Final Report

STUDY OF SELECTED THRUST VECTOR CONTROL SYSTEMS FOR SOLID PROPELLANT MOTORS

Prepared for

JET PROPULSION LABORATORY
Pasadena, California

Contract No. 951189 (NAS7-100)

Period Covered: 2 June 1965 to 2 August, 1965

Report No. SGC 884 FR-1

SPACE-GENERAL CORPORATION
9200 East Flair Drive
El Monte, California

SPACE GENERAL TIRE GENERAL

232

201

cy 1

Final Report

STUDY OF SELECTED THRUST VECTOR CONTROL SYSTEMS FOR SOLID PROPELLANT MOTORS

Prepared For

JET PROPULSION LABORATORY
Pasadena, California

Contract No. 951189 (NAS7-100)

Period Covered: 2 June 1965 to 2 August 1965

Report No. 884 FR-1

R. J. Thomson

R. J. Thomson,
Project Engineer

for R. J. Thomson

R. L. Phen, Manager
Advanced Technology
Center

SPACE-GENERAL CORPORATION
9200 East Flair Drive
El Monte, California

This work was performed for the Jet Propulsion Laboratory, California Institute of Technology, sponsored by the National Aeronautics and Space Administration under Contract NAS7-100.

Preceding page blank

NOTICE

CONTENTS

		Page
SECTION 1 - INTRODUCTION		1-1
SECTION 2 - SUMMARY		2-1
SECTION 3 - RECOMMENDATIONS		3-1
3.1	Auxiliary Systems	3-1
3.2	Movable Nozzle	3-1
3.3	Liquid Injection Thrust Vector Control	3-2
3.4	Plume	3-2
SECTION 4 - TECHNICAL DISCUSSION		4-1
4.1	Introduction	4-1
4.2	Control System Requirements	4-1
4.2.1	System Constraints	4-1
4.2.2	Duty Cycle	4-4
4.2.3	Basic Nozzle Design	4-8
4.3	Preliminary System Analysis	4-16
4.3.1	LITVC System	4-17
4.3.2	Auxiliary Hot or Cold Gas Systems	4-24
4.3.3	Movable Nozzle Systems	4-54
4.3.4	Actuation Force and Auxiliary Power System Weight Analysis	4-66
4.3.5	Reliability Analysis	4-74
4.4	System Selection	4-87
4.4.1	LITVC Systems	4-87
4.4.2	Auxiliary System Comparison	4-91
4.4.3	Movable Nozzle System Selection	4-91
4.5	Selected System Design Description	4-93
4.5.1	LITVC System Design Description	4-93
4.5.2	Cold Gas Auxiliary System - Design Description	4-98
4.5.3	Gimballed Nozzle Design Description	4-103
4.5.4	Development Status and Possible Improvement	4-109

APPENDIX

Appendix A - TVC Study Constraints Provided by JPL

Appendix B - Actuation Force and System Requirements Analysis

Appendix C - Performance of Conical and Contoured Nozzles for Motors with Aluminized Solid Propellants

Appendix D - Preliminary Stress and Deflection Analysis

Appendix E - Reliability Analysis

Appendix F - Nomenclature

Preceding page blank

TABLES

Table		Page
2-1	TVC System Summary	2-2
4-1	LITVC Summary (Cold Gas Pressurization)	4-27
4-2	LITVC Summary (Hot Gas Pressurization)	4-28
4-3	Cold Gas Blowdown Conditions	4-34
4-4	Monopropellant and Bipropellant System Comparison	4-50
4-5	Separate System Gas Generator	4-52
4-6	Nozzle and Actuation Systems Analyzed	4-59
4-7	Actuation System Design Conditions	4-62
4-8	Summary-System No. 1 - N_2 Pressurized Non-Recirculating Hydraulic System	4-70
4-9	Summary-System No. 2 - Non-Recirculating Gas Generator Pressurized Hydraulic System	4-71
4-10	Summary-System No. 3 - Electro-Hydraulic Motor Power Pump Recirculating System	4-72
4-11	Summary-System No. 4 - Gas Turbine Driven Pump Recirculating System	4-73
4-12	Nozzle Weight Comparison	4-75
4-13	Comparison of Gimballed and Translating Nozzles	4-76
4-14	Summary of System Reliability	4-77
4-15	LITVC System Comparison	4-88
4-16	Auxiliary System Comparison	4-89
4-17	Movable Nozzle Comparison	4-92
4-18	LITVC Size and Weight Summary F-114B2 Injectant with GN_2 Pressurization	4-96
4-19	Weight Summary - Gimballed Nozzle System	4-106

ILLUSTRATIONS

Figure		Page
1-0	Program Flow Chart	1-2
4-1	Main Motor Schematic	4-2
4-2	Main Motor Thrust vs Time.	4-3
4-3	Definition of Maximum Pitch Moment	4-6
4-4	Variation of Spacecraft c.g. Error Due to Motor Burn	4-7
4-5	Maximum Pitch or Yaw Moment Due to Thrust Misalignment for Spacecraft c.g. at X = 16.	4-9
4-6	Maximum Pitch or Yaw Moment Due to Thrust Misalignment for Spacecraft c.g. at X = 31.	4-10
4-7	Maximum Roll Moment Due to Thrust Misalignment	4-11
4-8	Baseline Nozzle.	4-12
4-9	Dimensional Tolerance Stack-up for Baseline Nozzle	4-15
4-10	LITVC Side Force Gain Curve.	4-19
4-11	Nozzle Wall Pressure Profile Due to Liquid Injection	4-20
4-12	Freon 114B2 Flow Rate vs Time for X = 16	4-22
4-13	Freon 114B2 Flow Rate vs Time for X = 31	4-23
4-14	LITVC System Schematic - Hot Gas Pressurization.	4-25
4-15	LITVC System Schematic - Cold Gas Pressurization	4-26
4-16	Cold Gas A.C.S. Weight Comparison.	4-30
4-17	Regulated Blowdown System Duty Cycle	4-31
4-18	Regulated Nitrogen System Sizing Parameters vs Time and System Pressure Ratio	4-33
4-19	Spherical Titanium Tank Shell Weight for 32.95 lb Gaseous Nitrogen	4-36

Figure		Page
4-20	Cold Gas Pitch or Yaw System Schematic	4-38
4-21	Monopropellant A.C.S. Schematic.	4-41
4-22	Monopropellant Pitch and Yaw System	4-43
4-23	Bipropellant A.C.S. System	4-51
4-24	Actuator Power vs Frequency.	4-55
4-25a	Actuator Weight vs Power	4-56
4-25b	Actuator Schematic	4-56
4-26	Gimballed Nozzle Preliminary Layout.	4-57
4-27	Translating Nozzle - Preliminary Layout.	4-58
4-28	Movable Nozzle Actuation System No. 1	4-60
4-29	Movable Nozzle Actuation System No. 2.	4-61
4-30	Movable Nozzle Actuation System Nos. 3 and 4	4-62
4-31	LITVC Reliability Trend vs Transit Time.	4-79
4-32	Cold Gas ACS Reliability Trend vs Transit Time	4-80
4-33	Solid Propellant Gas Generator Reliability Trend vs Transit Time	4-81
4-34	Monopropellant and Bipropellant ACS Reliability Trend vs Trend Time	4-82
4-35	Gimballed and Translating Nozzle, Non-Recirculating Hydraulic System, Reliability Trend vs Transit Time. .	4-83
4-36	Gimballed and Translating Nozzle, Recirculating Hydraulic System, Reliability vs Transit Time.	4-84
4-37	Gimballed and Translating Nozzle, Electro-mechanical Actuation System, Reliability Trend vs Transit Time. .	4-85
4-38	LITVC System Design Layout	4-95

ILLUSTRATIONS Cont.

Figure		Page
4-39	Cold Gas Auziliary System Design Layout	4-100
4-40	Cold Gas System Configuration	4-103
4-41	Gimballed Nozzle Design Layout.	4-105
4-42	Dimensional Tolerance Stack-up for Gimballed Nozzle	4-109

Section 1
INTRODUCTION

This study was conducted to evaluate several possible thrust vector control system/propellant combinations within the three concepts, liquid injection into rocket engine exhaust gases, auxiliary hot or cold gas systems, and gimballed nozzles. The general study plan is illustrated in the Program Flow Chart, Figure 1.0. The thrust vector control was to be provided to overcome moments introduced in a space vehicle by thrust misalignment during the firing of a solid propellant motor. The motor thrust axis was nominally aligned to pass through the spacecraft c.g. An evaluation of maximum thrust misalignments to be expected was made and the TVC system duty cycles were derived for two spacecraft c.g. locations.

Several systems of each type were considered and evaluated within each classification. One system of each of the three types was then selected as the best candidate of its type. Design layouts of each of the three systems were drawn and final system weights derived.

Preceding page blank

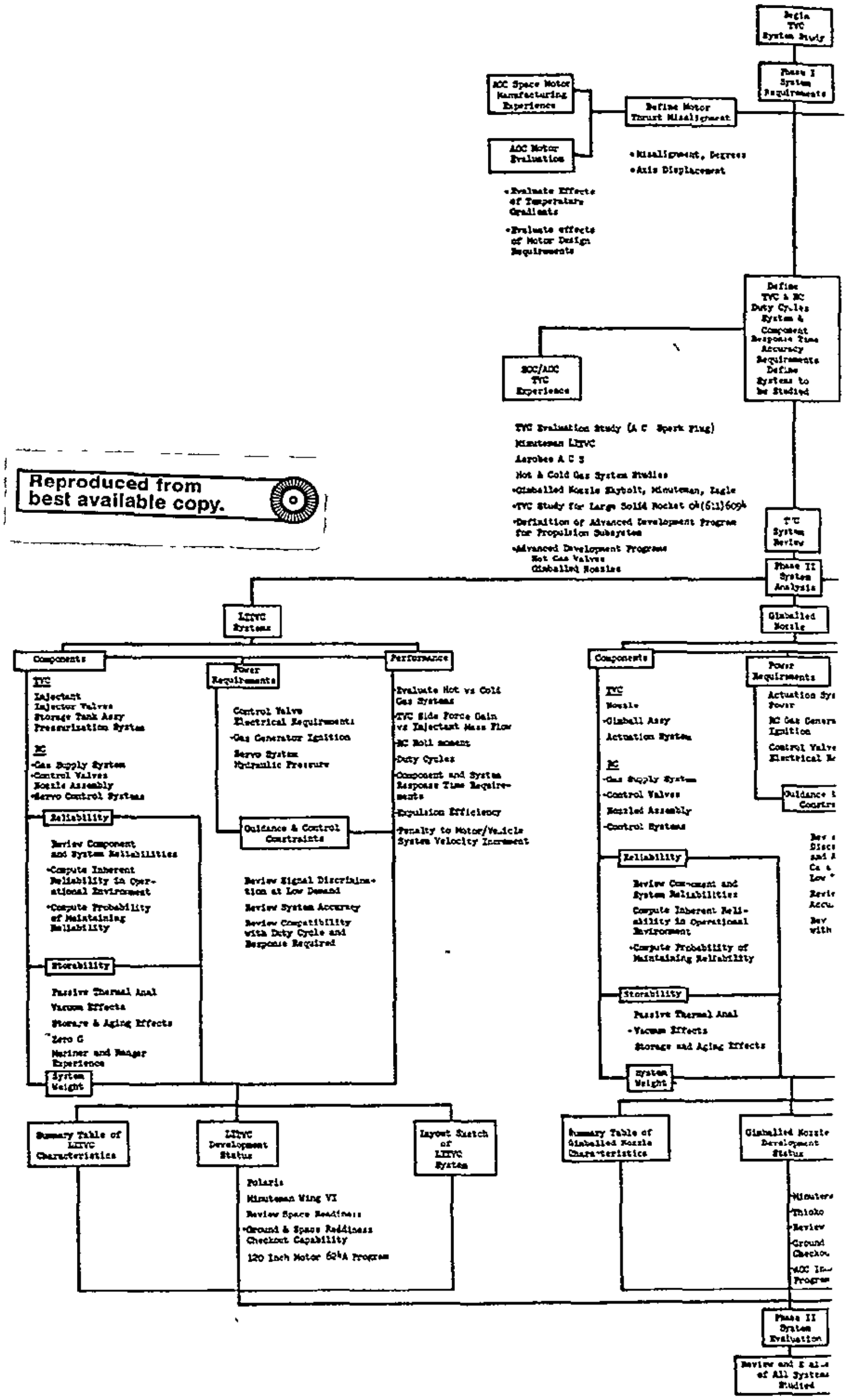


Figure 1-0 Prograr

A

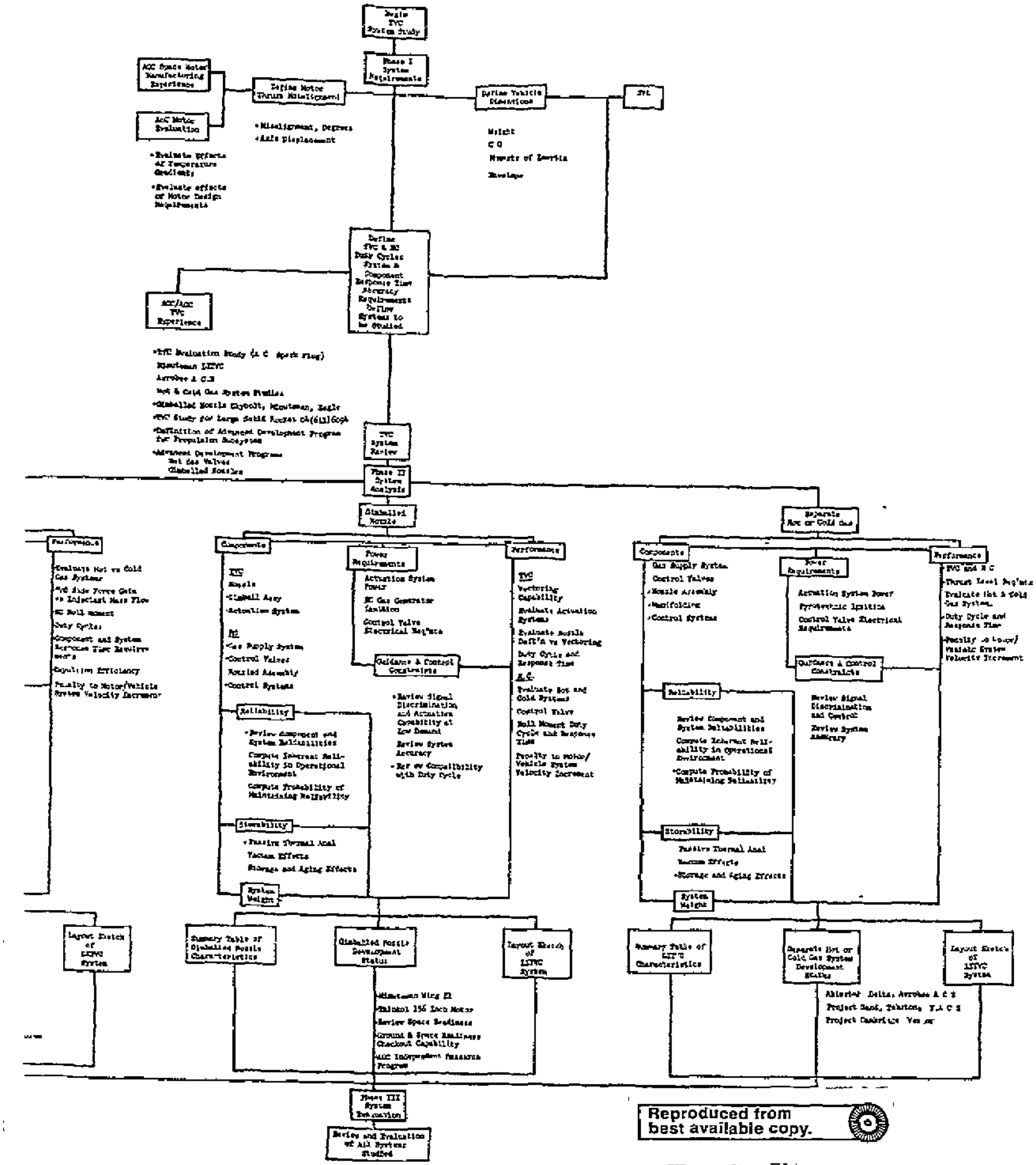


Figure 1-0 Program Flow Chart

B

Section 2

SUMMARY

Liquid injection systems, auxiliary hot or cold gas systems and gimballed nozzle systems were analyzed to determine the size of each type of system required to overcome the maximum possible moment due to thrust misalignment. Within each category several variations of propellant and pressurization systems were considered. Systems were evaluated on the basis of weight, reliability, space storability and state of development. A selection of the most suitable system of each type was made and a design layout of each system was made. The properties of the three systems selected are shown in Table 2-1. Design layouts of the three systems are shown in Figures 4-38, 4-39 and 4-41.

Manufacturing tolerances of solid propellant motors were reviewed and the expected maximum angular misalignment and lateral displacement of the thrust vector were determined. Based on the given thrust-time profile and spacecraft c.g. locations 16 inches and 31 inches aft of the motor case forward end, maximum moments in pitch, yaw and roll were determined. Maximum moment in pitch or yaw is 304 ft lb for the c.g. at 16 inches, and 203 ft lb for the c.g. at 31 inches. Maximum roll moment is 12.6 inch lb. Only the roll moment due to thrust misalignment was considered.

Total possible moment-time profile to be overcome in either the pitch or yaw axis is 15,875 ft lb sec for the c.g. at 16 inches, and 11,155 ft lb sec for the c.g. at 31 inches. System capacity required to overcome a moment between the pitch and yaw planes, with an additional 20 percent to satisfy transient conditions is 26,490 ft lb sec for the c.g. at 16 inches and 18,930 ft lb sec for the c.g. at 31 inches.

Only pitch and yaw control were considered in analysis of the gimballed nozzle and liquid injection thrust vector control system. Roll control was considered, as well, in the analysis of auxiliary hot or cold gas systems.

Preceding page blank

Table 2-1

TVC SYSTEM SUMMARY

System Type	LITVC	Auxiliary Cold Gas	Gimballed Nozzle
Propellant or Injectant	Freon 114B2	Nitrogen	
Pressurization System	Cold Gas		Solid Propellant Gas Generator
Actuation System	Freon Non-Recirculating	Electric Proportional Solenoid	Hydraulic Non-Recirculating
System Weight lb X = 16	133.44	138.39	53.2
System Weight lb X = 31	175.74		62.5
Reliability after six months	.98412	.99974	.99267
Space Storability	Good Some Freon permeates bladder	Good Gas supply seals may be improved by welding	Good if bearings and lubricants are sealed from space vacuum
Development Status	Technology exists for components developed for hot gas pressurization. Flight system can be tested before installation, difficult after installation. New injector valve development required. Motor tests required to establish side force data. The listed weights do not include roll control weight	Components are developed. Flight system can be tested after installation, then recharged. No motor firing tests required for development. The listed weights do not include roll control weight.	All concepts have been developed in other programs except movable submerged throat design. 10 development and 10 PFRT motor firing tests required for development. Gimbal actuation can be performed after installation using slave pressure and hydraulic systems. The listed weights do not include roll control weight

Section 3

RECOMMENDATIONS

On the basis of weight and complexity, the auxiliary cold gas system and the gimballed nozzle are preferred to the LITVC, although incomplete mission data and spacecraft interfaces were available to allow a selection of the most suitable system for the mission. In addition, it appears that cost of development will be less for the cold gas system. This coupled with its high inherent realiability, tend to offset its weight disadvantage.

3.1 AUXILIARY SYSTEMS

It is recommended that a more detailed design analysis be performed on the cold gas auxiliary system. It is expected that design refinements can be made on the proportional valve to integrate the required functions. This should result in some weight reduction in the valve assembly as well as a more compact design.

It is recommended that the monopropellant and bipropellant systems be reconsidered with a moment arm of 100 inches. It is believed that the propellant feed lines can be maintained at low temperature and the hot components limited to the combustion chamber, valving and nozzles at the 100 inch radius. By proper insulation and shielding, spacecraft components and structure can be protected from the hot components. Due to the higher performance of these systems, a considerable weight saving can be realized, and the use of redundant components may serve to improve system reliability.

3.2 MOVABLE NOZZLE

Certain spacecraft main motor features should be considered further if the gimballed nozzle design is pursued. A large improvement would result from the use of a contoured nozzle design. This would permit attainment of the same performance as obtained with the reference nozzle in a shorter envelope. The result would be a reduction in nozzle diameter at the point where it exits the chamber. In turn, the gimbal ring and seal diameters, and thus weight, could be reduced. This modification would also result in a decrease in actuation force requirements, and thus, power system weights would also be reduced. In view of the low estimated weight of the system studied a further reduction is very attractive.

A comparative study should be made between an electro-mechanical power system and the hydraulic system selected in this study. The electro-mechanical system is very sensitive to required actuation rates. A better definition of this requirement may permit the electro-mechanical systems to be competitive in weight.

Another area requiring further study is the interface between the nozzle and motor, particularly in the buried nozzle area. To permit this study, motor design must be defined such that propellant grain geometry in the vicinity of the buried portion of the nozzle is known.

A more thorough study of actuation frequency response requirements is also recommended. Present response rates (30 cps) are very high requiring heavy actuation and power supply systems.

3.3 LIQUID INJECTION THRUST VECTOR CONTROL

Further work in the LITVC area, if desired, should be directed to development of a small Freon actuated injector valve and the improvement in the permeability of the elastomeric bladder. (Viton AHV)

3.4 PLUME

It has been estimated that the main motor exhaust plume will expand through an angle of 116° from the motor centerline. A review of the spacecraft structural locations and the effects of impingement of hot gas on structure and subsystems should be made.

Section 4

TECHNICAL DISCUSSION

4.1 INTRODUCTION

The technical work has been organized into four basic parts. These are: (1) statement of the general system requirements; (2) preliminary analysis of each of the individual thrust vector control methods; (3) selection of the best control method for each of the three categories; and (4) design of the selected systems. The work in each of these areas is described in the following sections.

4.2 GENERAL SYSTEM REQUIREMENTS

4.2.1 SYSTEM CONSTRAINTS

At the orientation meeting with J.P.L. personnel, the geometry and performance constraints, and the interfaces between the spacecraft and thrust vector systems were defined. These are included as Appendix A of this report. The main motor geometry and thrust time profile are also shown as Figures 4-1 and 4-2, respectively.

Only pitch and yaw control were considered in the analysis of the gimballed nozzle and liquid injection thrust vector control system. Roll control was considered, as well, in the analysis of auxiliary hot or cold gas systems.

A moment arm advantage was given to cold gas auxiliary systems over the hot gas systems. Cold gas thrustors could be placed 100 inches from the main motor centerline, while hot gas thrustors could be placed only 40 inches from the centerline. All systems were constrained axially to a location between x = 45 and x = 66 where x is the distance in inches from the front of the main motor spherical case. (See Figure 4-1) In addition, the cold gas system could thrust both fore and aft, while hot gas systems were constrained to thrusting in the quadrant from aft to radially outward.

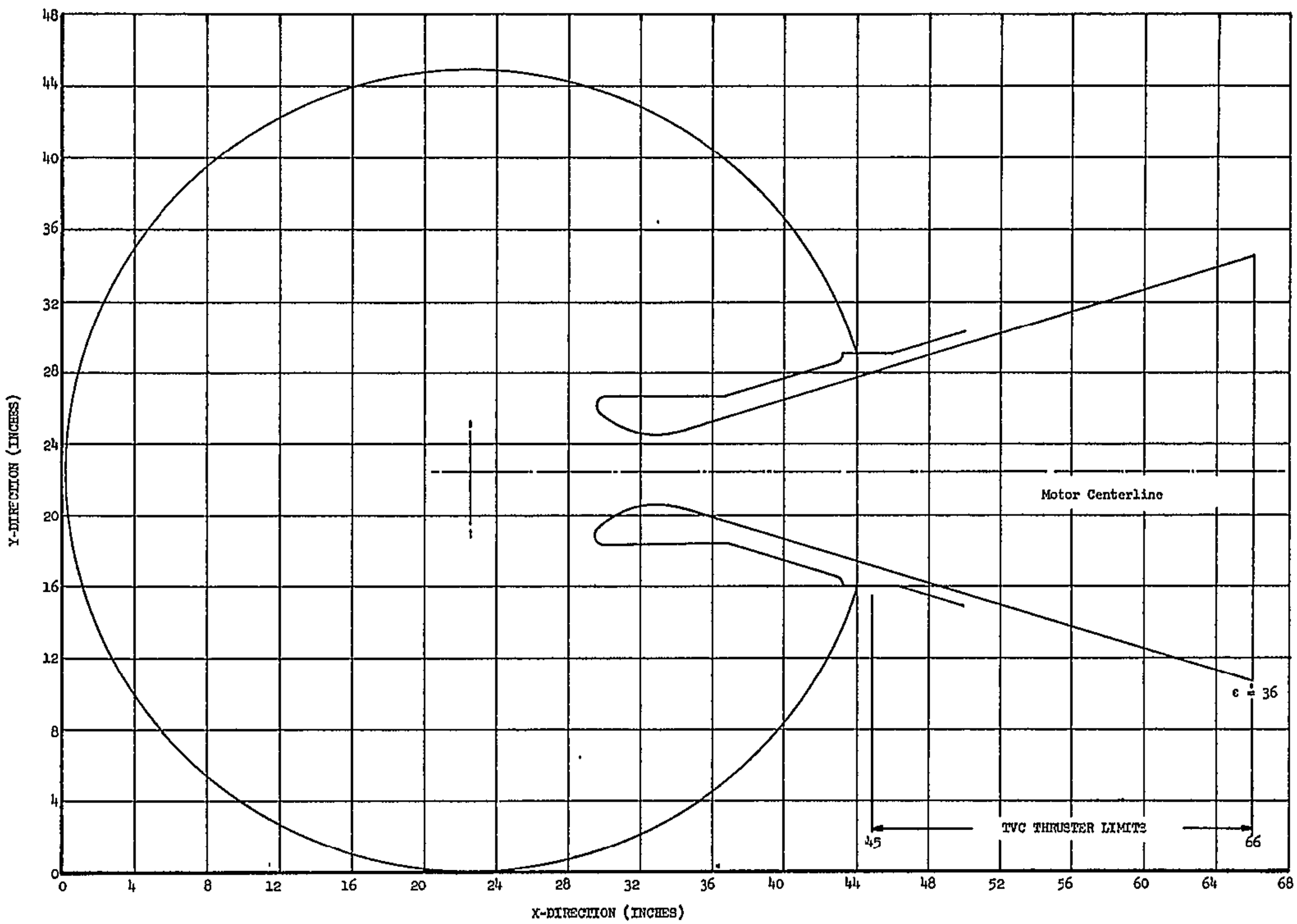


Figure 4-1. Main Motor Schematic

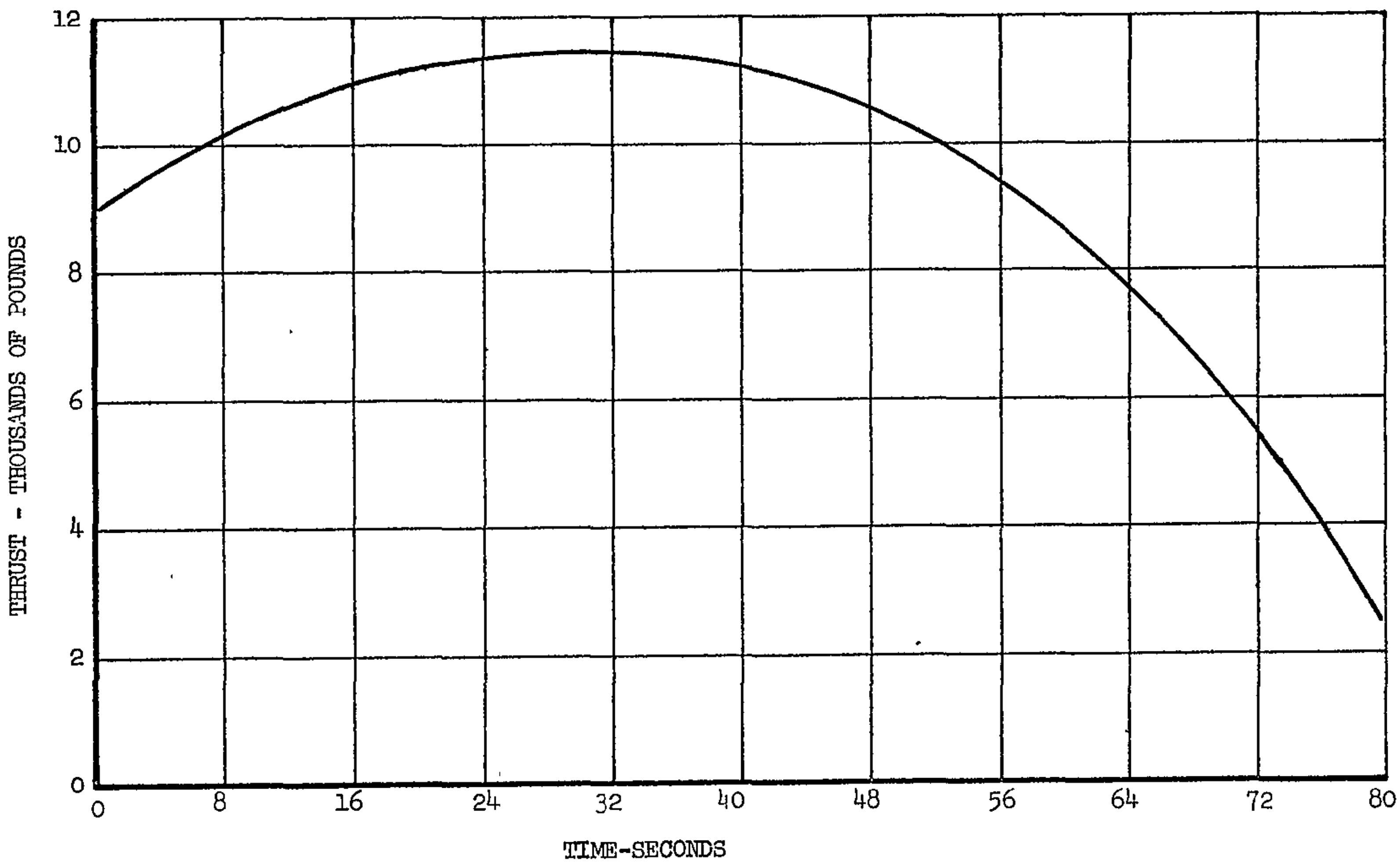


Figure 4-2. Main Motor Thrust vs Time

Two locations of spacecraft c.g. at x = 16 and x = 31 were considered in defining the thrust vectoring requirements. The LITVC and gimballed nozzle systems were sized to meet the requirements for both c.g. locations. The auxiliary systems were sized only for the c.g. located at x = 31.

The thrust vectoring requirement arises due to the thrust vector being angularly misaligned, and/or displaced, so that it does not act through the spacecraft c.g. The radial error in payload c.g. was defined as 0.25 inch. Errors in motor c.g. and thrust displacement and misalignment are defined in the following section of this report.

The TVC system capacity was defined as 1.2 times the steady state requirement in order to account for transient conditions. In addition, an initial side force capability of twice the initial steady state value was required for the first three seconds to overcome initial transients.

Propellants or fluids expelled by the thrust vectoring device were to be used or dumped so that the net uncertainity of TVC weight expended at any time during the motor firing is less than 0.3 percent of the total weight expended including main motor propellant.

4.2.2 DUTY CYCLE

The maximum possible pitch, yaw and roll moments were determined based upon the misalignment of the thrust vector from the nominal motor/spacecraft centerline and the uncertainity in the spacecraft c.g. location.

4.2.2.1 REVIEW OF SOLID PROPELLANT MOTOR DATA

Solid propellant rocket motor manufacturing data and techniques were reviewed with the following results: (See Section 4.2.3.5)

A. For the motor design presented in Figure 4-1, dimensional errors on the nozzle in both perpendicularity and eccentricity will be negligible.

B. The throat insert may be offset 0.012 inch or cocked at an angle of $0^{\circ}14'$ but not both conditions in the same direction, simultaneously.

C. Maximum possible eccentricity between both halves of the aft flange (nozzle mounting) is .005 inch.

D. Based on data from a large diameter glass motor case with a single nozzle, nonperpendicularity of the nozzle due to case deformation under pressure is $0^{\circ}4'$.

E. Error in motor c.g. measurement is 0.030 inch.

4.2.2.2 MAXIMUM PITCH OR YAW MOMENT

The maximum moment in the pitch or yaw plane was computed over time using the thrust-time curve given, Figure 4-2, and the following assumptions:

1. There is no throat erosion or nozzle spalling which could give rise to thrust misalignment during motor burn.

2. The geometric nonperpendicularity of the throat is assumed to be the angular misalignment of the thrust vector.

3. The eccentricity of the aft flange is assumed to be a lateral displacement of the thrust vector from the motor centerline.

4. Radial uncertainity of spacecraft c.g. location is defined as proportional to the weights of the payload and motor at any time and their respective c.g. measurement errors.

$$\text{at } t = 0 \quad r = .25 - (.25 - .030) \times \frac{2750}{2750 + 1500} = .108 \text{ inch}$$

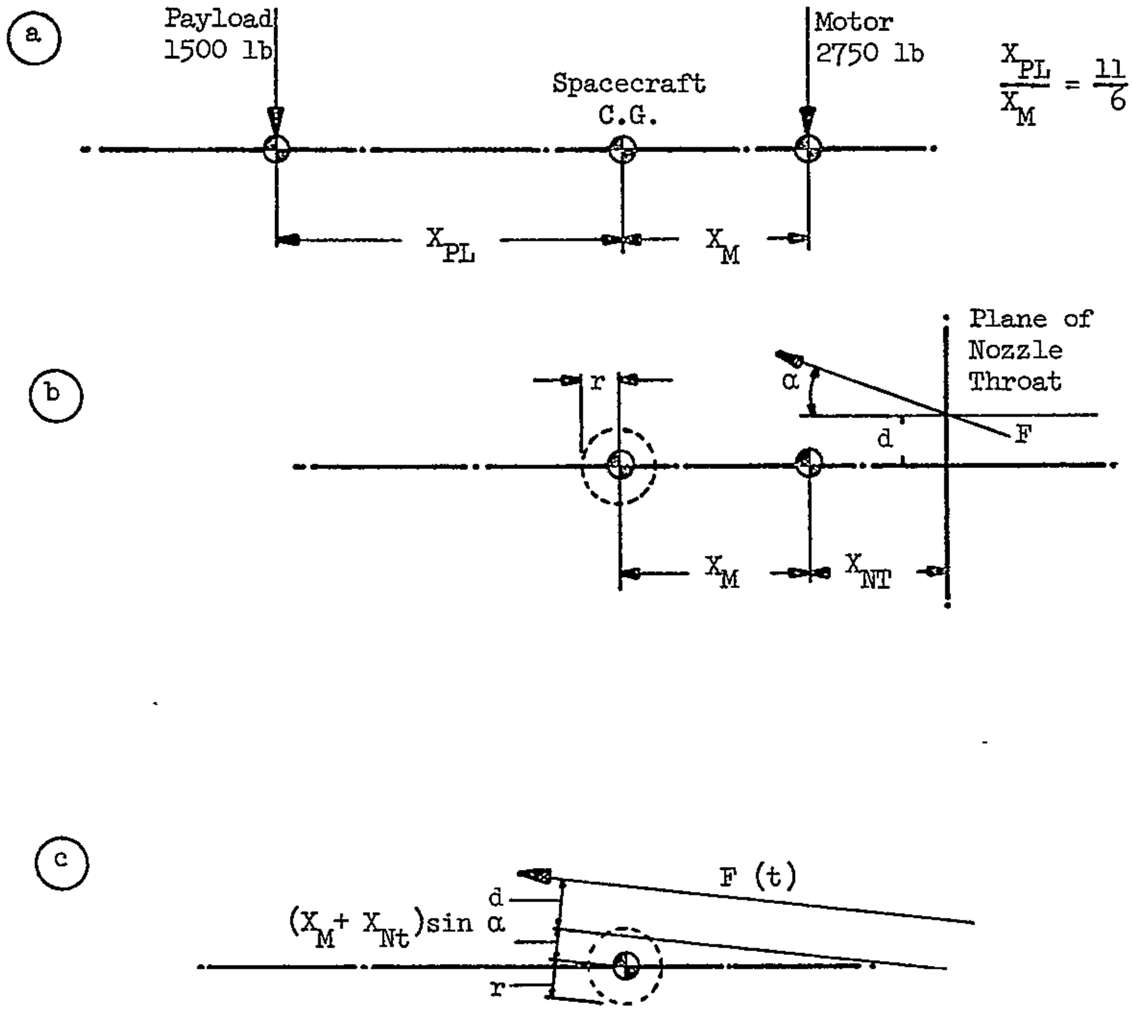
$$\text{at } t = 80 \quad r = .25 - (.25 - .030) \times \frac{250}{250 + 1500} = .219 \text{ inch}$$

(where r is the uncertainity in spacecraft c.g. location)

5. Propellant weight loss is linear with time.

6. The thrust vector acts at the plane of the nozzle throat.

The variables affecting the pitch and yaw moments are shown in Figure 4-3. The uncertainity in spacecraft c.g. is a function of time due to expulsion of motor propellant. The variation of this uncertainity with time is assumed to be linear, consistent with assumption number 5 above, and is shown in Figure 4-4.



Maximum Pitch Moment

$$M_p(t) = F(t) \left\{ \left[\left(X_M + X_{NT} + r(t) \right) \sin\alpha + d \right] + r(t) \right\}$$

Figure 4-3. Definition of Maximum Pitch Moment

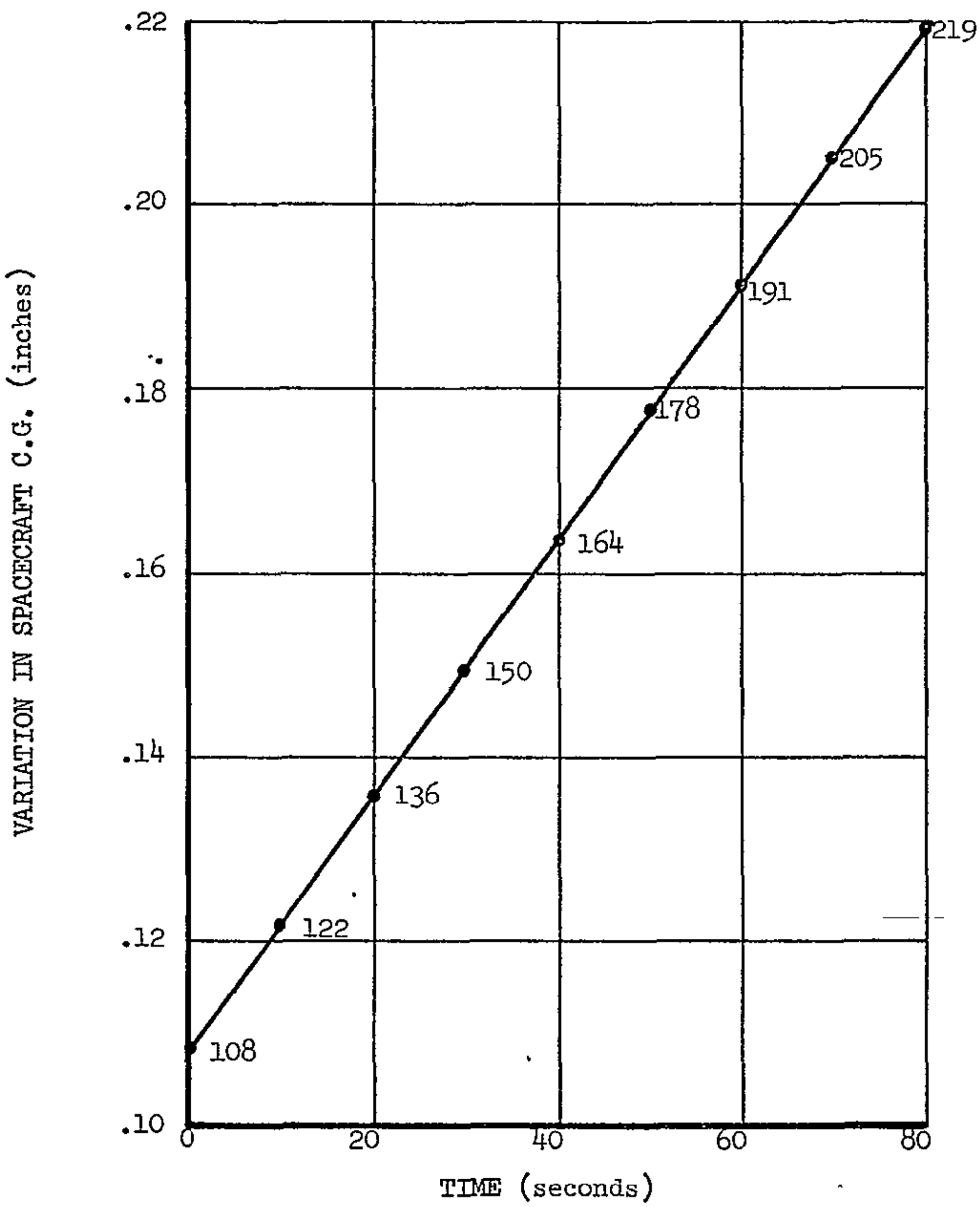


Figure 4-4. Variation of Spacecraft c.g. Error Due to Motor Burn

4.2.2.3 MAXIMUM PITCH MOMENT

The maximum pitch moment has been computed as a function of time and plotted in Figure 4-5 and 4-6 for spacecraft c.g. locations of x = 16 and 31.

The total system capacity for the two c.g. locations are as follows:

x = 16; 15,875 ft lb sec

x = 31; 11,155 ft lb sec

The capacity of the system was increased by 20 percent, as required, to cope with transients. In addition, since this moment could occur halfway between the pitch and yaw axes, the system must be capable of providing .707 of the full moment in both pitch and yaw simultaneously.

