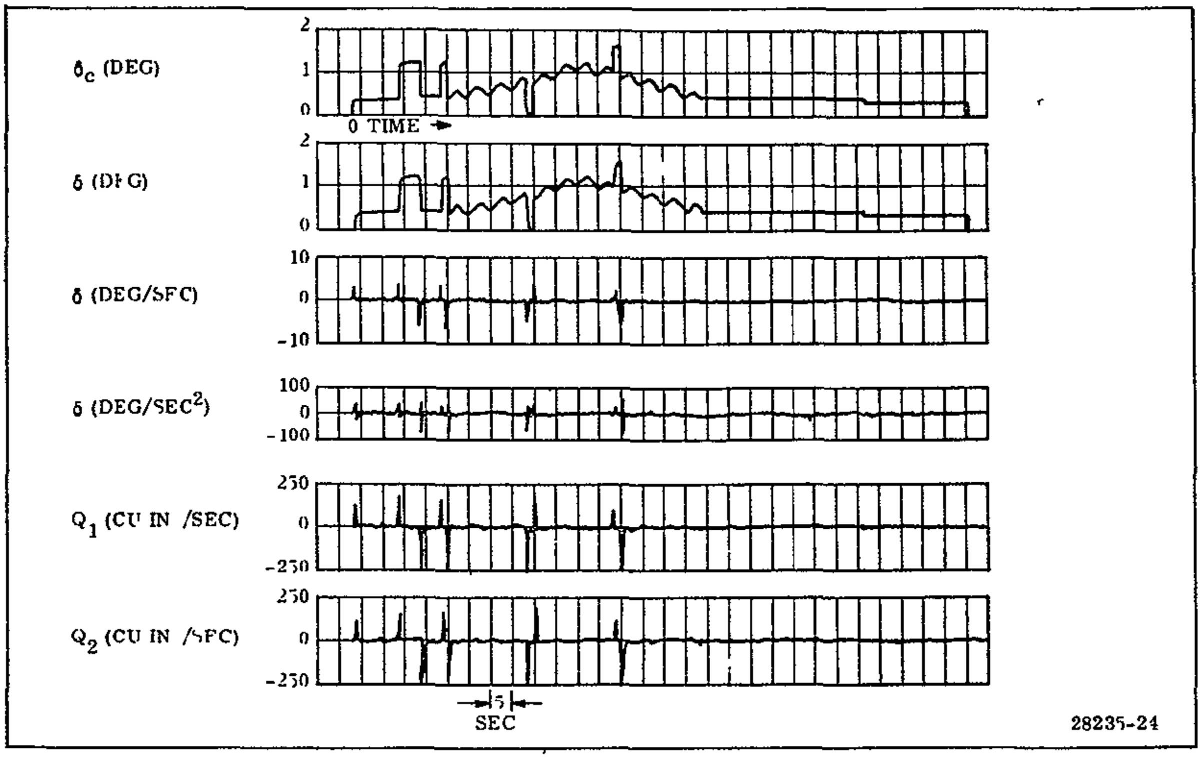


Figure 16 Analog Analysis

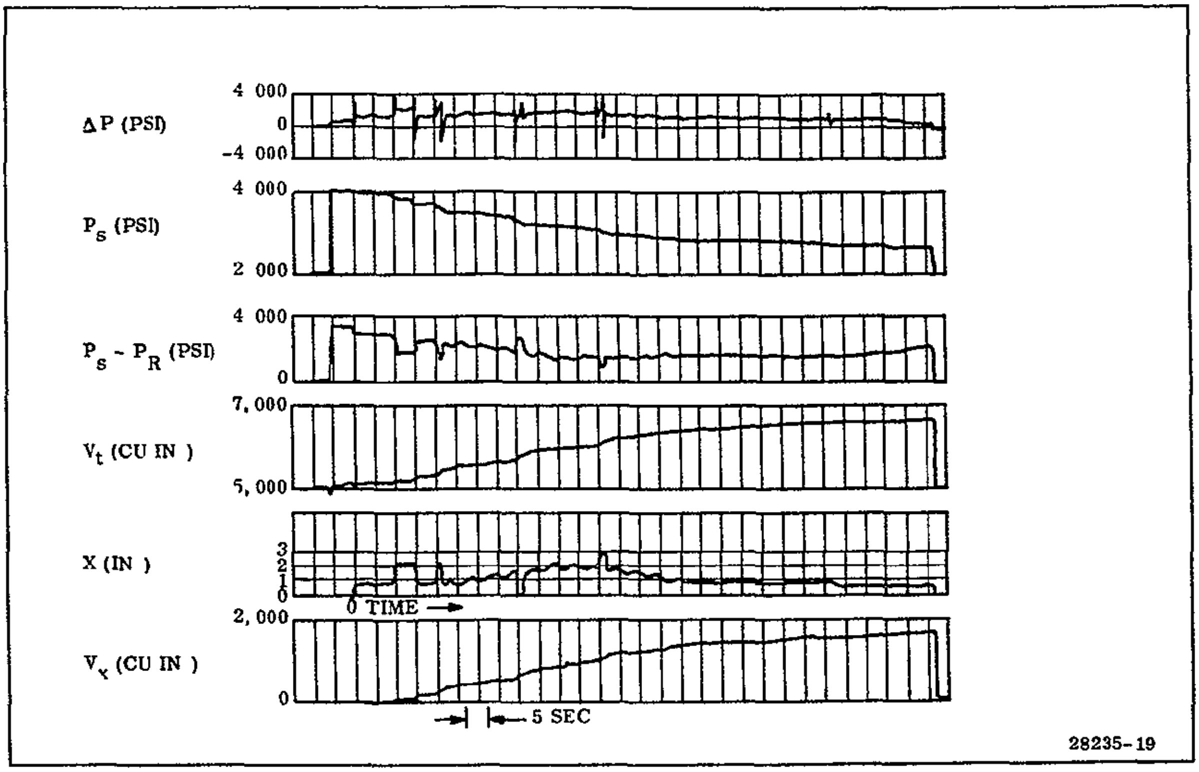


Figure 17. Analog Analysis

Using the duty cycle tape as the input, the constants listed in Table XI were varied in order to determine an optimum system. Final values are those listed in the table.

TABLE XI

CONSTANTS USED IN COMPUTER STUDY

A_p	30 sq in (193.5 cm^2)	T_c	7.5 x 10^4 in -lb (0.847 x 10^4 m-N)
I_n	5.296 x 10^6 in -lb-sec^2 (0.597 x 10^6 m-N-sec^2)	V_o	90 cu in (1.47 l)
K_a	2 x 10^6 lb/in (0.354 x 10^6 kg/cm)	β	250,000 psi (1.725 x 10^9 N/m^2)
K_{fb}	5.0 v/in (1.97 v/cm)	ζ	1.0
K_I	2.1 ma/v	ω	75.39 rad/sec
K_n	1.52 x 10^8 in -lb/rad (0.172 x 10^8 m-N/rad)	f_v	3.5 x 10^6 in -lb sec/rad (0.396 x 10^6 m-N sec/rad)
K_2	0.518 in ^{4}/sec $lb^{1/2}$ ma (32 cm^4/sec $kg^{1/2}$ ma)	P_1	4,000 psi (27.6 x 10^6 N/m^2)
l	94.5 in (240 cm)	V_1	5,060 cu in (82.6 l)
P_o	50 psi (0.345 x 10^3 N/m^2)	γ	1.4
		I_{max}	10 ma

5.8.2 Servoactuator Design--The design of the servoactuator is primarily dependent upon three parameters force, stroke, and linear rate. The force is derived from nozzle torque and actuator geometry. The stroke can be readily determined from the required nozzle vector angle and the lever arm. The linear rate can be obtained from the nozzle slew rate and lever arm. The actuator was designed for a stroke of ± 2 90 in (7 36 cm) and an effective area of 30 sq in. (193.5 cm^2).