The system capacity required is

x = 16; (15,875 x 1.4142) 1.20 = 26,490 ft lb sec

x = 31; (11,155 x 1.4142) 1.20 = 18,930 ft lb sec

For x = 16, the maximum moment is due to the angular misalignment of the thrust vector. For x = 31, the maximum moment is due to lateral displacement of the thrust vector.

4.2.2.4 MAXIMUM ROLL MOMENT

The maximum roll moment is very small since the angularity of the thrust vector is only $0^{\circ}18'$ and the displacement from the centerline is not greater than .017 inch. Motor swirl is assumed to produce negligible roll torque.

The maximum roll moment as a function of time is shown in Figure 4-7. The total system capacity required is 689.5 x 1.20 = 827.4 in. lb sec.

4.2.3 BASIC NOZZLE DESIGN

Since the comparison of system weights must be made on the basis of increases over a motor with no TVC system, a basic nozzle, based on the Minuteman nozzle design philosophy, was laid out, and a weight for it was determined. Any changes in the nozzle were charged to the gimballed nozzle and LITVC systems as part of the system weight. The baseline nozzle is shown in Figure 4-8. The baseline nozzle weight is 84.4 lb.

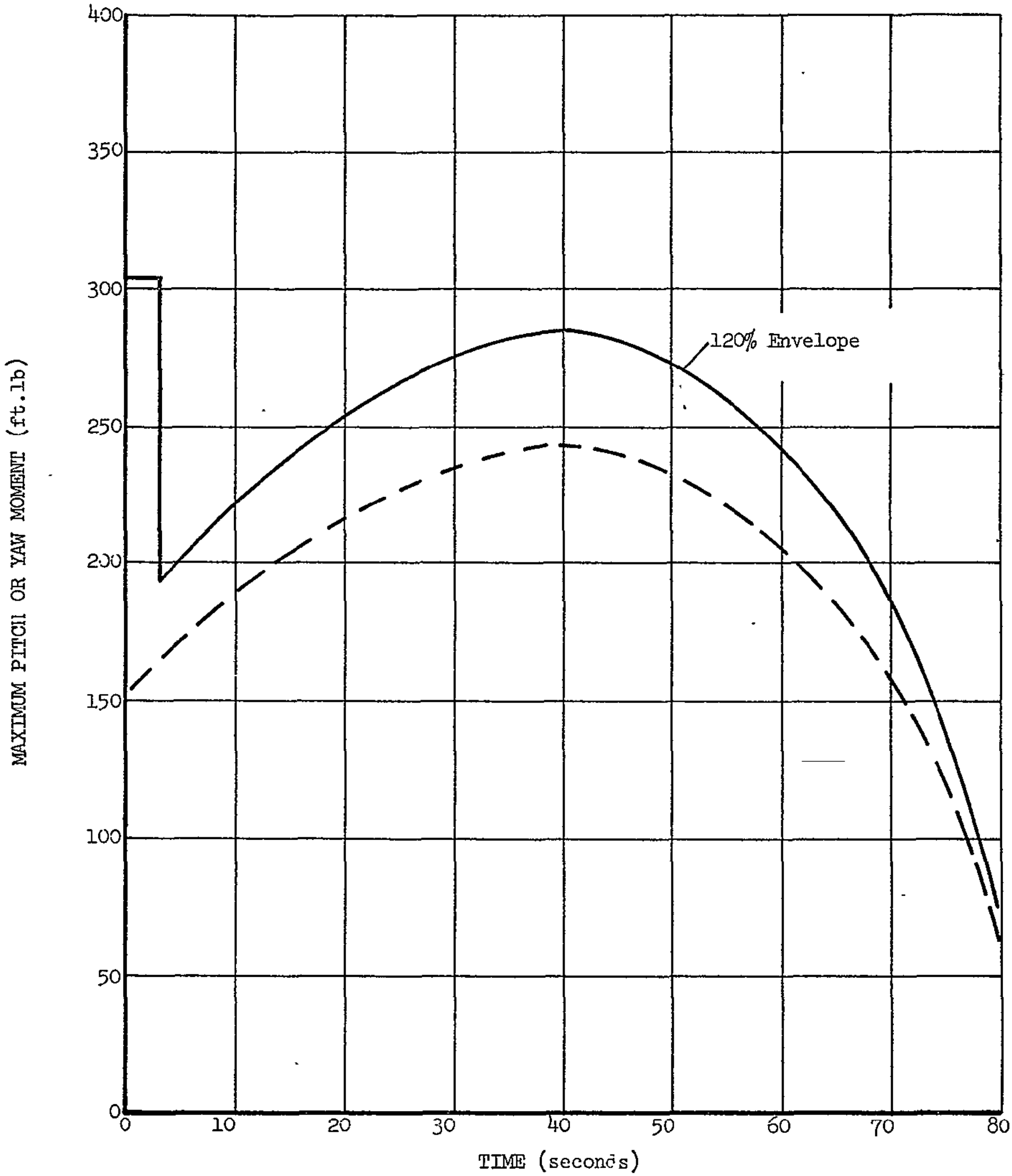


Figure 4-5. Maximum Pitch or Yaw Moment Due to Thrust Misalignment for Spacecraft c.g. at X = 16

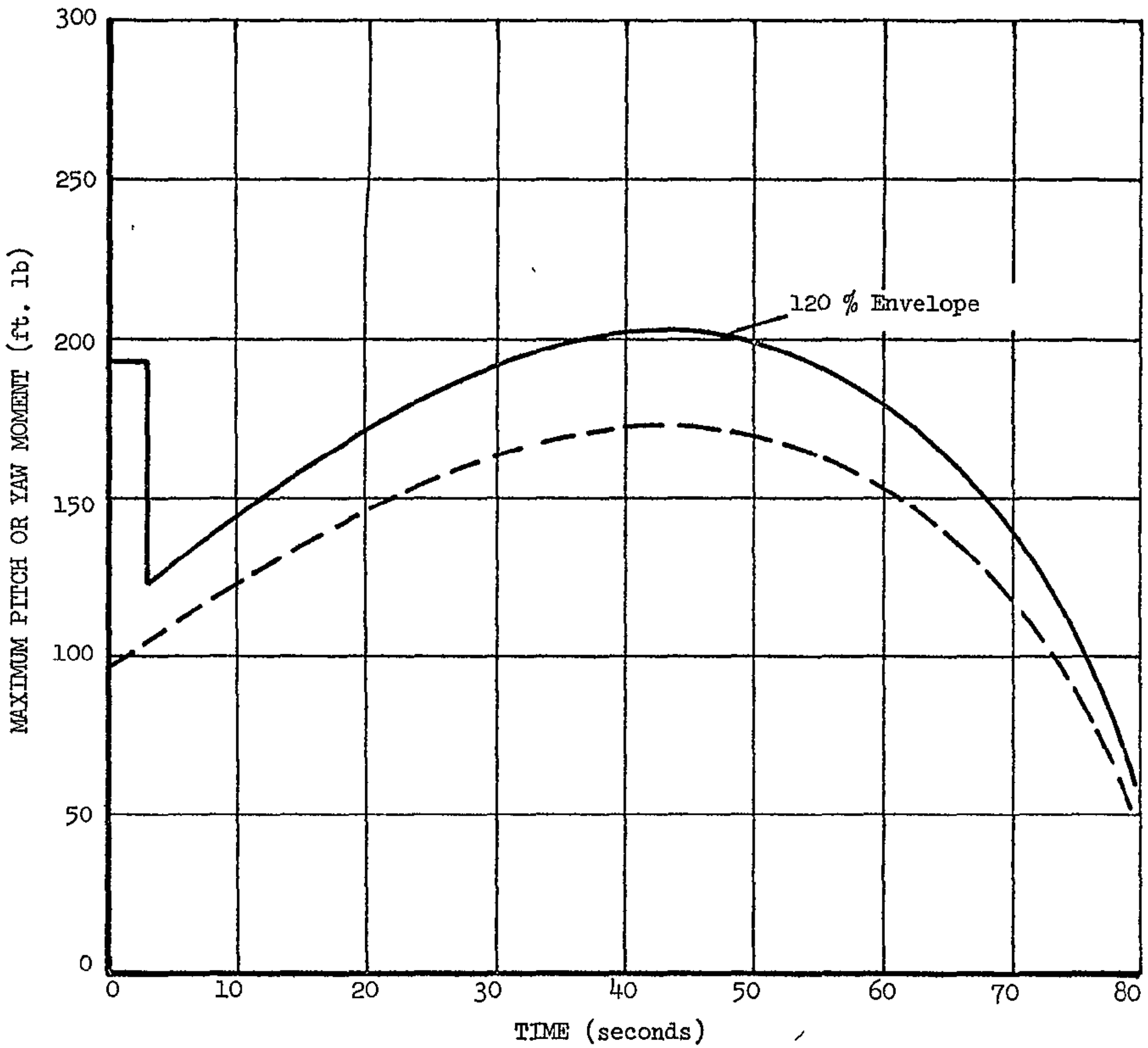


Figure 4-6. Maximum Pitch or Yaw Moment Due to Thrust Misalignment for Spacecraft c.g. at X = 31

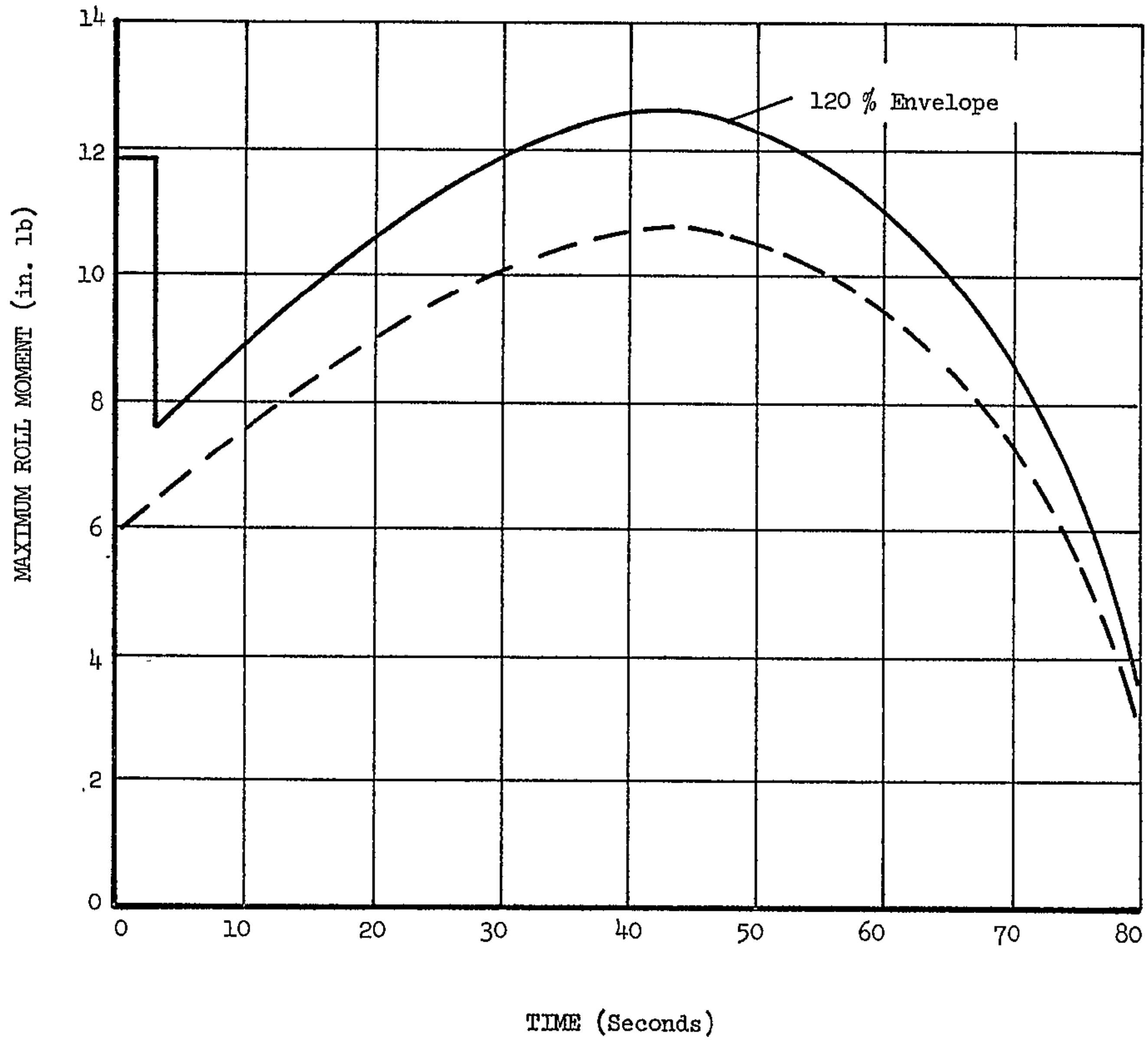
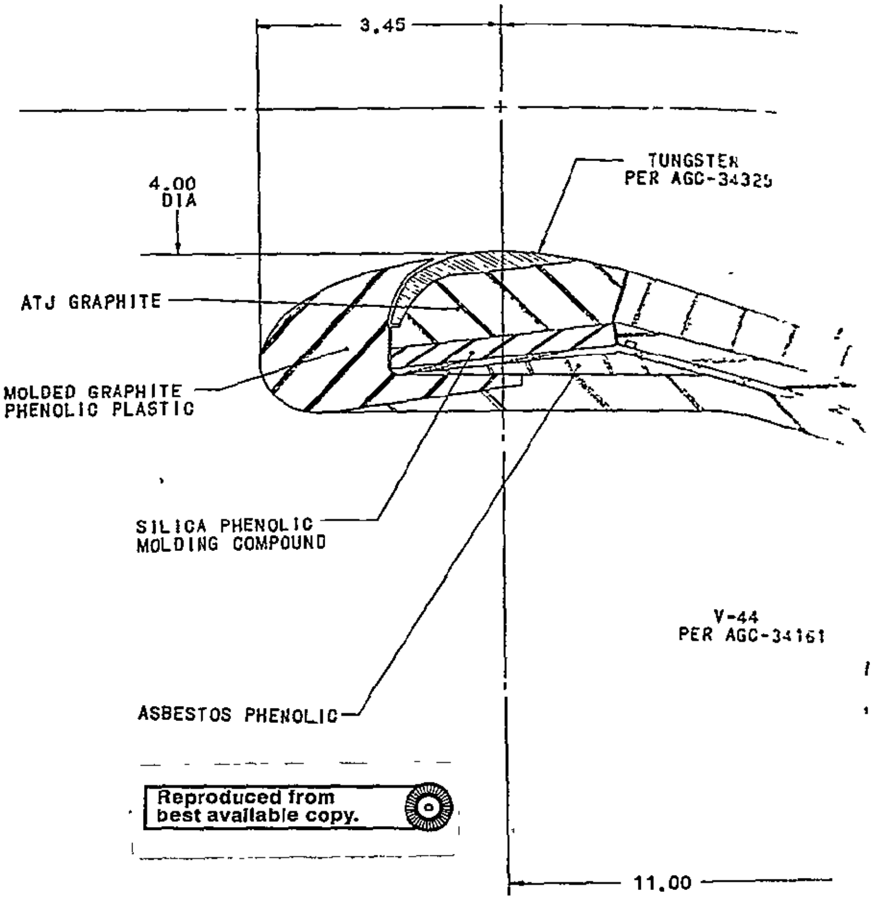


Figure 4-7. Maximum Roll Moment Due to Thrust Misalignment


3.45
4.00
DIA
TUNGSTEN
PER AGC-34325
ATJ GRAPHITE
MOLDED GRAPHITE
PHENOLIC PLASTIC
SILICA PHENOLIC
MOLDING COMPOUND
V-44
PER AGC-34161
ASBESTOS PHENOLIC
11.00

A

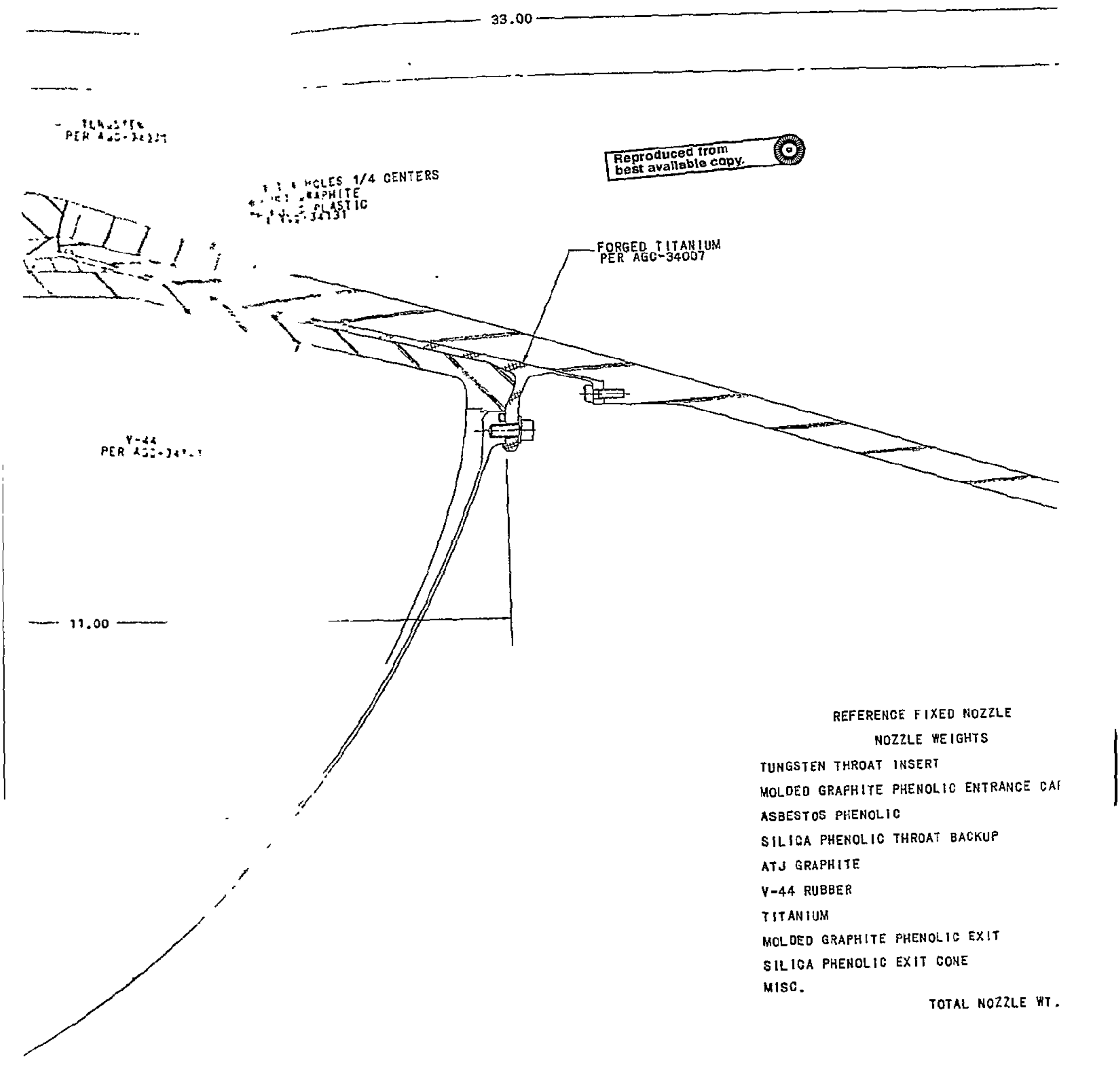
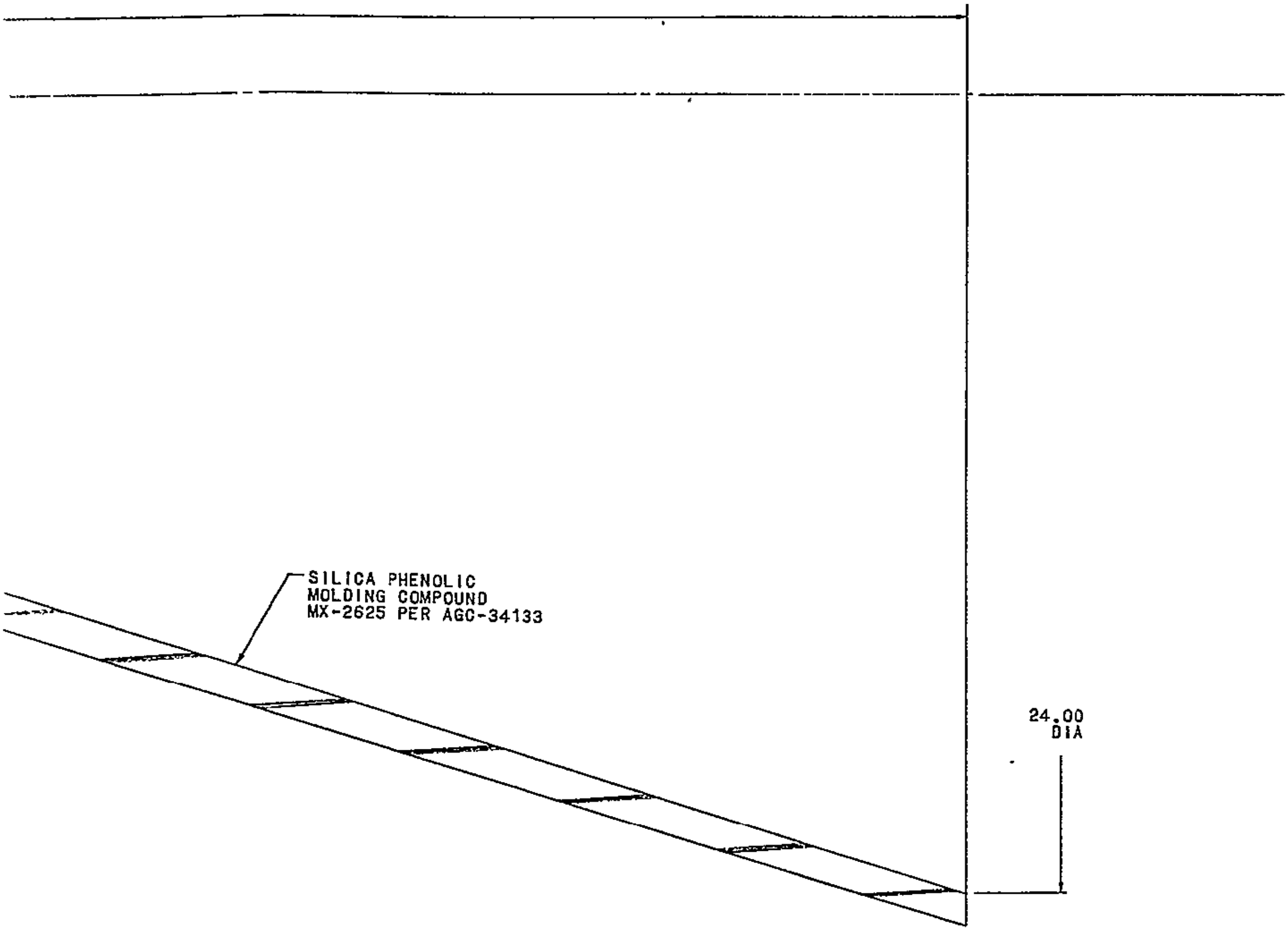


Figure 4-8. Baseline Nozzle

4-11-6

B



E FIXED NOZZLE

ZLE WEIGHTS

NSERT	5.5
HENOLIC ENTRANCE CAP	3.9
	1.0
HROAT BACKUP	1.2
	2.8
	8.1
	10.5
HENOLIC EXIT	2.8
XIT CONE	47.6
	1.0
TOTAL NOZZLE WT. =	84.4

4.2.3.1 DESIGN CONSTRAINTS

The baseline nozzle was designed in accordance with constraints specified in Appendix A. These included:

1. Throat location at x = 33 inches along motor centerline from a reference point at the motor forward end.
2. Nozzle exits the motor envelope at x = 44 inches.
3. 15° half angle.
4. 36:1 expansion ratio (exit at x = 66 inches).
5. Propellant of 304 lbf sec/lbm I_{sp}.
6. Duration - 80 sec.
7. Maximum chamber pressure - 500 psia.
8. Maximum thrust 11,500 lbf.

4.2.3.2 DESIGN APPROACH

The nozzle design was based on present day technology. In this respect, a heat sink, tungsten-lined, throat section and reinforced-plastic-lined exit cone assembly were used. Construction and design features closely parallel those of the Minuteman Wing VI second stage design, which is a highly successful submerged configuration. The design therefore is completely based on present technology for long-duration, high-performance solid rocket motors containing aluminized propellant.

4.2.3.3 DESIGN DESCRIPTION

The baseline nozzle preliminary layout is shown in Figure 4-8. It incorporates a 6Al-4V titanium support shell insulated with rubber base insulation; an entrance cap of molded graphite cloth-phenolic plastic, a tungsten throat insert with a graphite heat sink, and a combination graphite cloth-phenolic and silica cloth-phenolic, high pressure molded exit cone. It is suitable for present day aluminized propellants with flame temperatures up to $6000^{\circ}F$. Suitability for more advanced propellants is not known as no operational designs are available for higher energy propellant formulations.

The nozzle insulation thicknesses are defined by the allowance for normal ablation and char, and provision for sufficient insulation such that no temperature rise occurs in the structural components. As a result, the exit cone tends to approach constant thickness in downstream areas where ablation is negligible.

4.2.3.4 BASELINE NOZZLE WEIGHT SUMMARY

The nozzle weight by component is also shown in Figure 4-8. The total weight is 84.4 lb. This compares favorably with operational nozzles of recently developed motors when adjusted to the reference expansion ratio, operating duration, and scale.

4.2.3.5 TOLERANCE ANALYSIS

A tolerance buildup analysis was made for the baseline nozzle design to permit incorporation of those tolerances in TVC force requirements studies. A dimensional analysis of the chamber was also defined for the same purpose.

The progressive and final stack-up of dimensional tolerances for the reference nozzle as indicated by Figure 4-9 are presented assuming the following schedule of fabrication operations:

a. Machine nozzle shell complete (Figure 4-9 (a).

b. Fabricate exit cone, finish machine O.D. surfaces and assemble nozzle shell. (Figure 4-9 (b).

c. Fabricate and finish machine throat section as an assembly allowing .010 in. on O.D. for bonding to shell (Figure 4-9 (c).

d. Bond throat section to shell (Figure 4-9 (c). Tolerances shown on sketch are referenced to the face and centerline of flange "A". Eccentricity and non-perpendicularity are negligible for all nozzle components except the throat insert.

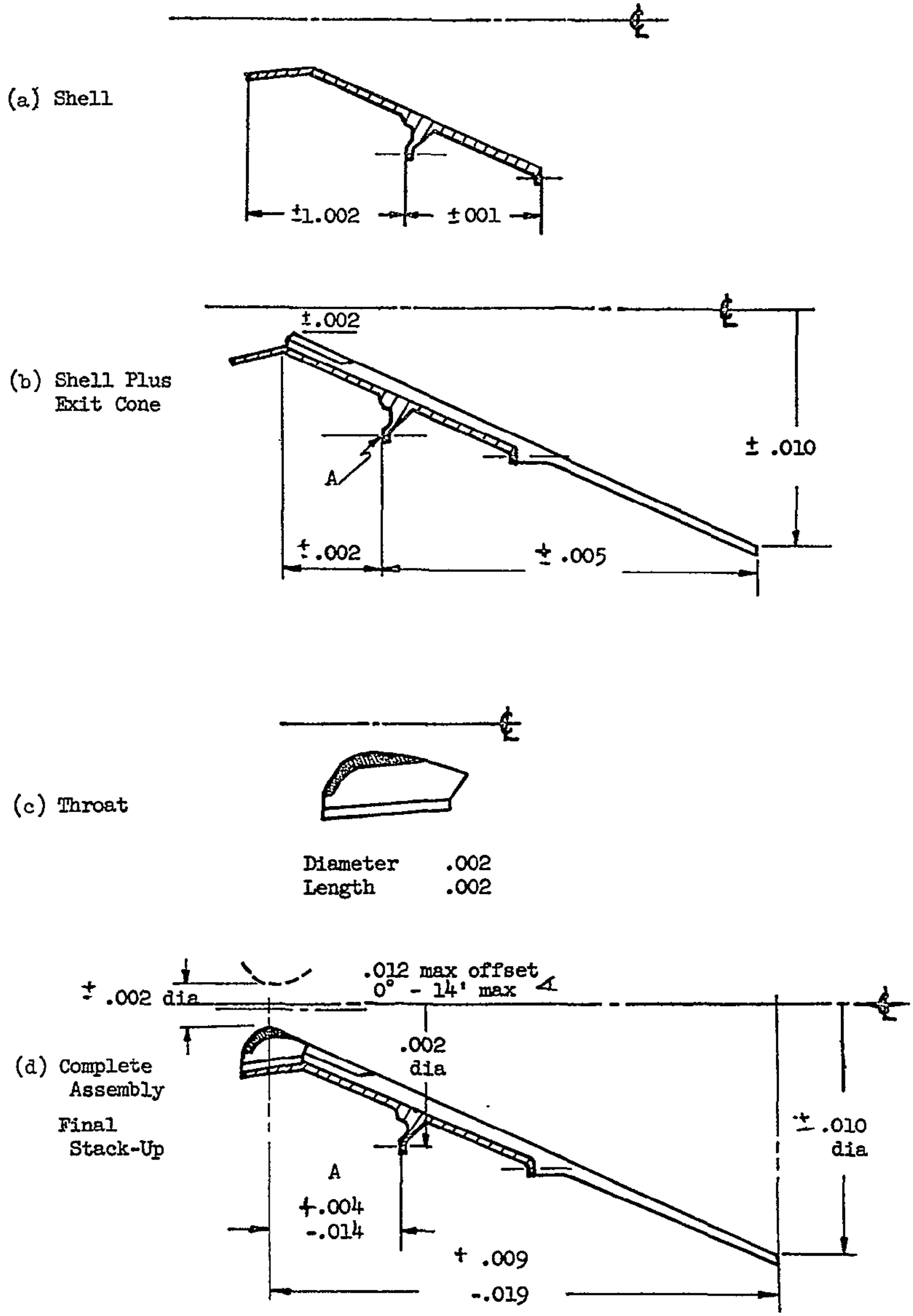


Figure 4-9. Dimensional Tolerance Stack-up for Baseline Nozzle

Maximum offset due to clearance between the chamber flange O.D. and the shear lip of the mating nozzle flange is 0.005 inches. The expected cocking of the nozzle due to motor pressurization is 0° - 4 min. based on actual measurement of a large, single nozzle, filament-wound motor.

The motor case will probably be fabricated using one of the following candidate materials: titanium, maraging steel, or filament wound glass. Although these materials have widely varied mechanical properties and are fabricated using quite different manufacturing techniques, the chamber tolerances with respect to the reference flange for all three candidates falls between 0.02 and 0.03 inches maximum offset. Similarly, the propellant casting core can be located within the same tolerance range thus fixing the propellant maximum c.g. offset and, for all practical purposes, the motor maximum c.g. offset at 0.02 to 0.03 inches.

All tolerances are based on normal shop practice in motor manufacture. Tighter dimensional control is possible, but does not seem warranted in this case in view of the relatively large uncertainity in spacecraft c.g. location of $\pm$ .25 inch.

4.3 PRELIMINARY SYSTEM ANALYSIS

Three basic types of systems were considered for thrust vector control. However, within each category a range of possible working fluids and power systems exist. In order to concentrate the effort on those systems most likely to be applicable, selections of fluids and power systems were made on the basis of experience and applicability in the time period required.

The systems to be considered were selected as follows:

1. Auxiliary Systems

1.1 Stored gas - Candidates N_2, He

1.2 Monopropellants - Candidates N_2H_4, H_2O_2

1.3 Bipropellants - Candidates N_2O_4-N_2H_4, N_2O_4-Aerozine 50

1.4 Solid Propellant Gas Generator (2000^{o}F)

1.5 Solid Rocket Motors

All systems except the solid rocket motors were considered with two or three position valves, proportional valves and gimballed thrustors. Solid rocket motors were considered only in the gimballed configuration.

2. LITVC Systems

2.1 Injectant candidates - Freon 114B2 and N_2O_4. Strontium perchlorate and hot gas injection were excluded.

2.2 Pressurization candidates - cold gas (N_2), and solid propellant gas generator.

This resulted in eight possible combinations which were analyzed.

3. Movable Nozzle Systems

3.1 Translating Nozzles

3.2 Gimballed Nozzles

3.3 Actuation Systems - Cold gas non-recirculating hydraulic, gas generator non-recirculating hydraulic, electric motor driven pump recirculating hydraulic, gas turbine driven recirculating hydraulic, and electromechanical.

The analyses leading to the comparative evaluation of these systems are described below.

4.3.1 LITVC SYSTEM

4.3.1.1 CONTROL METHOD

The LITVC system consists of a source of high pressure injectant fluid which is piped to injectant control valves (injector valves) mounted on the exhaust nozzle of a rocket motor. The injection of a liquid, through small ports in the nozzle wall, into the supersonic exhaust gas causes an oblique shock wave to form. The shock wave is generated by the injectant penetrating into the supersonic gas stream. This causes boundary layer separation to occur; shock waves are formed which reinforce the separation, and the resultant high pressure region ahead of the jet of injectant causes a multiplication of the side force due to the high pressure field acting on the nozzle wall. The side force is used to control the vehicle in the pitch and yaw planes by locating injection points at 90 degree intervals around the nozzle in the pitch and yaw planes. Vehicle control is accomplished by means of feedback to the injector valves from the vehicle attitude sensors to maintain the desired attitude of the thrust axis.

4.3.1.2 INJECTANT REQUIREMENTS

Two control duty cycle requirements are defined in Figures 4-5 and 4-6 representing thrust misalignment moments for spacecraft c.g. locations at $x = 16$ and $x = 31$, respectively. The flow rate of injectant required to provide a compensating thrust vector moment can be computed if the side force is known and if the effective moment arm of the side force from the vehicle c.g. is known.

It is noted from the layout drawing of the baseline nozzle that a convenient location for installation of the injector valves is at an expansion ratio of 8.5. Since the side force gain curve is relatively flat, as a function of expansion ratio at the point of injection, no serious loss in performance will occur due to this arbitrary choice of plane of injection. In addition, considerable test data is available for injection at an expansion ratio of 8.5. The gain curves for both injectants Freon 114B2 and N_2O_4 are shown in Figure 4-10. From this curve the side force may be computed using the motor thrust and mass flow. In order to calculate the moment generated by the side force, it was assumed that the average pressure on the nozzle wall, due to the asymetrical shock, is located at the point of injection. Figure 4-11 is a plot of experimental data from Minuteman Stage II motor static firings. It can be seen that the assumption that the centroid of the integrated pressure profile is at the point of injection is conservative.

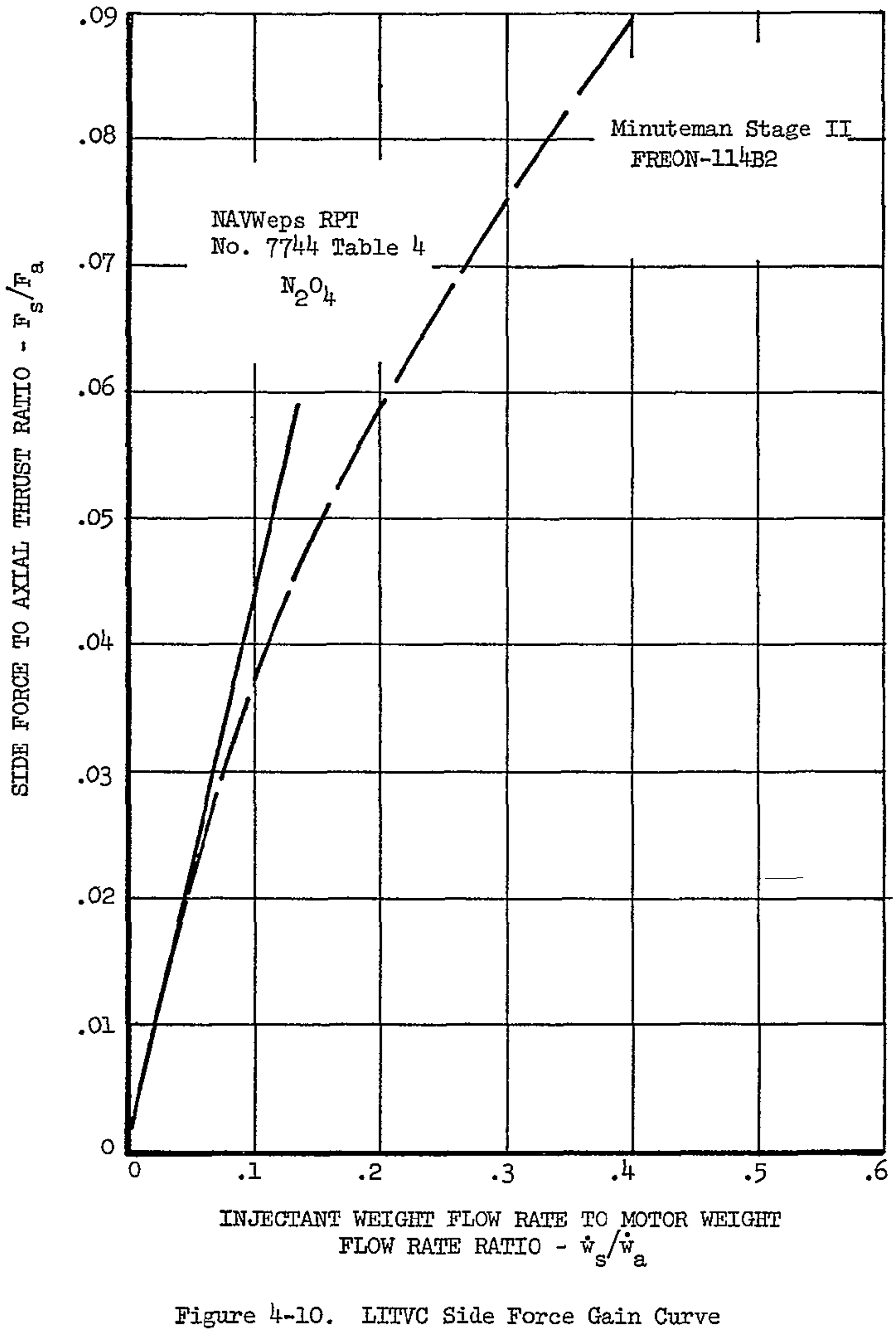


Figure 4-10. LITVC Side Force Gain Curve

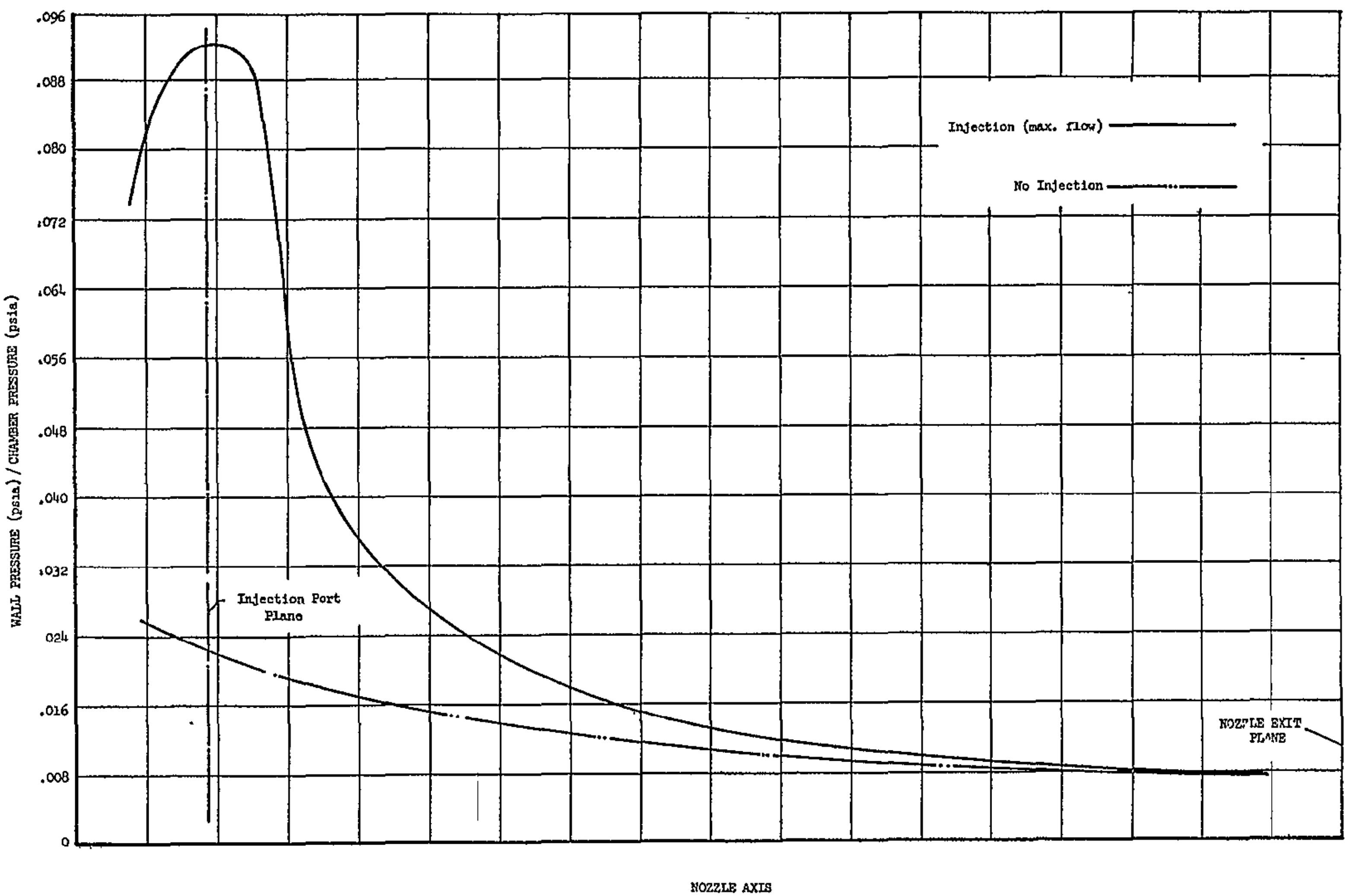


Figure 4-11. Nozzle Wall Pressure Profile Due to Liquid Injection

Moment arms of 30.434 and 15.434 inches were computed corresponding to spacecraft c.g. locations of x = 16 and x = 31.