5 8.3 Pressurization Tank--The pressurization was sized to have a total volume of 7,590 cu in (124.5 l) The tank was constructed of 4340 steel and heat treated to 200,000 psi (1 38 x 10^9 N/m^2) The tank operates at 4,000 psi (27 6 x 10^6 N/m^2) and is designed for a proof pressure of 6,000 psi (41.4 x 10^6 N/m^2) and burst pressure of 10,000 psi (68 9 x 10^6 N/m^2).

5 8 4 Component Weight Analysis--Weights of the actuator, pressurization tank, and brackets were computed from drawings Other component weights were obtained from vendors or standard tables. The total weight of the actuation system is 881 4 lb (400 kg) which includes the hydraulic fluid and the pressurant Including the nozzle weight of 54,893 7 lb (24,900 kg), the total launch weight is 55,775.1 lb (25,300 kg) During the motor firing, hydraulic fluid will be expelled and some nozzle material will be eroded away The weight expended amounts to 5,000 lb (2,270 kg) for the nozzle and 50 lb (22 7 kg) of hydraulic fluid The burnout weight is 50,725 lb (23,000 kg). Component weights are shown in Table XII

TABLE XII

ACTUAL AND COMPUTED COMPONENT WEIGHT
FOR MOVABLE NOZZLE - FLEXIBLE SEAL

Item		Weight (lb)	kg
Actuator (2)		257.0	116.5
Servovalve (2)		5.5	2 49
Actuator bracket (2)		66 1	30.0
Tank		244.5	111 0
Solenoid valve		5.2	2 36
Tank mounting brackets		14.5	6 57
GN_2		58.0	26 3
Filter bracket		30.1	13 65
Filter		4.5	2 04
Tubing and fittings		38 7	17 55
Hydraulic fluid		106.1	48 2
Miscellaneous brackets and hardware		36 3	16.45
Accessory equipment		14.9	6 75
	Subtotal	881.4	400 00
Nozzle weight		54,893.7	24,900 00
	Total	55,775.1	25,300 00
Burnout weight (lb)	50,725	23,000	

5.9 Cost Analysis for Detail Design

Extensive planning was essential in preparing meaningful cost estimates for the development and production of the movable nozzle flexible seal TVC system This planning included preparation of (1) manufacturing plans detailing the various assembly and inspection operations and (2) development program plans describing what is considered to be a reasonable development and qualification effort for the TVC system.

The overall cost summary for the movable nozzle-flexible seal program is spread in Table XIII. Table XIV provides a breakdown of the system components on a unit cost basis. The nozzle components were priced at $650,522 with 35,000 labor hours.

6. MECHANICAL INTERFERENCE TVC SYSTEMS

6.1 Literature Search

Using reliability as the main criterion, a literature search was conducted for mechanical interference TVC systems. The six systems studied were mechanical probes jetavators, jet tabs, supersonic splitline, flexible exit cone, and jet vanes. Information was scarce and generally not applicable to large motors with small vector angles

6.1.1 Mechanical Probes--Available information on mechanical probes was related to high vector angles on small motors. A great deal of development effort is required before considering probes as a high reliability method of TVC

6.1.2 Jetavators--A jetavator is an aerodynamically contoured ring or ring segment that fits around the nozzle circumference at the exit plane It is mounted on bearings on opposite sides of the nozzle so that it can be rotated past the rim of the nozzle and down into the exhaust stream. A shock wave is formed in the nozzle. Downstream of this shock there is a high pressure region that acts on the jetavator ring providing the necessary side force. Here again the literature revealed no experience with either large motors or small vectoring angles.

6.1.3 Jet Tabs--The jet tab concept is based, as in the case of a mechanical probe, on the generation of a shock wave around the leading edge of a blunt object inserted in the exhaust stream. Higher pressures are generated behind the shock than on the opposing wall of the nozzle, thereby providing the control force Unlike the probe, however, the jet tab is located at the exit plane of the nozzle. The literature search revealed experience with large motors using jet tab TVC. Lockheed Propulsion Company's 156 in. motor provided an important source of information for 260 in. application

6.1.4 Supersonic Splitline--Because of the many advantages of movable nozzles for TVC, an extensive effort has been conducted during the last decade on the development of movable nozzle concepts. Two TVC systems that have evolved from movable nozzle technology are the supersonic splitline and the flexible exit cone (Flex-X). In both concepts, the joint between the movable and fixed portions of the nozzle is located downstream of the throat in the supersonic flow section Optimum splitline location appears to lie between expansion ratio of 1 5 and 2.5.

TABLE XIII

FLEX BEARING TVC SYSTEM SUMMARY

	1971 First	1971 Second	1972 First	1972 Second	1973 First	1973 Second	1974 First	1974 Second	1975 First	1975 Second	1976 First	1976 Second	1977 First	1977 Second	Total
1 Design															
Labor	96 000	100 200	20 340	14 140	--	--	--	--	--	--	--	--	--	--	230 680
2 Component development and system testing															
Labor	3 143	70 631	--	-	--	--	--	--	--	-	--	--	--	--	73 774
Material	377 814	201 075	--	--	-	--	--	-	--	--	-	--	--	--	578 889
3 Qualification (3 R & D systems)															
Labor	--	2 531	848 886	--	-	--	--	--	--	-	-	--	--	--	851 417
Material	-	265 000	2 153 716	--	--	--	--	--	-	--	-	--	--	--	2 418 716
4 PFRT (7 PFRT systems)															
Labor	--	--	219 512	1 801 093	--	--	--	--	--	-	--	--	--	--	2 020 605
Material	-	-	684 572	4 107 432	-	-	--	--	--	-	--	-	--	--	4 792 004
5 Production (70 systems)															
Labor	--	--	--	--	522 386	544 343	552 427	575 187	583 271	607 697	616 585	642 551	651 534	679 003	5 974 984
Material	--	-	--	--	1 369 144	1 369 144	1 369 144	1 369 144	1 369 144	1 369,144	1 369 144	1 369 144	1 369 144	1 369 144	13 691 440
6 Administration and support															
Labor	84 281	87 873	89 110	92 927	94 266	98 327	99 777	104 018	105 525	110 038	111 633	116 409	118 078	123 149	1 435 341
Other direct	8,782	11,914	49 125	78,630	25,320	26,360	26,742	27 822	28 205	29,362	29,782	31,012	31,438	32,740	437,231
Total direct cost	570 000	739 174	4 065 261	6 094 222	2 011 116	2 038 174	2 048 090	2 076 171	2 086 145	2 116 241	2 127 144	2 159 116	2 170 194	2 204 036	32 505 084
Estimated overhead	346,910	488,903	2,409,629	3 804,975	1,230,487	1,269,383	1,283,647	1,323,993	1,338,320	1,381,575	1,397,238	1,443 138	1,459,072	1,507,636	20,684,904
Total cost	916 910	1 228 077	6 474 890	9 899 196	3 241 603	3 307 557	3 331 737	3 400 164	3 424 465	3 497 816	3 524 382	3 602 254	3 629 266	3 711 672	53 189 989