Motor mass flow rate is found from the relation

$$\dot{w}_a = \frac{F}{I_{sp_{vac}}}$$

Thrust vs time is given in Figure 4-2 and motor $I_{sp_{vac}}$ was given as 304 sec.

Injectant weight is determined from the side force ratio, $\frac{F_s}{F_a}$, required to overcome the moments, Figures 4-5 and 4-6, and the gain curve, Figure 4-9 from which $\frac{\dot{w}_s}{\dot{w}_a}$ vs time is determined. Injectant weight flow vs time is plotted in Figures 4-12 and 4-13 for spacecraft c.g. at x = 16 and x = 31, respectively. Integration of the injectant flow rate vs time resulted in the following injectant requirement in pounds, for control in the pitch or yaw plane.

x	Freon 114B2	N_2O_4
16	60.1	53.0
31	84.4	75.0

In the event that control is required in a plane halfway between the pitch and yaw planes, the injectant flow rate required in each of the pitch and yaw planes is $1/\sqrt{2}$ times that required if the moment is in the pitch or yaw plane. Consequently, an injectant flow rate $\sqrt{2}$ times that calculated above is required to control this condition. This results in injectant requirements, in pounds, as follows:

x	Freon 114B2	N_2O_4
16	85.0	75.0
31	119.4	106.0

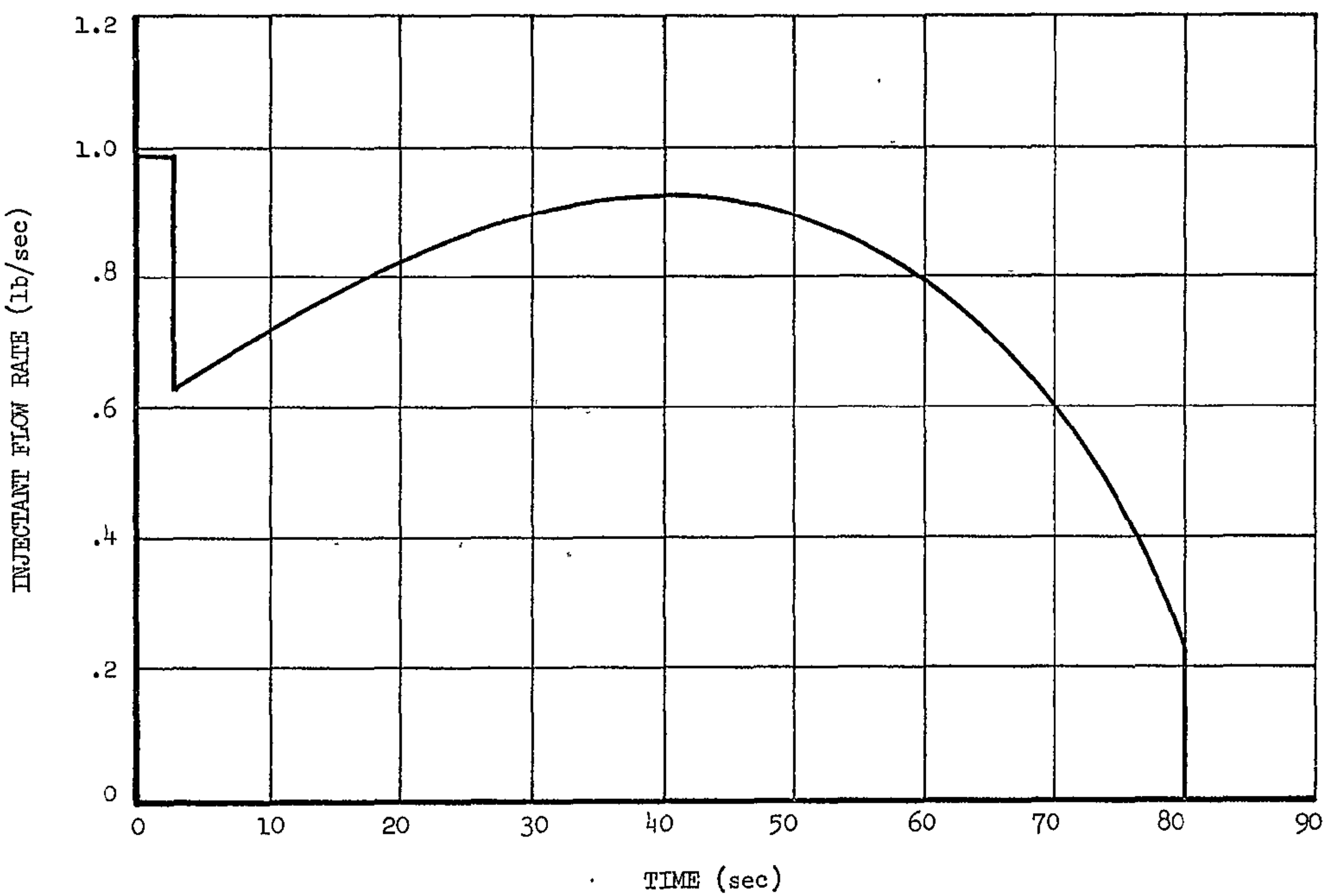


Figure 4-12. Freon 114B2 Flow Rate vs Time for X = 16

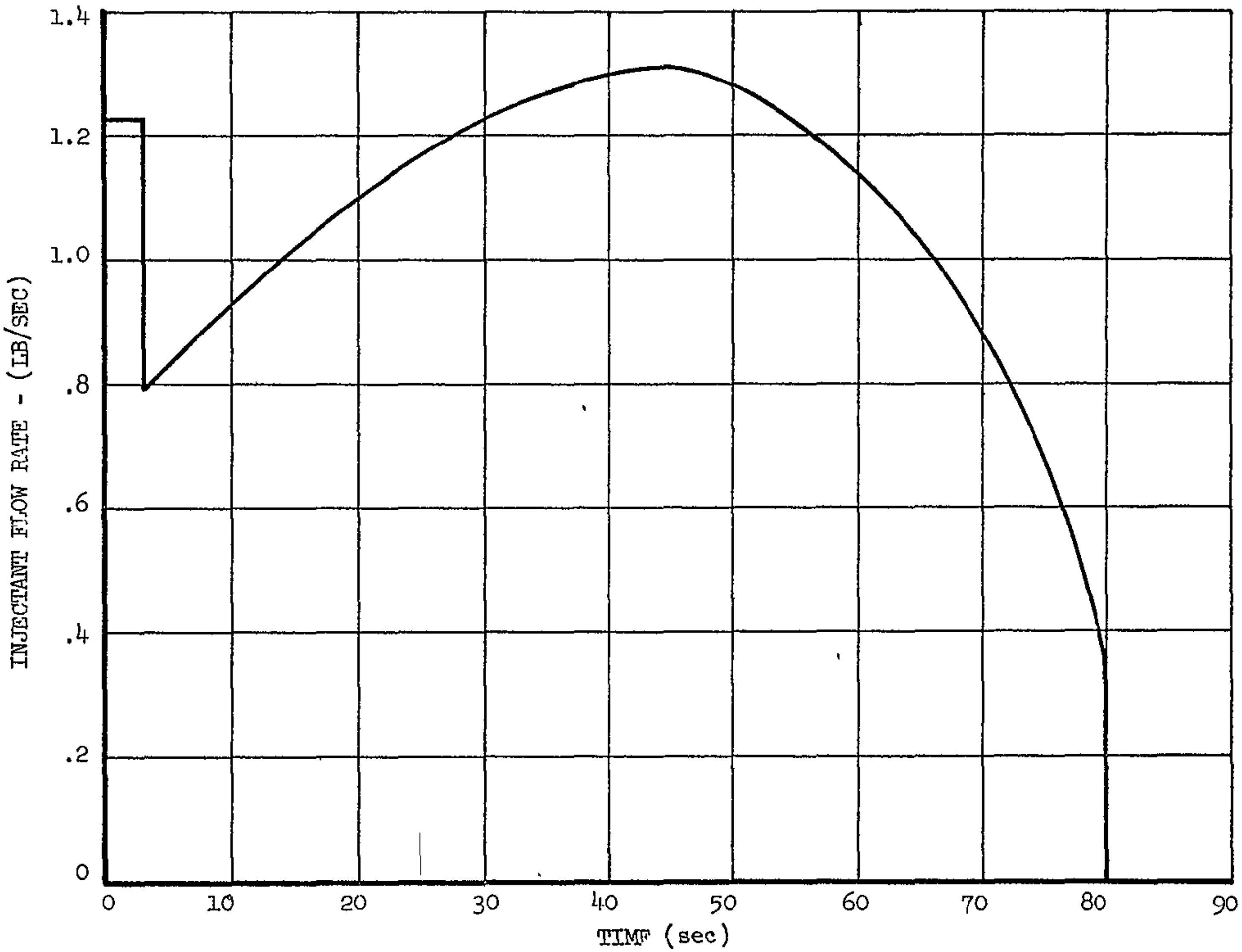


Figure 4-13. Freon 114B2 Flow Rate vs Time for X = 31

4.3.1.3 PRELIMINARY SYSTEM SIZING

The general configuration of the Minuteman second stage LITVC system was selected to perform comparative weight analysis of the eight system combinations. Schematic representations of the systems are shown in Figures 4-14 and 4-15.

The toroidal tank was sized to contain the injectant required, the elastomeric bladder, and the injectant distribution tube, and an ullage space in the tank insert section. The tank was assumed to be made of titanium with a conservative yield strength of 110,000 psi and a density of 0.162 lb/in^3. Wall thickness was scaled down from the Minuteman tank to .071 in. Lines were sized to pass the injectant flow required and the pressure relief valve and injector valve weights were also scaled from the Minuteman system. Since the injector valves are hydraulically servo controlled, the weight of a hydraulic actuation system was included. The weights are tabulated in detail in Tables 4-1 and 4-2.

4.3.2 AUXILIARY HOT OR COLD GAS SYSTEMS

In this section comparison is made among stored gas, monopropellant, bipropellant and solid propellant systems. By their nature these systems do not interfere with or change the basic nozzle geometry. In effect, they are attitude control systems. The cold gas systems are allowed an advantage over the hot gas systems, since they can have a moment arm of 100 inches from the centerline of the spacecraft, and can thrust both fore and aft, or radially outward, if desired. The hot gas systems are sized for a 40-inch moment arm, but may thrust only aft or radially outward, since thrusting forward would cause impingement of the system exhaust on the spacecraft structure.

In order to meet the expelled weight control requirement, all systems are considered to operate continuously, dumping, radially outward, or fore and aft simultaneously, that proportion of flow not required for control.

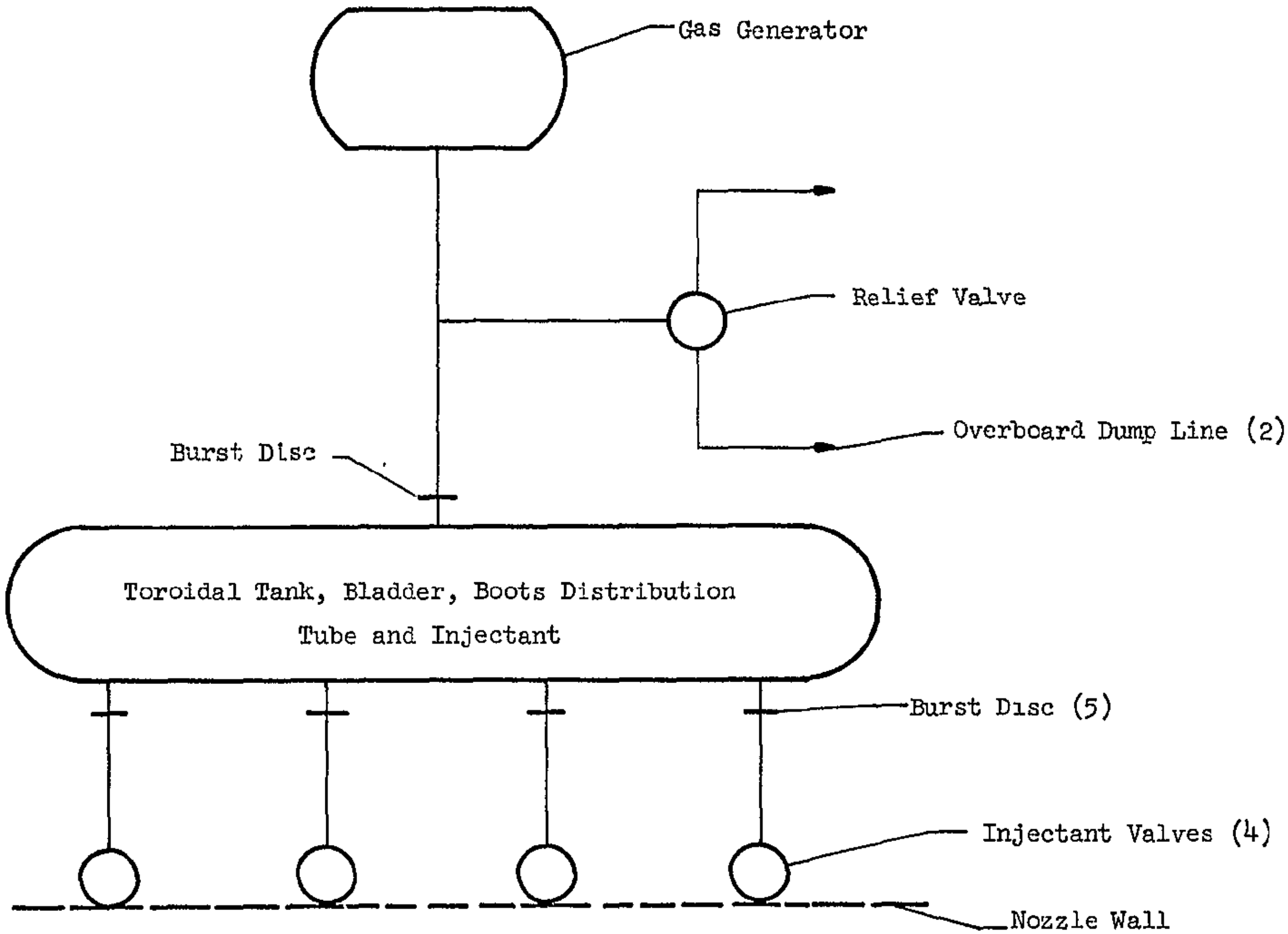


Figure 4-14. LITVC System Schematic - Hot Gas Pressurization

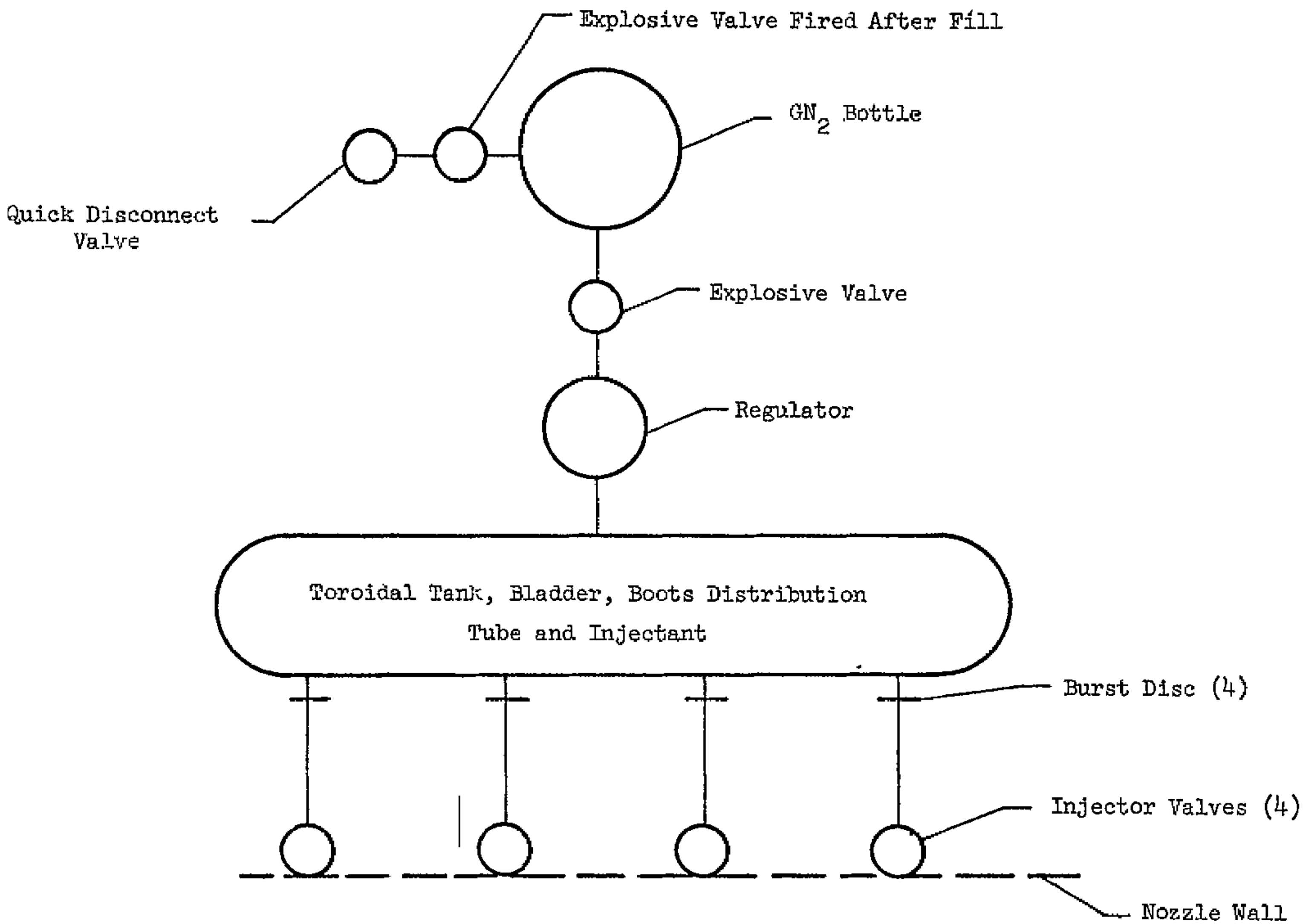


Figure 4-15. LITVC System Schematic - Cold Gas Pressurization

Table 4-1. LITVC Summary (Cold Gas Pressurization)

Injectant Fluid	Station in	Injectant Density lb/ft³	Required Pitch or Yaw lb	Required Pitch & Yaw lb	Injectant Line ID in	Line Residual in³	4 Injector Residual in³	Loaded Injectant in³	Tank Ullage Volume in³	Bladder Volume in³	Injectant Tank Volume in³	Tank CL Major Dia. in	Tank Inside Minor Dia. in	GN_2 Volume in³
F-114B2	16	135.0	60.1	85.0	0.275	8.65	12.8	1110.15	142.5	50.3	1302.25	30	4.194	203.9
F-114B2	31	135.0	84.4	119.4	0.250	7.16	12.8	1547.46	200.0	56.0	1804.28	31	4.656	284.2
N_2O_4	16	89.2	53.0	75.0	0.281	9.25	23.2	1485.70	196.6	55.1	1737.06	31	4.766	272.9
N_2O_4	31	89.2	75.0	106.1	0.312	19.10	23.2	2096.95	220.0	61.6	2379.29	31	5.578	395.2

Injectant Fluid	Station in	Loaded Injectant lb	Injectant Tank Wall in	Injectant Tank Shell lb	Tank End Flange lb	Tank Fill & Outlets lb	Tank Insert Section lb	Total Tank Wt. lb	Bladder Weight lb	Dist. Tube Weight lb	4 Injectant Line Weight lb	4 Injector Valve Weight lb
F-114B2	16	87	0.071	24.11	2.09	1.33	3.31	30.84	3.32	0.84	0.50	12.
F-114B2	31	121	0.071	28.67	2.40	1.33	3.80	36.20	3.70	0.80	0.45	12.
N_2O_4	16	77	0.071	28.19	2.36	1.33	3.74	35.62	3.64	0.89	0.50	12.
N_2O_4	31	108	0.071	32.77	2.74	1.33	4.34	41.18	4.07	0.98	0.50	12.

Injectant Fluid	Station in	Hydraulic System lb	Regulator Valve lb	QD Valve lb	Nozzle Extension lb	Total System Weight lb	Expended System Weight lb
F-114B2	16	39.14	2.5	0.5	6.05	207.15	93.95
F-114B2	31	39.14	2.5	0.5	6.05	252.14	104.54
N_2O_4	16	39.14	2.5	0.5	6.05	206.70	103.50
N_2O_4	31	39.14	2.5	0.5	6.05	250.40	118.10

* Contains 28.2 lb Hydraulic Fluid Pressurized by GN_2

Note: The weights in this table are for comparative purposes only. Improvement can be made in the weights and they should not be used for design purposes ation)

GN_2 Volume in^3	GN_2 Bottle Dia. in	GN_2 Line in	GN_2 $\dot{W}$ lb/sec
203.93	7.30	.070	0.0214
284.27	8.14	.080	0.0300
272.92	8.04	.080	0.0291
385.21	9.02	.090	0.0388

4 Injector Valve Weight lb	4 Burst Disc. Weight lb	4 Injector Block Weight lb	Explosive Valve (2) lb	Tank Support lb	GN_2 Bottle lb	GN_2 Weight lb	GN_2 Bottle Support lb	Line Support lb
12.	0.04	4.	1.	10.55	5.60	1.72	1.05	0.5
12.	0.04	4.	1.	12.39	7.96	2.40	1.51	0.5
12.	0.04	4.	1.	12.19	7.43	2.30	1.40	0.5
12.	0.04	4.	1.	14.11	10.58	3.25	2.00	0.5

Preceding page blank

Injectant Fluid	Station in	Injectant Density lb/ft^3	Required Pitch or Yaw lb	Injectant Pitch & Yaw lb	Injectant Line Dia. in
F-114B2	16	135.0	60.1	85.0	0.275
F-114B2	31	135.0	84.4	119.4	0.250
N_2O_4	16	89.2	53.0	75.0	0.281
N_2O_4	31	89.2	75.0	106.1	0.312

Injectant Fluid	Station in	Loaded Injectant lb	Injectant Tank Wall in	Injectant Tank Shell lb	Tank Flange End lb
F-114B2	16	87.0	0.095	32.15	2.09
F-114B2	31	121.0	0.095	38.22	2.40
N_2O_4	16	77.0	0.095	37.58	2.36
N_2O_4	31	108.0	0.095	43.69	2.74

Injectant Fluid	Station in	Tank Support lb	Line Support lb	Line Insulation lb	Hydraulic* System lb
F-114B2	16	10.55	0.5	0.5	39.14
F-114B2	31	12.39	0.5	0.5	39.14
N_2O_4	16	12.19	0.5	0.5	39.14
N_2O_4	31	14.11	0.5	0.5	39.14

*Contains 28.2 lb hydraulic fluid pressurized by GN_2

Note: The weights in this table are for comparative purposes only. Improvement can be made in the weights and they should not be used for design purposes.

Table 4-2. LITVC Summary (Hot Gas Pressurization)

red or Yaw	Injectant Pitch & Yaw lb	Injectant Line Dia. in	Line Residuals in^3	4 Injector Residual in^3	Loaded Injectant in^3	Tank Ullage Volume in^3	Volume Boot in^3	Volume Bladder in^3	Injectant Tank Vol. in^3
1	85.0	0.275	8.65	12.8	1110.15	142.5	17.9	71.8	1342.40
4	119.4	0.250	7.16	12.8	1547.46	200.0	20.0	80.0	1847.46
0	75.0	0.281	9.25	23.2	1485.70	196.6	19.66	78.64	1785.10
.0	106.1	0.312	19.10	23.2	2096.95	220.0	22.00	88.0	2424.95

ant all	Injectant Tank Shell lb	Tank Flange End lb	Tank Fill & Outlets lb	Tank Insert Section lb	Total Tank Wt. lb	Boot Weight lb	Bladder Weight lb	Bladder Dist. Tube lb	4 Injectant Line Wt. lb
5	32.15	2.09	1.33	6.62	42.19	1.18	4.74	0.84	0.50
[illegible]	38.22	2.40	1.33	7.60	49.55	1.32	5.28	0.80	0.45
5	37.58	2.36	1.33	7.48	48.75	1.30	5.19	0.89	0.50
5	43.69	2.74	1.33	8.67	56.43	1.45	5.81	0.98	0.50

ne pport b	Line Insulation lb	Hydraulic* System lb	Nozzle Extension lb	Total System Weight lb	Expended System Weight lb
.5	0.5	39.14	6.05	223.05	107.25
.5	0.5	39.14	6.05	270.25	118.99
.5	0.5	39.14	6.05	224.83	118.14
5	0.5	39.14	6.05	269.85	130.74

d by GN_2

parative purposes only.
s and they should not

Preceding page blank

ation)

ctant Vol. 3	Tank CL Major Dia. in	Tank Inside Minor Dia. in	Gas Generator Req. W. lb	Gas Generator Avg. W lb/sec	Burning Area in^2	Burning Dia. in	Propellant Length in	Tank Outside Minor Dia. in
.40	30	4.258	1.840	0.0230	7.233	3.035	10.60	4.272
46	31	4.914	2.581	0.0323	10.157	3.596	10.60	5.104
10	31	4.830	2.465	0.0308	9.686	3.512	10.60	5.220
95	31	5.630	3.399	0.0425	13.365	4.125	10.60	5.820

ıjectant e Wt.	4-Injector Valve Wt. lb	5-Burst Disc. lb	4-Injector Block lb	Propellant Weight lb	G.G. Case Weight lb	Relief Valve lb	Hot Gas Line lb	G.G. Suppt Bracket lb
)	12.	0.045	4.	4.44	2.80	2.50	3.0	1.08
5	12.	0.045	4.	6.24	3.97	2.50	3.0	1.52
)	12.	0.045	4.	5.96	3.87	2.50	3.0	1.45
)	12.	0.045	4.	8.21	4.63	2.50	3.0	2.00

4.3.2.1 COLD GAS SYSTEMS

4.3.2.1.1 PRELIMINARY WEIGHT ESTIMATE

Helium and nitrogen were considered as candidates for the stored gas auxiliary systems. For a system requirement of 18,930 ft lb sec ($x = 31$), and a moment arm of 100 inches, the total impulse required from the cold gas system in each axis is 2272 lb sec. A preliminary weight of 63.4 lb for the nitrogen system and 82.9 lb for the helium system is found from Figure 4-16. On this basis a nitrogen system was selected and no further consideration was given to helium for this application.

4.3.2.1.2 PRELIMINARY SYSTEM SIZING

In order to meet the duty cycle requirement of Figure 4-6, it is apparent that a blowdown system would require an extremely high initial pressure. Consequently, a pressure-regulated system was considered. However, if regulated pressure were maintained throughout the firing, the system would continue to operate for some time after main motor burnout, eventually blowing down after the supply system pressure had dropped below regulated pressure. In order to provide the minimum amount of propellant at the end of motor firing time the supply system was sized to drop to regulated pressure at some time before main motor burnout, and then blowdown.

The system capacity chosen is based upon the capability to provide maximum thrust for 70 seconds and blowdown beyond 70 seconds. This is illustrated in Figure 4-17. The auxiliary system pressure will have blown down to 1 percent of regulated chamber pressure at $t = 118$ seconds.

4.3.2.1.3 MATCHING REGULATED AND BLOWDOWN CHARACTERISTICS

For a regulated system, the supply pressure after operation for time, t, is:

Preceding page blank

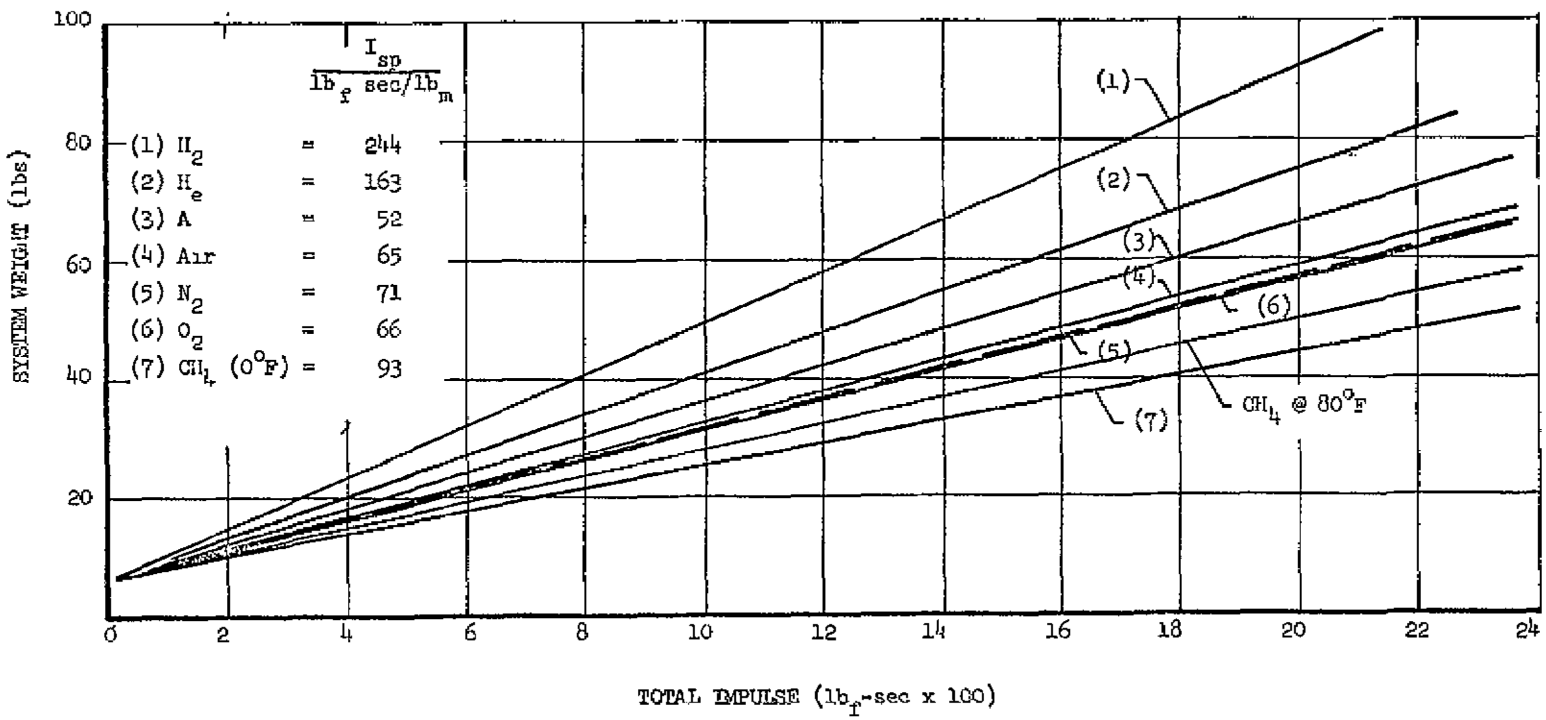


Figure 4-16. Cold Gas A.C.S. Weight Comparison

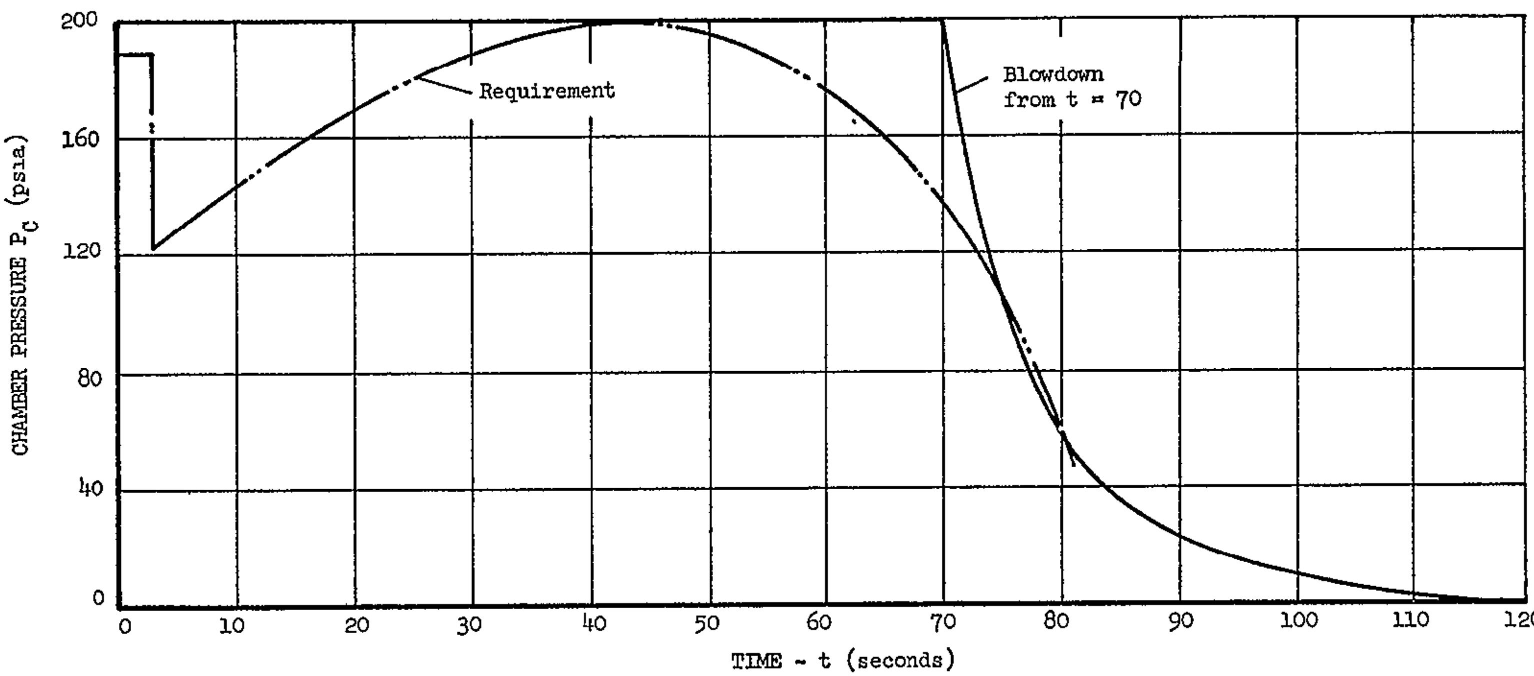


Figure 4-17. Regulated Blowdown System Duty Cycle

$$P = P_o \left[- \left(\frac{2}{\gamma+1}\right)^{\frac{3-\gamma}{2(\gamma-1)}} A_t \frac{\sqrt{g\gamma R\ T_o}}{V/Z_o} \frac{P_c}{P_o} t + 1 \right]^{\frac{2\gamma}{\gamma+1}} \quad (1)$$

For blowdown after supply pressure has dropped to regulated pressure,

$$\frac{P_f}{P_c} = \left[\frac{\gamma - 1}{2} \frac{A_t}{V/Z_o} \eta_{\ell} \sqrt{g\gamma R\ T_o} \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{2(\gamma-1)}} t + 1 \right]^{\frac{2\gamma}{1-\gamma}} \quad (2)$$

It can be seen that the regulated system can be matched to the blowdown system at any time t through the parameter V/A_tZ_o.

Figure 4-18 shows the relation of V/A_tZ_o to P_c/P_o and t, for a regulated system. The operating point shown was selected by matching the blowdown requirement that the moment be down to 54 ft lb at t = 80 seconds (see Table 4-3). From this, it is noted that V/A_tZ_o = 78,000 inches and P_c/P_o = .105 for matched conditions at t = 70 seconds.

4.3.2.1.4 PROPELLANT REQUIREMENT

The weight of nitrogen required to satisfy this duty cycle can be found from the relationship

$$W = \frac{P_oV_o}{Z_oR_oT_o}$$

$$= \frac{P_oV_o}{3.575 \times 10^5\ Z_o}$$

It is noted from Figure 4-6 that the maximum moment required is 203 ft lb. Thus for a moment arm of 100 inches the maximum thrust required is 24.4 lb. Also, P_oV_o can be found from the relationships

$$V_o/A_tZ_o = 78{,}000 \text{ in.}, \ \frac{P_c}{P_o} = .105 \text{ and } F = C_FP_cA_t \text{ lb}$$

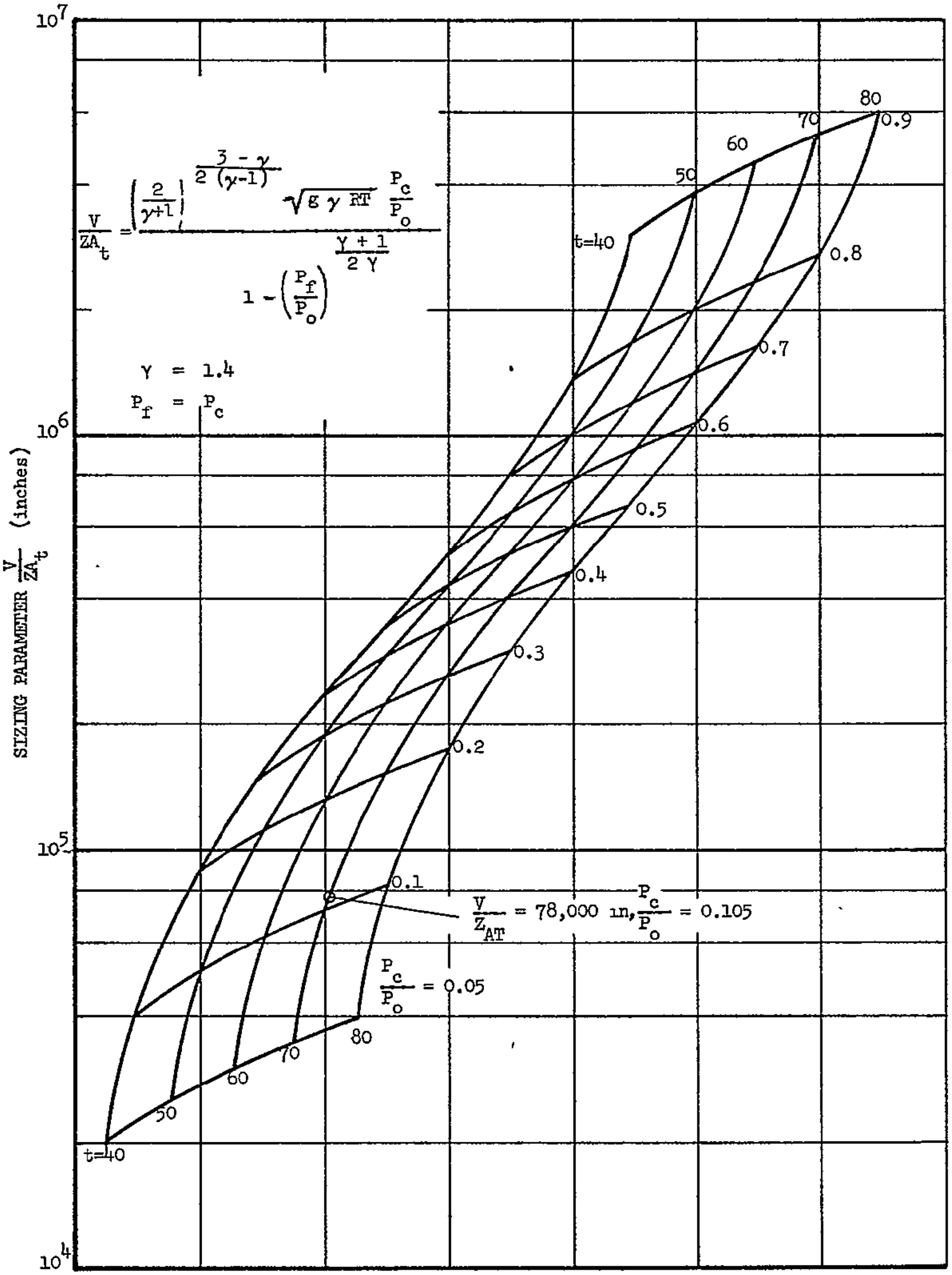


Figure 4-18. Regulated Nitrogen System Sizing Parameter vs Time and System Pressure Ratio

Table 4-3

COLD GAS BLOWDOWN CONDITIONS

$$\frac{V}{Z\,A_t} = \frac{136\,t}{\frac{1}{\left(\frac{P_f}{P_c}\right)^{1/7}} - 1} \times 12 \text{ inches}$$

$\frac{P_f}{P_c}$	$\left(\frac{P_f}{P_c}\right)^{1/7}$	$\frac{1}{\left(\frac{P_f}{P_c}\right)^{1/7}}$	$\frac{1}{\left(\frac{P_f}{P_c}\right)^{1/7}} - 1$	t	$\frac{V}{Z\,A_t}$
.266	.828	1.209	.209	1	7,800
				5	39,000
				10	78,000

Maximum moment = 203 ft lb

Moment at t = 80 sec = 54 ft lb

Then at t = 80 sec, P_c must have decayed to P_f, so that

$$\frac{P_f}{P_c} = \frac{54}{203} = .266$$

and we have:

$$P_oV_o = 126 \times 10^5 \text{ lb-in.}$$

from which the nitrogen required is:

$$W = 32.95 \text{ lb} = \frac{P_oV_o}{3.575 \times 10^5 Z_o}$$

4.3.2.1.5 TANK WEIGHT

Two materials were considered in determining tank weight, aluminum and titanium. Weight of the spherical tank shell is determined from

$$W_T = 1.5 \; P_oV_o \frac{\rho}{S}$$

For Aluminum

$$\rho = 0.1 \text{ lb/in}^3 \text{ and } S = 62{,}800 \text{ lb/in}^2$$

hence, $\frac{\rho}{S} = 1.591 \times 10^{-6} \text{ in}^{-1}$

and $W_T = 2.385 \times 10^{-6} \; P_o \; V_o$

For Titanium

$$\rho = 0.16 \text{ lb/in}^3 \text{ and } S = 129{,}000 \text{ lb/in}^2$$

hence, $\frac{\rho}{S} = 1.24 \times 10^{-6} \text{ in}^{-1}$

and $W_T = 1.86 \times 10^{-6} \; P_oV_o$

Minimum gage was taken at t = 0.03 in. for Aluminum and
t = 0.02 in. for Titanium.