TABLE XIV

MOVABLE NOZZLE SYSTEM COMPONENTS
(ROM Cost Summary)

Item No.	Component	Vendor Tooling and Devel Costs	Per Unit Costs
1	Pressurization tank No. TUL 13098	$112,191	$ 7,057
2	Solenoid valve	--	385
3	Quick disconnect	--	40
4	Burst disc assembly	--	20
5	Pressure transducer - (2 each at $1,200 each)	--	2,400
6	Liquid level sensor	--	1,800
7	Hydraulic fluid (15.3 gal at $2.25/gal)	--	34
8	GN_2 - (800 cu ft at $0.01 SCF)	--	8
9	Brackets and clamps		
	Nozzle clevis (2)	--	--
	Actuator mount (2)	--	--
	Filter (1)	--	--
	Flex hose mounting (4)	--	--
	Tank mounting (4)	--	--
	Main hydraulic supply line (3)	--	--
	Pressure and return clamp (4)	--	--
	Total 20 units = 141.5 lb - No. 4130 steel at $0.47 lb	--	67
10	Actuators (No. TUL 1309?) - (2 each at $4,620 each)	44,745	9,240
11	Servovalve - (2 each at $1,000 each)	--	2,000
12	Filter	--	165
13	Check valve	--	103
14	Quick disconnects - (2 each at $50 each)	--	100
15	Servoamplifiers/elec harness	--	9,000
16	ΔP transducers - (2 each at $500 each)	--	1,000
17	Tubing		
	1-1/4 in. x 0.089 S/Steel (136 in. at $3.50/ft)	--	40
	1-1/4 in. x 0.035 aluminum (16 in. at $3.50/ft)	--	5
	1 in. x 0.065 S/Steel (142 in. at $3.50/ft)	--	41
	1 in. x 0.035 aluminum (142 in. at $3.50/ft)	--	41
18	Flex hose (high pressure) - (2 each at $85)	--	170
19	Flex hose (low pressure) - (2 each at $85)	--	170
20	Swivel connectors 1 in. (4 each at $15)	--	60
21	Unions 1 in. (8 each at $5)	--	40
22	Tee 1 in. (2 each at $5)	--	10
23	90° elbow - 1-1/4 in. (2 each at $5)	--	10
24	Tee - 1-1/4 in. (2 each at $7)	--	14
		$156,936	$34,020

NOTE

All estimates are Thiokol Engineering estimates or catalog prices, except items numbered (1) pressurization tank (2) solenoid valve, (4) burst disc assembly (6) liquid level sensor, (10) actuators, (11) servovalve, (12) filter, and (13) check valve, which were obtained from a vendor quote

6.1.5 Flexible Exit Cone--The flexible exit cone (Flex-X) consists of a standard nozzle - submerged or external in which a section of the exit cone is replaced by a flexible joint composed of layers of elastomer and plastic reinforcements. Thiokol is currently conducting a program, funded by AFRPL, to demonstrate this concept which combines the advantages of the supersonic splitline (lower nozzle ejection loads and side force amplification) with those of a flexible bearing (no gimbal ring or splitline seal). The demonstration phase has not yet been completely successful. Problems appear to lie in the area of joint processing and fabrication. There is no development experience for large motor Flex-X TVC systems.

6.1.6 Jet Vanes--Jet vanes are aerofoils located in the exhaust stream of a nozzle, usually just aft of the exit plane. Deflection of the vane produces a lift force, which is a lateral force relative to the direction of axial thrust, resulting in a turning moment about the vehicle cg. A drag force on the vane always exists during firing resulting in a continuous loss in axial thrust. The literature revealed that major material development problems would occur with the extended burning time of the 260 in. motor.

6.2 Design Requirements and Selection Criteria

Each mechanical interference TVC system was evaluated with respect to specified design requirements. Selection of the most promising system was based primarily on its reliability with respect to current technology and its potential cost. Secondary factors such as weight, development history, etc, were considered when necessary.

The duty cycle was multiplied by 1.16. Total injection impulse was 69.6°-sec (1.215 rad-sec). Maximum equivalent TVC angle was 1.4° (0.0244 rad). This applied for an equivalent point of side force insertion located 772 in. (19.6 m) aft of the initial vehicle center of gravity. The magnitude of the side force requirement varied depending upon its point of application in the nozzle. Adjustments were made accordingly and the turning moment acting on the vehicle was maintained constant at 109.6 x 10^6 in.-lb (12.4 x 10^6 N-m). Maximum slew rate was 3°/sec (0.0524 rad/sec) and motor burning time was 143 sec. Combustion gas temperature was assumed to be about 5,800°F (3,478°K). These requirements are tabulated in Table XV.

TABLE XV

MITVC DESIGN REQUIREMENTS

Parameter	English Unit Value	SI Unit Value
Total injection impulse	69.6°-sec	1.215 rad-sec
Maximum equivalent TVC angle	1.4°	0.0244 rad
Equivalent point of side force insertion - distance aft of cg	772 in	19.6 m
Maximum required equivalent slew rate	3°/sec	0.0524 rad/sec
Motor burning time	143 sec	143 sec
Combustion gas temperature	5,800°F	3,478°K

6.3 Preliminary Design and Screening

Only those systems which are (or have been) operational, or are under development were investigated. This restriction was imposed primarily by considerations of reliability and cost, the two most important criteria of this study.

Mechanical probes could be either cooled or uncooled. Supersonic splitline could employ either a gimbal ring or flexible bearing to provide thrust vectoring capability. Each of these, in turn, was investigated. Jetavators, jet tabs, Flex-X, and jet vanes were also considered.

To insure inherent reliability of each system a conservative approach was taken. Existing materials, material configurations, and fabrication techniques previously demonstrated were employed wherever possible. However, in the case of jet vanes, it appears that a breakthrough in current materials technology is necessary before a vane can be built which will reliably withstand the relatively long burning time of the 260 in. motor.

Experimental and theoretical data were used to size specific control elements, tabs, probes, etc. It should be realized, however, that a general lack of scale-up data and in some cases (probes) lack of data at small TVC angles, resulted in many approximations. Wherever possible, system parameters were optimized (probe location, pivot point, splitline location, etc) but often parametric data of this kind were severely lacking.

Although sizes, weights, and performance penalties are preliminary, all reflect the same state-of-the-art and completeness in design and are considered valid for comparative purposes.

6.3.1 Mechanical Probes--

6.3.1.1 Probe Sizing and Location--The most significant parameter in determining available side force and probe size from mechanical probe systems is blockage ratio.