It can be seen that the use of Titanium will result in a ligher tank.

Tank shell weight vs pressure is shown in Figure 4-19 for a titanium tank. It is observed that minimum weight is obtained by using a pressure of at least 250 psi. Taking 3000 psi as the design pressure, and

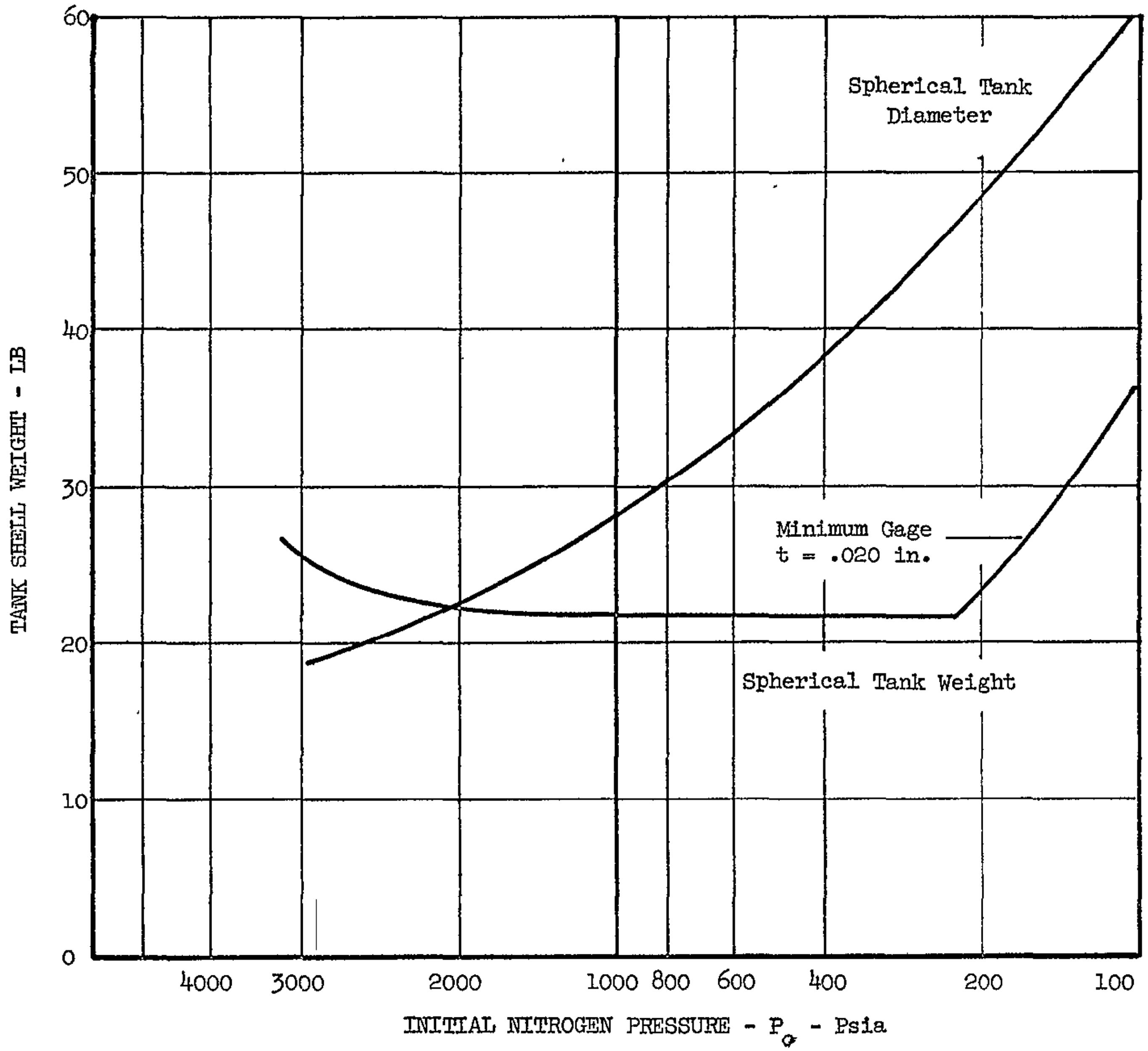


Figure 4-19. Spherical Titanium Tank Shell Weight for 32.95 lb Gaseous Nitrogen

adding 20 percent for fittings, the tank weight is 23.35 lb. Tank diameter is 20.0 inches. Note that the compressibility factor, Z_o, begins to cause an increase in tank weight above a pressure of about 2000 psi.

4.3.2.1.6 GAS LINE SIZING

The gas lines must be sized to pass the peak mass flow without severe losses. Peak mass flow is simply determined from

$$\frac{\dot{w}_{max}}{W_{gas}} = \frac{F_{max}}{I_{tot}}$$

from which $$\dot{w}_{max} = \frac{24.4 \times 32.95}{2272} = .353 \text{ lb/sec}$$

This mass flow is required at t = 43 seconds to provide the maximum thrust of 24.4 lb. The supply pressure at that time is very close to half the initial pressure. The line size required for a line inlet Mach number of 0.25 at this time, is 1/4 inch ID for an initial pressure of 1500 psi and 3/8 inch ID for 800 psi. The respective line weights for a 4.5 foot length are 0.09 lb and 0.18 lb. Assume the larger line and add 0.3 for fittings, so that line weight is 0.48 lb.

4.3.2.1.7 ESTIMATED VALVE WEIGHTS

Valves are required of sufficient size to pass the flow from 3/8 inch lines. On the basis of existing hardware weights the following weight estimates were made:

3 position valve	1.35 lb
Pressure regulator	1.0 lb
Explosive valve	1.0 lb

4.3.2.1.8 PITCH SYSTEM CONFIGURATION

The system configuration is shown schematically in Figure 4-20. It consists of a spherical nitrogen tank connected to a valve capable of

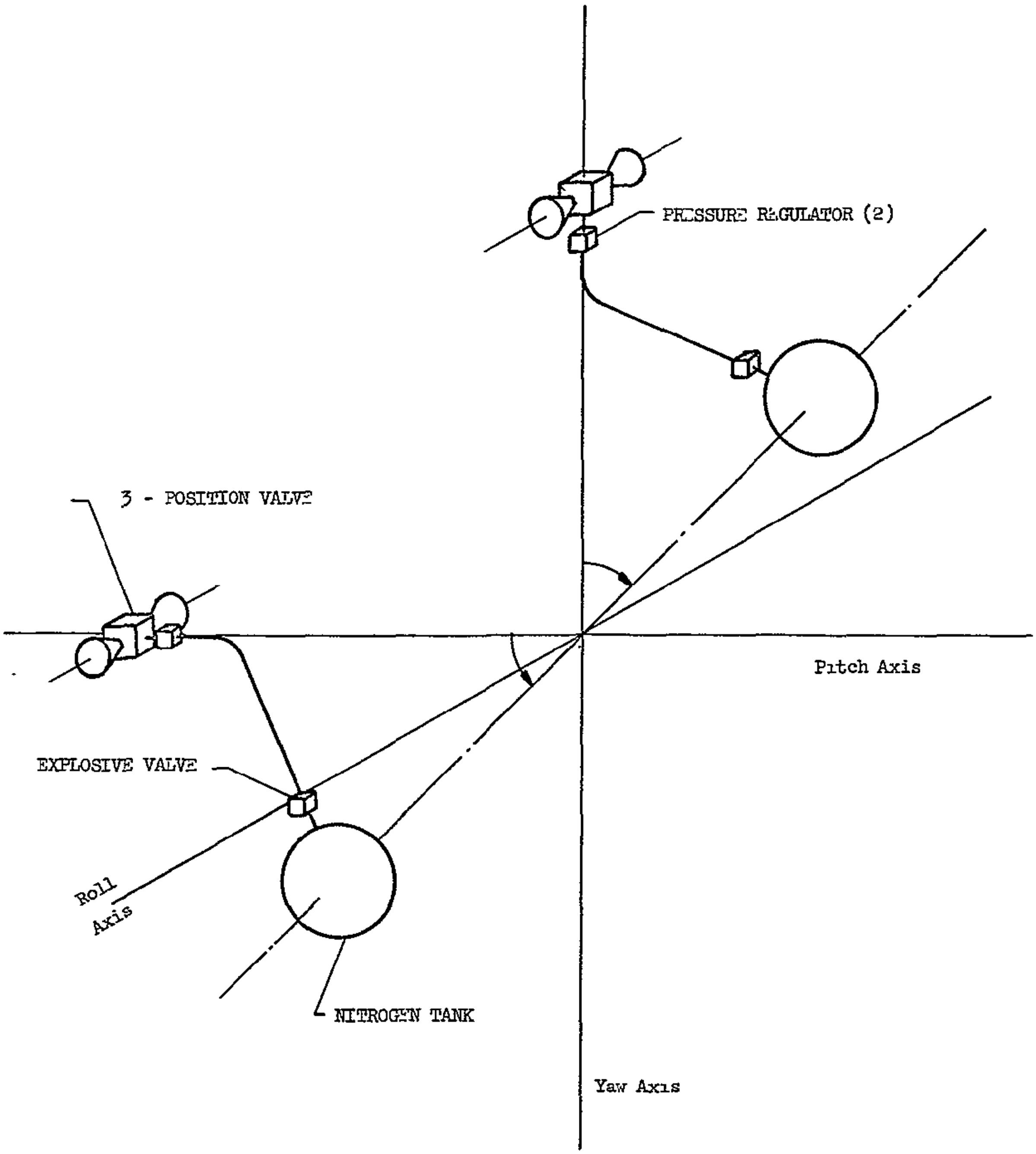


Figure 4-20. Cold Gas Pitch or Yaw System Schematic

thrusting in two directions. Pressure in the valve is controlled by a pressure regulator. System operation is initiated by activation of an explosively-opened valve at the tank. The tank is filled through a quick disconnect fittings and sealed by an explosively closed valve. The quick disconnect fitting backs up the seal of the explosive valve providing a highly reliable seal.

The weight of the system is as follows:

Nitrogen	32.95
Nitrogen tank shell	23.35
fittings	4.66
Gas line (4.5 ft) and fittings	.48
Valve	1.35
Pressure Regulator	1.0
Explosive Valves	1.0
	64.79 lb

4.3.2.1.9 PITCH AND YAW SYSTEM WEIGHT

Since the system described above is required in two axes the combined weight is 129.58 lb.

4.3.2.1.10 PROPORTIONAL AND GIMBALLED VALVES

The weight estimate given above is that for a three position (bang bang) valve thrusting either forward or aft, as commanded, or dumping both ways with the valve in the null position. Due to the possibility of introducing undesirable perturbations to the spacecraft with this type of operation, the possibility of using a proportional valve or gimballing a valve with one nozzle through 180° was considered.

It was found that the weight of a proportional valve of this size is essentially the same as the three position valve, while the gimballed system is about 6 pounds heavier for each system, or 12 pounds heavier for pitch and yaw. In addition, the frequency response of the gimballed system would be considerably less than that of the other systems.

4.3.2.1.11 ROLL CONTROL SYSTEM

The roll control system was sized in a manner similar to the pitch and yaw systems. To overcome the maximum moment of 12.6 in. lb at 100 inches, the thrust required is only 0.126 lb. For the same chamber pressure and supply pressure as the pitch and yaw systems the weight of nitrogen gas required to meet the roll moment requirement is only W = .146 lb.

This is such a small amount that it is not reasonable to provide a separate supply system for the roll control nozzles. Consequently, a valve configuration in which the roll valves are clustered with the pitch or yaw valves will be considered. Gas supply to the roll valves will be included in the main system.

4.3.2.2 MONOPROPELLANT SYSTEMS

The monopropellant thrust vector control system is shown schematically in Figure 4-21. The system contains the following elements:

a. Pressurization tank of titanium containing helium at 3000 psia.

b. Two fill and disconnect valves.

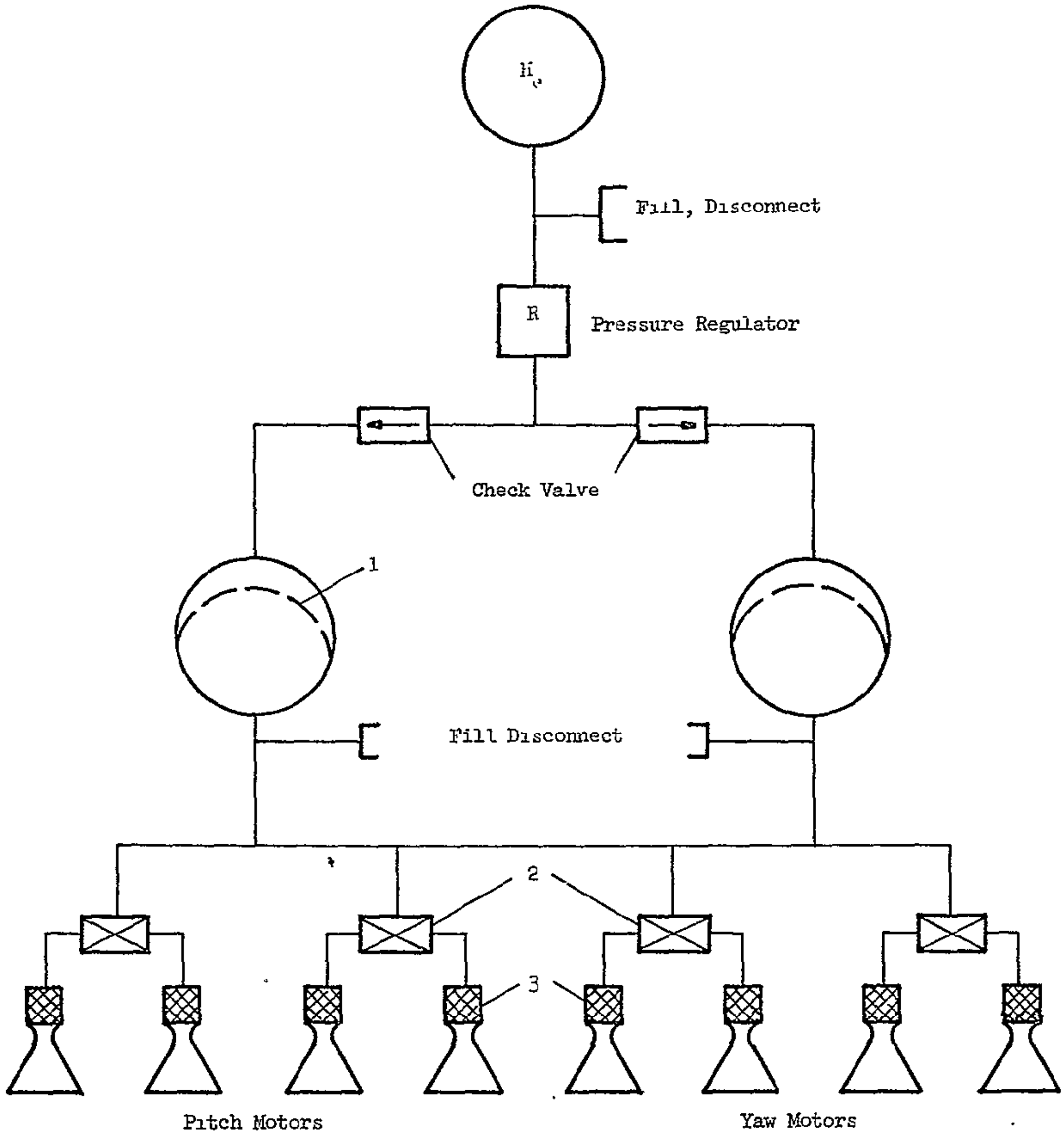
c. Pressure regulator set at 200 psi.

d. One check valve.

e. Two propellant tanks of 347 stainless steel with positive expulsion bladders.

f. Four two-way valves either solenoid or proportional.

g. Eight thrust chambers and catalyst packs.



1. Bladder - Positive Expulsion
2. Two-way Valve – Proportional or Solenoid
3. Catalyst Pack

Figure 4-21. Monopropellant A.C.S. Schematic

The system configuration within the vehicle is shown in Figure 4-22. The purpose of the two propellant tanks in the pitch yaw plane is to minimize the c.g. shift as the propellant is consumed.

The system operation is characterized by a constant mass flow of propellant. When the torque generated by thrust misalignment of the main motor is zero, the motors on the pitch and yaw axis, with thrust axis parallel to the roll axis, are cut on. This creates a small translation of the vehicle but no rotation. When the misalignment torque is finite these motors are cut off, and, the motors with thrust direction normal to the roll axis are cut on so as to reduce this misalignment torque to zero.

All four motors will be brought into operation two seconds before main motor ignition. This will ensure that any of the four motors may be used immediately. As soon as the thrust misalignment moment occurs, correction will be demanded of one, or at most two, auxiliary motors. The others will be shut down since the moment will remain one sided.

Consequently, the propellant requirements are defined by two 60.9 lb thrust motors operating for 80 seconds or 4860 lb seconds of total impulse each. To account for start up of four motors and subsequent operation of two, size the system for 10,000 lb sec.

In the study, two monopropellants were considered: 90% hydrogen peroxide (H_2O_2) and hydrazine (N_2H_4). The propulsion parameters and system weights are presented for these systems.

1. 90% Hydrogen Peroxide System
    a. Propulsion Parameters
        Specific Impulse $I_{sp} = 160$
        Expansion ratio $\epsilon = 40:1$
        Thrust Coefficient $C_F = 1.83$

The thrust level (F_N) for the motors with axis normal to roll axis is

$$F_N = \frac{\text{Maximum Moment}}{\text{Moment Arm}} = 203 \left(\frac{12}{40}\right) = 60.9 \text{ lb}$$

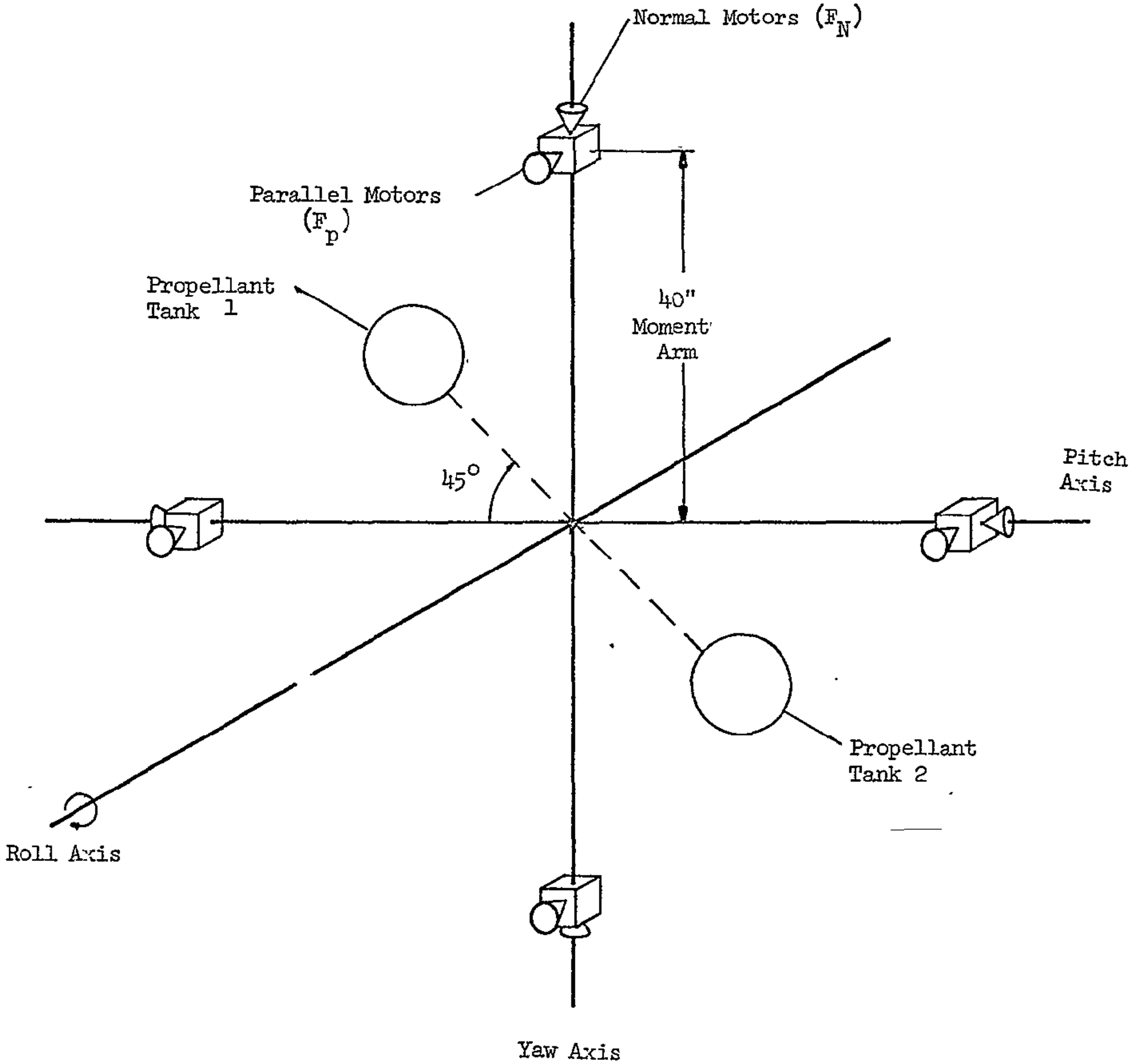


Figure 4-22. Monopropellant Pitch and Yaw System

Similarly, for the parallel motors,

$$F_p = 203 \left(\frac{12}{40}\right) = 60.9 \text{ lb}$$

From the thrust level and thrust coefficient the product of chamber pressure P_c and throat area A_t are given by

$$P_c A_t = \frac{F}{C_F}$$

Assuming a chamber pressure of 100 psi the throat area for the parallel and normal thrust motors is

$$(A_t)_p = \frac{F_p}{P_c C_F} = \frac{60.9}{100 \times 1.83} = .3324 \text{ in}^2$$

$$(A_t)_N = \frac{F_N}{P_c C_F} = \frac{60.9}{100 \times 1.83} = .3324 \text{ in}^2$$

The corresponding throat radii are

$$(r_t)_p = \left\{ \frac{(A_t)_p}{\pi} \right\}^{1/2} = .324 \text{ in.}$$

$$(r_t)_N = \left\{ \frac{(A_t)_N}{\pi} \right\}^{1/2} = .324 \text{ in.}$$

The propellant weight flow rate for the system is

$$\dot{W} = \frac{2 F_N}{I_{sp}} = .728 \text{ lb/sec}$$

b. System Weight

The total system weight is the sum of the propellant weight (W_p), propellant tank weight (W_t), pressurization system weight (W_{ps}), components weights (W_c) consisting of valves, regulator, thrust chamber, lines and fitttings. For comparison purposes the line and fitting weight was assumed to be two pounds. The other system weights are computed from the system parameters as follows.

The total propellant weight (W_p) is defined as

$$W_p = \frac{\text{Total impulse}}{\text{Specific impulse}} = \frac{(I_T)}{(I_{sp})} = \frac{10{,}000 \text{ lb sec}}{160 \text{ sec}} = 62.5 \text{ lb}$$

The propellant tank weight can be computed from the propellant volume, density of tank material and tank wall thickness. The propellant volume is simply

$$V_p = \frac{\text{Propellant weight}}{\text{Propellant density}} = \frac{(W_p)}{(\rho_{H_2O_2})} = \frac{36.53}{0.0513} = 1220 \text{ in}^3$$

The propellant is contained in two tanks of 610 in^3 each. The radius of each tank is

$$r_t = \left\{\frac{3\,V_p}{8\,\pi}\right\}^{1/3} = 5.3 \text{ in.}$$

The total propellant tank weight

$$W_t = \text{tank material density x volume of tank material}$$

$$W_t = 2\rho_{ss}\left[\frac{4\pi}{3}(r_t + t)^3 - \frac{V_p}{2}\right] = 10.08 \text{ lb}$$

where

ρ_{ss} tank material density = 0.28 lb/in^3

t tank wall thickness = 0.05 in.

The pressurization system consists of the pressurization tank and gas (helium). The tank and gas weights are computed using the perfect gas law and volume of the propellant required V_p. The total mass of the pressurization gas is mass required to displace (M_{req}) the propellant and the residual mass (M_{res}).

$$M_{Tg} = M_{req} - M_{res}$$

where

$$M_{Tg} = \frac{P_i\ V_b}{Z_i\ RT_i}$$

$$M_{res} = \frac{P_f \; V_b}{Z_f \; RT_i}$$

V_b = Volume of pressurization tank

T = Temperature, ^oR

P = Pressure, psi

Z = compressibility factor of Helium at specified temperature and pressure

Subscripts i and f denote initial and final values.

Solving for V_b gives

$$V_b = \frac{M_{req}}{\dfrac{P_i}{Z_i \; RT_i} - \dfrac{P_f}{Z_f \; RT_f}}$$

Assuming adiabatic expansion of the gas the final temperature T_f is

$$T_f = T_i \left(\frac{P_f}{P_i}\right)^{\frac{\gamma}{1-\gamma}} \quad ; \qquad \gamma' = \text{ specific heat ratio}$$

The required mass (M_{req}) is

$$M_{req} = \frac{P_p V_p}{R \; T_p}$$

T_p = temperature in propellant tank

P_p = gas pressure in propellant tank.

The pressurization tank weight (W_T) is given by

$$W_T = \frac{3}{2} P_i \quad \frac{\rho PT}{s_{PT}} \quad V_b \qquad \text{or} \qquad \rho_{PT} \left[\frac{4}{3} \; \pi \; (r_{PT} + t_{PT})^3 - V_b\right]$$

assuming $t_{PT} >$ minimum guage

where

ρ_{PT} = density of pressurization tank material = 0.17 lb/in^3

s_{PT} = stress level of tank = 1.3×10^5 psi

V_b = volume of pressurization tank

t_{PT} = tank wall thickness

The pressurization system parameters (W_T, V_b, M_{req}, T_f) are now computed using the following system parameters

V_p = 1220 in^3

P_i = 3000 psi

P_f = 400 psi

T_i = 510 ^oR

γ_{He} = 1.67

R = 2.68 ft lb/lb(mass) ^oR

P_p = 200 psi

T_p = 510^oR

Z_i = 1.13

Z_f = 1.03

They are

$$T_f = T_i \left(\frac{P_f}{P_i} \right)^{\frac{\gamma - 1}{\gamma}} = 229 \ ^oR$$

$$M_{req} = \frac{P_T \ V_p}{R \ T_p} = 0.1060 \text{ lbs (mass)}$$

$$V_b = \frac{M_{req}}{\frac{P_i}{Z_i \ RT_i} - \frac{P_f}{Z_f \ RT_f}} = 140.0 \text{ in}^3$$

$$M_{Tg} = \frac{P_i \; V_b}{Z_i \; RT_i} = .1574 \text{ lb}$$

$$M_{res} = \frac{P_f \; V_b}{Z_f \; RT_f} = 0.0514 \text{ lb}$$

The pressurization tank radius r_{PT} is

$$r_{PT} = \left(\frac{3 \; V_b}{4 \pi} \right)^{1/3} = 3.22 \text{ inches}$$

Assuming a wall thickness (t_{PT}) of 0.05 inches, the pressurization tank weight is

$$W_T = \rho_{PT} \left[\frac{4\pi}{3} (r_{PT} + t_{PT})^3 - V_b \right] = 1.07 \text{ lbs.}$$

The total pressurization system weight (W_{PS}) is thus

$$W_{PS} = W_T + W_{Tg} = 1.2274 \text{ lbs.}$$

The total weight of the system components (W_c) is 9.75 lb, broken down as follows:

1 regulator	0.8 lb
2 check valves	0.4 lb
4 solenoid valves	3.0 lb
8 thrust chambers	3.75 lb
Misc. lines and fittings	2.0 lb
3 fill and disconnect valves	0.75 lb

The total system weight W_S for the H_2O_2 monopropellant system is thus

$$W_S = W_p + W_T + W_{PS} + W_c = 84.0 \text{ lbs}$$

2. A similar analysis was conducted for hydrazine (N_2H_4)

Table 4-4 summarizes the propulsion parameters and system weights for both hydrazine and hydrogen peroxide. It shows that hydrazine has a weight advantage over hydrogen peroxide at about 20 lbs due primarily to its higher specific impulse.

4.3.2.3 BIPROPELLANT SYSTEMS

A bipropellant thrust vector control system is shown schematically in Figure 4-23. The system contains the following elements.

a. Pressurization tank of titanium containing helium at 5000 psi.
b. Three fill and disconnect valves
c. Pressure regulator.
d. Two check valves.
e. An oxidizer and propellant tank of 347 stainless steel with positivie expulsion bladders.
f. Eight combination oxidizer-propellant valves, either solenoid or proportional
g. Eight thrust chambers.

Figure 4-22 shows the system configuration within the vehicle. The system operation is the same as for the monopropellant system except that we have an oxidizer and propellant tank instead of two propellant tanks. The bipropellant system was analyzed exactly as the monopropellant system for two oxidizer-propellant combinations (N_2O_4 - Aerozine and N_2O_4 - N_2H_4). Table 4-4 summarizes this analysis.

The table also shows the system weights assuming proportional valves and gimballed thrust chambers. These variations increase the total system weight due to the increased weight of the components. Discussion of these systems is given in section 4.3.2.6

4.3.2.4 SOLID PROPELLANT GAS GENERATOR SYSTEM

A system with the same general valving configuration as the monopropellant and bipropellant systems was analyzed when a solid propellant gas generator is used as the gas supply. Hardware weights were scaled from existing Minuteman second stage roll control system components.

System data is tabulated in Table 4-5.

4.3.2.5 SOLID PROPELLANT MOTORS

The use of gimballed solid propellant motors to meet the thrust vectoring requirements was briefly considered. A literature search revealed a system developed for vector control, Reference 2, which had approximately the correct thrust and total impulse. The complete system weight was 135 lb.

System Type	Total Impulse I_T lb.sec	I_{sp} sec	Expansion ratio ϵ	Thrust Coeff. C_F	Chamb Pres P_c psi
Monopropellant					
H_2O_2	10,000	160	40:1	1.83	100
N_2H_4 (bang-bang)	10,000	240	40:1	1.72	100
(proportional)	10,000	240	40:1	1.72	100
(gimbal)	10,000	240	40:1	1.72	100
Bipropellant					
N_2O_4-Aerozine (bang-bang)	10,000	299*	40:1	1.83	100
(proportional)	10,000	312	40:1	1.83	100
(gimbal)	10,000	312	40:1	1.83	100
N_2O_4-N_2H_4 (bang-bang)	10,000	302*	40:1	1.83	100
(proportional)	10,000	250	40:1	1.83	100
(gimbal)	10,000	250	40:1	1.83	100

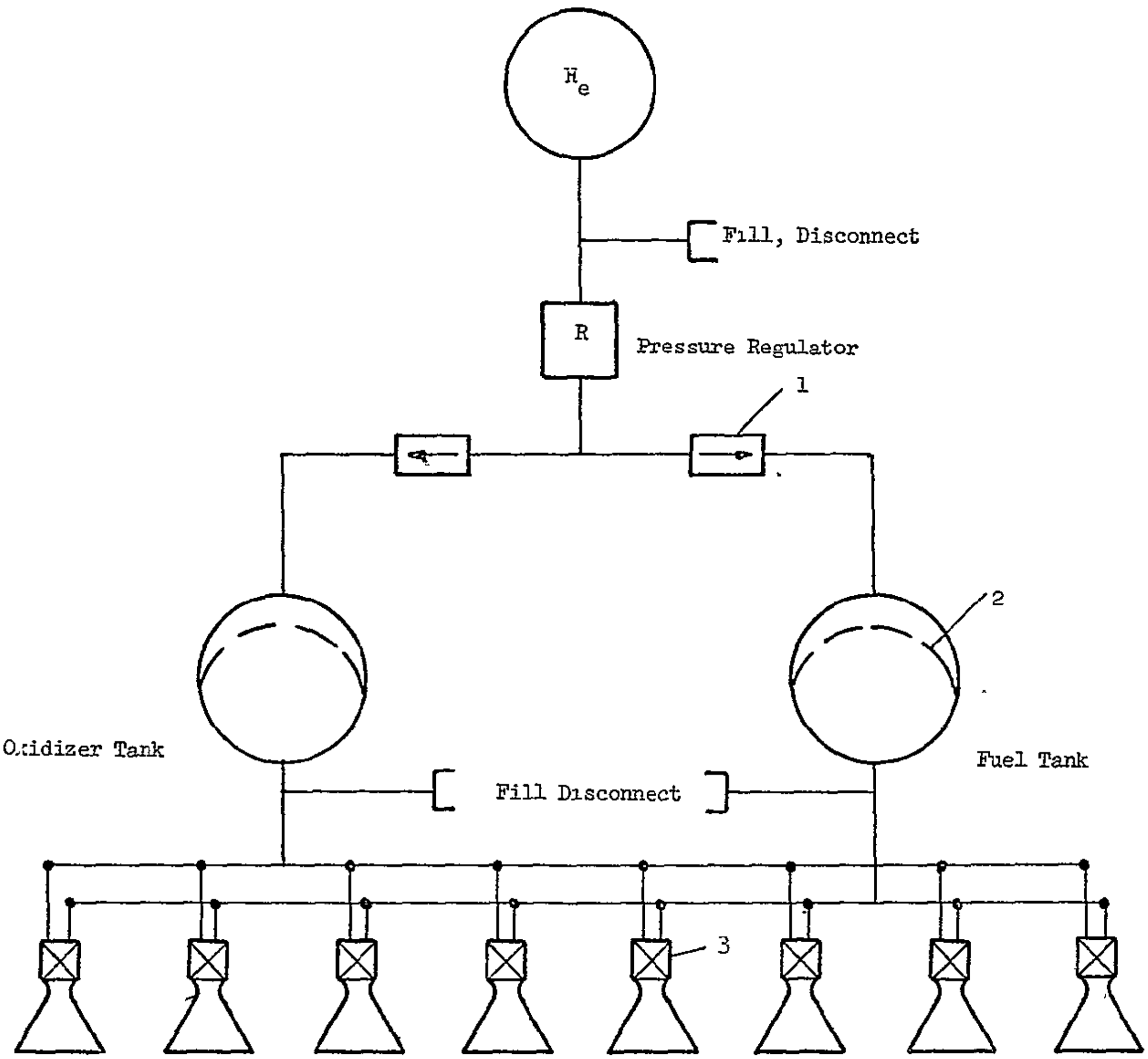
Note: * Corrected for drag, recombination and geometrical losses (

Table 4-4. Monopropellant and Bipropellant System Comparison

Expansion ratio ϵ	Thrust Coeff. C_F	Chamber Pressure P_c psi	Thrust Level F_N lbs	F_P lbs	Throat Radii $(r)_N$ in.	$(r_T)_P$ in	Total Wt. Flow Rate $\dot{W}$ lbs/sec	Propellant Weight Fuel lbs	Oxidiz lbs
40:1	1.83	100	60.9	15.225	.324	.324	0.728	62.5	N.A.
40:1	1.72	100	30.45	15.225	.238	.1635	.5075	41.7	N.A.
40:1	1.72	100	30.45	15.225	0.238	.1635	.5075	41.7	N.A.
40:1	1.72	100	30.45	15.225	0.238	.1635	.5075	41.7	N.A.
40:1	1.83	100	60.9	15.225	.324	.1635	0.20	10.8	22.6
40:1	1.83	100	60.9	15.225	.324	.1635	.020	10.8	22.6
40:1	1.83	100	60.9	15.225	.324	.1635	.020	10.8	22.6
40:1	1.83	100	60.9	15.225	.324	.1635	.3972	15.8	17.4
40:1	1.83	100	60.9	15.225	.324	.1635	.3972	15.8	17.4
40:1	1.83	100	60.9	15.225	.324	.1635	.3972	15.8	17.4

tion and geometrical losses (Reference 1) mparison

:opellant Weight		Propellant Tank Weight		Propellant Tank Radii		Press. System Weight W_{PS} lbs	Component Weight W_C lbs	Total Weight W_S lbs
	Oxidizer lbs	Fuel	Oxidizer	Fuel in	Oxidizer in			
5	N.A.	10.08	N.A.	5.26 (2 tanks)	N.A.	1.227	10.20	84.0
7	N.A.	8.96	N.A.	5.16 (2 tanks	N.A.	1.248	10.20	62.1
7	N.A.	8.96	N.A.	5.16	N.A.	1.248	13.70	65.6
7	N.A.	8.96	N.A.	5.16	N.A.	1.248	21.83	73.73
3	22.6	2.8	3.08	4.39	4.70	0.86	10.20	50.34
3	22.6	2.8	3.08	4.39	4.70	0.86	13.70	53.84
3	22.6	2.8	3.08	4.39	4.70	0.86	21.83	61.97
3	17.4	3.05	2.7	4.68	4.31	.83	10.20	49.98
3	17.4	3.05	2.7	4.68	4.36	.83	13.70	53.48
3	17.4	3.05	2.7	4.68	4.31	.83	21.83	61.11



1. Check Valve
2. Bladder - Positive Expulsion
3. Combination Oxidizer - Propellant Solenoid or Proportional Valve

Figure 4-23. Bipropellant A.C.S. System

Table 4-5

SEPARATE SYSTEM GAS GENERATOR

40" Moment Arm

Item	Units	C.G. Station 16	C.G. Station 31
Required Thrust per Nozzle	lb	45.6	30.45
Thrust Coefficient	-	1.708	1.708
Nozzle Throat Diameter	in	0.476	0.389
Flow Rate per Nozzle	lb/sec	0.2206	0.1473
Propellant Burning Area per Nozzle	in^2	83.2	55.6
Line Size ID	in	0.625	0.500
Line Wall Thickness	in	0.078	0.078
Line Weight	lb	14.24	12.22
Igniter Weight	lb	0.80	0.80
Insulation Weight	lb	3.50	3.50
Propellant Weight per Nozzle	lb	70.60	47.12
Gas Generator Case Weight	lb	29.36	24.14
Valve Weight	lb	37.6	37.6
Nozzle Weight	lb	6.16	6.16
Support Weights	lb	14.00	14.00
Total Loaded Subsystem Weight	lb	176.26	145.54
Total Expended Subsystem Weight	lb	104.86	97.62

4.3.2.6 PROPORTIONAL VALVES AND GIMBALLED THRUSTORS

The weights of the auxiliary systems described above have been determined using two-and three-position valves. To avoid undesirable high frequency pulses, which might interact with the spacecraft, continuously flowing proportional valves, or, gimballed thrustors were reviewed to determine the weight penalty, if any, due to their use.

4.3.2.6.1 PROPORTIONAL VALVES

A cold gas proportional valve, which was under development in 1959, and had a capability of 20 lb of thrust, was used in the study. This valve weighs 1.1 lb, which is not essentially different from the three-position valve assumed. By appropriate remote mounting of the electrical parts of the valve, it is assumed that this valve could be adapted for hot gas use. However, the actuator size must be increased in the hot gas valves due to the highter thrust level, hence higher actuation forces. The actuator power output is found from the relationship

$$P = \frac{F \times S}{t_r} \times \frac{1}{12 \times 550} \text{ hp}$$

where

P = output power, hp

F = thrust, lb

S = valve stroke

t_r = response time

For all the hot gas systems considered, and a system response of 30 cps (10 ms rise time), the output power requirement for the actuator is approximately .0556 hp or 40 watts.

From empirical data actuator weight is 2.75 lb. For the purposes of comparison, the greater part of the cold gas valve weight was assumed to be due to the actuator, so that system weight was increased approximately 1.75 lb in each plane, when a proportional system was considered.

4.3.2.6.2 GIMBALLED THRUSTORS

A cold gas thrustor, gimballed through 180° (i.e., full forward to full aft) was considered. For the valve size considered the torque requirements for frequencies from 1 to 30 cps were calculated. The actuator power required is plotted as a function of frequency in Figure 4-24. It is seen that it is unreasonable to expect a competitive system with a response of 30 cps. Consequently for sizing comparisons, 5 cps was selected, corresponding to 0.15 hp. Actuator weight vs power is shown in Figure 4-25. A schematic of the actuator system to which this weight applies is shown in the lower part of Figure 4-25.

As before, isolation of hot components from electrical systems is assumed for hot gas valves. It can be seen from Figure 4-25, that the vectoring systems will weigh approximately 7 lbs per valve.

4.3.3 MOVABLE NOZZLE SYSTEMS

4.3.3.1 PRELIMINARY SYSTEM ANALYSES

4.3.3.1.1 CONCEPTS STUDIED

In accordance with the requirements of Figures 4-5 and 4-6 correction for spacecraft upsetting moments was defined for spacecraft c.g. locations at X = 16 and X = 31 inches aft of the motor reference point. This variation in location has considerable effect on conventional gimballed nozzle actuation requirements because the resulting change in distances from c.g. to center of rotation varies the required correction angle, (nozzle rotation). As a result, two designs were compared - a conventional gimballed nozzle, and a new concept, termed a translating nozzle, which is relatively independent of the axial c.g. location. The concepts are shown in the design layouts of Figures 4-26 and 4-27.