Analysis of available probe data indicates that the side force ratio F_s/F_a of an optimum probe system is directly proportional to the blockage area ratio at the probe insertion point, ie,

$$F_s/F_a \doteq K\frac{A_p}{A_1} \quad \text{where } K = 1$$

F_s = side force

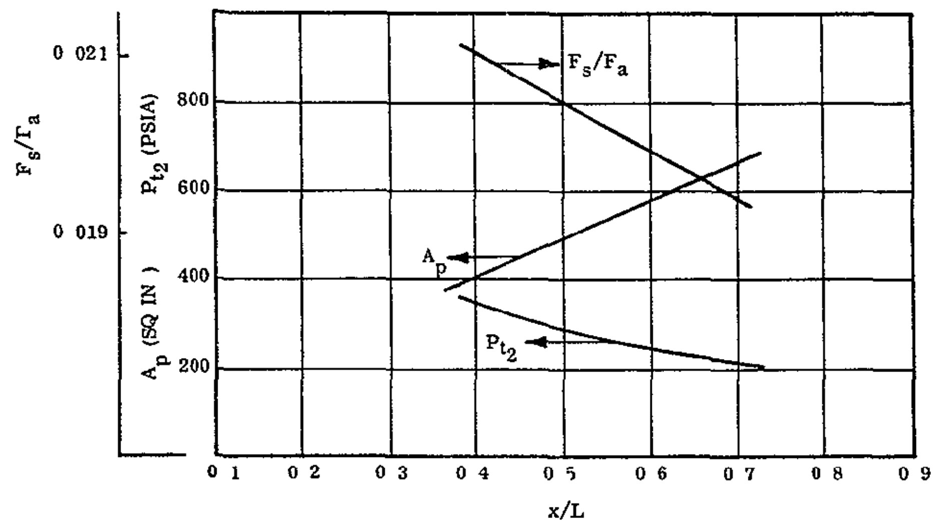
F_a = nominal axial thrust

A_p = probe projected area

A_1 = nozzle cross sectional area at probe insertion point

To maintain a constant turning moment about the vehicle cg, side force ratio requirements necessarily vary with probe location. Figure 18 shows the side force and probe projected area requirements at various locations within the nozzle of the 260 in. vehicle. The pressure immediately behind the bow shock wave acting on the front face of the probe is also shown.

It can be seen that as probe location moves closer to the throat the required projected area of the probe becomes less, resulting in a smaller probe. However, at low x/L ratios, there is the possibility that the shock produced by the probe may interact with the opposite wall of the nozzle causing a reduction in the side force produced.



NOTES 1 ALL POINTS ALONG F_s/F_a CURVE GIVE CONSTANT TURNING MOMENT FOR VEHICLE
2 $F_s/F_a = A_p/A_t$

28235-17

Figure 18 Probe Projected Area Requirements

The optimum probe location was determined to be between x/L = 0.5 and 0.7 inserted perpendicular to the nozzle wall Table XVI shows the variation of probe size for x/L ratios of 0.4, 0.5, and 0.6, and for one, two, and three probes per quadrant. Probe sizes indicated, are extremely large, relative to those previously tested, most of which have been less than 1 in. in diameter. A single cooled probe 1 33 in. (3.378 cm) in diameter was tested by Bendix, but this only made one insertion and retraction before it became stuck. The test proved inconclusive.

6.3.1.2 Design Considerations--Many factors influence the overall probe design, bending moment, probe grouping and materials, and nozzle orifice size The combined impact of these factors make probes unattractive for large motors with extended burning times.

Bending moments acting on the probe are very high. The minimum distance from the center of pressure of the probe (at full insertion) to any kind of bearing surface is 1.5 times the full insertion depth, or 33.2 in. (84.2 cm). Since the bearing must be thermally protected from hot exhaust gases passing through the nozzle cutout/

probe gap, actual distance to the bearing surface will probably be greater than this Figure 18 shows that the pressure acting on the front face of the probe decreases as probe location moves nearer the exit plane It decreases at approximately the same rate as the probe area requirement increases, resulting in an approximately constant probe loading of 141, 000 lb (632, 000 N)

TABLE XVI

APPROXIMATE PROBE DIMENSIONS

x/L = 0 4 A_p = 405 sq in			x/L = 0 5 A_p = 490 sq in.			x/L = 0 6 A_p = 580 sq in		
No Probes	D_p	H	No Probes	D_p	H	No Probes	D_p	H
1	17 8	22 7	1	5	98 0	1	5	116 0
1	22 3	18 2	1	10	49 0	1	10	58 0
1	26 7	15 2	1	20	24 5	1	20	29 0
1	31 2	13 0	1	30	16 3	1	30	19 3
1	35 6	11 4	1	40	12 3	1	40	14 5
2	5	40 5	2	5	49 0	2	5	58 0
2	10	20 3	2	10	24 5	2	10	29 0
2	15	13 5	2	15	16 4	2	15	19 3
2	20	10 2	2	20	12 3	2	20	14 5
2	30	6 8	2	30	8 2	2	30	9 7
3	5	27 0	3	5	32 6	3	5	38.6
3	10	13 5	3	10	16 3	3	10	19 3
3	15	9 0	3	15	10 9	3	15	12 9
3	20	6 8	3	20	8 2	3	20	9 7
3	30	4 5	3	30	5.5	3	30	6 45

A_p = Approximate probe projected area (sq in)

D_p = Approximate probe diameter (or width) (in)

H = Approximate probe inserted height (in)

An estimate of probe performance loss was obtained from cold flow test data from Bendix and LMSC, in which excellent correlation was noted. The data show a thrust loss of approximately 0 5 percent at a TVC angle of 1 175° (0 0205 rad) This is the thrust vector requirement at a probe location of x/L = 0 5 to maintain the turning moment on the vehicle specified in the design requirements of this report.

$F_a = 6.047 \times 10^6$ lb ΔF_a = (0.005) (6.047×10^6) = 30,200 lb (135,200 kg)

Total injection impulse = 60 x 1.16 = 69.6°-sec (1.215 rad-sec)

Impulse loss = 30,200/1.175 (69.6) = 1 789 x 10^6 lb-sec = 0.21%

Additional propellant necessary to achieve total impulse

= 1.789 x 10^6/254 = 7,040 lb (31,500 N)

6.3.1.3 Cooled Probes--Cooled probes have the potential for reducing probe size, but have the disadvantage of increasing the overall system weight by the amount of coolant required For this reason cooled probes were not considered for further design effort.

Although mechanical probes have been shown to be feasible, and may be attractive from a weight standpoint, extensive development is still required in many areas to show that they are a reliable method for TVC. In view of their rather poor development history mechanical probes were eliminated from further consideration.

6.3.2 Jetavators--

6.3.2.1 Design Considerations--Jetavators applicable to 260 in. solid rocket motors would be extremely heavy and would require extensive material development The spherical jetavator was selected as the best tradeoff profile.

It became apparent from the literature search that application of the jetavator concept to a 260 in. nozzle would result in an extremely large and very heavy control element Jetavator deflection requirements directly affect the width of the jetavator ring which in turn affects the weight of the ring Since the mean diameter of the jetavator ring will be somewhat greater than 260 in. only a small increase in width is necessary to produce a significant increase in weight. It was thus desirable to keep deflection requirements to a minimum.

Of the various shapes that the inner ring surface may take, a spherical profile offers the minimum jetavator deflection for small TVC angles (Figure 19b). In addition, it can be seen that the side force produced by a spherical jetavator is a linear function of angular position. Figure 19a shows the relative actuation torque requirements and Figure 19c shows the relative thrust loss for the same inner ring surface profiles Actuation torque requirements are dependent upon the location of the jetavator pivot axis, however, in the case of the spherical jetavator, the force vector passes through (or very close to) the pivot axis reducing the actuation torque almost to zero

6.3.2.2 Performance Loss--One of the major disadvantages of jetavators is the inherent performance loss associated with the insertion of the rings into the exhaust stream. Preliminary calculations based on Polaris and Bomarc data indicate a total impulse loss of 2.16×10^6 lb-sec (9.7×10^6 N-sec).