The design comparison required preliminary analysis of auxiliary power and actuation system as well. Four systems were selected and sized for each nozzle design. Thus three nozzle cases were studied, each with four power systems. A summary of the systems studied is given in Table 4.6. Schematic diagrams for each power system studied are shown in Figure 4-28, 4-29 and 4-30.

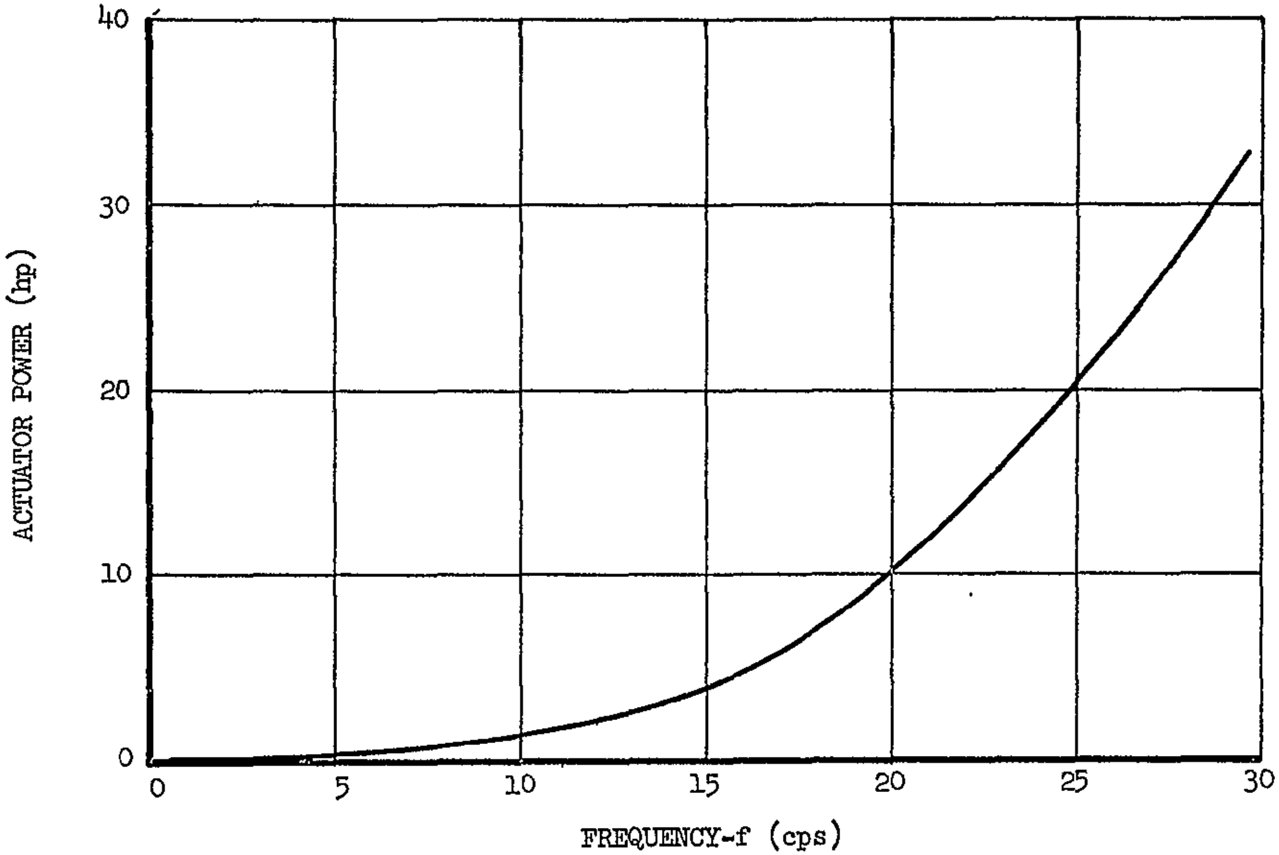


Figure 4-24. Actuator Power vs Frequency

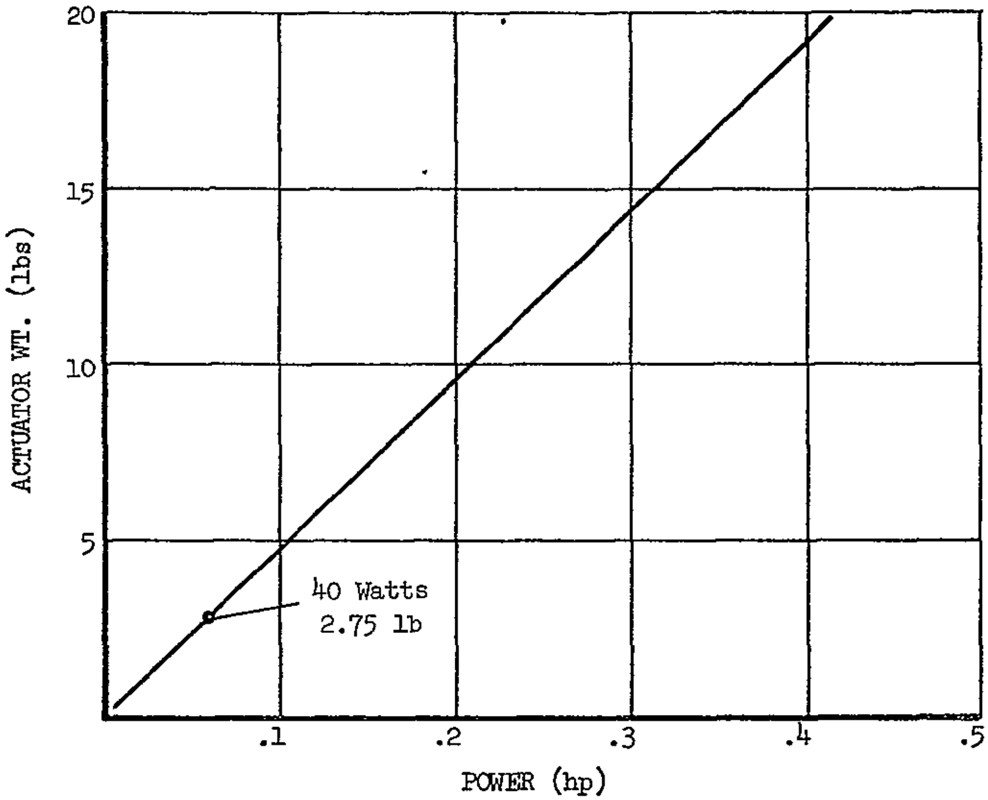
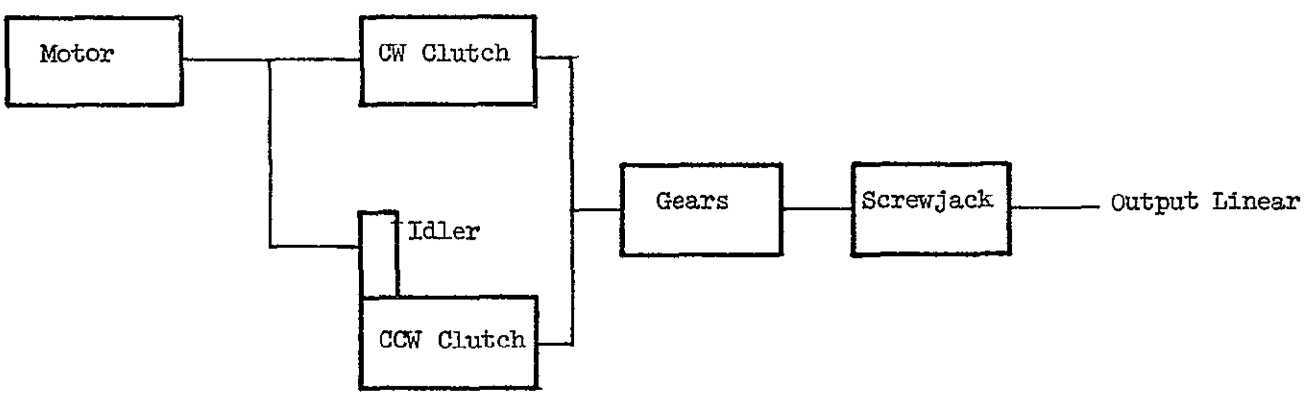


Figure 4-25a. Actuator Weight vs Power



MAGNETIC CLUTCH

TORQUE = f (control current)

Figure 4-25b. Actuator Schematic

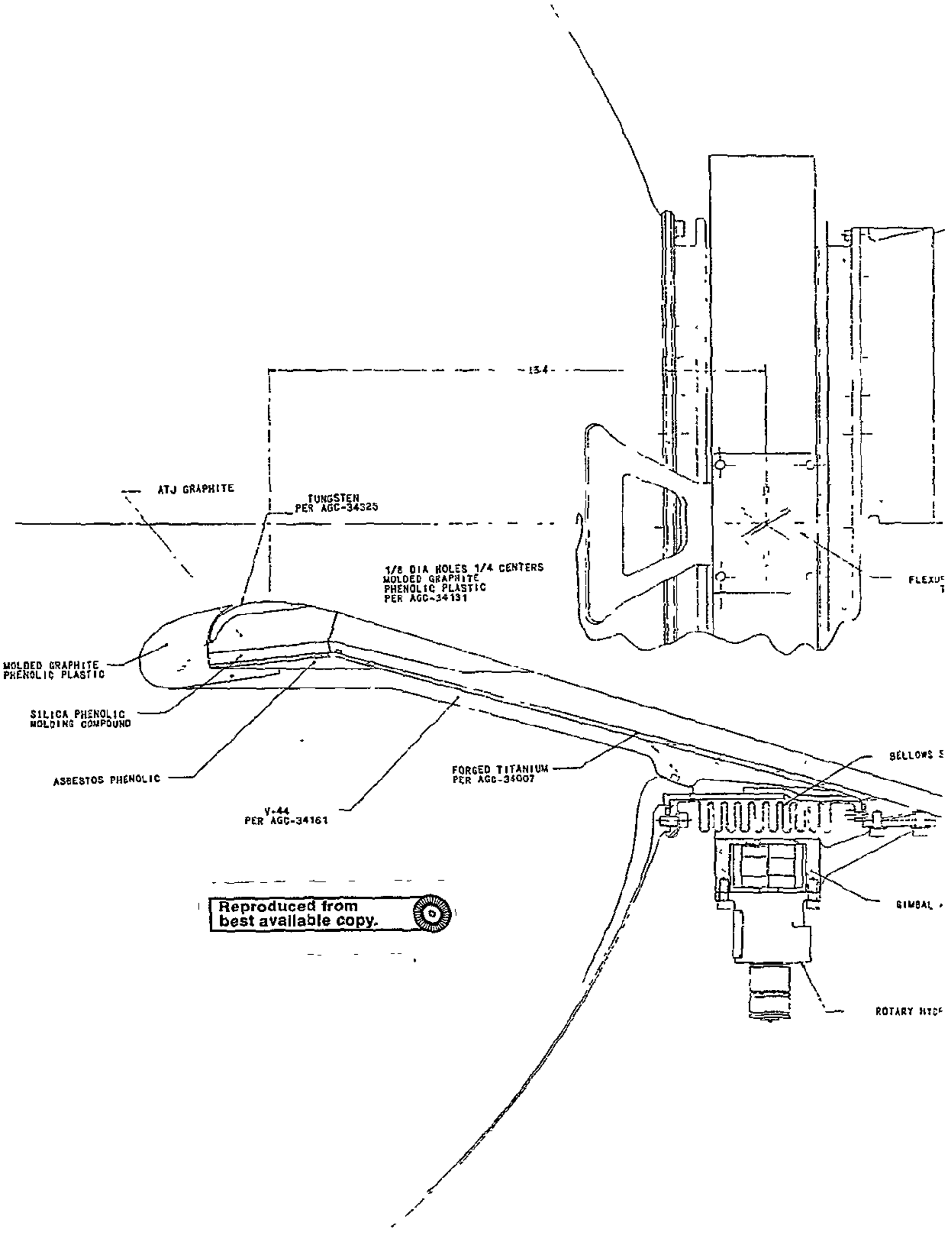
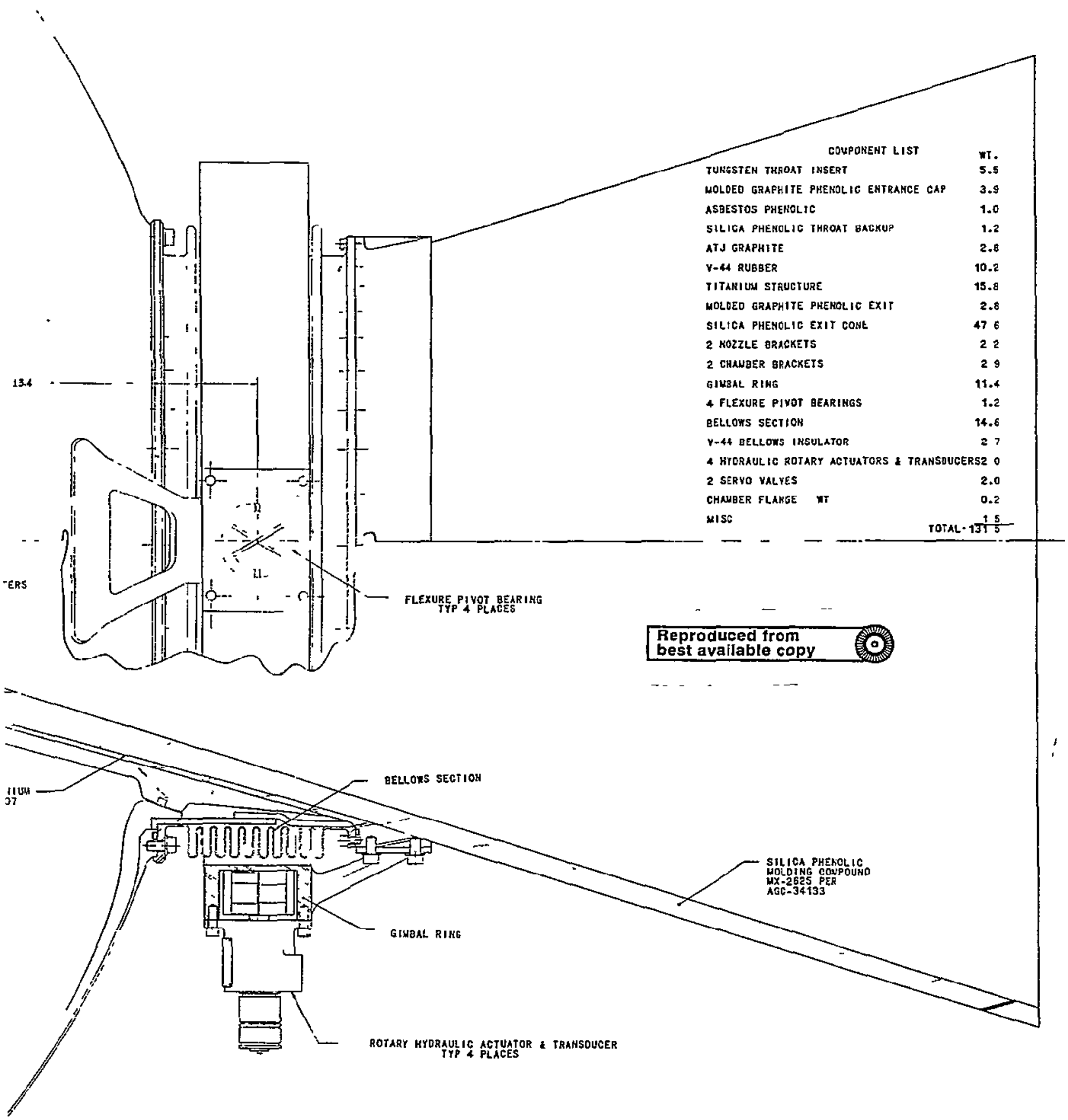


Figure 4-26. Gimballed Nozzle Prelimina



COMPONENT LIST	WT.
TUNGSTEN THROAT INSERT	5.5
MOLDED GRAPHITE PHENOLIC ENTRANCE CAP	3.9
ASBESTOS PHENOLIC	1.0
SILICA PHENOLIC THROAT BACKUP	1.2
ATJ GRAPHITE	2.8
V-44 RUBBER	10.2
TITANIUM STRUCTURE	15.8
MOLDED GRAPHITE PHENOLIC EXIT	2.8
SILICA PHENOLIC EXIT CONE	47 6
2 NOZZLE BRACKETS	2 2
2 CHAMBER BRACKETS	2 9
GIMBAL RING	11.4
4 FLEXURE PIVOT BEARINGS	1.2
BELLOWS SECTION	14.6
V-44 BELLOWS INSULATOR	2 7
4 HYDRAULIC ROTARY ACTUATORS & TRANSDUCERS	2 0
2 SERVO VALVES	2.0
CHAMBER FLANGE WT	0.2
MISC	1 5
TOTAL	131 5

e 4-26. Gimballed Nozzle Preliminary Layout

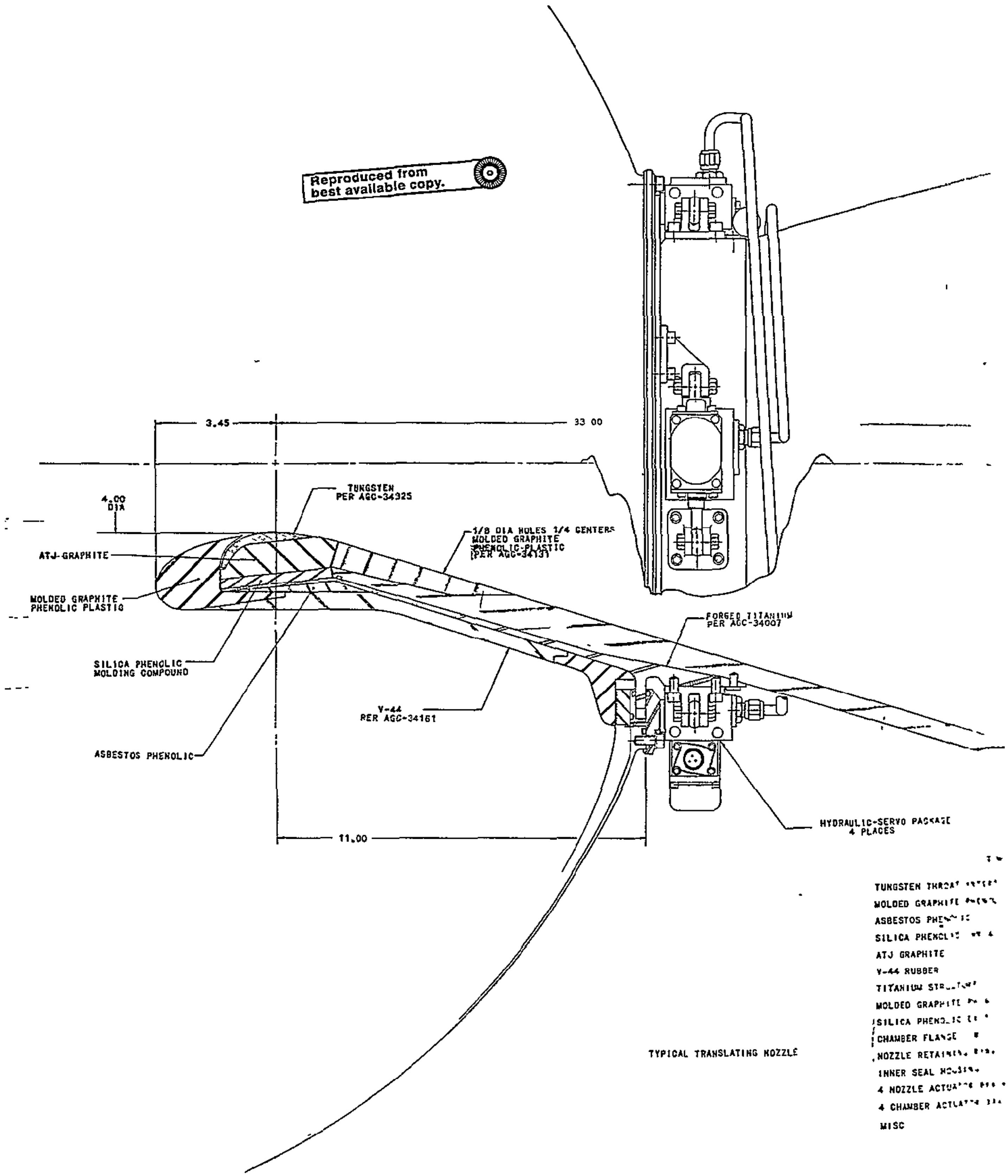
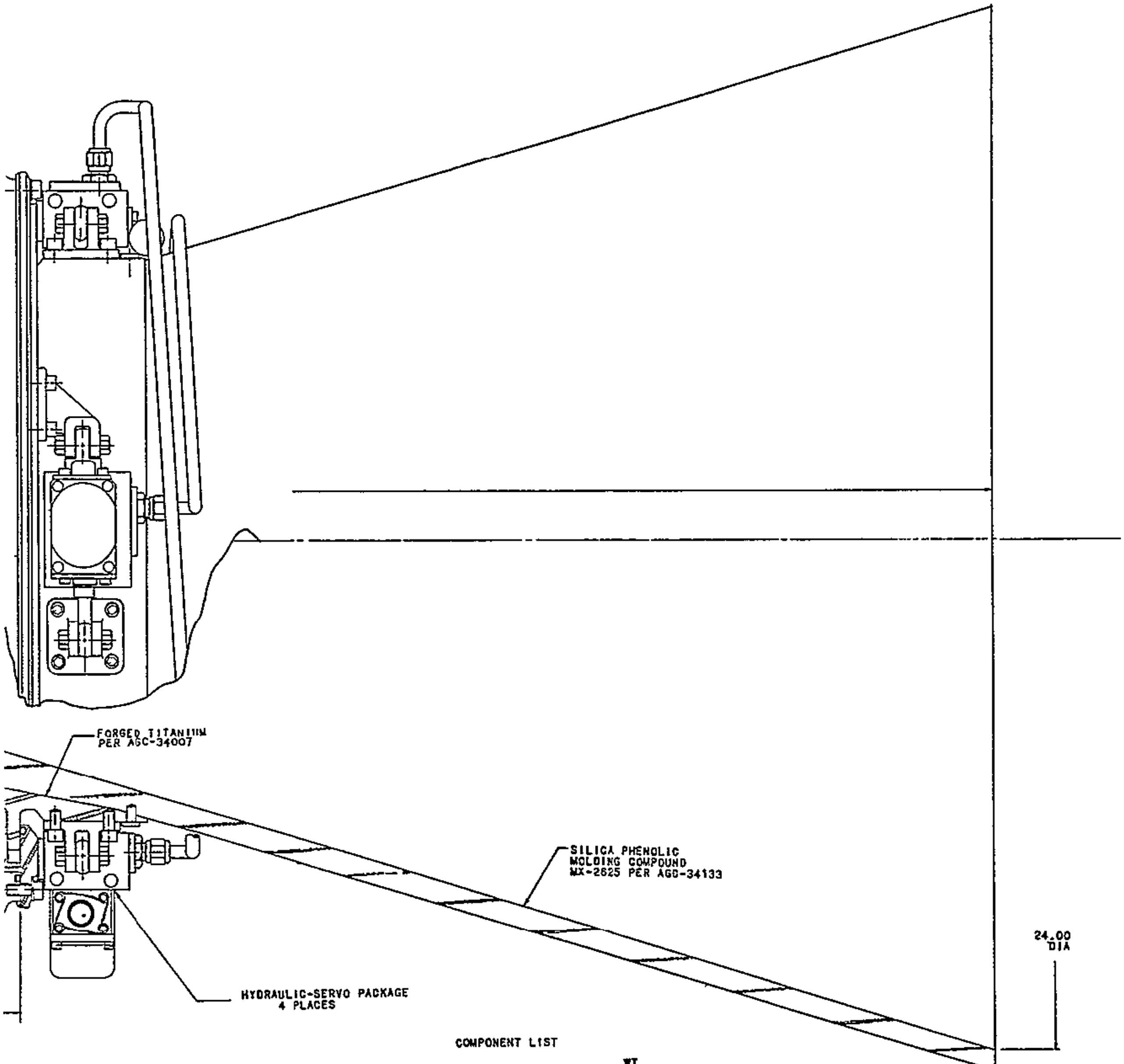


Figure 4-27. Translating Nozzle - Preliminary Layt



COMPONENT LIST

	WT
TUNGSTEN THROAT INSERT	5.5
MOLDED GRAPHITE PHENOLIC ENTRANCE CAP	3 9
ASBESTOS PHENOLIC	1.0
SILICA PHENOLIC THROAT BACKUP	1.2
ATJ GRAPHITE	2 8
V-44 RUBBER	10 8
TITANIUM STRUCTURE	12.4
MOLDED GRAPHITE PHENOLIC EXIT	2 8
SILICA PHENOLIC EXIT CONE	48 1
CHAMBER FLANGE WT.	0.4
NOZZLE RETAINING RING	4 9
INNER SEAL HOUSING	1.3
4 NOZZLE ACTUATOR BRACKETS	0 8
4 CHAMBER ACTUATOR BRACKETS	1.0
MISC.	1 5
TOTAL	98 4

TYPICAL TRANSLATING NOZZLE

anslating Nozzle - Preliminary Layout

Table 4-6

NOZZLE AND ACTUATION SYSTEMS ANALYZED

Nozzle Case	Actuation System
1. Gimballed Nozzle c.g. at 31"	1. N_2 Pressurized Hydraulic Actuator Non-recirulating Figure 4-28
2. Girnballed Nozzle c.g. at 16"	2. Gas Generator Pressurized Hydraulic Actuator Non-Recirculating Figure 4-29
3. Translating Nozzle c.g. at 31" or 16"	3. Electro-Hydraulic Motor Driven Hydraulic Pump Recirculating Figure 4-30
	4. Gas Generator Turbine Driven Hydraulic Pump Recirculating Figure 4-30

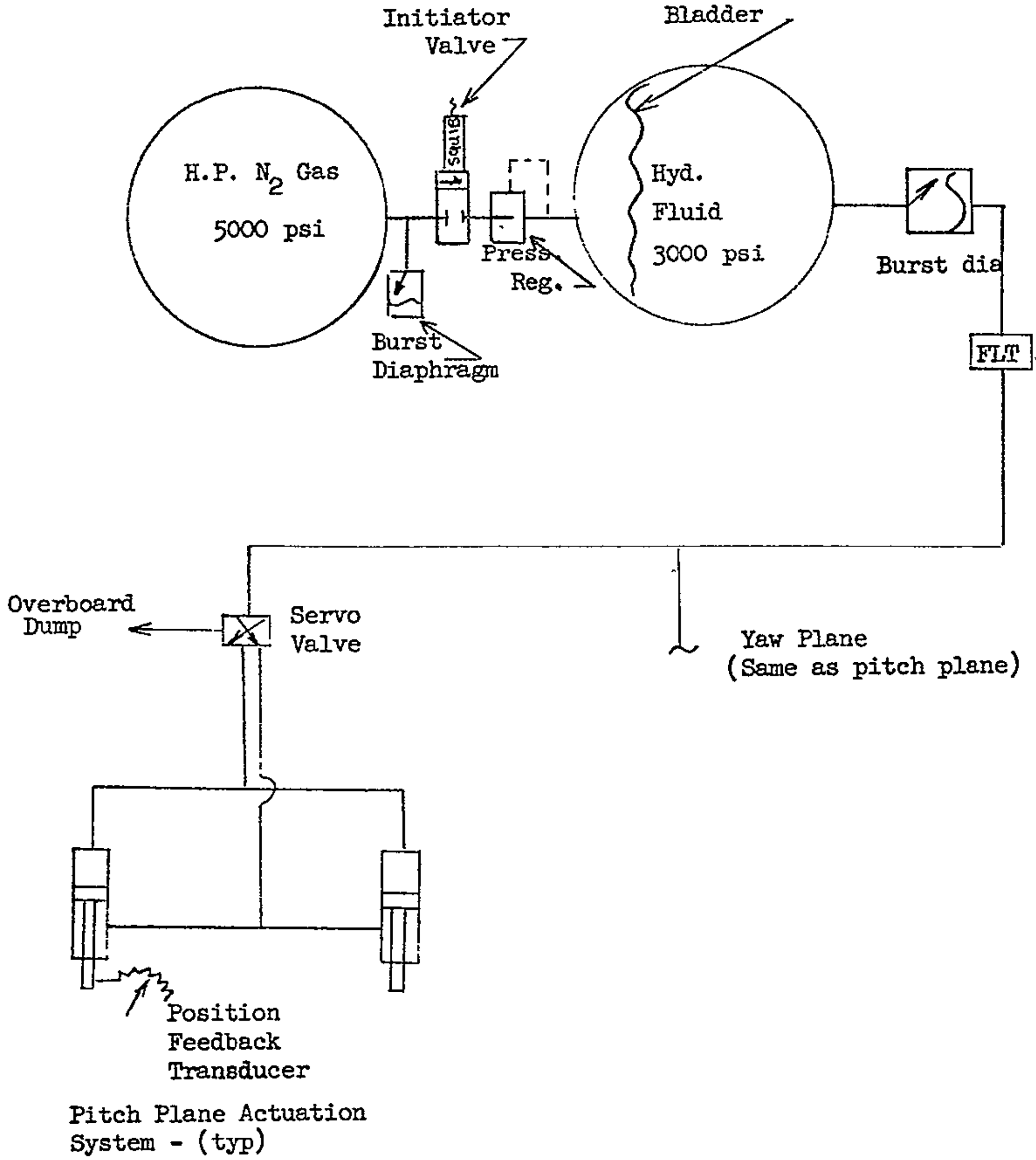


Figure 4-28. Movable Nozzle Actuation System No. 1

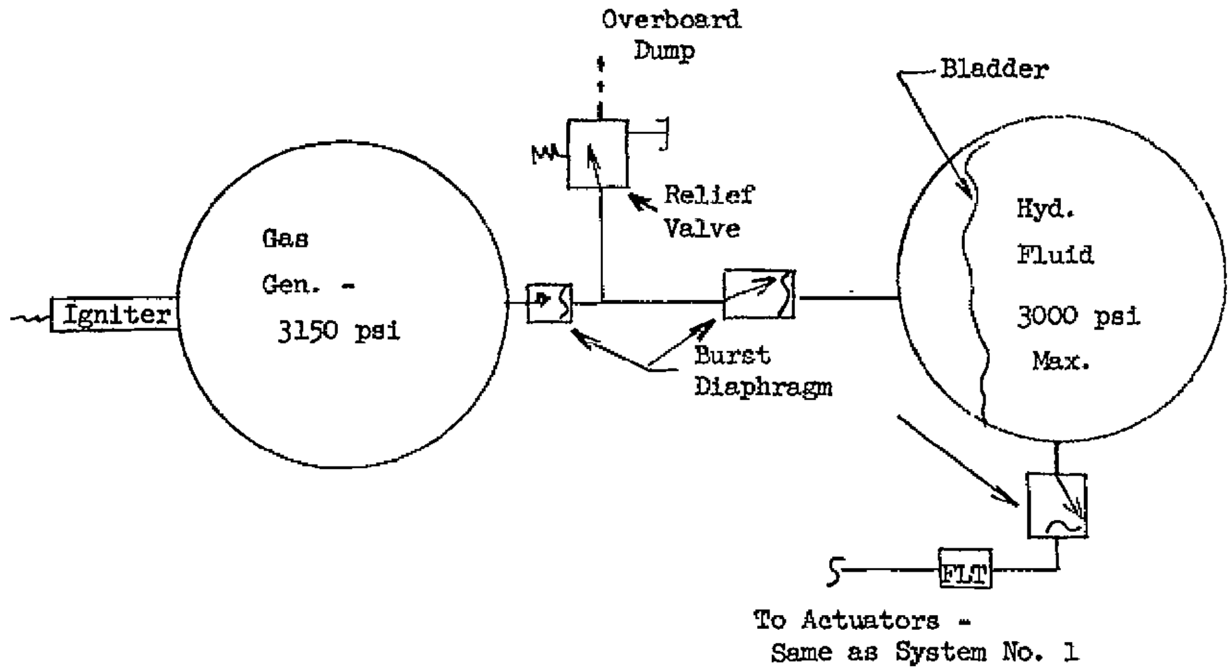
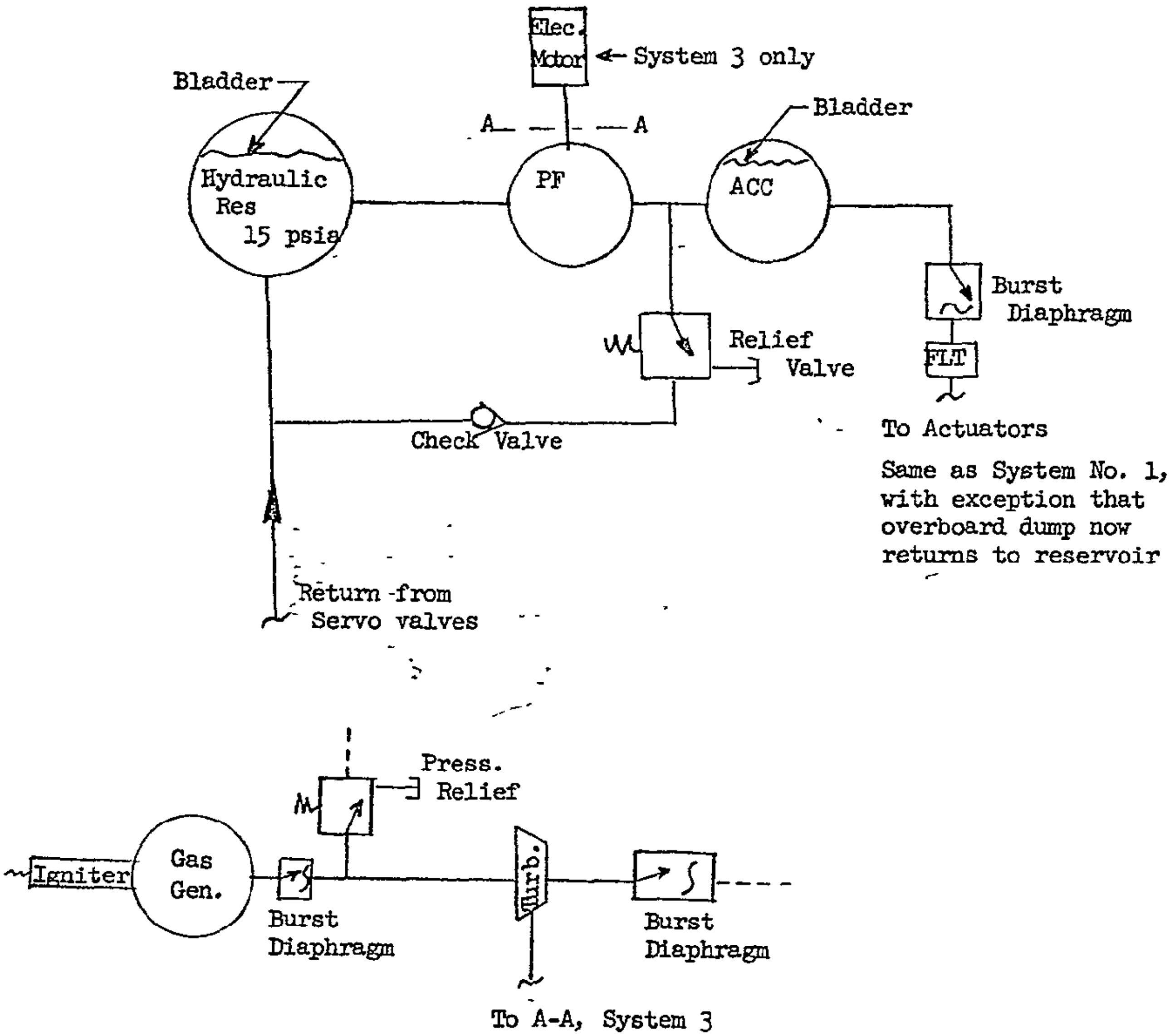


Figure 4-29. Movable Nozzle Actuation System No. 2



System No. 4

Figure 4-30. Movable Nozzle Actutation System Nos. 3 and 4

4.3.3.2.1 REQUIREMENTS AND ASSUMPTIONS

The system comparisons were based primarily on the following design criteria and assumptions.

1. Nozzle throat location at x = 33" (same as reference nozzle)
2. Nozzle exit location at x = 66", (expansion ratio = 36:1)
3. Maximum chamber pressure = 500 psia
4. Spacecraft c.g. locations at x = 16" and x = 31"
5. Maximum c.g. location uncertainty ± .219" at t = 80 sec Figure 4-4.
6. Auxiliary power reserve + 20% of nominal power
7. Power consumption based on 3 full deflection cycles plus dither at 10% full defelection for 85 seconds at 30 cps., deflections assumed to occur 45° between pitch and yaw control planes.

4.3.3.3.1 NOZZLE DESIGN DESCRIPTION

The two nozzle designs considered were the gimballed nozzle shown in Figure 4-26, and translating nozzle shown in Figure 4-27.

1. Gimballed Nozzle - the gimballed nozzle is a conventional design closely paralleling the Skybolt second stage nozzle design. The nozzle is a fully gimballed design supported by a box-section titanium gimbal-ring. The four hing points each mount to the axes, flexural pivots to permit ± 1 1/2° rotation about the pivot axis. As discussed later, this rotation is ample to provide TVC for any c.g. location forward of the x = 31" location. Weight requirements are very little affected by design rotation with the exception of the actuation system, as discussed later.

The flexible portion of the nozzle which acts as the hot gas seal permitting movements between fixed and movable portions is a stainless steel bellows, insulated with V-44 rubber sleeves, and further protected with silicone grease. It was assumed that the motor would be slightly pressurized during space storage so there would be no tendency for the grease to boiloff. The grease also serves to prevent blowing of the V-44 rubber sleeves into the bellows convolutions during initial pressurization. The sleeves are vented to permit pressure equalization across them during the balance of the firing. The use of metallic bellows is attractive in that it is a positive seal, easily checked and proofed, is tolerant to gimbal ring deflection, and requires no elastomeric components which could be exposed to vacuum. Historically this sealing technique has required high actuation forces because of bellows spring torque. However, the low deflection (1.5°) reduces this requirement relative to earlier applications.

A wiper seal is used to reduce gas circulation in the seal cavity. This is standard practice in swivel nozzles. The seal consists of split graphite or plastic rings which slide on the aft closure insulation. They are not intended to seal high pressure gases, and vents in the insulation are provided to permit rapid pressurization of the seal cavity upon motor ignition. In actual development, use of these circulation seals may be found unnecessary with the submerged design.

Four aluminum rotary actuators are used, one being mounted at each gimbal ring pivot point. The actuator shaft splines into the movable pivot sleeve of each flexure. The balance of the nozzle is similar in construction to the fixed reference nozzle. All structure is of forged 6Al-4V titanium which is presently used in the Minuteman Second Stage Wing VI design.

The proposed design differs from the Skybolt gimballed nozzle design in three areas:

a. The entrance and throat sections are buried in the motor chamber. Thus, the seal location and split line between fixed and movable portions is in a quiescent region. In the Skybolt design, the split line was located in the entrance cap where the gas flow achieves a Mach No. of .4. The present design thus alleviates the seal problem, in that, there is much less likelihood of unequal circumferential pressure distributions causing circulation of hot gases in the seal cavity.

b. The gimbal ring is pivoted on flexure assemblies rather than bearings. This simplifies space storage of the system as no lubricants or metal contact of sliding surfaces is required. Flexure pivots are also used in the Titan III transtage motor gimbal ring, and have, thus, been flight-proven.

c. Rotary, rather than linear actuators are used which reduces weight requirements for support bracketry.

Assembly and tolerance buildup of the nozzle is discussed for the nozzle selected, in section 4.5.3. The weight of this design is estimated at 127.5 lbs without actuators.

2. Translating Nozzle - The translating nozzle design shown in Figure 4-27 is capable of moving in any direction, $\pm$ .256 inches in a plane perpendicular to the thrust axis. Thus any c.g.-thrust axis misalignment can be cancelled by proper translation of the thrust axis. The design is insensitive to the c.g. location, except for minor differences due to possible thrust axis misalignment. Assuming maximum misalignment of 14' in the nozzle, and 4' due to chamber pressurization (the same values as for the fixed nozzle), additional deflection capability of $\pm$ .08 inches is required for the c.g. at x = 16" location, and a negligible amount of the x = 31" location. For preliminary screening, the system was designed for the c.g. location at x = 31" only.

The nozzle consists of a sliding, dry lubricated, titanium bearing, in which O-ring gas seals are mounted. The bearing, nozzle c.g., and actuator load points are all located in close proximity to the same axial location at the chamber exit plane. With the exception of the seal area, the design is consistent with the fixed and gimballed nozzle designs.

The seal cavity is protected from gas recirculation by a labyrinth sliding seal between the aft closure insulation and an extension of the movable structure insulation. This serves the same purpose as the sliding ring wiper seals in the gimballed nozzle.

Actuation is obtained by use of 4 linear hydraulic actuators. These are mounted to the aft closure seal clamping ring through which the seal bearing loads are also transmitted. The two pitch actuators are hydraulically interlocked, as are the yaw actuators. Each interlocked pair is operated by one servo valve. The actuator forces are oriented tangentially with respect to the exit cone cross section. Thus, two actuators, (one pitch and one yaw), must fail before rotation about the x axis can occur.

Nozzles of this or similar design concepts have been proposed in the past, but no firing experience is available for this approach. There is no particular area where major development problems are anticipated. The use of dynamic O-ring seals has been repeatedly shown effective in Minuteman First Stage swivel nozzles, and in numerous R & D applications with good success. The major problem areas are anticipated to be the effect of space storage environment on the O-ring seal and the metal to metal contact bearing.

The assembly and tolerance buildup of this design was not completed in detail as it was not selected as the final study design. The weight was estimated to be 98.4 lbs without actuators.