6.3.2.3 Jetavator Weight Estimate, Configuration, and Torque Requirements--The concentric ring approach was selected for preliminary sizing purposes These rings would weigh approximately 11,040 lb (5,010 kg). Actuation torque requirements would be 290,000 in.-lb (32,800 N-m) per jetavator The jetavator was eliminated from further consideration during the screening phase due to its weight and overall complexity

6.3.3 Flexible Exit Cone--The flexible exit cone (Flex-X) concept, in which a section of the exit cone is replaced by a flexible joint to permit vectoring, offers considerable potential over other methods of TVC It combines the advantages of a supersonic splitline nozzle (lower nozzle ejection loads and force amplification) with the advantages of a flexible bearing (elimination of the gimbal ring and O-ring

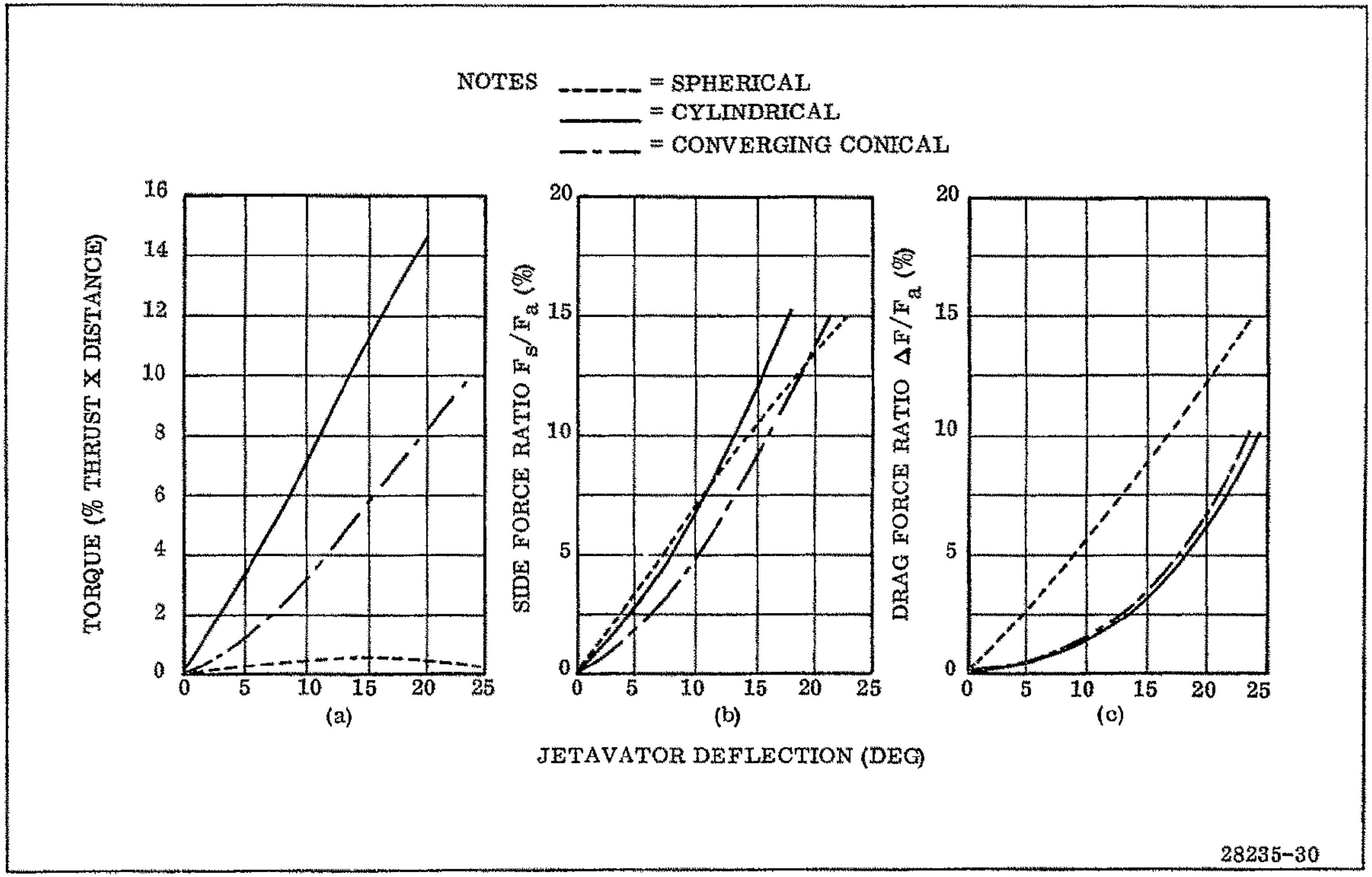


Figure 19. Relative Effect of Jetavator Inner Surface Profile on Torque, Side Force, and Drag

seal). The result is a lightweight nozzle, which, because of the smaller, simpler flexible seal, offers a high reliability potential The major drawback appears to be large actuation requirements as a result of the high internal aerodynamic torque

Development of this concept is still in its early stages. Subscale materials tests have shown that the flexible exit cone nozzle joint can survive exposure to the rocket exhaust gas environment.

The flexible exit concept was eliminated from further design consideration in view of its limited development history

6.3.4 Jet Vanes--Design data on jet vanes proved to be scarce. Theoretical predictions of the flow around a vane deflection system have been of little use to the designer, primarily because of the nonuniform flow in a rocket exhaust and the significant modification to the flow caused by the deflecting vane. Consequently, vane design, particularly profile, has proceeded largely on an experimental basis and usually for a specific application as in the Sergeant and Pershing missile programs.

Jet vanes are necessarily subjected to continuous exposure of the exhaust environment. The resulting materials problem has never been fully solved, despite two extensive materials testing programs conducted during the development of the above two missiles. Severe erosion occurred in both cases although total burning time was relatively short compared to that of other existing rocket motors The Sergeant motor burned for about 26 sec and the Pershing for approximately 39 sec In the latter case, the final acceptable vane configuration sustained a 10 percent loss in planform area The vane was constructed of 85 percent tungsten and 15 percent molybdenum.

Jet vanes were eliminated from further consideration because of the material development problems associated with constant exposure to the 260 in motor exhaust throughout the 143 sec operating time

6.3.5 Supersonic Splitline--

6 3 5.1 Design Concepts--The supersonic splitline approach to TVC has evolved from movable nozzle technology. The splitline between the fixed and movable sections of the nozzle is located in the supersonic section of the nozzle The main advantages being lower nozzle ejection loads and force amplification. Considerations in selection of pivot point location and joint location are the same for all supersonic splitline concepts including that of the flexible exit cone discussed in a previous subsection. Cold flow test data suggest a joint location at an expansion ratio of 2.0 1 is near optimum Pivot point location, depends partly on joint design, but ideally should be located as near to the splitline as possible.

Following selection of the pivot point and joint locations, the supersonic splitline may take one of two configurations (1) the aft movable portion of the exit cone may be vectored by means of a gimbal ring situated around the exit cone at the splitline or (2) the movable portion of the exit cone may be connected to the fixed section by a flexible bearing comprised of alternate layers of elastomer and steel shims. The lightweight and development history of the supersonic splitline concept made it a candidate for further design effort.

6.3.5.2 Torque and Actuation Requirements--One of the disadvantages of the supersonic splitline concept is the high torque requirement. For the two systems considered, the gimbal ring maximum torque was 24 x 10^6 in.-lb (2.71 x 10^6 N-m) and the flexible bearing 27 x 10^6 in.-lb (3.05 x 10^6 N-m)

A tradeoff of various actuation systems (Section 5) also involved high power requirements, approximately 17 x 10^6 in.-lb (1.92 x 10^6 N-m)

The most promising means of supplying this power requirement appears to be a warm gas turbine system driving a variable displacement pump. To satisfy peak power demands, an accumulator is incorporated on the delivery side of the pump. A typical combination would be a Vickers PV3-300 pump incorporating a 500 cu in. accumulator.

6.3 5.3 Description of Candidate Design--The supersonic splitline TVC system selected for the 260 in. motor may be divided into three basic sections: (1) flexible bearing, (2) nozzle support structure, and (3) actuation system

Location of the splitline was at an expansion ratio of 2 0 1 and the pivot point was located approximately 11 6 in (29 4 cm) downstream of the throat.

Of the mechanical interference TVC nozzle designs studied, this concept required the greatest amount of modification to the basic convergent-divergent nozzle The exit cone was "split" into two separate sections with the section forward of the splitline fixed, and the section aft of the splitline movable The interface between the forward and aft sections of the exit cone was spherical in contour and the two sections were joined by a flexible seal consisting of 20 spherical, metal (304 CRES) shims and 21 layers of elastomer. The metal shims were each 0.050 in (0.127 cm) thick, while the elastomer layers were each 0 025 in. (0 0635 cm) thick.

The nozzle assembly weight was calculated to be 58,890 lb (27,600 kg), an increase of 10,990 lb (4,980 kg) over the basic fixed nozzle. Of this increase, 220 lb (99.8 kg) was attributable to the flexible seal, 4,693 lb (2,125 kg) resulted from the fixed section structure (including forward end ring) buildup, and the remaining 6,077 lb (2,760 kg) was in the support structure of the movable section.

The total torque required to vector the nozzle was 27 18 million in.-lb (3.06 x 10^6 N-m) broken down as follows·

	in.-lb	N-m
Internal aerodynamic torque	15,486,575	1.748 x 10^6
Offset torque	3,871,643	0.437 x 10^6
Gravity torque	5,113,798	0.579 x 10^6
Seal torque	2,343,989	0.265 x 10^6
Boot torque	366,662	41,400

Vectoring of the movable portion of the exit cone is achieved by hydraulic linear servoactuators driven by a variable displacement pump Warm gas turbine system supplies the power for the pump. This type of actuation system was the most attractive from a weight and reliability standpoint. A servopump system was also considered but as servopumps are not generally off the shelf items they were rejected for reasons of cost.

The weight breakdown of the supersonic splitline is as follows:

	lb	kg
Nozzle assembly (with bearing)	58,890	26,700
Servoactuators (2)	400	181.5
Gas generator	280	127
Pump	28	12.7
Turbine gearbox	42	19.05
Hydraulic fluid	76	34.5
Accumulator	33	14.98
Miscellaneous (lines, filters, reservoir, etc)	226	102.5
Total weight	59,975	27,200

6.3.6 Jet Tabs--Jet tab design was largely based on data from Lockheed's 156 in. diameter motor program. Two main reasons for this were (1) Lockheed's tabs alone would produce almost 60 percent of the side force requirement of the 260 in. diameter launch vehicle and (2) a tab configuration had evolved from materials evaluation testing, conducted during the 156 in. program, that successfully demonstrated the capability for survival in the extreme conditions of the exhaust environment. Much of Lockheed's technology thus could be applied directly to the 260 in. diameter motor jet tab design.

Figure 20 shows the relationship between exhaust jet deflection and exit area blockage ratio. At the exit plane, a TVC angle of 1.03° (0.018 rad) or side force ratio (F_s/F_a) of 0.017 is required. This results in a blockage ratio of 0.03 or a tab projected area of 1,592 sq in. (10,280 cm^2). Construction and handling of tabs with these dimensions would be exceedingly difficult. Adopting two tabs per quadrant results in a tab area of 850 sq in. (5,480 cm^2), or slightly more than half that of a single tab. In any case, the single tab violates the aft skirt envelope of the 260 in. launch vehicle.

6.3.6.1 Design Considerations--Jet tab construction is a composite structure comprising a refractory face plate, a backup plate also refractory, heat sink, insulation, steel support structure and outer insulation.

Preliminary data were used to arrive at a typical jet tab configuration for the 260 in. motor application from which an estimated weight could be obtained. The face plate of each tab is composed of 3/8 in. (0.952 cm) thick segmented unalloyed tungsten. This facing is backed by 3/8 in. (0.952 cm) thick sections of 70 percent molybdenum, 30 percent tungsten plate. The heat sink is ATJ graphite, approximately 2.5 in. (6.35 cm) thick, backed by an insulator of silica cloth phenolic. Each tab assembly is held together with refractory bolts. Two typical face retention configurations are shown in the preliminary layout drawing (Figure 21). The first (Detail-A) shows short tungsten bolts threaded into a block of 70 percent molybdenum, 30 percent tungsten, which extends into the graphite heat sink. This, in turn, is bolted to the steel structure