4.3.4 ACTUATION FORCE AND AUXILIARY POWER SYSTEM WEIGHT ANALYSIS

As mentioned previously, the nozzle design cases and actuation power systems analyzed are summarized in Table 4-6. An analysis was made of the system requirements for each case, the results of which are summarized in Table 4-7. The analythical methods and assumptions used in arriving at the design points shown in Table 4-7 are given in Appendix B.

Four actuation power systems were considered. These were shown schematically in Figures 4-28, 4-28, and 4-30, and consist of:

1. A cold N_2 pressurized, non-recirculating hydraulic system.
2. A warm gas generator pressurized, non-recirculing hydraulic system.
3. An electro-hydraulic pump driven recirculating hydraulic system.
4. A solid gas generator gas turbine driven hydraulic pump recirculating system.

Table 4-7

ACTUATION SYSTEM DESIGN CONDITIONS

1. GENERAL

a. Performance

Max. servo inlet pressure - 3000 psi
Max. servo valve pressure drop - 1000 psi
Actuation displacement - 3 cycles full deflection, followed by 85 seconds of 30 cps sinusoidal dither at $\pm$ 10% full deflection

Plane of Action - 45° between pitch and yaw planes

Displacement Reserve - 20% of max. requirement

b. Design

Pressurized vessel margin of safety + 1.0 min. to burst
Pressurized vessel material - 6Al-4V titanium
Minimum tensile - 150,000 uts
Storage ullage and outage 10% of capacity
Hydraulic fluid specific gravity = 1.0
Max. N_2 storage pressure - 5000 psia

Gas Generator Max. Mass Fraction - .5

Min. operating temperature + $30^{\circ}F$

2. CASE I NOZZLE

Max. rotation angle - $\pm$ 1.5°
Max. actuation torque = 8360 in-lb
Max. duty cycle volume displacement 190 in^3

Max. average power consumption - 1.0 Horsepower

3. CASE II NOZZLE

Max. rotation angle - $\pm$ 1.266°
Max. actuation torque = 7050 in-lb
Max. duty cycle volume displacement - 114 in^3

Max. average power consumption - .6 Horsepower

4. CASE III NOZZLE

Max. deflection - $\pm$ .256 in.
Max. actuation force per control plane - 3389 lb
Max. duty cycle volume displacement - 758 in^3

Max. average power consumption - 4.0 Horsepower

System No. 1

In system No. 1, an N_2 tank stores N_2 at 5000 psia. A positive sealing squib valve isolates the tank from the rest of the system. The pressure regulator maintains pressure on the hydraulic tank at 3000 $\pm$ 1000 psi. A relief burst diaphragm is supplied to vent the N_2 tank if over-pressure occurs. The N_2 tank is pre-filled at the suppliers to rated pressure, and all valves and fittings are welded in place. There are no seals in the system.

The hydraulic tank contains and elastomeric bladder to permit zero g operation. Storage is at near sea level pressure. This system is also isolated by welded fittings (burst diaphragm) and no seals are used which can be exposed to vacuum conditions.

Release of the system by actuation of the squib valve ruptures the burst diaphragms and delivers fluid to the servo valves and actuators. There is one servo valve per control plane. Each valve operates two hydraulically interlocked actuators. Control is through position feedback transducers mounted on each actuator.

The system is designed for a maximum pressure drop in the servo valve of 1000 psi when operating at maximum actuator displacement rate. Each system is designed to permit the nozzles to dither sinusoidally at $\pm$ 10% maximum deflection when nulled at maximum deflection where actuation forces are at peak levels.

System No. 2

System No. 2 is identical to System No. 1 except the hydraulic fluid is pressurized by a gas generator. Pressure is regulated by a relief valve which dumps unused gas overboard. The generator has a booster grain which permits high capacity flow for the first 3 seconds of burn time. This will allow high rates of actuator displacement during start up transients. Average gas temperature in the hydraulic fluid tank was assumed to be $1000^{\circ}F$.

The system is initiated by ignition of the generator which fails the welded burst diaphragms. The burst diaphragms completely isolate the system components prior to start up.

System No. 3

System No. 3 is a conventional pump driven system, recirculating the hydraulic fluid. The pump is driven by a D.C. electric motor. An accumulator is supplied to accommodate peak loads with smaller motor size. The motor and pump are, thus, sized to deliver the average required horsepower. Complete isolation of this system from external environment is more difficult in that rotating machinery is involved. For space application, components may need to be added to isolate points of potential leakage and hermetically seal the pump - motor combination for vacuum storage. Weight penalties for these modifications were not considered. The system as shown is initiated by start up of the pump which then charges the accumulator to operating pressure.

System No. 4

System No. 4 is the same as System No. 3, except the pump is now driven by a hot gas turbine operating from a solid propellant gas generator. Turbine inlet pressure is regulated by a hot gas relief valve, pump outlet pressure is regulated by a bypass liquid relief valve. A governor is supplied on the turbine to regulate speed. The system has isolation problems for space storage as noted for System No. 3. The gas generator ignition initiates the system. Peak loads are supplied through the accumulator and the turbine runs at constant speed supplying the estimated maximum average horsepower requirement.

System weights were calculated using generalized data from Reference 3 where applicable. Component and weight summaries for each auxiliary power system are given in Tables 4-8, 4-9, 4-10, and 4-11 for each nozzle case considered. System No. 4 is the lightest in all cases except in Case II where System No. 2 proved to be the lightest. For the gimballed nozzles (Cases I and II),

Table 4-8

SUMMARY-SYSTEM NO.1

N_2 PRESSURIZED, NON-RECIRCULATING HYDRAULIC SYSTEM

		Nozzle Case No.					
		I		II		III	
	Qty.	Vol, in^3	Wt, lb	Vol, in^3	Wt, lb	Vol, in^3	Wt, lb
N_2 Tank	1	422	4.05	253	2.42	1688	16.20
N_2	-	422	6.75	253	4.05	1688	27.00
Hydr. Fluid Tank	1	208	1.20	125	.72	834	4.85
Hydr. Fluid	-	190	6.87	114	4.13	758	27.40
Servo Valves	2	-	.80		.80		1.50
Actuators	4		4.00		4.00		6.00
Press. Reg.	1		.75		.75		1.50
Squib Valve	1		.50		.50		.90
Burst Diaphragm	2		.20		.20		.40
Sub Total			25.12		17.57		85.75
Plumbing, Fittings @10%			2.51		1.76		8.58
Sub Total			27.63		19.33		94.33
Insulation,Structure,Misc @10%			2.76		1.93		9.43
TOTAL			30.39		21.26		103.76

Table 4-9

SUMMARY SYSTEM NO. 2

NON-RECIRCULATING - GAS GENERATOR PRESSURIZED HYDRAULIC SYSTEM

		Nozzle Case No.					
		I		II		III	
	Qty.	Vol, in^3	Wt, lb	Vol, in^3	Wt, lb	Vol, in^3	Wt, lb
Gas Gen.	1	29.2	1.2	16.9	.72	113	4.8
Propellant	-	24	1.2	14.4	.72	96	4.8
Hydraulic Fluid	-	190	6.87	114	4.13	758	27.40
Hydraulic Tank	1	208	1.20	125	.72	834	4.85
Servo Valves	2		.8		.8		1.5
Actuators	4		4.0		4.0		6.0
Relief Valve	1		.4		.4		.8
Burst Diaphragms	2		.3		.3		.6
Sub Total			15.97		8.4		50.75
Plumbing and Fittings @10%			1.6		.8		5.1
			17.57		9.2		55.85
Insulation, Structure @10%			1.8		.9		5.6
TOTAL			19.37		10.1		61.45

Table 4-10

SUMMARY OF SYSTEM NO. 3

ELECTRO-HYDRAULIC MOTOR DRIVEN PUMP RECIRCULATING SYSTEM

		Nozzle Case No. I		Nozzle Case No. II		Nozzle Case No. III	
	Qty.	Vol, in^3	Wt, lb	Vol, in^3	Wt, lb	Vol, in^3	Wt, lb
Pump	1		.6		.5*		2.4
Motor	1		6.0		4.0		12.0
Relief Valve	1		.3		.3		.5
Accumulator	1	4	.4	2	.3	12	1.2
Check Valve	1		.2		.2		.4
Servo Valves	2		.8		.8		1.5
Actuators	4		4.0		4.0		6.0
Reservoir	1	56	2.8	38	1.9	170	8.5
Hydraulic Fluid		32	1.2	26	.94	80	2.9
Sub Total			16.3		12.94		35.4
Plumbing and Fittings @10%			1.6		1.3		3.5
Sub Total			17.9		14.24		38.9
Insulation,structure,Misc. @10%			1.8		1.4		3.9
TOTAL			19.7		15.64		42.8

Note: Wt. of electrical power supply not included

Table 4-11

SUMMARY SYSTEM NO. 4

GAS TURBINE DRIVEN PUMP RECIRCULATING SYSTEM

		Nozzle Case No.					
		I		II		III	
	Qty.	Vol, in^3	Wt, lb	Vol, in^3	Wt, lb	Vol, in^3	Wt, lb
Gas Gen Propellant		6.8	.34	4.0	.2	28	1.4
Gas Gen	1	11.3	.5	6.65	.3	35	1.4
Turbine	1		1.5		1.2		4.0
Hot Gas Relief Valve	1		.2		.2		.4
Burst Diaphragms	3		.3		.3		.6
Pump	1		.6		.5		2.4
Liq. Relief Valve	1		.3		.3		.5
Accumulator	1	4	.4	2	.3	12	1.2
Check Valve	1		.2		.2		.4
Servo Valve	2		.8		.8		1.5
Actuators	4		4.0		4.0		6.0
Reservoir	1	56	2.8	38	1.9	170	8.5
Fluid		32	1.2	26	.94	80	2.9
Sub Total			13.14		11.14		31.2
Plumbing and Fittings @ 10%			1.3		1.1		3.1
Sub Total			14.44		12.24		34.3
Structure, Insulation, Misc. @ 10%			1.4		1.2		3.4
TOTAL			15.84		13.44		37.7

however, power Systems 2, 3, and 4 are competitive. Should actuation rate requirements be reduced, System 2 will probably be found superior in these cases. A reduction in actuation rates will reduce power requirements very significantly in the gimballed nozzle because inertia torque represents about 1/2 the total actuation force (See Appendix B).

The translating nozzle (Case III) requires considerably greater actuation power because of the inherent high friction loads. If the seal could be placed closer to the throat diameter, the ejection force of 60,000 lb could be reduced, with a sizable reduction in the actuation power. Inertia loads are only about 10% of the total torque (See Appendix B). Thus, a reduction in actuation rate would not greatly reduce this system's requirements. The recirculating power systems are definitely superior in weight for this nozzle design.

The effective increase in weight over the basic nozzle weight for the various combinations is shown in Table 4-12. In addition, the advantages and disadvantages of each nozzle type are given in Table 4-13.

4.3.5 RELIABILITY ANALYSIS

Inherent design reliabilities were calculated for 17 combinations of attitude control systems considered for use on the solid propellant retromotor. The results are illustrated in Table 4-14. All values were calculated for pitch and yaw capability for system comparison purposes.

The addition of roll control capability (estimated in the second column of Table 4-14) has a definite effect on the liquid injection, the translating and gimballed nozzle and the solid propellant gas generator systems. It has less effect on the monopropellant and bipropellant reaction jet systems and an insignificant effect on the cold gas reaction jet systems. In the case of the cold gas reaction jet systems, a small roll control valve could be mounted on the valve body of either the pitch or yaw valve assembly, using the supply of gas coming to the pitch or yaw valve, since the roll requirements are very small. Such an addition lowers the inherent reliability very little. For

Table 4-12

NOZZLE WEIGHT COMPARISC

CASE	NOZZLE WT.	ACTUATION SYSTEM	ACTUATION SYSTEM WT.	TOTAL SY
I Gimballed Nozzle, C.g. at x = 31"	·127.5	1	30.4	157.
		2	19.4	146.
		3	19.7	147.
		4	15.8	143.
II Translating Nozzle	98.4	1	103.8	262.
		2	61.5	159.
		3	42.8	141.
		4	37.7	136.

Table 4-12

NOZZLE WEIGHT COMPARISON

ACTUATION SYSTEM WT.	TOTAL SYSTEM WT.	REF. NOZZLE WT.	TOTAL WT. PENALTY
30.4	157.9	84.4	73.5
19.4	146.9		62.5
19.7	147.2		58.9
15.8	143.2		
103.8	262.2		117.8
61.5	159.9		75.5
42.8	141.2		56.8
37.7	136.1		51.7

Table 4-13

COMPARISON OF GIMBALLED AND TRANSL

NOZZLE	ADVANTAGES
Gimballed	• Proven Concept • Positive Bellows Seal • Low Actuation Torque • No Bearings Req'd • Motion Positively Controlled
Translating	• Lower Weight • Simpler Design and Manufacture

COMPARISON OF POWER SYSTEMS 2 A
(System 2 is used on gimballed nozzle. S
on translating nozzle)

SYSTEM	ADVANTAGES
2 - Gas Generator Pressurized Hydraulic Non-Recirculating	• Simple design - few parts - low cost • Proven concept for hydraulic pressurization (Ground stored systems) • Completely sealed • No moving parts • Low weight (at low duty cycle) • Storage at low pressure • Low magnetic effects
4 - Gas Generator Turbine Driven Hydraulic Pump Recirculating	• Low weight for high duty cycle • Proven concept (for ground storage systems) • Storage at low pressure • Low magnetic effects

Table 4-13

COMPARISON OF GIMBALLED AND TRANSLATING NOZZLES

ADVANTAGES	DISADVANTAGES
n Concept ive Bellows Seal ctuation Torque arings Req'd n Positively Controlled	• More Costly Manufacture • Higher Weight
Weight er Design and Manufacture	• Sliding Bearing • Elastomeric Gas Seal • High Actuation Force • Unproven Concept • Motion Control Less Certain

COMPARISON OF POWER SYSTEMS 2 AND 4
m 2 is used on gimballed nozzle. System 4 is used on translating nozzle)

ADVANTAGES	DISADVANTAGES
e design - few parts - low cost n concept for hydraulic pressuri- n (Ground stored systems) etely sealed ving parts eight (at low duty cycle) ge at low pressure agnetic effects	• Cannot be test run prior to firing • Need to control hot gases
eight for high duty cycle n concept (for ground storage stems) ge at low pressure agnetic effects	• Requires dynamic seals and bearings • Cannot be test run prior to firing • Need to control hot gases • Difficult to seal for space storage • Complicated system - more costly

Table 4-14

SUMMARY OF SYSTEM RELIABILITY

	Reliability 6 Month Transit Mission P and Y Capability	Reliability 6 Month Transit Mission P, Y and R Capability
LITVC - Cold Gas Pressurized	.98412	.98029
LITVC - Hot Gas Presurized	.98123	.97741
Cold Gas Reaction Jet ACS	.99974	.99972
Solid Propellant Gas Generator Reaction Jet ACS	.99224	.98838
Monopropellant Reaction Jet ACS	.98329	.98320
Bipropellant Reaction Jet ACS	.97414	.9740
Translating Nozzle TVC-Cold Gas Pressurized, Hydraulic Servo-Actuation System	.99421	.99034
Translating Nozzle TVC-Hot Gas Pressurized, Hydraulic Servo-Actuation System	.99219	.98833
Translating Nozzle TVC-Recirculating Hydraulic Servo-Actuation -with Electric Motor/Pump	.99177	.98790
Translating Nozzle TVC-Recirculating Hydraulic Servo-Actuation - with Turbine-driven Pump	.98986	.98600
Translating Nozzle TVC-Electro-Mechanical Servo-Actuation	.99455	.99068
Gimballed Nozzle TVC-Cold Gas Pressurized, Hydraulic Servo-Actuation	.99473	.99086
Gimballed Nozzle TVC-Hot Gas Pressurized, Hydraulic Servo-Actuation	.99267	.9888
Gimballed Nozzle TVC-Recirculating Hydraulic Servo-Actuation - with Electric Motor/Pump	.99224	.98838
Gimballed Nozzle TVC-Recirculating Hydraulic Servo-Actuation - with Turbine-driven Pump	.99034	.98650
Gimballed Nozzle TVC - Electro-Mechanical Servo-Actuation	.99474	.99087

the monopropellant and bipropellant systems, another set of propellant lines containing the CW and CCW roll valves and nozzles could be extended from downstream of the propellant tanks.

The estimate of the addition of roll control capability to each system was made by using the above modifications for the cold gas, monopropellant and bipropellant systems and with use of a hot gas reaction jet roll control system for the LITVC, translating and gimballed nozzle TVC systems.

The effects of variable mission transit times were considered in the calculations with the mathematical model of each attitude control system. Calculations were made on a 6, 8, 10 and 12 month transit time basis and the results are shown plotted in Figures 4-31 through 4-37, "System Reliability Trend vs Transit Time." All curves are calculated with consideration of pitch and yaw capability for each system.

Section 4.6 lists the sources of component failure rate and reliability data used in the evaluation of the attitude control systems. References 4, 6, 7, 8, 10 and 12 provide data from modern aircraft flight environment, test data from the unclassified sections of the Minuteman LITVC report, pyrotechnic test data and failure data experienced on tests of the Ablestar upper stage vehicle. Use of these data tends to provide a more realistic reliability value that each system may attain. In cases where it was necessary to use laboratory level data, higher environmental (severity) factors were used to adjust failure rates to from 300 to 1500 times the laboratory environmental level during the retro-thrust (operational) part of the mission profile.

Reliability calculations are shown in Appendix E. Tables E-2 through E-14 of Appendix E record the component failure and reliability data for all the attitude control systems considered. Environmental stress factors (K_1) of varying levels are applied to adjust all component failure rates from the stress levels at which the data were obtained to the varied stress levels of the Mars mission profile. Application stress factors (K_2) are also used to further adjust the data as a result of component functional performance internal to the system design.

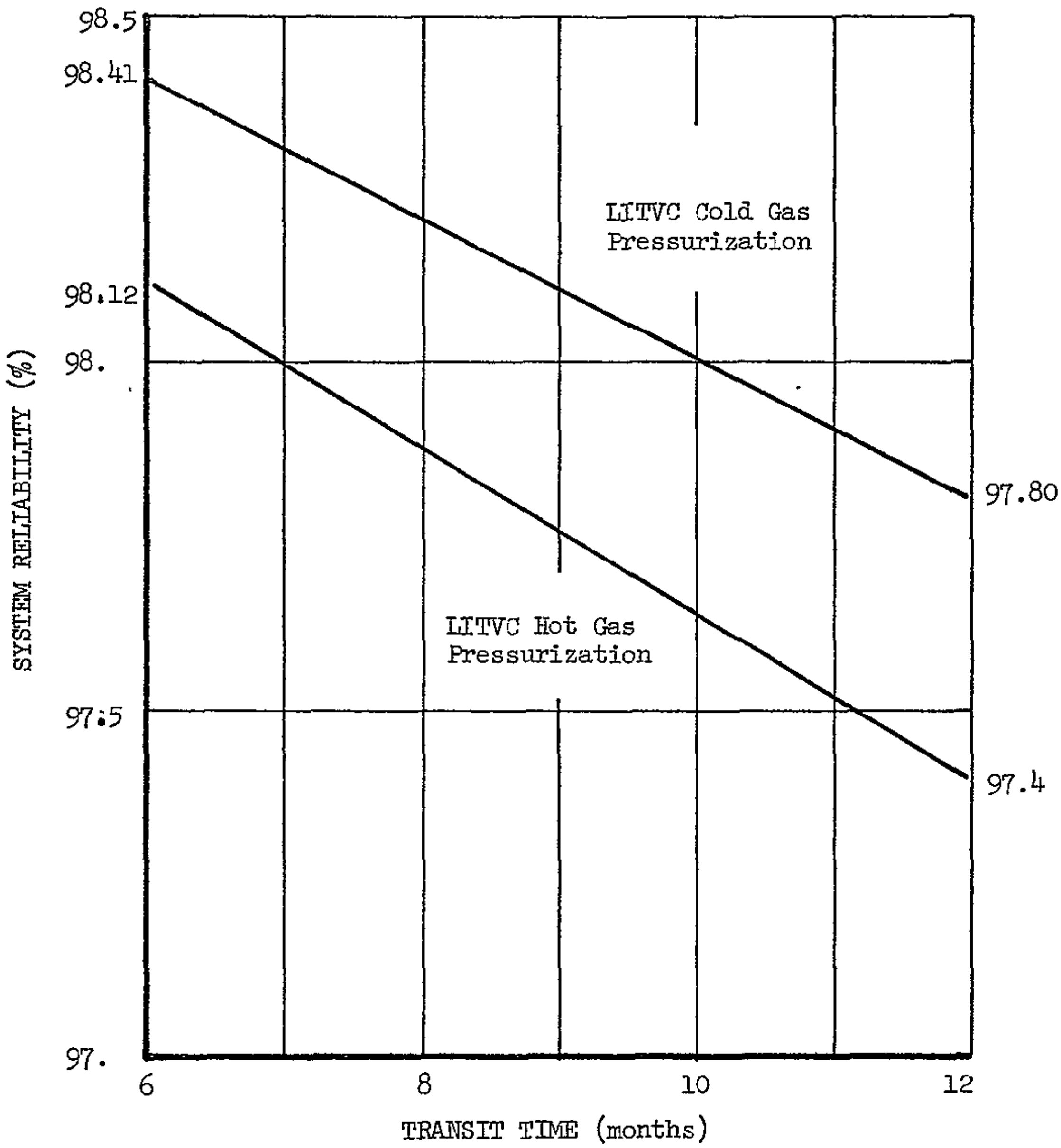


Figure 4-31. LITVC Reliability Trend vs Transit Time

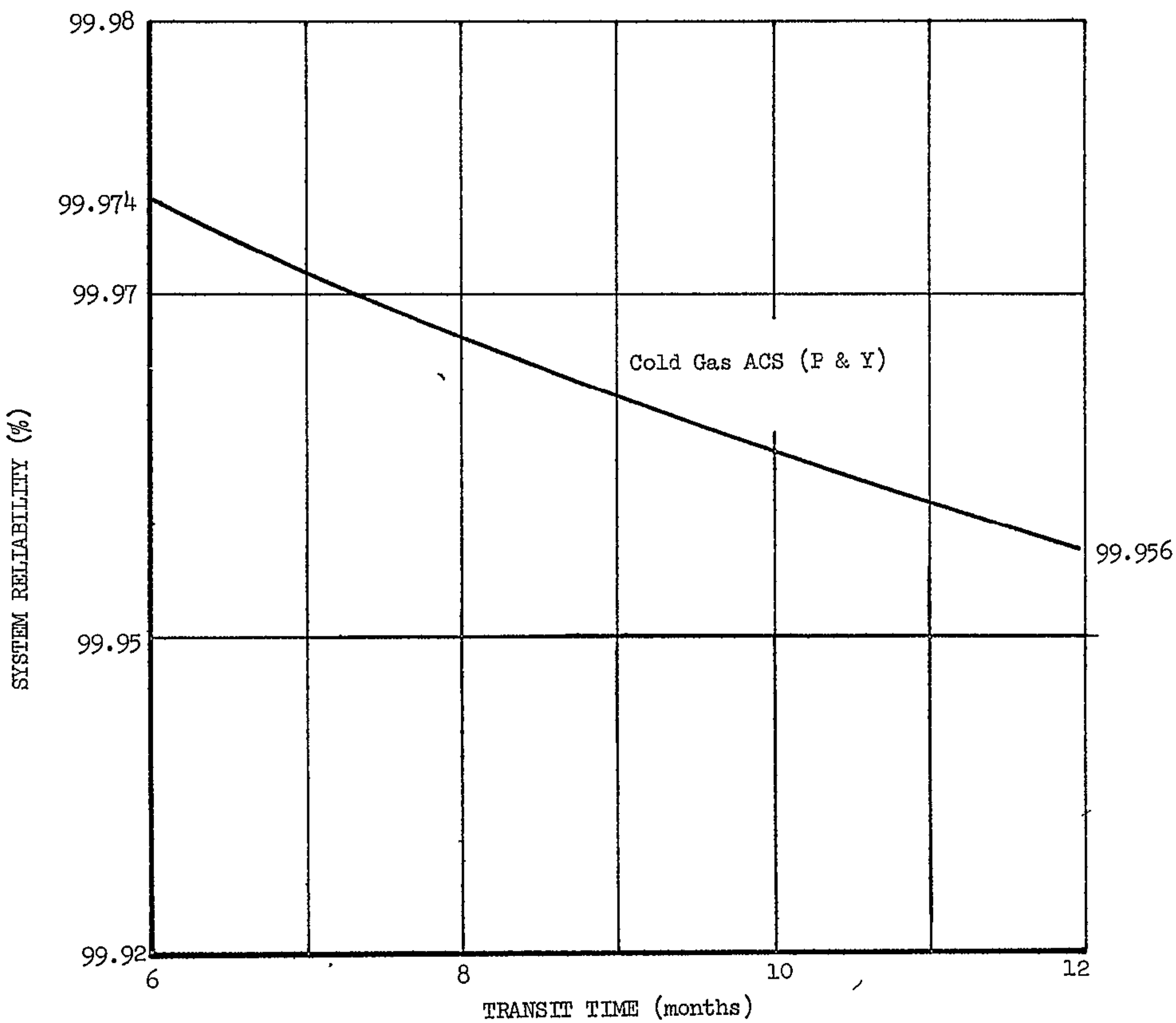


Figure 4-32. Cold Gas ACS Reliability Trend vs Transit Time

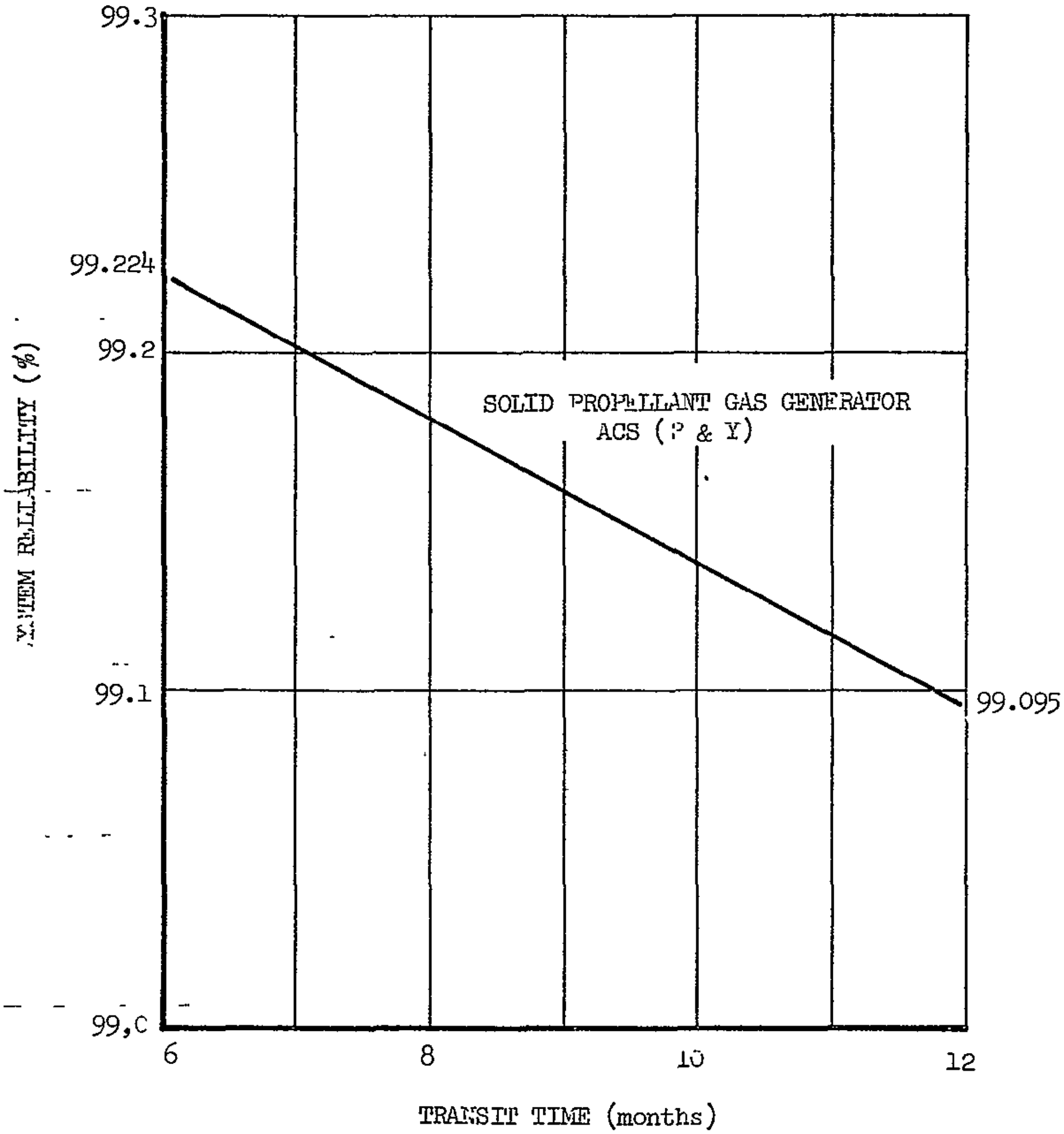


Figure 4-33. Solid Propellant Gas Generator Reliability Trend vs Transit Time

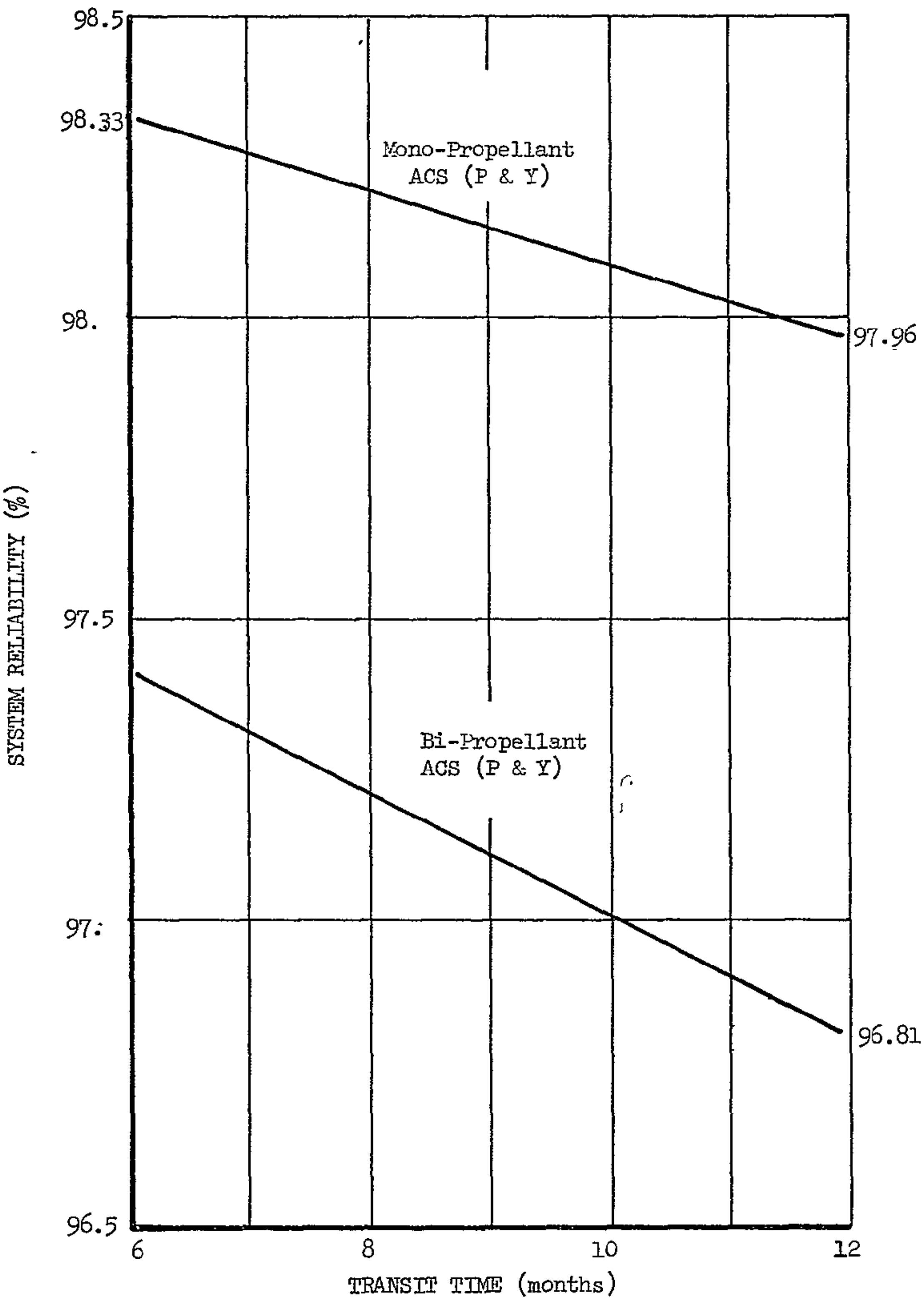


Figure 4-34. Monopropellant and Bipropellant ACS Reliability Trend vs Trend Time

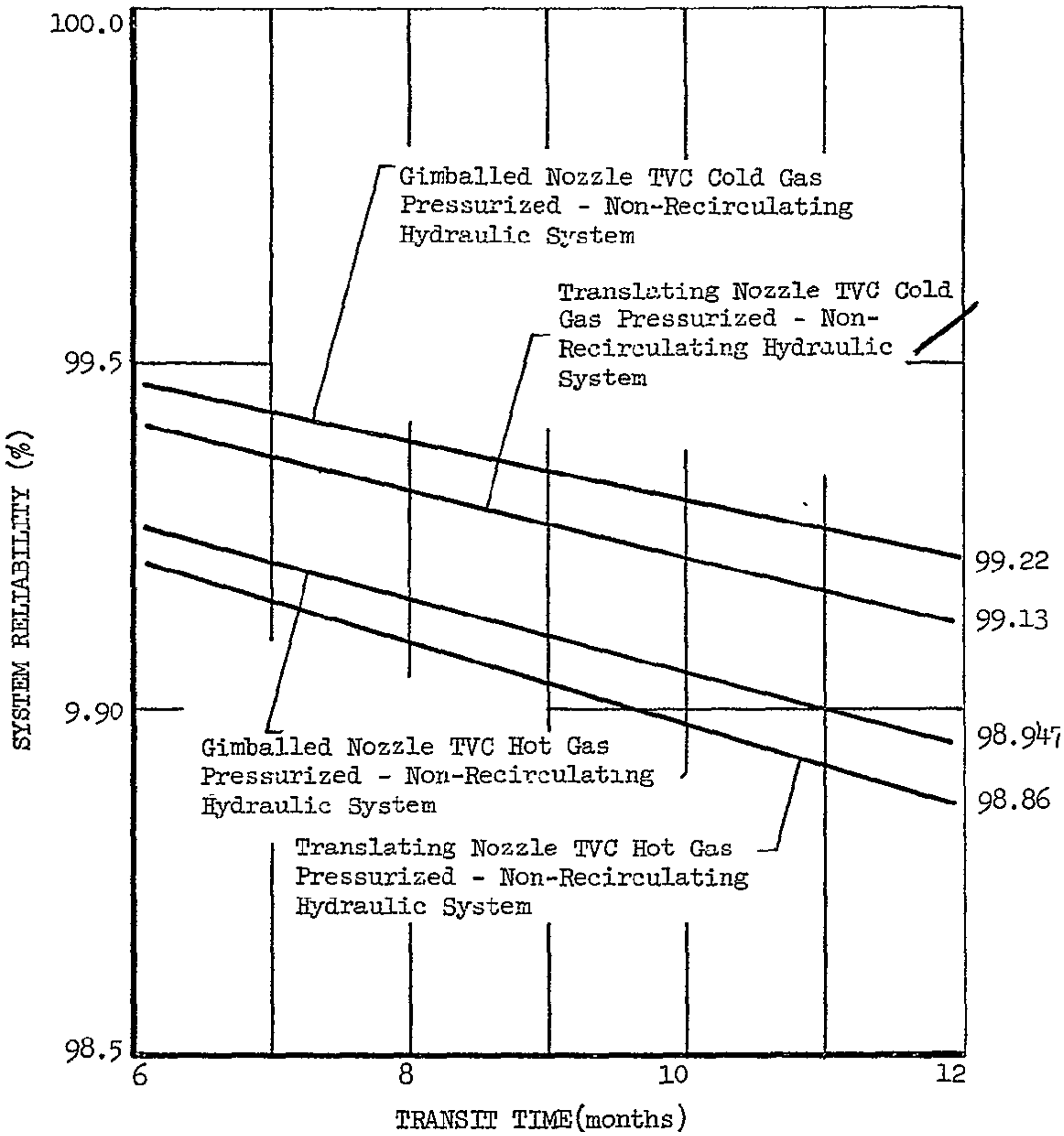


Figure 4-35. Gimballed and Translating Nozzle, Non-Recirculating Hydraulic System, Reliability Trend vs Transit Time

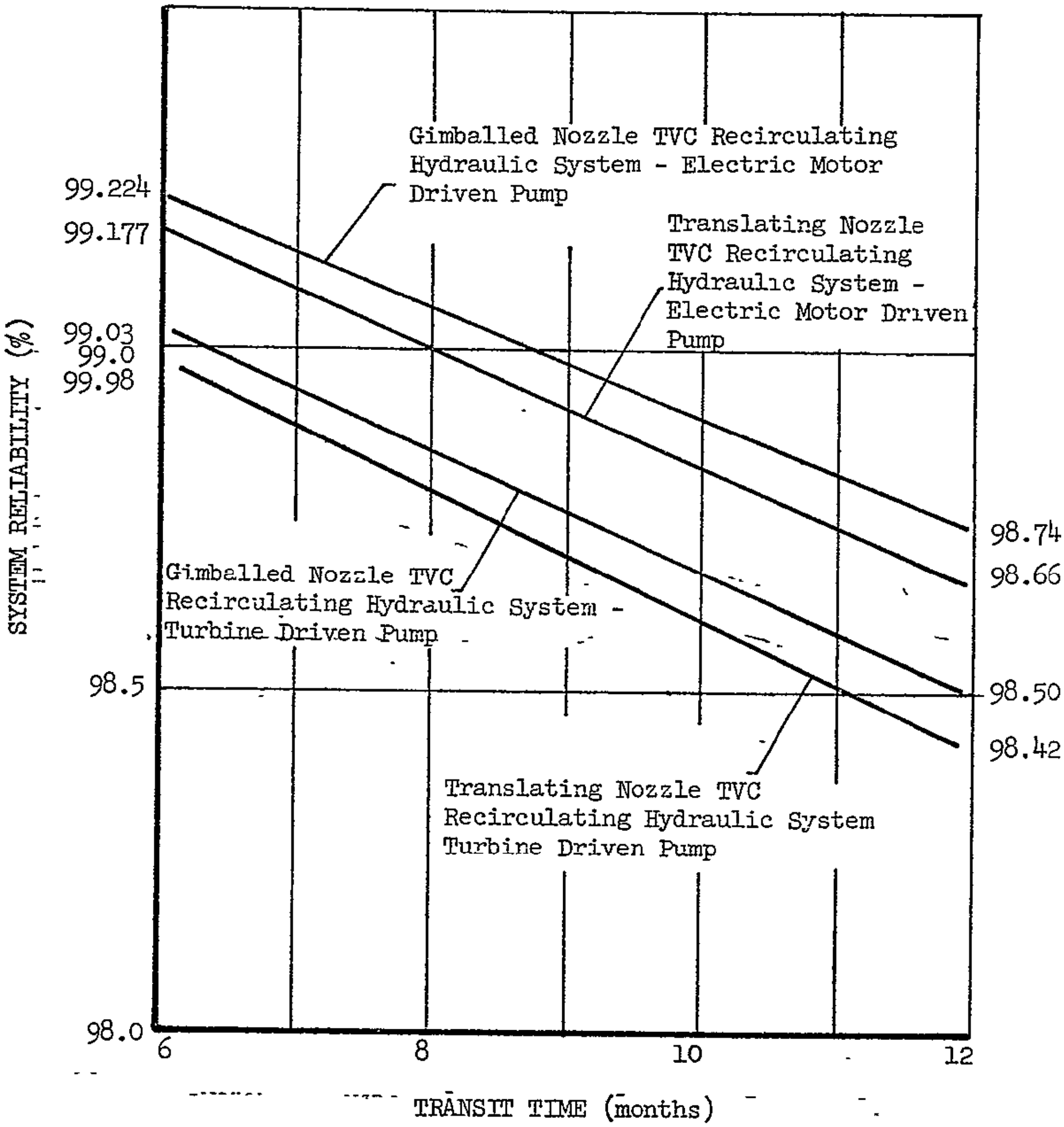


Figure 4-36. Gimballed and Translating Nozzle, Recirculating Hydraulic System, Reliability vs Transit Time

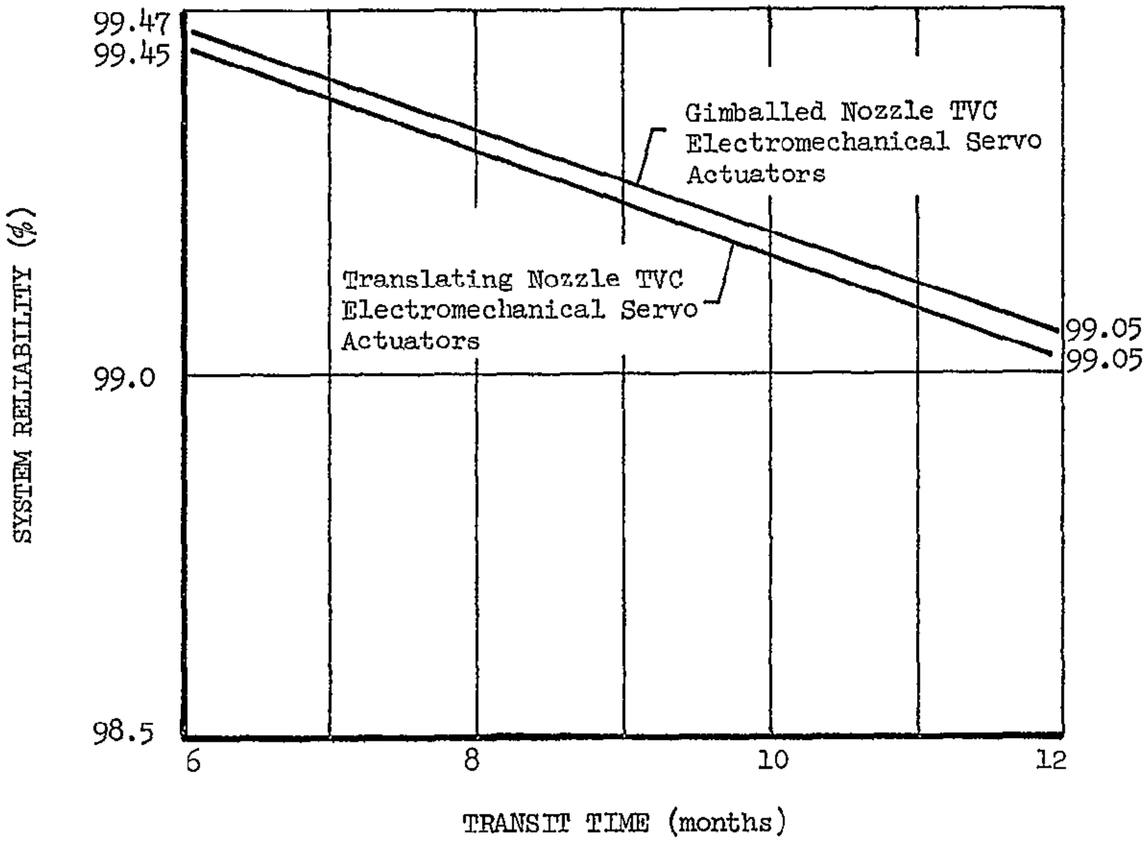


Figure 4-37. Gimballed and Translating Nozzle, Electromechanical Actuation System, Reliability Trend vs Transit Time

The mathematical reliability model is shown in Appendix E for each system. Calculation sheet (Table E1)illustrates the periods of the mission during which the highest stress levels are reached (lift-off, Column 1; and retro-thrusting, Column 10), low (1st, 2nd and interplanetary injection stages, Column 13) and the lowest (inactive transit period, Column 19).

The Cold Gas Reaction Jet attitude control systems rank considerably higher in inherent design reliability than the other systems, due to their simplicity and the fact that the lines, regulator and valves remain unpressurized until ready for use at the retro-thrust period. The normally closed explosive valve at the tank outlet, which provides this unstressed condition, also results in a very low probability of nitrogen leakage during the transit period. This leakage probability is also held to the minimum possible by use of a normally open explosive valve at the tank fill port, with a quick disconnect fill valve mounted on the explosive valve. After the tank is pressurized to the required amount through the quick disconnect and checked for leakage, the explosive valve is fired closed just prior to launch. This procedure provides two closed valves in series, redundant in leakage, with a reliability sufficiently high in the leakage mode to be considered, practically, as 100%.

The system with the next highest inherent reliability is the gimballed nozzle TVC with cold gas pressurized hydraulic servo-actuation or the gimballed mechanical servo-actuation systems. Some variation slightly downward with other actuation systems is shown in Table 4-14. The electro-mechanical servo-actuation unit considered in the analysis is made up of a continuously rotating electric motor driving CW and CCW mechanical clutches (disengaged) through gear trains. Signals to CW and/or CCW rotary solenoids, mounted on the clutch drive shaft, cause either clutch to engage and, by means of another gear train, to drive an hourglass worm gear either direction. A gear sector operates from the worm, for CW and CCW nozzle movement. Four of these units are spaced 90° around the nozzle gimbal ring, in the same manner as the rotary servo-actuators of the hydraulic system.

The gimballed nozzle appeared to have better sealing than the translating nozzle design, and probably less friction of movement.

The calculated reliabilities of the monopropellant and bipropellant reaction jet systems were the lowest of all considered, due to system complexity.

4.4 SYSTEM SELECTION

System weights, propellant requirements, reliability and general features were compiled into tables in order that they could be compared and evaluated, as follows:

Table 4-15	LITVC System Comparison
Table 4-16	Auxiliary System Comparison
Table 4-17	Movable Nozzle Comparison

One system of each type was selected to be described in more detail and a layout drawing of each selected system was made. The selections were made at a meeting attended by JPL, Space-General and Aerojet-General representatives.

4.4.1 LITVC SYSTEMS

LITVC system data, for the eight combinations considered, is presented in Table 4-15. It is observed that the loaded system weights are all over 200 lb and the weight increase due to movement of the spacecraft c.g. from $x = 16$ to $x = 31$ is approximately 50 lb. Since the weight percentage variations are not great between systems, the cold gas pressurized Freon system was selected for further evaluation, since its space storability is superior to the N_2O_4 system.

In comparison with the other systems, the LITVC systems are very heavy. The comparative hardware weights were derived largely by scaling existing Minuteman LITVC component weights; while the comparative evaluation is valid, the system weight can probably be reduced considerably by a more detailed review of the system components.

Table 4-15

LITVC SYSTEM COMPARISON

Injectant	X	Pressurization System: Cold Gas	Pressurization System: Gas Generator	Total System Weight	Weight Expended	Final System Weight	6 Mos Reliability	Space Storability
Freon 114B2	16	X		207.15	113.2	93.95	.9841	Good
	31	X		252.14	147.6	104.54		
	16		X	223.05	115.8	107.25	.9818	Good
	31		X	270.25	151.26	118.99		
N_2O_4	16	X		206.7	103 2	103.5	.9841	Fair
	31	X		250.4	134.3	116.1		
	16		X	224.83	106.42	118.41	.9818	Fair
	31		X	269.88	139.14	130.74		

Table 4-16. Auxiliary System Compar

System Type	Total Impulse	Prelim. Weight Estimate	Moment Arm	Thrust Level	Prelim. Design Weight	State of Development	
Stored Gas							
H_e	2272	82.9	100	24.4			
N_2	2272	63.4	100	24.4			
Bang-Bang					129.58	Developed	
Proportional					129.58	Developed	
Gimballed					142.	Developed	
Monopropellant							
H_2O_2	10,000	62	40	61	84.0	Developed	
N_2H_4	10,000	52	40	61			
Bang-Bang					62.1	Developed	
Proportional					65.6	See Remarks*	
Gimballed					73.7	See Remarks*	
Bipropellant							
N_2O_4-Aerozine	10,000	35	40	61			
Bang-Bang					50.3	Developed	
Proprtional					53.8	See Remarks*	
Gimballed					62.0		
N_2O_4 - N_2H_4	10,000	66	40	61			
Bang-Bang					50.0	Developed	
Proportional					53.5	See Remarks*	
Gimballed					61.1	See Remarks*	
Solid Gas Generator							
Bang-Bang	5680		40	61	170.6	Developed	
					143.8	Developed	
Solid Propellant Motors	4800			60	135	Developed	

t	6 Mos Reliability	Space Storability	Remarks
	99974	Good	
		Good	20 lb thrust valve developed by Bendix
		Good if packaged	30 cps response unreasonable. weight based on 5 cps
		Poor	
	.9833	Good	
s*		Good	*Developed for cold gas will work if Actuator mounted remote from hot valve
s*		Good if packaged	
	.9741	Fuel Good Oxidizer Poor	
s*			
	.9741		
.s*			
.s*			
	.9924	Good	X = 16
		Good	X = 31
		Good	Four Motors packaged with Actuators Requires Repackaging with some weight increase

4-89-B

It was decided at the evaluation meeting to proceed with a design layout of a cold gas pressurized Freon LITVC system, and to endeavor to reduce system weight. Two major areas of weight reduction were to be investigated: (1) reduction in major diameter of the toroidal tank, and (2) elimination of the hydraulic power system. In addition, calculation of the weight of a single spherical Freon tank was to be made to compare with the final Freon tank weight.

4.4.2 AUXILIARY SYSTEM COMPARISON

The auxiliary system data were presented in Table 4-16. The bipropellant systems are the lightest due to their high I_{sp}. However, the complexity of the systems coupled with their relatively low reliability offset the weight advantage. In addition, the space storability of the oxidizer is questionable for a six month time period. The monopropellant systems are heavier, but reliability is better. However, the complexity due to the catalyst pack weighs against this system.

The simplicity and high reliability of the cold gas system led to the selection of this system even though the weight is higher than that of monopropellant systems. Since there is no significant weight difference between 3 position (bang bang) valves and proportional valves, the proportional cold gas system was selected for detailed layout. The solid propellant systems were not competitive on the basis of weight and so were not considered further.

4.4.3 MOVABLE NOZZLE SYSTEM SELECTION

There does not appear to be a significant weight difference between nozzles and power systems designed for a c.g. location at x = 31" as opposed to the x = 16" location. As a result, the weight comparisons to be made below consider only the Case I and the Case III nozzles, both with the spacecraft c.g. at x = 31".

A weight summary of the two nozzle cases is given in Table 4-17. Minimum weight penalty for the gimballed nozzle is 58.9 lb and for the translating nozzle, 51.7 lb. This is using power System No. 4 in each case. Power

Preceding page blank

Nozzle Type	Case	X	Actuation System	Non Recirculating Hydraulic		Recircul Hydr
				Cold Gas N_2	Gas Generator	Electric Motor Driven
Gimballed	1	31	1	X		
			2		X	
			3			X
			4			
	2	16	1	X		
			2		X	
			3			X
			4			
Translating	3	16,31	1	X		
			2		X	
			3			X
			4			

Table 4-17. Movable Nozzle Comparison

...culating ...aulic	Recirculating Hydraulic		Electric Actuator Weight	Actuation System Weight	Movable Nozzle Weight	Total Nozzle System Weight	Baseline Nozzle Weight	Weight Increase	6 Mos Reliability
Gas Generator	Electric Motor Driven	Gas Gen. Turbine Drive							
			(30)	30.4	127.5	157.9	84.4	73.5	.99473
X				19.4	127.5	146.9	84.4	62.5	.99267
	X			19.7	127.5	147.2	84.4	62.8	.99224
		X		15.8	127.5	143.2	84.4	58.9	.99034
			(14)	21.3	127.5	148.8	84.4	64.4	.99473
X				10.1	127.5	137.6	84.4	53.2	.99267
	X			15.6	127.5	151.6	84.4	67.2	.99224
		X		13.4	127.5	140.9	84.4	56.5	.99034
			*(>60)	103.8	98.4	262.2	84.4	117.8	.99421
X				61.5	98.4	159.9	84.4	75.5	.99219
	X			42.8	98.4	141.2	84.4	56.8	.99177
		X		37.7	98.4	136.1	84.4	51.7	.98986

$ Hos ...liability	Space Stora-bility	Advantages	Disadvantages
99473	Good	Gimballed Nozzle • Proven Concept • Positive Bellows Seal • Low Actuation Torque • No Bearings Required • Motion Positively Controlled	• More costly to manufacture • Heavier
99267	Good	Actuation System No. 2 • Simple Design • Few parts - Low Cost • Proven Concept for • Hydraulic Pressurization (Earth stored systems) • Completely sealed • No moving parts • Low weight (at low duty cycle) • Storage at low pressure • Low Magnetic Effects	• Cannot be test run prior to firing • Need to control Hot Gas Flow
99224 99034	Good Fair	Actuation System No. 4 • Low Weight for • High Duty Cycle • Proven Concept (Earth stored systems) • Storage at low pressure • Low Magnetic Effects	• Requires Dynamic seals and bearings • Cannot be test run prior to firing • Need to control Hot Gas Flow • Difficult to seal for space storage • Complicated System More costly
9473 9267 9224 9034	Good Good Good Fair		
9421 9219 9177 3986	Good Good Good Fair	Translating Nozzle Lower Weight Simple Design and manufacture	Sliding Bearing Elastomeric Gas Seal High Actuation Force Unproven Concept Motion Control less certain *Electric Actuator size beyond state-of-the-art.

Systems No. 2 and 3 for the gimballed nozzle case are of competitive weight at 62.5 lb and 62.8 lb, respectively. The weight differences cited above do not vary greatly from system to system, and selection must therefore be made on the basis of other than weight alone.

A qualitative comparison of the competitive combinations is also given in Table 4-17. Auxiliary power system No. 3 was eliminated on the basis that it was not known if the necessary electric power was available from the spacecraft system at the required levels, and the magnetic effects and shielding requirements of the system were not known. However, both this and electro-mechanical systems should be further considered in future studies, particularly if actuation frequency requirements are reduced for the gimballed nozzle.

The gimballed nozzle was selected over the translating nozzle, for further analysis on the basis that it was a proven concept, known to be amenable to a trouble-free development cycle, and space storability was judged superior because bearings and elastomeric dynamic seals are not required. The slight weight advantage of the translating nozzle concept was not felt sufficient justification for its selection in view of the above considerations.

Potential weight reduction for the gimballed nozzle is quite good, in that, as previously mentioned, a reduction of actuation response requirements will have a large effect on power system weight. The translating nozzle does not benefit significantly from a response requirement reduction because actuation forces are predominately due to bearing friction.

Both nozzle designs would benefit from a seal diameter reduction which could be achieved at no loss in performance in the same envelope by use of a contoured nozzle. Appendix C summarizes a comparison between the two nozzle contours. Weight reductions would be very significant in each case, as the ejection load, and thus structural weight, is proportioned to the square of the seal diameter. In addition actuation torque would be reduced because bellows spring torque is a function of the diameter, and in the translating nozzle, bearing friction is proportioned to ejection loads. The design restraints imposed in the program thus create a higher movable nozzle weight penalty than should be observed in final optimization and reduction to practice.

For the gimballed nozzle system, the gas generator pressurized, non-recirculating hydraulic system (System No. 2) was selected. The weight of this system was equal to the weight of either recirculating system within the accuracy of the estimates. However, this system is much less complex and reliability will be high. Development time and cost should be less extensive than for recirculating systems. Space storability is excellent, in that, the system is completely sealed and stored at relatively low pressures prior to activation.

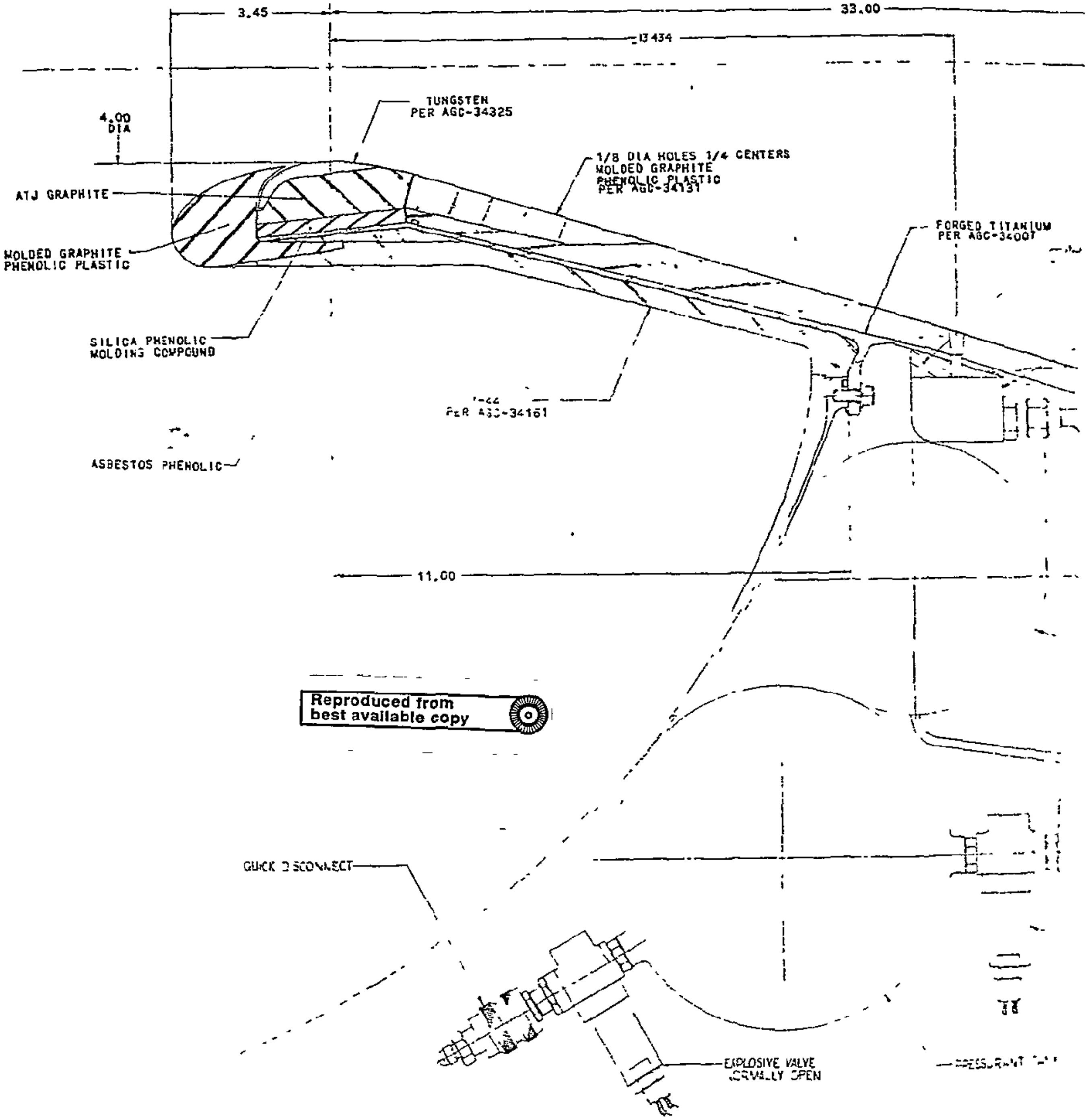
4.5 SELECTED SYSTEM DESIGN DESCRIPTIONS

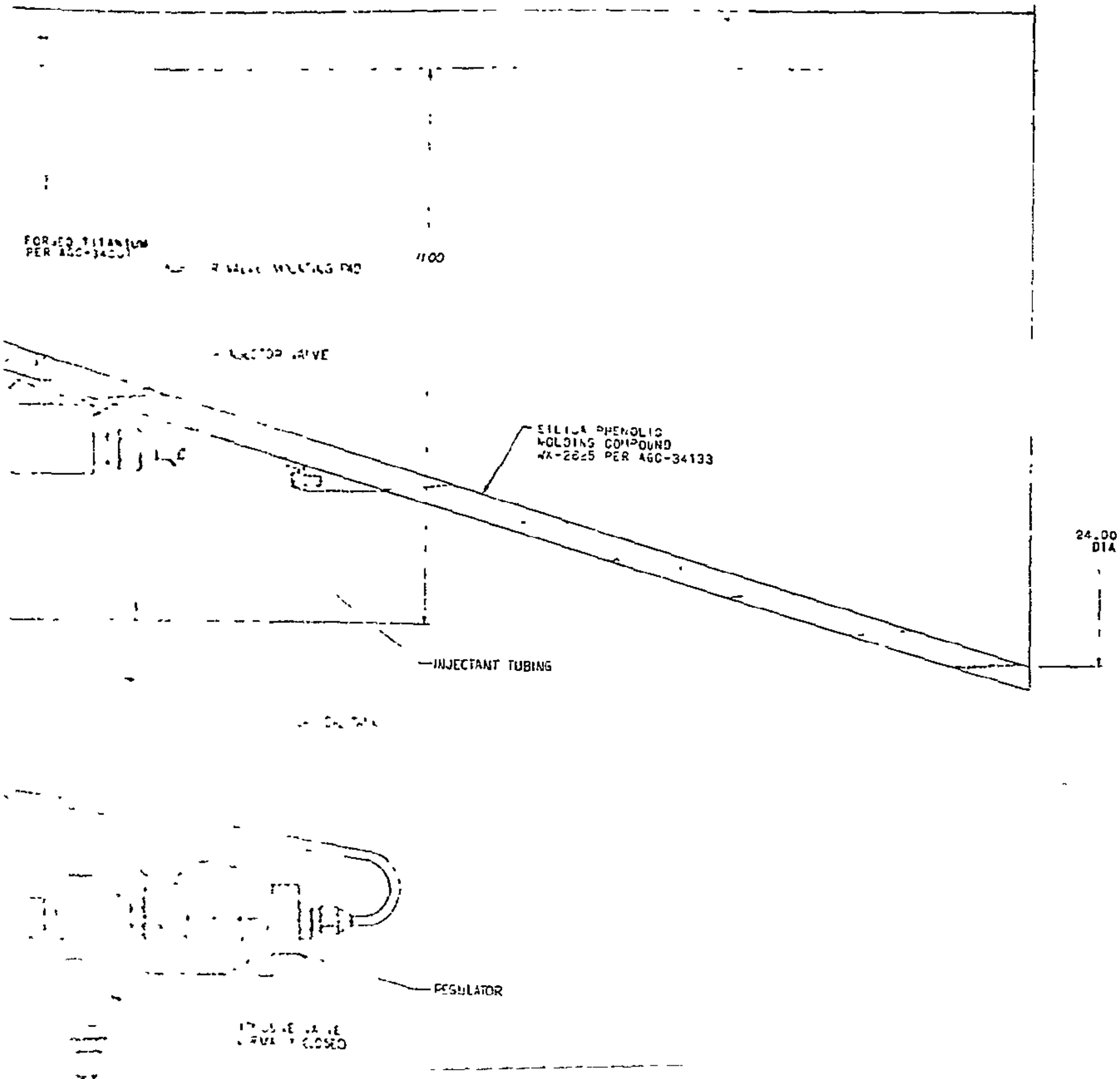
4.5.1 LITVC SYSTEM DESIGN DESCRIPTION

4.5.1.1 SYSTEM DESCRIPTION

The LITVC subsystem is comprised of an injectant tank and bladder assembly, to contain the injectant fluid, a pressure regulator to maintain injectant tank pressure, four injector valves for controlling injectant flow rates into the rocket engine nozzle, a high pressure gas supply and line supplying high pressure gas to the injectant tank, injectant manifolds. The design layout of the cold gas pressurized Freon LITVC system is shown in Figure 4-38. System weight and size data are shown in Table 4-18. The system was sized as described in Section 4.3.1. However, the toroidal tank major diameter was reduced, since at the evaluation meeting it was not considered necessary that the tank be large enough to be fitted over the nozzle. It was felt, rather, that the nozzle can be attached to the motor after installation of the tank. This, along with a reduction in tank wall thickness resulted in a reduction in tank weight from 30.84 lb to 7.29 lb for x = 16 and from 36.2 lb to 8.88 lb for x = 31.

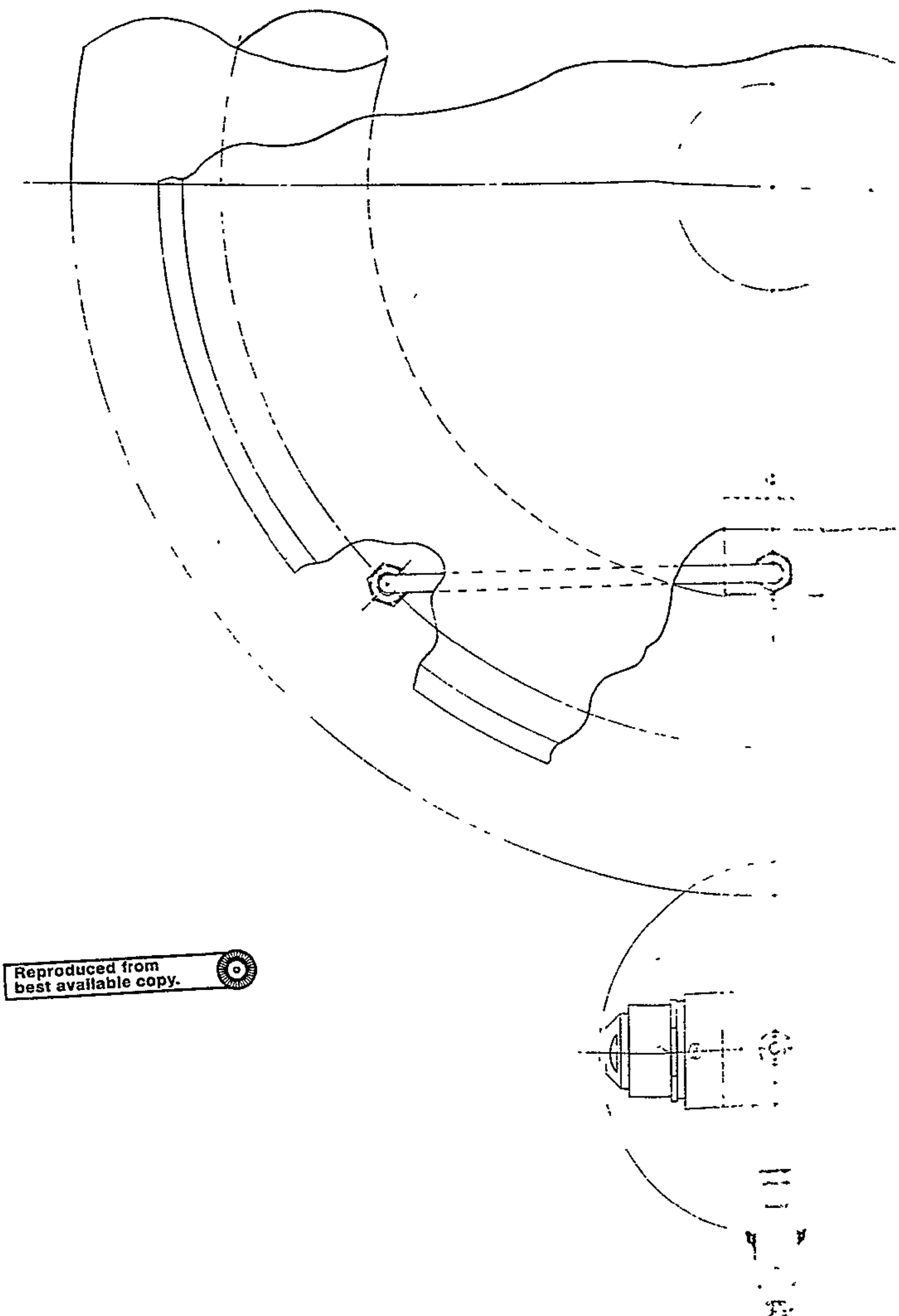
Another major area of weight reduction was elimination of the hydraulic power system. An injector valve of the size required is currently under development. This valve uses the available pressurized Freon as the actuating fluid. The other components remain essentially as described earlier.


3.45
33.00
13.434
4.00 DIA
TUNGSTEN PER AGC-34325
1/8 DIA HOLES 1/4 CENTERS MOLDED GRAPHITE PHENOLIC PLASTIC PER AGC-34131
ATJ GRAPHITE
MOLDED GRAPHITE PHENOLIC PLASTIC
FORGED TITANIUM PER AGC-34007
SILICA PHENOLIC MOLDING COMPOUND
ASBESTOS PHENOLIC
11.00
QUICK DISCONNECT
EXPLOSIVE VALVE NORMALLY OPEN



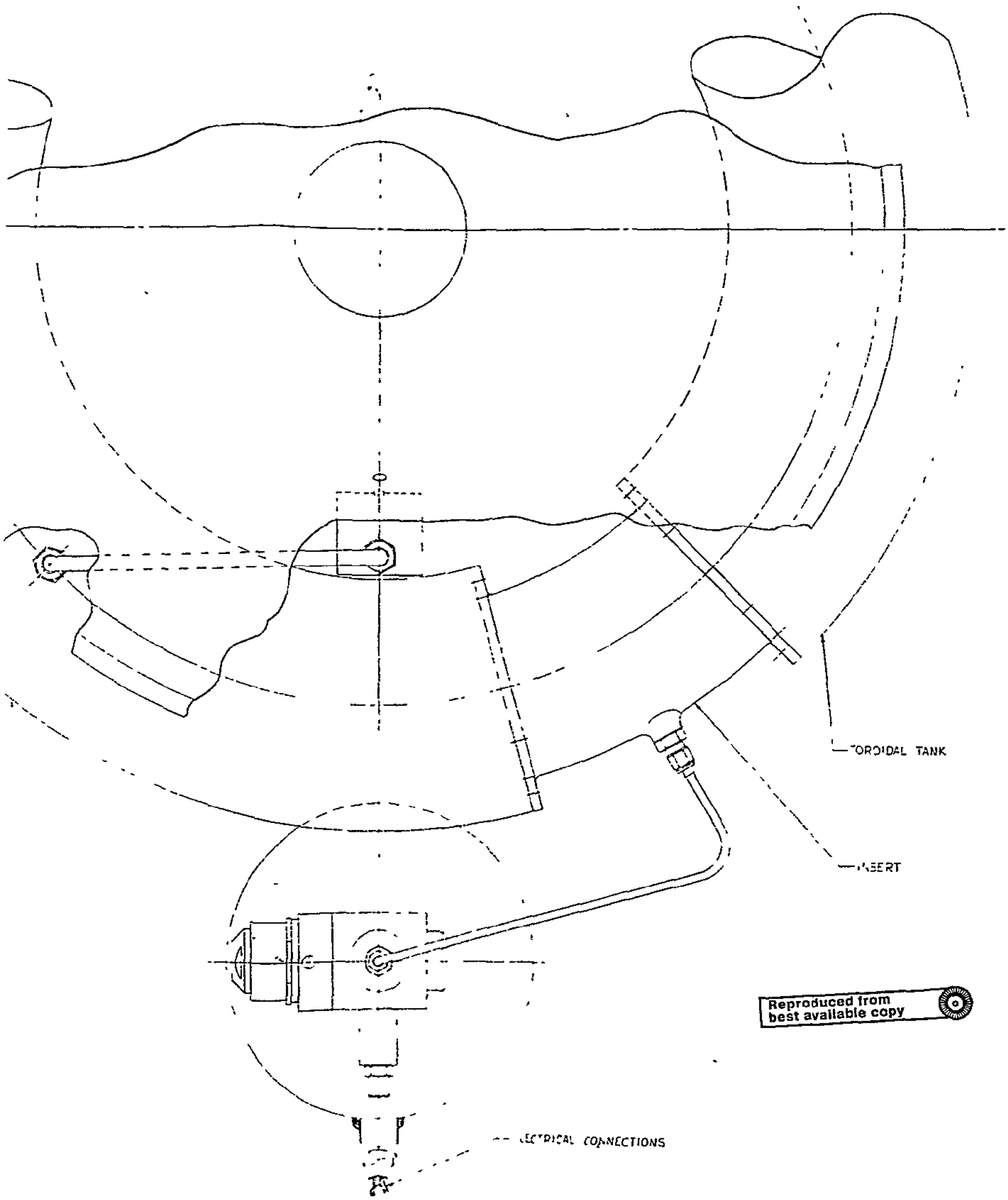
Reproduced from
best available copy.

Figure 4-38. LITVC System Des



4-95-C

...gn Layout



TOROIDAL TANK
INSERT
ELECTRICAL CONNECTIONS

Table 4-18
LITVC SIZE AND WEIGHT SUMMARY
F-114B2 Injectant with GN_2 Pressurization

Item	Units	C.G. Station 16	C.G. Station 31
Injectant density	lb/ft^3	135	135
Required Injectant for Vector	in^3	1088.00	1528.32
Injectant line OD	in	0.375	0.375
Injectant, line, residual	in^3	8.65	9.16
Injector residual (4)	in^3	4.00	4.00
Injectant permeated through bladder	in^3	34.00	34.00
Injectant used by 4 injector valves (Hydraulic)	in^3	4.86	4.86
Total loaded injectant	in^3	1139.51	1580.34
Injectant tank ullage	in^3	112.44	167.94
Injectant tank bladder	in^3	50.3	56.0
Injectant tank volume	in^3	1302.25	1804.28
Injectant tank Major Centerline diameter	in	21	22
Injectant tank Minor ID	in	5.014	5.766
Injectant tank wall thickness	in	0.20	0.22
GN_2 Spherical volume	in^3	203.93	284.27
GN_2 Spherical diameter	in	7.300	8.140
Injectant tank weight			
Tank shell	lb	3.36	4.48
Tank end flange	lb	1.22	1.40
Tank fill and outlets	lb	0.78	0.78
Tank insert section	lb	1.93	2.22

Table 4-18 - Cont.

Item	Units	C.G. Station 16	C.G. Station 31
Explosive valve (2)	lb	1.00	1.00
Injectant tank saddle	lb	10.55	12.39
GN_2 Spherical bottle weight	lb	1.20	3.45
GN_2 weight	lb	2.37	3.31
GN_2 bottle support	lb	1.05	1.51
Line support	lb	0.50	0.50
Pressure regulator valve	lb	2.50	2.50
Quick disconnect valve	lb	0.50	0.50
Nozzle extension	lb	6.00	6.00
Loaded injectant weight	lb	89.02	123.77
Total loaded subsystem weight	lb	133.44	175.74
Expended weight	lb	85.38	119.78
Total subsystem weight or burnout	lb	48.06	55.96
Subsystem reliability after 6 months		0.9841	0.9841

Preceding page blank

4.5.1.2 LITVC SUBSYSTEM FILL PROCEDURE

The injectant bladder, installed in the toroidal tank, is evacuated to approximately 10 mm of mercury and then filled with the required weight of F-114B2. This procedure eliminates the formation of air bubbles in the injectant bladder. The high pressure gaseous nitrogen bottle is filled through a quick disconnect coupling and a normally-open explosive valve. When the bottle reaches the desired pressure, it is maintained until prior to lift off. At this time, the normally-open explosive valve is firedand the high pressure system is sealed off.

4.5.1.3 LITVC SUBSYSTEM OPERATION

The LITVC subsystem is activated by an electrical signal which initiates combustion in the normally closed explosive valve, to allow gas flow through the pressure regulator. Pressure buildup in the toroidal injectant tank ruptures the burst diaphragms at the outlets of the tank. The system pressure rises continuously until the regulation pressure is reached. At this time, the injector valves (one or adjacent pairs), on command, are capable of metering the injectant required to give the necessary side force (negative or positive pitch and/or yaw) to redirect the vehicle as commanded by the guidance system. The injectant fluid not required for vehicle control is dumped overboard through either two opposing injectors or all four injectors simultaneously at preprogrammed flow rates.

4.5.1.4 LITVC SUBSYSTEM STORABILITY

The storability of the subsystem is very good. Flight tests conducted in Minuteman program proved system operation after storage periods up to 6 months prior to firing. Leakage of nitrogen from the cold gas system is expected to be negligible since the explosive valve seal is backed up by the quick disconnect fitting seal.

4.5.1.5 LITVC DESIGN PRESSURES

The selected nominal injectant tank operating pressures of 600 psia were derived from a 500 psi differential across the valve, 50 psi pressure drop from the injectant tank to inside of the valve cavity, an approximate nozzle wall pressure behind the shock of 35 psi, and a 15 psi safety factor. The 5000 psia pressure selected for the gaseous nitrogen bottle is arbitrary, since the envelope may be such that lower pressures may be desirable.

4.5.2 COLD GAS AUXILIARY SYSTEM - DESIGN DESCRIPTION

4.5.2.1 SYSTEM DESCRIPTION

The system consists of separate pitch and yaw systems, each sized to provide 24.4 lb of thrust at a 100 inch moment arm from the motor centerline. In addition, roll control valve assemblies are mounted to the pitch valves and operate on a small bleed from the pitch system gas supply.

The pitch and roll system configuration is shown in Figure 4-39. The system sized for an initial pressure of 3000 psia, consists of a spherical titanium gas bottle, filled through a quick disconnect fitting and a normally open explosive valve. The bottle exhausts to the control valves through a normally closed explosive valve and a pressure regulator. Downstream of the pressure regulator the flow is split at a tee and fed to two proportional flow valves, exhausting through nozzles, one thrusting forward, the other thrusting aft. The roll control valves are mounted on the pitch valves and flow is routed to the valves through two lines from the tee. The roll valves are similar to the pitch valves but smaller in size. Size of the roll valves is limited to minimum fitting and servovalve sizes. The flow through the roll system is extremely small and will be controlled by installation of metering orifices within the system.

The yaw system is identical to the pitch system, with the exception that no roll control valves are mounted on the yaw system.

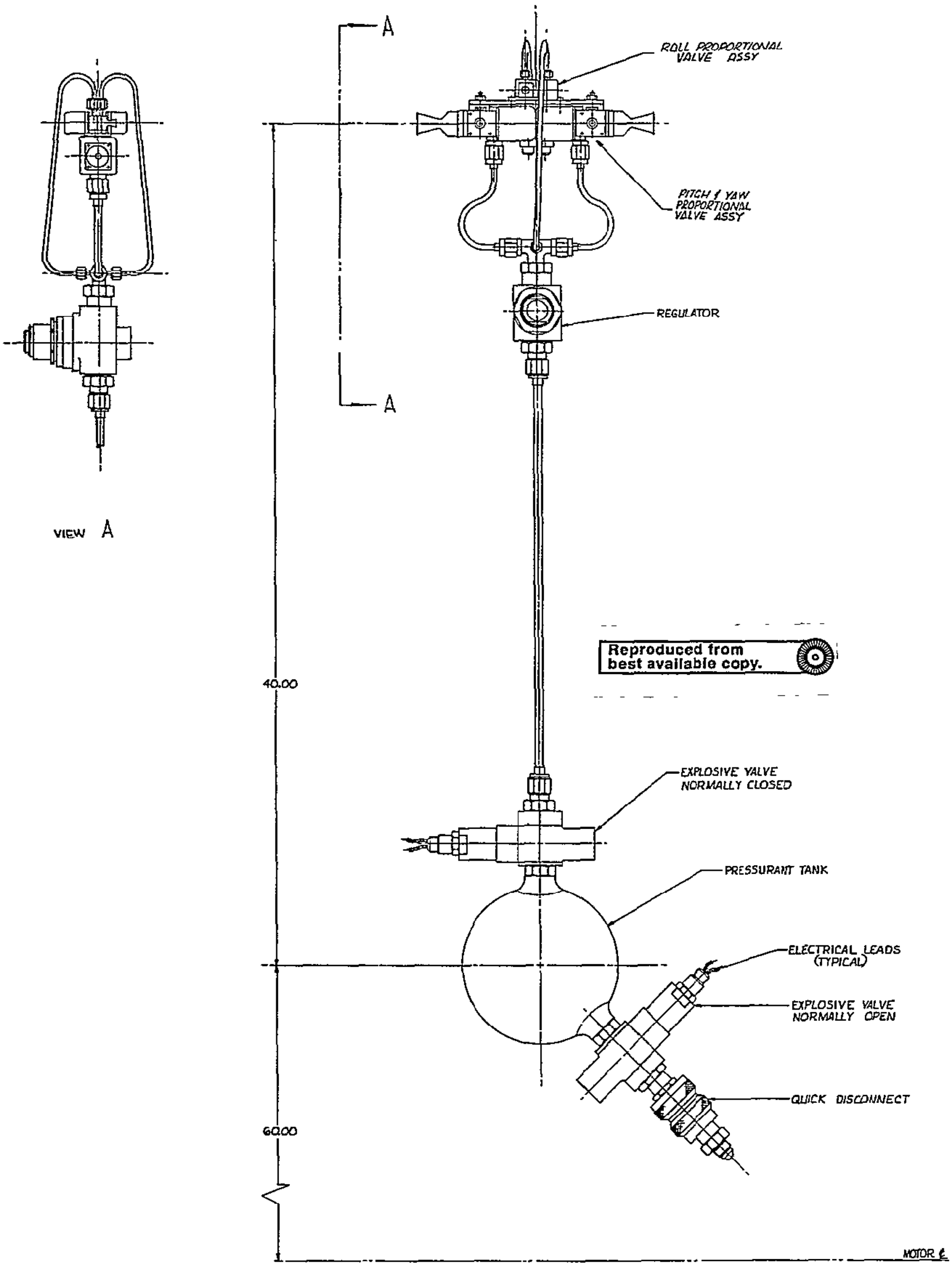


Figure 4-39. Cold Gas Auxiliary System Design Layout

4.5.2.2 SYSTEM OPERATION

Before launch each nitrogen bottle will be filled through the quick disconnect fitting. When the system is full, the normally open explosive valve will be fired to close the system. A hand operated valve could also be used here. The fill line will be removed and the quick disconnect fitting will remain with the system to provide a back-up seal to the explosive valve, now closed. At the retro motor ignition signal, the normally clased explosive valve on the tank outlet will be fired and the nitrogen will flow through the pressure regulator to the proportional valves. If no pitch, yaw or roll correction is required, the valves will flow equally in each direction until the nitrogen supply is exhausted throughout the motor firing time. If a corrective moment is required, the appropriate pair of valves will be actuated until the unbalanced thrust, caused by opening one valve and closing its partner, balances the disturbing moment. The valve design and guidance command will cause the valves to move so that the total flow area remains constant, and the system will exhaust the nitrogen supply at the same rate as the system at null.

4.5.2.3 SYSTEM PERFORMANCE

Maximum thrust of 24.4 lb is required at approximately t = 43 seconds. The initial pressure of 3000 psia will have decayed to 1488 psia at 43 seconds and to 315 psia at 70 seconds. For a line inlet Mach number of 0.1 at 43 seconds a line ID of 0.292 inch is required. Using 3/8 inch line results in an inlet Mach number of 0.06 at 43 seconds and 0.3 at 70 seconds. Therefore, a line size of 3/8 inch upstream of the pressure regulator should give reasonable line pressure loss. System line and fitting sizes were then determined on this basis.

The proportional control valves are representative of components already developed and available. The valve used was developed for a thrust of 20 lb but can be sized to provide the 24.4 lb required simply by increasing throat area, increasing valve chamber pressure or both.