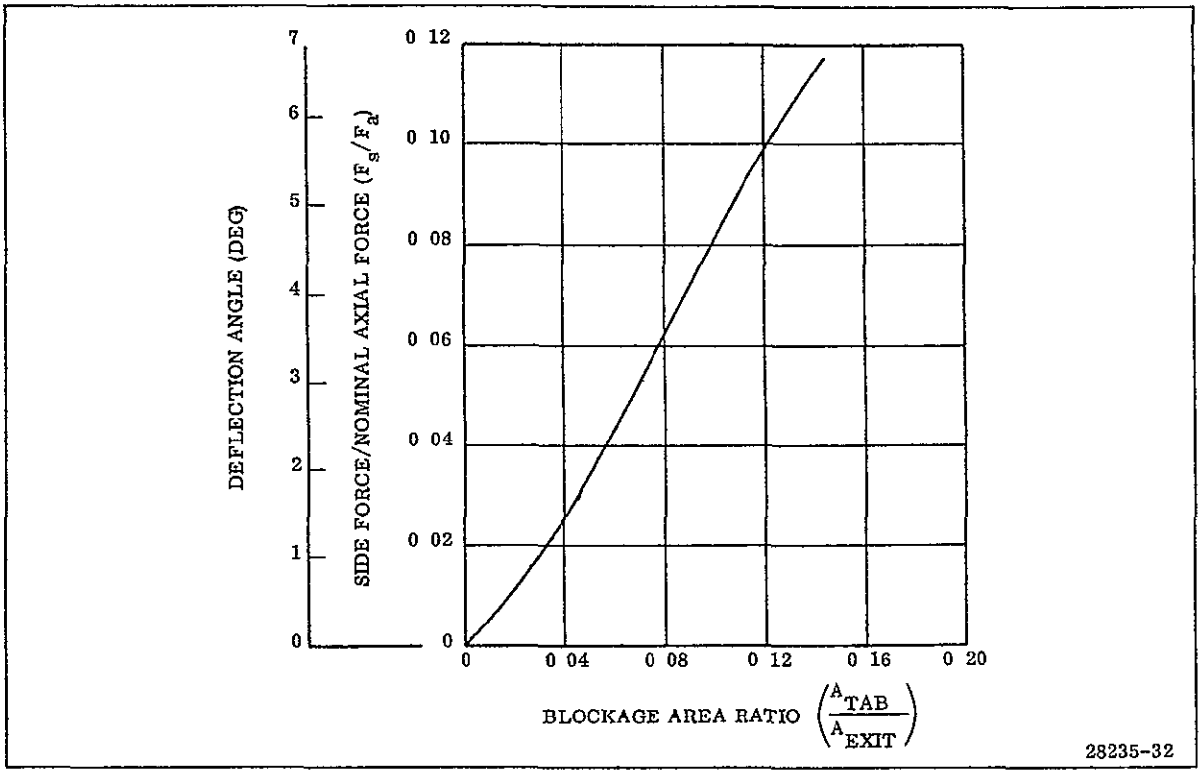


Figure 20 Typical TVC Angle and Side Force Ratio vs Jet Tab Blockage Area Ratio

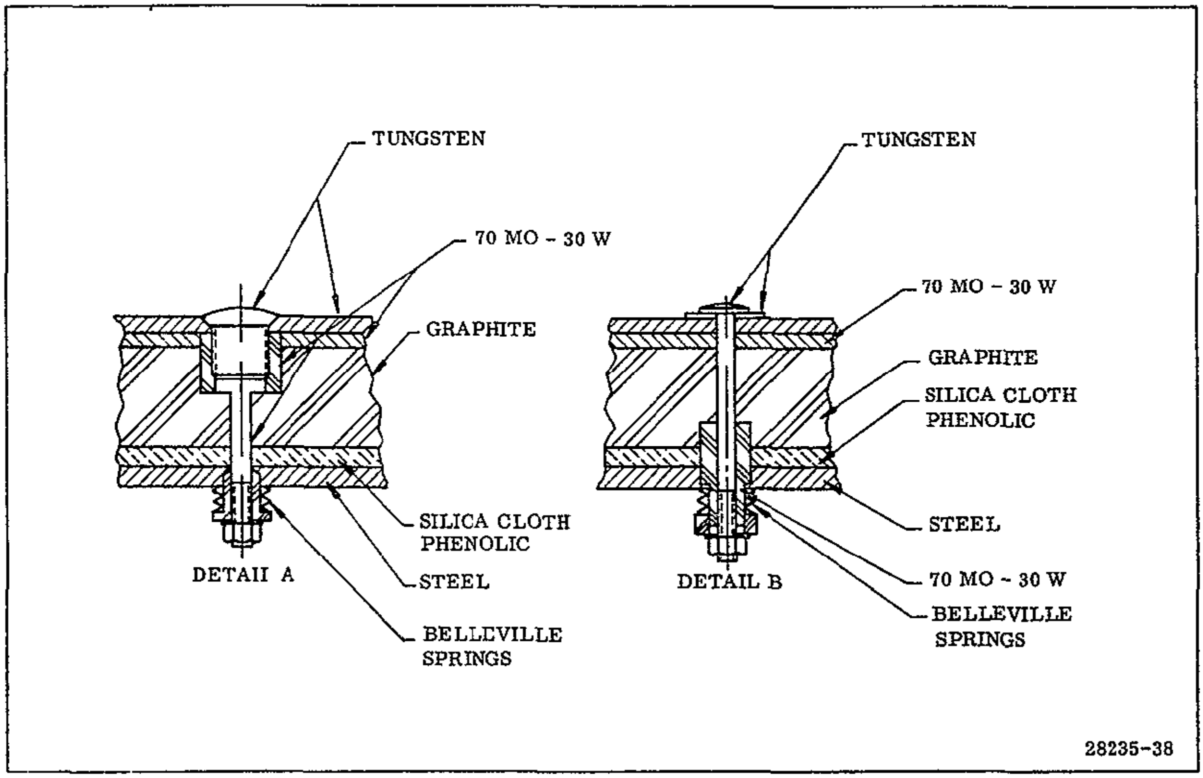


Figure 21 Typical Jet Tab Face Plate Retention Configuration

by means of molybdenum bolts. This type of construction allows for thermal expansion of the face plates and minimizes the loads taken by the tungsten bolts The second (detail-b) simply shows tungsten bolts passing through the complete tab section to the steel support structure. In both cases, Belleville washers maintain constant tension in the bolts as the tab structure expands.

6.3.6.2 Actuation System and Power Requirements--The maximum torque requirement for a 260 in. SRM jet tab system is approximately 107,800 in.-lb (12,200 N-m) Because of weight advantage, a warm gas turbine system using linear hydraulic servoactuators was selected for the jet tabs actuation system

A comparison was made between linear and rotary actuators and between a warm gas turbine and warm gas blowdown system to meet the power requirements of the jet tab system. The results are summarized below

		System Weight		Torque	
	Actuator	(lb)	(kg)	(in.-lb)	(N-m)
Blowdown	Linear	2,988	1,355	120,000	13,560
	Rotary	4,217	1,910	120,000	13,560
	Linear	29.8	13.5	100,000	11,300
	Linear	33.5	15.2	120,000	13,560
	Linear	37.2	16.85	140,000	15,810
Turbine	Linear	1,138	516	120,000	13,560
	Rotary	1,931	875	120,000	13,560
	Rotary	87.0	39.4	100,000	11,300
	Rotary	95.5	43.3	120,000	13,560
	Rotary	102.5	46.5	140,000	15,810

6.3.6.3 Description of Candidate System--Design of the candidate jet tab system included an efficient multiple tab system Redesign of the last 45 in (114.1 cm) of the exit cone to accommodate the jet tabs raised the nozzle weight by 17,593 lb (7,960 kg). The actuation system consisting of a warm gas, high speed turbine driving a fixed displacement hydraulic pump (with accumulator) was designed to produce a torque of 140,000 in.-lb (15,810 N-m)

Figures 22 and 23 show the preliminary layout of the jet tab TVC system selected for the tradeoff study. The design is based largely on the results of Lockheed's 156 in diameter motor test program which successfully demonstrated jet tabs to be an effective and reliable means of TVC on large motors. In fact, Lockheed's tabs, per se, would provide over 60 percent of the side force requirements of the 260 in. launch vehicle under consideration

The selected actuation system weight is approximately 835 lb (378 kg), assuming one actuator per tab. Should torque requirements be increased, the pump selected is capable of a 25 percent increase in power output simply by increasing its speed. The only weight penalty incurred is that of additional propellant in the warm gas generator. For the full 25 percent increase in pump horsepower, the additional propellant would weigh about 31 lb (14.05 kg)

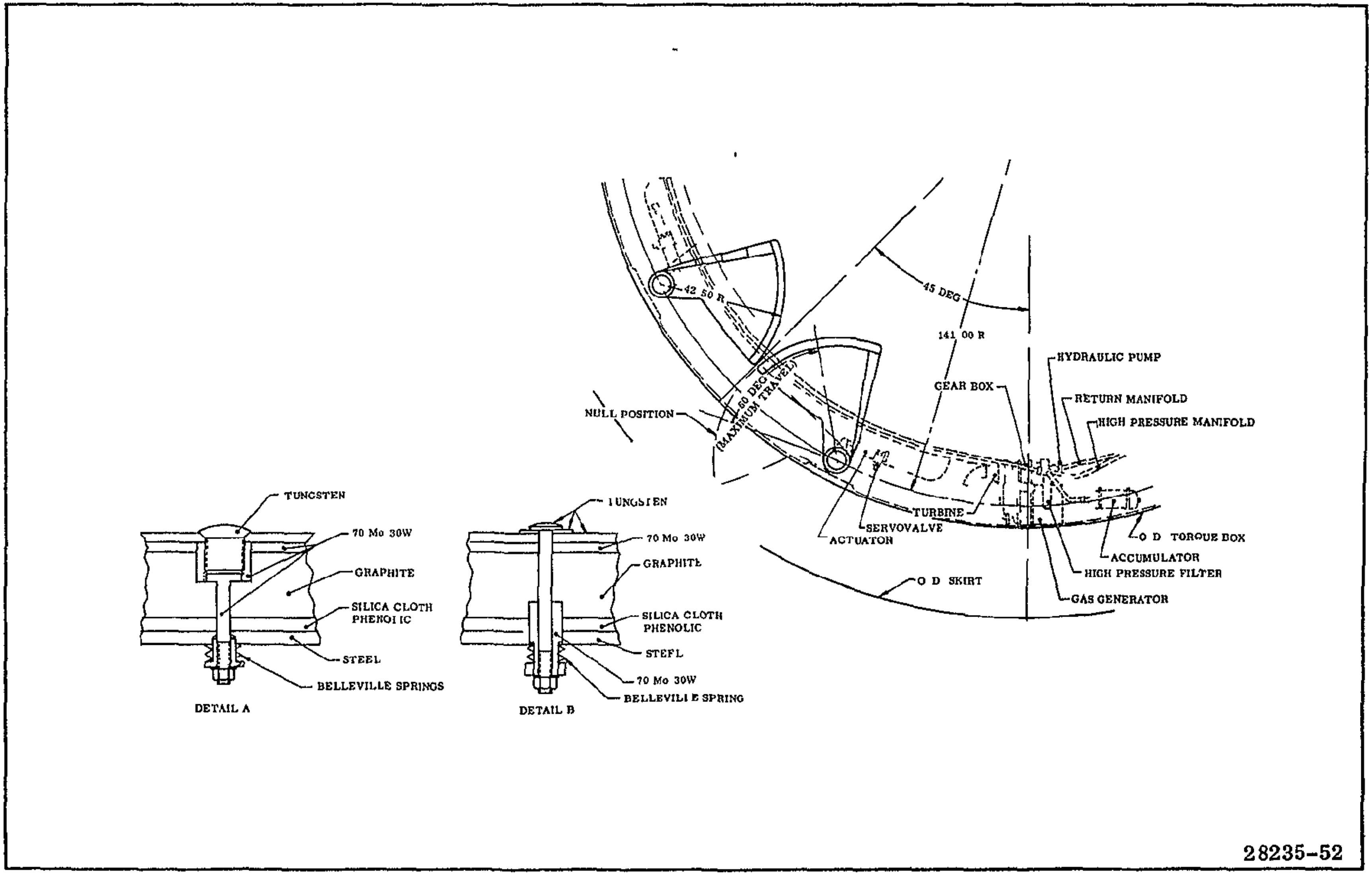


Figure 22. Jet Tabs

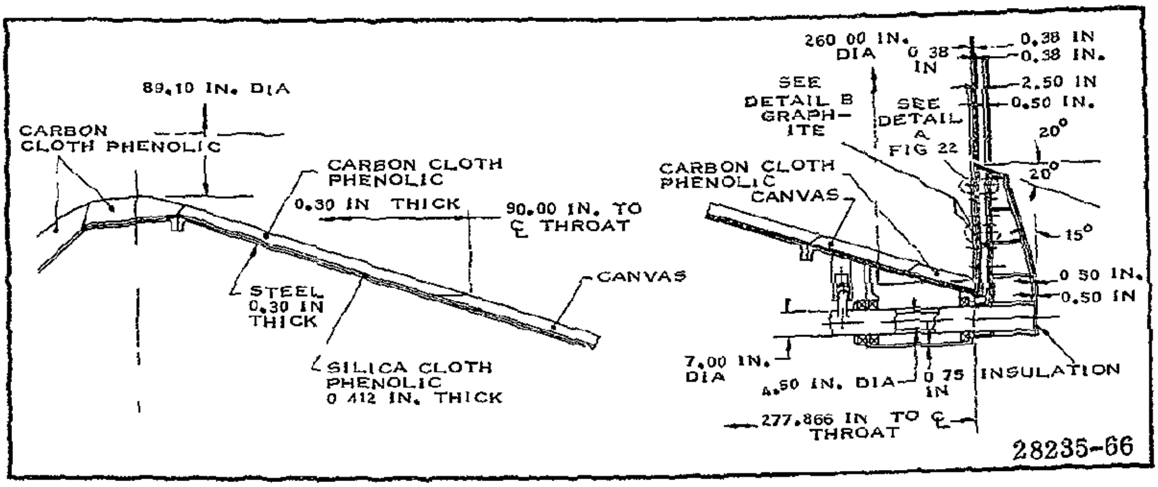


Figure 23 Jet Tabs

The following is a weight breakdown, by component, of the selected jet tab TVC system.

	lb	kg
Modified nozzle (excluding torque box)	65,360	29,600
Torque box	12,000	5,440
Shafts (8)	2,128	965
Tabs (8)	6,264	2,840
Servoactuators (8)	280	127
Pump	20	9.06
Turbine gearbox	40	18.12
Hydraulic fluid	35	15.88
Accumulator	25	10.32
Miscellaneous (lines, filter, disconnect and etc)	200	90.6
Total	86,475	39,200

6.3.6.4 Performance Loss--One of the disadvantages of the jet tab concept is the performance loss incurred as the result of inserting the tab into the motor exhaust. Performance (total impulse) loss was computed to be 2.365×10^6 lb-sec (4.121×10^4 rad-sec)

6.3.6.5 Results of Preliminary Design Review--Following the recommendation of the most promising TVC system in each category (mechanical interference, liquid injection, and movable nozzle) it became clear that MITVC was inferior to the other two systems from many aspects.

Development risk was significantly greater with the MITVC system, primarily because of the severe materials problem. More than 9,000 lb (4,040 kg) of additional propellant are necessary to overcome the performance loss of the jet tab system. Performance loss of the movable nozzle is negligible and LITVC actually provides thrust augmentation. The total preliminary weight estimate of the jet tab TVC system, including the nozzle, was 86,475 lb (39,200 kg) compared to 57,300 lb (25,700 kg) for the movable nozzle and 82,900 lb (37,200 kg) for LITVC. Accordingly, completion of a detailed design of the jet tab TVC system was considered unnecessary and no further work was done on MITVC systems.

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FINAL REPORT SUMMARY

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