4.5.2.4 SYSTEM CONFIGURATION

The pitch and yaw systems have been designed to have separate gas supply bottles, so that they may be mounted in the spacecraft in such a configuration that spacecraft c.g. will not change significantly during operation. Such a configuration is suggested in Figure 4-40. While spacecraft structure is not known, it is expected that symmetry of structure will exist and that c.g. shift during operation can be controlled in the manner shown.

4.5.2.5 COLD GAS SYSTEM WEIGHT

The system weight is summarized below.

Weight Summary

Pitch or Yaw System	
Nitrogen	32.95
Nitrogen bottle	28.01
Explosive valves (2)	.74
Quick Disconnect	.25
Pressure Regulator	1.75
Control Valve Assemblies (2)	2.20
3/8 inch line	.16
1/4 inch line	.05
Fittings	2.31
	68.42
Roll System	
Nitrogen	.15
Control Valve Assemblies (2)	1.00
3/16 inch lines	.04
Fittings	.36
	1.55
Pitch, Yaw and Roll System	138.39

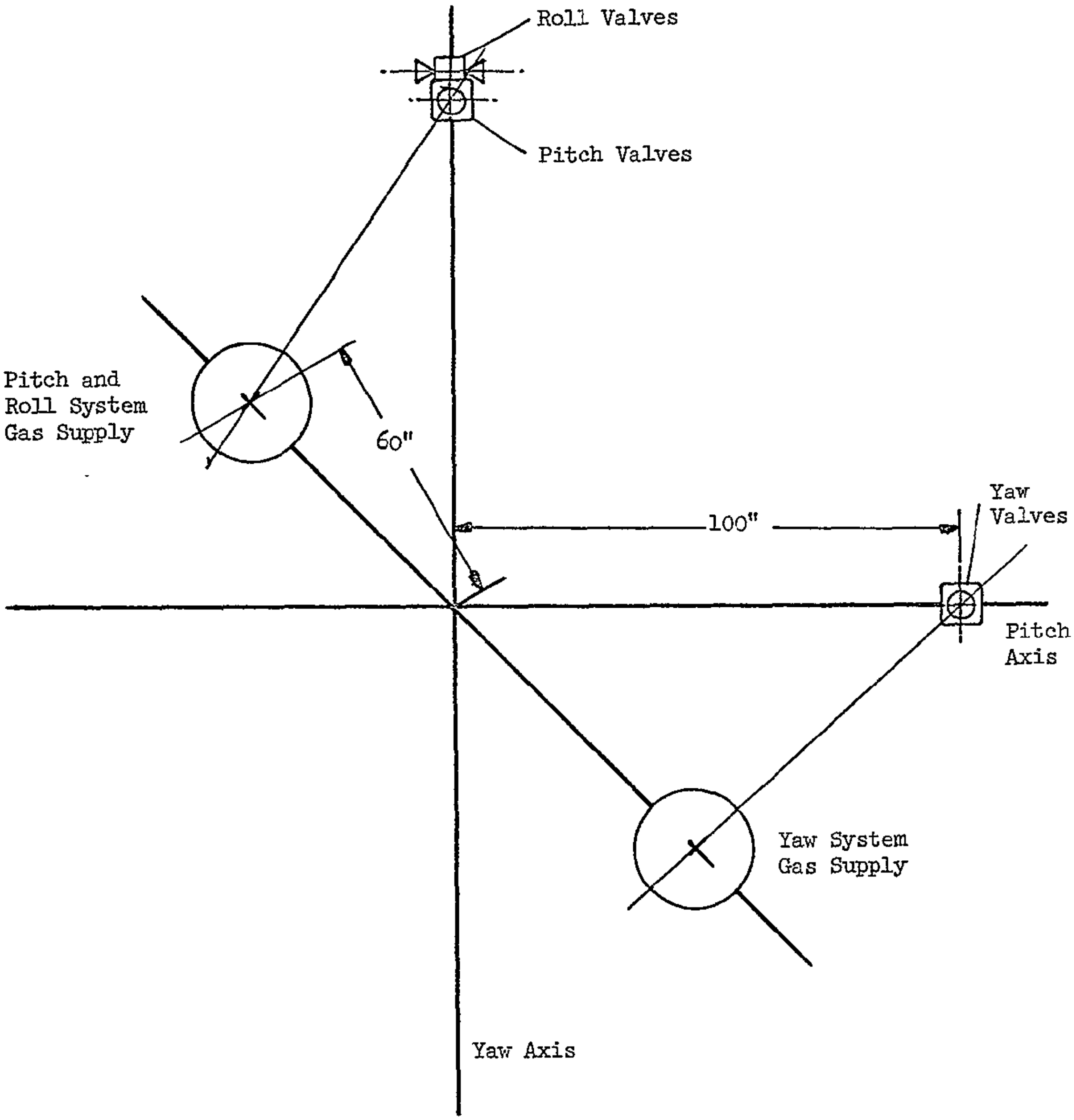


Figure 4-40. Cold Gas System Configuration

4.5.3 GIMBALLED NOZZLE DESIGN DESCRIPTION

The gimballed nozzle preliminary design described in Section 4.3.3.3 was not significantly changed in the final analysis. Also, actuation requirements remained unchanged. Thus, the weight breakdown and design description given earlier for this TVC system remain as already presented. The purpose of further design work was to verify that assumptions made earlier were valid, and to complete the nozzle layout to include the actuation hydraulic system. (Figure 4-41) To accomplish this, brief load and force analyses were made to permit the performance of sufficient stress analysis, to prove that the design is realistic, and to verify the estimated weight. A tolerance buildup analysis was also made in order to assure that thrust misalignments would not be radically different from those assumed in the preliminary studies. The results of these analyses are presented below.

In addition, a discussion is presented concerning gimballed nozzle development status and possible improvements in the system, some of which have already been mentioned.

Finally, the selected actuation system was included in the preliminary layout drawing to indicate how the components could be mounted. System weight is tabulated in Table 4-19.

4.5.3.1 SYSTEM LOADS AND FORCE ANALYSIS

The only major system load, with the exception of the actuation loads previously described in Section 4.3.3.3.1, is the nozzle ejection load, or net force due to distributed static pressure acting on the nozzle, tending to eject it. Since this force is transmitted by the gimbal ring, it must, therefore, be determined.

Taking the ejection force as chamber pressure times the projected area from nozzle bellows flange to nozzle throat,

$$F_1 = P_c \pi \quad (r_o^{\,2} - r_t^{\,2})$$

$$F = 500\,\pi \quad (6.8^2 - 2^2) = 66{,}100^{\#}$$

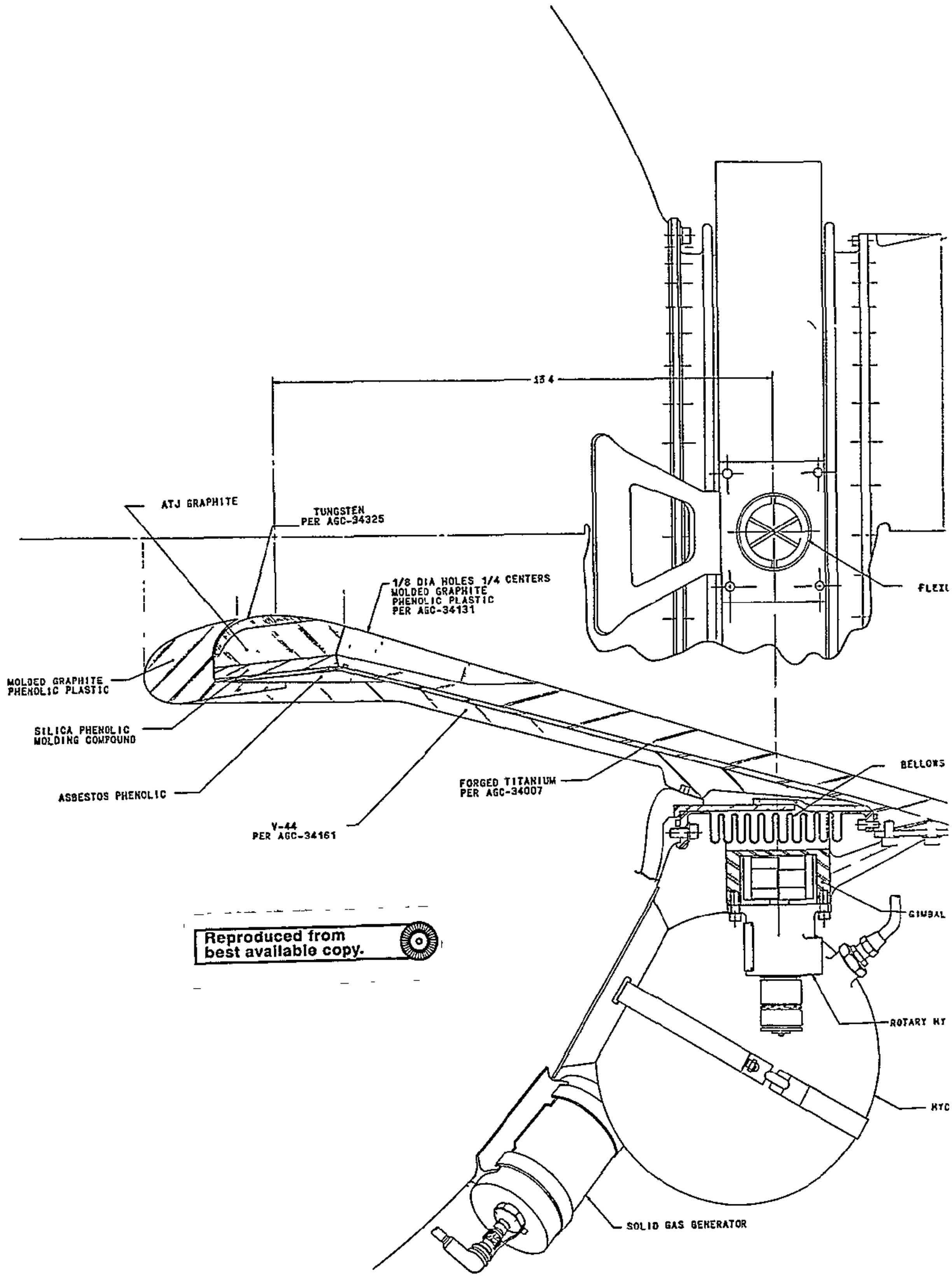


Figure 4-41. Gimballed Nozzle Desi

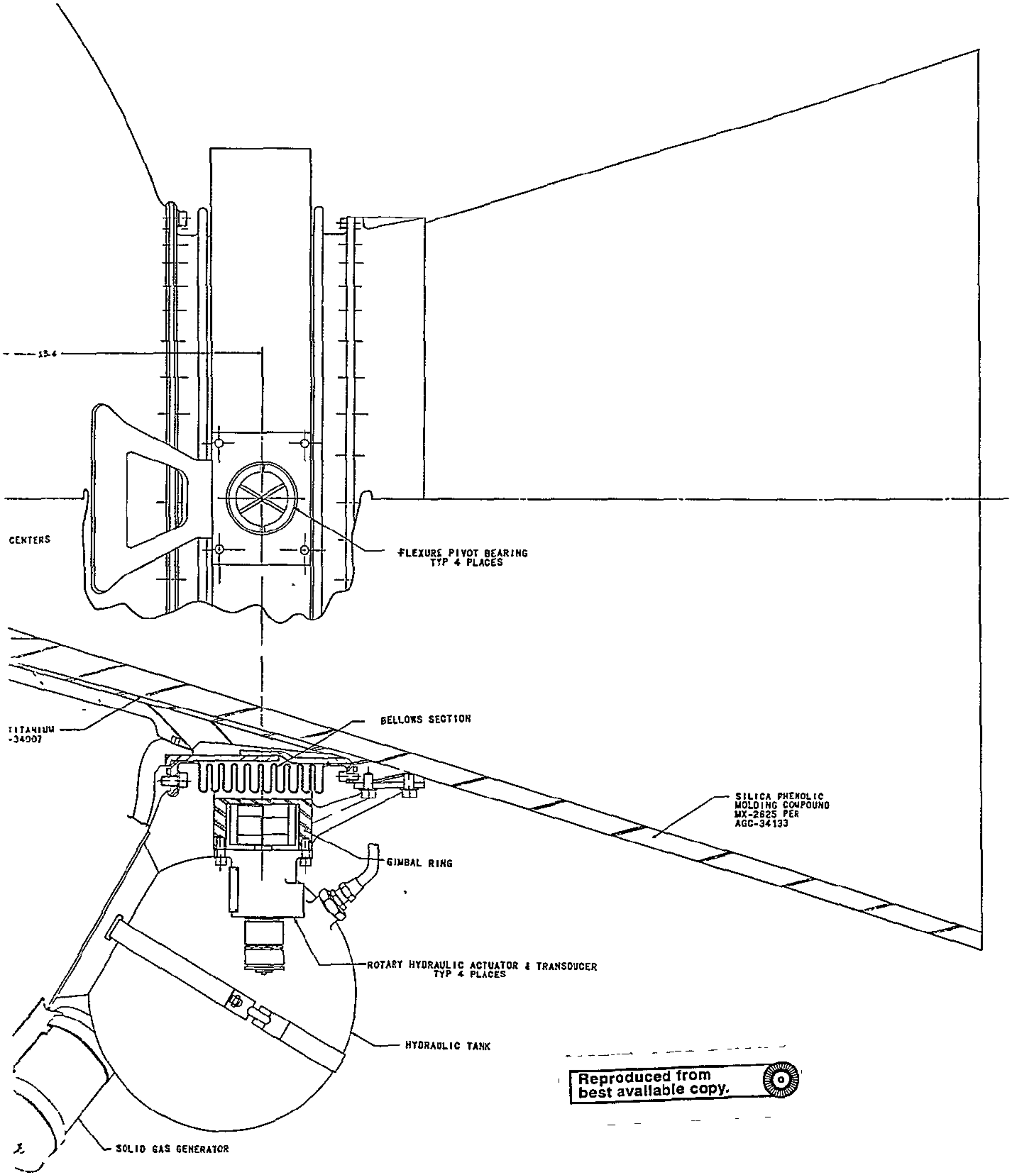


Figure 4-41. Gimballed Nozzle Design Layout

Table 4-19

WEIGHT SUMMARY

GIMBALLED NOZZLE SYSTEM

Nozzle Components	Weight - lb.
Tungsten Throat Insert	5.5
Molded Graphite Phenolic Entrance Cap	3.9
Asbestos Phenolic	1.0
Silica Phenolic Throat Backup	1.2
ATJ Graphite	2.8
V-44 Rubber	10.2
Titanium Structure	15.8
Molded Graphite Phenolic Exit	2.8
Silica Phenolic Exit Cone	47.6
2 Nozzle Brackets	2.2
2 Chamber Brackets	2.9
Gimbal Ring	11.4
4 Flexure Pivot Bearings	1.2
Bellows Section	14.6
V-44 Bellows Insulator	2.7
Chamber Flange Δ Wt	0.2
Misc.	1.5
Total Nozzle Weight	127.5

Actuation System Components

Gas Generator	1.2
Propellant	1.2
Hydraulic Fluid	6.87
Hydraulic Tank	1.20
Servo Values	.8
Actuators	4.0
Relief Valve	.4
Burst Diaphragms	.3
Plumbing and Fittings	1.6
Insulation and Structure	1.8
Total Actuation System Weight	19.37
Total Gimballed Nozzle System Weight	146.9

The pressure force in the exit cone acting to resist ejection may be calculated using:

$$F = P_2 A_2 \; (1 + \gamma M_2^{\,2}) - P_1 A_1 \; (1 + \gamma M_1^{\,2})$$

$$F = 283 \times 12.56 \; (1 + 1.2 \times 1^2) \; 1.2 \times 452 \; (1 + 1.2 \times 4.17^2)$$

$$F = 6632\#$$

The net ejection load therefore is:

$$66{,}100 - 6632 = 59{,}468 \rightsquigarrow 60{,}000\#$$

4.5.3.2 CRITICAL STRESSES AND DEFLECTIONS

A preliminary stress analysis was performed to substantiate the structural integrity of the gimballed nozzle, and to provide a basis for nozzle weight calculation. Sample calculations for the gimbal ring and the submerged portion of the nozzle shell are given in Appendix D.

The gimbal ring is made of 6AL-4V titanium heat treated to 155,000 psi allowable tensile yield stress. The minimum margin of safety (.02) is due to transverse shear and torsional stress 45° from the bearings. The bending stress produces an M.S. = +.23 at the bearings. Under present design conditions the gimbal deflection normal to its plane of curvature is .55 inches. If the gimballed nozzle is given further analysis, a design modification should be made to increase the ring section modulus, at slight cost in weight, and limit deflection to about 0.2 inch. This amount of deflection has been proven acceptable by the Transtage engine in which the gimbal flexure pivot bearings are assembled 0.2 inch off-center to accommodate deflection.

The submerged portion of the nozzle shell is subjected to differential pressure acting inward, and it must therefore be designed to resist buckling instability collapse. The margin of safety for this part, as shown in Appendix D, is 0.30.

It is concluded that the major structural components of this design are of adequate strength and that the weight estimate is correct.

However, some geometric rearrangement may be required in a final design to make better use of the structural materials.

4.5.3.3 TOLERANCE ANALYSIS

A tolerance analysis was conducted for the gimballed nozzle based on the analysis conducted for the reference fixed nozzle. As in the reference fixed nozzle analysis, tolerances are given with respect to the chamber aft flange, with the assumption of standard manufacturing practices for nozzle components of the size and material shown on the gimballed nozzle drawing, Figure 4-41.

4.5.3.3.1 DIMENSIONAL TOLERANCE STACK-UP FOR GIMBALLED NOZZLE

The final stack-up of dimensional tolerances for the gimballed nozzle as indicated in Figure 4-42 is presented assuming the following schedule of fabrication operations:

a. Fabricate nozzle assembly per schedule for reference fixed nozzle. Tolerance stack-up will be essentially the same for both nozzles.

b. Weld gimbal ring attach brackets to chamber and machine integral with chamber. All dimensions will be $\pm$ .005 inch.

c. Machine gimbal ring. All dimensions will be $\pm$ .001 inch.

d. Machine nozzle attach fittings. All dimensions will be $\pm$ .001 inch.

e. Assemble - Assembly of all the above nozzle parts will constitute an additional diametrical tolerance of $\pm$ .008 inch.

As shown in Figure 4-42, the total offset due to tolerance stack-up is .027 inch. This possible maximum offset requires an additional 5 minutes of gimballing arc for the most severe design case in which the center of gravity is located at x = 31. Ten minutes of additional arc has been provided in the nozzle analysis to meet this requirement.

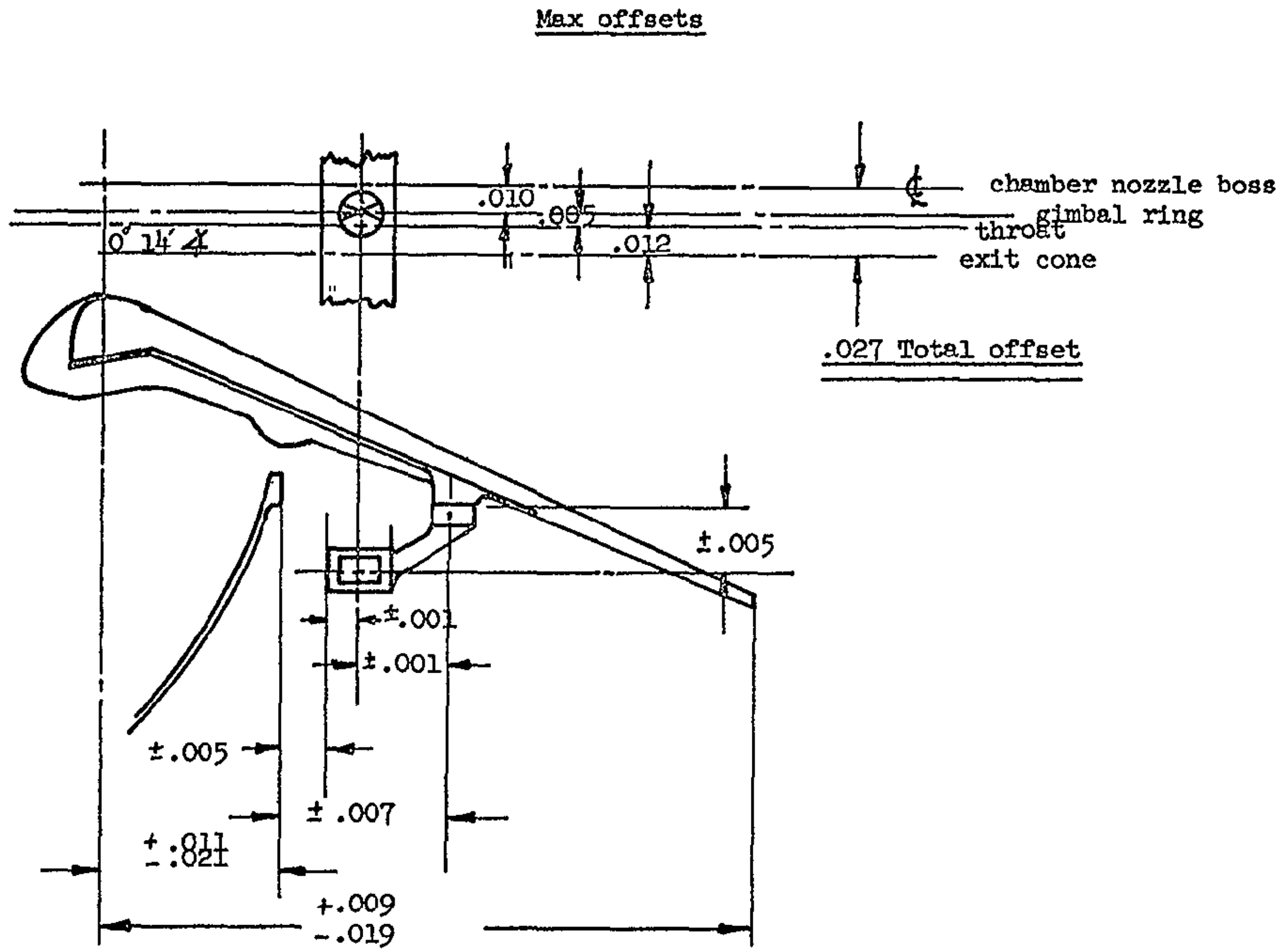


Figure 4-42. Dimensional Tolerance Stack-up for Gimballed Nozzle

4.5.4 DEVELOPMENT STATUS AND POSSIBLE IMPROVEMENT

The gimbal nozzle design presented herein makes use of components the design principles of which have been well-proven in several solid rocket nozzle developments.

4.5.4.1 BELLOWS SEAL

The bellows seal has been demonstrated repeatedly in swivel and gimballed nozzle use. Internally pressurized units have been successfully designed and tested by Aerojet and Allison Division of General Motors up to 16-in-dia size. Several commercial manufacturers are qualified to produce bellows for this service. Each application usually requires a new design, however, and qualification of the part. The most fully developed application was the Skybolt second stage nozzle bellows seal, 10 in. in diameter. This seal was flight qualified. One bellows failure was observed in the R & D test program. This was attributed to inadequate acceptance criteria permitting acceptance of a faulty part.

Many bellows design approaches are available. Depending on the design, spring torques for the bellows may vary by factors of more than 2 to 1. Actual values are hard to predict analytically, and must usually be determined in test.

4.5.4.2 GIMBAL RING

Several gimballed nozzles have been tested, all of which were of conventional, box section design. Again the most fully developed unit was used on the Skybolt nozzle. This ring was constructed of 4130 steel, the mean diameter was approximately 12 inches, and deflection was as predicted under load at about .070 inch. The ring designed for the present application is constructed of titanium to allow lighter weight and avoid use of magnetic materials. The applicability of titanium as a structural material in solid rocket applications is well established through its extensive use on flight rated second stage Minuteman Wing II and Wing VI chambers and nozzle structures.

The gimbal ring flexures are a departure from test experience on solid rockets, but are used to support 16,000 lb thrust loads in the Titan III Transtage motor. Similar, double flexure pivots have been manufactured and tested to support loads in excess of 100,000 lbs. These items are considered commercially available.

4.5.4.3 NOZZLE STRUCTURE

The major structural component with the exception of the gimbal ring is the nozzle shell. This titanium unit is designed to buckling criteria in the buried portion. The Minuteman second stage Wing VI nozzle also incorporates a buried titanium support shell. The design criteria are thus well-proven.

4.5.4.4 THERMAL PROTECTION

The nozzle components exposed to hot gas are identical to Minuteman second stage Wing VI design with an adjustment in thickness to allow for changes in duration and scale. The design criteria precludes temperature rise in any primary structural component. The materials and construction used are all identical to those qualified in the Minuteman Wing VI fixed buried nozzle design.

4.5.4.5 SEAL PROTECTION

As mentioned previously, seal protection is simplified in this design relative to the Skybolt gimballed nozzle, because the split line is placed in a quiescent gas region. The feasibility of a submerged gimbal nozzle has been demonstrated by the Air Force Rocket Propulsion Laboratory in a nozzle using an O-ring seal.

4.5.4.6 ACTUATORS

The rotary actuators and servo-valve systems are considered commercially available. However, some weight and storability advantages may be obtained by development of new items. The components are all well within the range of presently qualified equipment.

4.5.4.7 DEVELOPMENT PROGRAM

The development program for a nozzle of this type should closely parallel the one required to develop the Skybolt gimballed nozzle. In that program, 13 R & D and 18 PFRT firings were made. These tests included motor development, so all firings cannot be charged to nozzle development. Three nozzle failures occurred, all in the R & D phase. The last failure occurred on the 12th test, but the component that failed had been previously eliminated from the PFRT design because of marginal performance in earlier testing.

Based on the Skybolt nozzle experience, and results of the buried gimbal nozzle test conducted by the Air Force, it is recommended that 10 R & D and 10 PFRT tests should be sufficient to qualify the proposed design.

4.5.4.8 POSSIBLE IMPROVEMENTS

The gimbal nozzle weight and actuation requirements can both be reduced considerably by a reduction in seal diameter. This could be accomplished by contouring the nozzles and thus maintaining performance with a shorter submerged section which would allow a smaller diameter at the nozzle attach flange.

A reduction in frequency response requirements would considerably reduce actuation system weights. Further analysis of requirements in this area is needed.

The use of foldable and/or radiation cooled exit cone extensions may be considered to improve overall motor performance. Although application of these concepts has not yet been made, feasibility has been proven, and R & D is continuing for both solid and liquid propellant rocket motors.

4.6 REFERENCES

1. Study of High Effective Area Ratio Nozzles for Spacecraft Engines - Report NAS7-136-F Volume I - Aerojet-General Corporation, June 1964.

2. Development of a Solid Propellant Attitude Control System for Missiles and Space Vehicles (U), A. J. Sobey and R. C. Fall, Allison Division, General Motors Corp., Indianapolis, Indiana, Report No. EDR 2090 (Confidential).

3. Final Report Design Study of Actuation and Control System for Large Booster Steering Motors, Contract AF 04(611)-8158 SSD-TDR-62-143, Allison Division General Motors Corp., Indianapolis, Indiana, Engineering Department, Report No. 2987, 28 September 1962.

4. Report No. SGC 262/355 Ref - 26 "Development of a Liquid Injection Thrust Vector Control System for the Improved Minuteman Stage II Motor".

5. BUWEPS Failure Rate Data Program (FARADA) Sept. 1964.

6. AD 330 024; ASD-TDR-62-219, Compilation and Analysis of Reliability Data on Selected Flight Control Components", prepared for Flight Control Lab., Aeronautical Systems Div., Wright-Patterson AFB, by Planning Research Corp.

7. AD 273286; "Failure Rates and Failure Modes of Small Rotary Electrical Devices", prepared for Aeronautical Systems Div., Wright-Patterson AFB, by ARINC Research Corporation.

8. WADD-TR-60-330; AD 270462; "A Compilation of Component Field Reliability Data Useful in Preliminary Design", prepared for Aeronautical Systems Div., Wright-Patterson AFB, by Systems Technology Inc.

9. Aerospace Rept. No. 1923-1-89, Electronic Components

10. Conax Corp., McCormick-Selph Associates, Explosive Devices.

11. Papers published in the Proceedings of the 9th National Symposium on Reliability and Q.C., San Francisco, Calif., Jan. 1963.

12. Ablestar-Aerobee experiences failure rates, Subsystem & Component Field Test Procedures.

Appendix A

TVC STUDY CONSTRAINTS PROVIDED BY JPL

1.0 DEFINITIONS

1.1 Spacecraft Consists of:

Propulsion system
Payload

1.2 Propulsion System Consists of:

Motor
TVC system

1.3 Motor Consists of:

Case

Nozzle

Insulation - Liner
Propellant
Igniter
Case Attachments
See Figure A-1

1.4 TVC System Consists of:

Valves, Actuators, seals, injectant, tankage, regulators, indicators, etc., required to provide TVC during motor firing. The TVC system extends to the electrical actuation signal interface. It does not include the control system (autopilot, computers, etc.)

1.5 Steady-state TVC requirements are those needed to correct for the displacement of the thrust vector from the S/C C.G. Steady-state TVC requirements do not include dynamic or initial-transient requirements

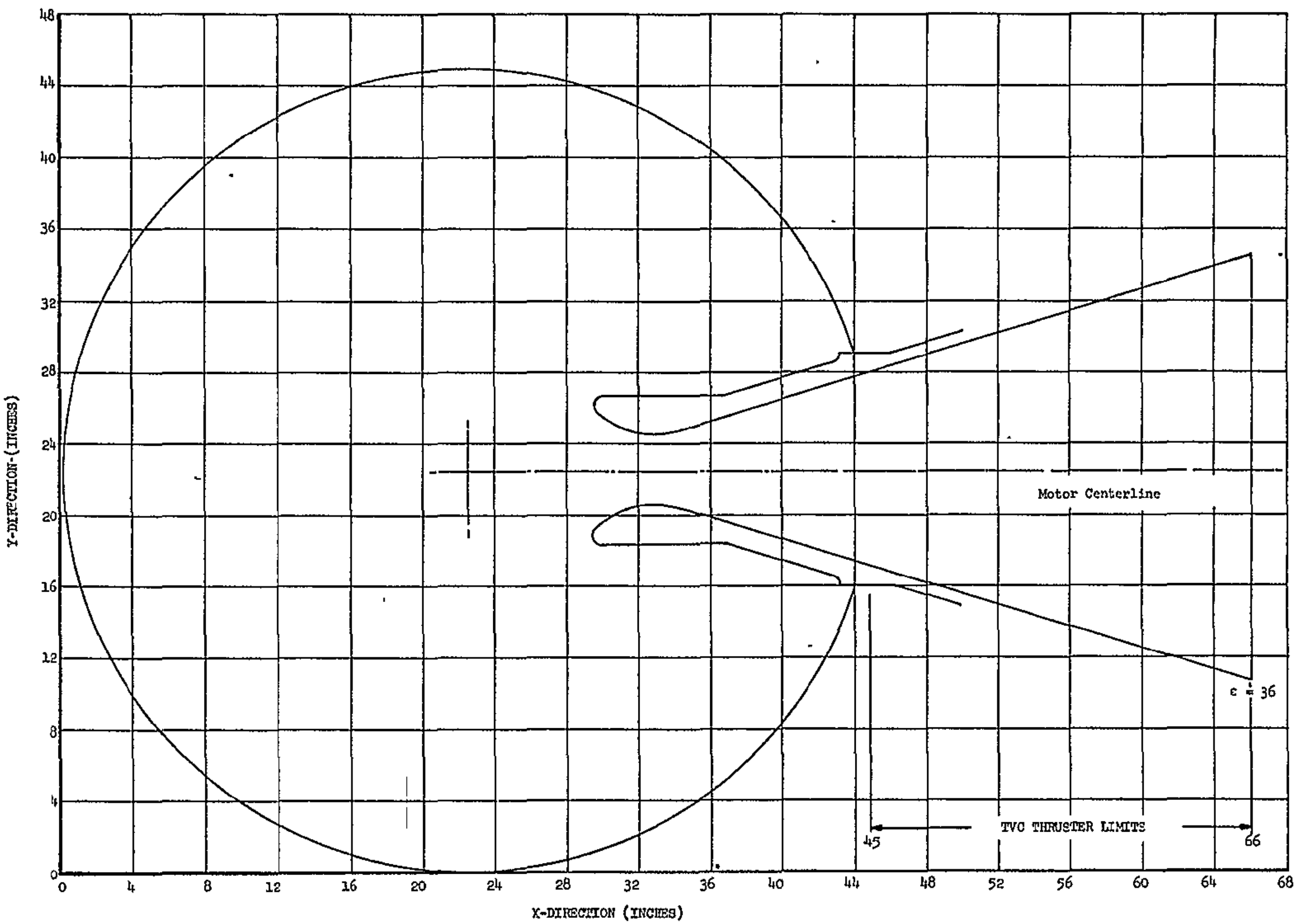


Figure A-1. Main Motor Schematic

2.0 TVC SYSTEMS TO BE CONSIDERED

2.1 Gimballed nozzle for pitch and yaw. Roll control to be ignored. Two moment arms to be considered.

2.2 Fluid injection for pitch and yaw. Roll control to be ignored. Two moment arms to be considered.

2.3 Auxiliary System for pitch, roll, and yaw. Two types of systems to be considered.

2.3.1 Cold gas at very large moment arm

2.3.2 Hot gas (N_2H_4, or solid-prop gas generator) at medium moment arm.

3.0 WEIGHTS

3.1	Payload	1500 lbs
3.2	Motor, Total	2750 lbs
	Propellant Weight	2500 lbs
	Nozzle Weight (without TVC)	60 lbs*
	Case, Insulation, Igniter, Attachments, Weight Total	190 lbs

3.3 Propulsion System, Total

Total propulsion system weight = Motor Wt. + TVC System Weight, TVC System weight to be determined by Contractor.

---

* This weight was preliminary; nozzle design weight given in section 4.23 was used.

4.0 LOCATION OF AUXILIARY SYSTEMS

4.1 Cold Gas System

Thrusters located 100" along the y-axis from the motor centerline at x = 45. Tanks located 60" from thrusters. (See Figure A-1).

4.2 Hot Gas System

Thrusters located 40" along the y-axis from the motor centerline at $x \geq 45$. The x position is constrained by possible exhaust impingement on main motor. Additional constraint is that thruster exit plane be located at $x \leq 66$.

5.0 NOMINAL C.G. LOCATION ALONG 'X' AXIS

5.1 For Fluid Injection

Two cases to be considered:

1. Nominal S/C C.G. constant at x = 31
2. Nominal S/C C.G. constant at x = 16

5.2 For Gimballed Nozzle

Two cases to be considered:

1. Nominal S/C C.G. constant at x = 31
2. Nominal S/C C.G. constant at x = 16

5.3 For Auxiliary Systems

One case to be considered:

Nominal S/C C. G. constant at x = 31

6.0 MOMENTS OF INERTIA

Moments of inertia are referenced to the S/C C. G.

	Ix	Iy = Iz (slug-ft^2)
Motor Ignition	1000	700
Motor Burn Out	800	600

7.0 INPUT DATA FOR DETERMINING DISPLACEMENT OF THRUST VECTOR FROM S/C C.G.

7.1 Payload

The radial error in C.G. measurement of the payload is 0.25".

7.2 Propulsion System

The following input data shall be determined by the contractor.

7.2.1 Distance between motor centerline and propulsion system C.G.

7.2.2 Error in C.G. measurement of the propulsion system.

7.2.3 Thrust offset of the motor at the nominal S/C C.G.

7.2.4 Thrust Malalignment of the motor

8.0 MOTOR PERFORMANCE

8.1 Propellant Vacuum Specific Impulse is 304 lbf-sec/lbm.

8.2 Propellant C* is 5400 ft/sec.

8.3 Motor thrust as a function of time is given in Figure A-2.

9.0 TVC FLUID (AUXILIARY SYSTEM PROPELLANT OR FLUID INJECTANT) FOR DYNAMIC AND TRANSIENT REQUIREMENTS

The steady-state TVC fluid requirement is the minimum amount of TVC fluid required to correct for the displacement of the thrust vector from the S/C C.G. The total TVC fluid requirement includes fluid for the initial transient and for dynamics.

Total amount of TVC fluid = (1.2)(steady-state TVC fluid)

10.0 SIDE FORCE REQUIREMENT FOR THE INITIAL TRANSIENT

The initial transient side force capability required at motor ignition will be 2 times the initial steady-state value. The system shall be capable of supplying the initial transient side force for 3 sec. after motor ignition.

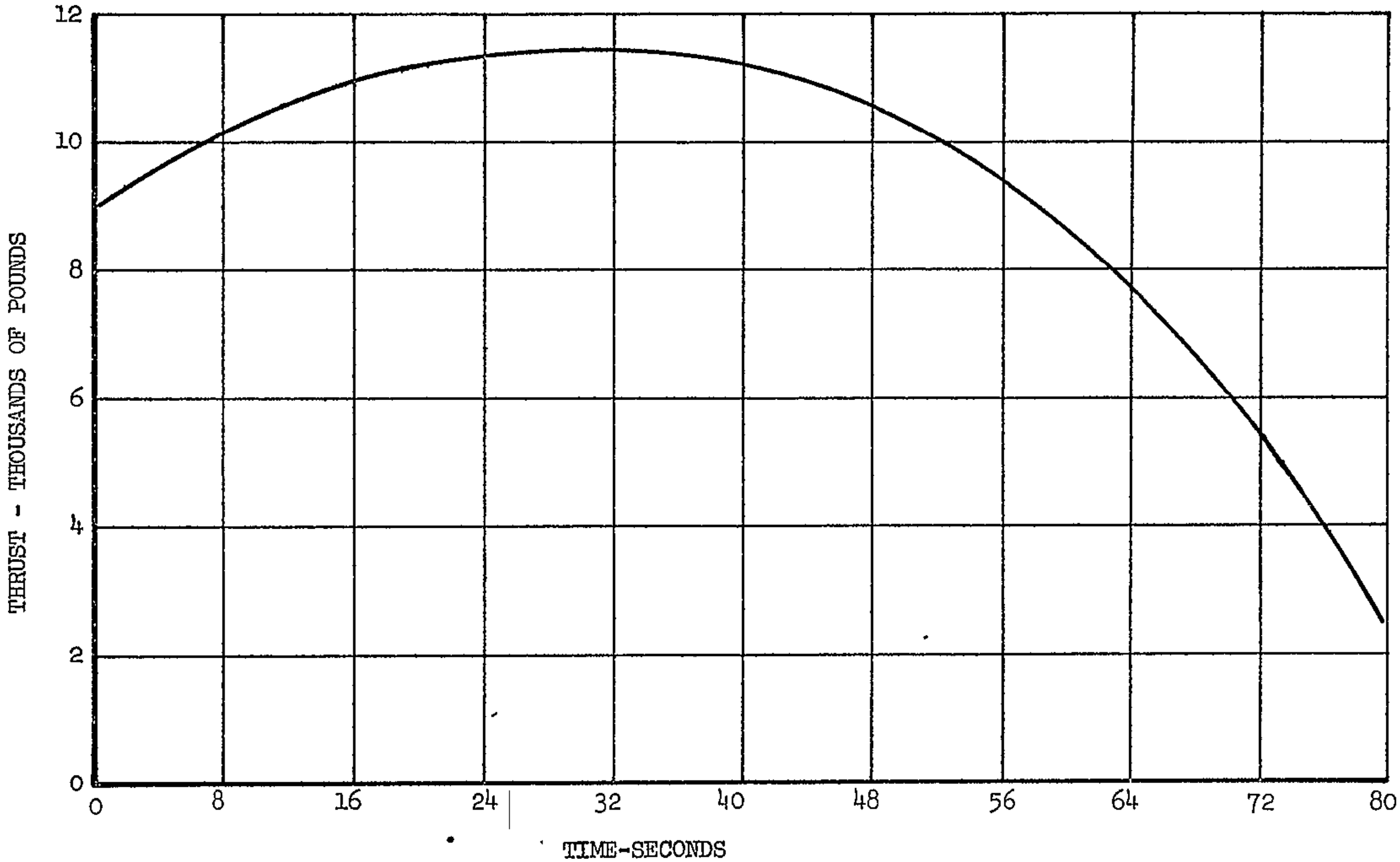


Figure A-2. Motor Thrust as a Function of Time

11.0 DUMP PROGRAM FOR TVC FLUID (FLUID INJECTANT OR AUXILIARY SYSTEM PROPELLANT)

The TVC fluid is to be used or dumped in such a manner that the net uncertainty in TVC fluid weight expended at any time during the motor burn is 0.3% of the total (main motor propellant + TVC fluid) weight expended.

Appendix B

ACTUATION FORCE AND SYSTEM REQUIREMENTS ANALYSIS

As mentioned in Section 4.3.1.1, Table 4-6 shows the systems analyzed to assist in selection of a combined movable nozzle - actuation system for final analysis. The nomenclature established in Table 4-6 is referred to in this section to identify the nozzle and power system being discussed.

1.0 ACTUATION FORCE REQUIREMENTS

1.1 Case I - Major gimballed nozzle actuation torque requirements are set primarily by bellows seal torque, inertia torque, and pressure induced torque due to misalignment between the axis of rotation and the ejection force centerline. Other torques include friction and jet damping. These were not calculated for this application, but some reserve was provided to allow for them.

Maximum nozzle deflection was calculated for the upsetting moments specified in Reference 2. Maximum moment per unit thrust occurs at $t = 0$. Thrust is 9000 lb at this time, and the required TVC moment is 192 ft-lb. The offset distance from center of rotation to the C.G. is 14". Calculated nozzle deflection is thus $\beta = \arctan \frac{(192(12)}{(9000)(14)} = \underline{1.05^\circ}$. In addition, the estimated thrust misalignment is 28 min or $.466^\circ$ based on assumed 10' angular misalignment increase over that of the fixed nozzle-aft closure combination. Total deflection was thus $\pm 1.516^\circ$; $\pm 1.5^\circ$ was taken as the design level.

Bellows torque requirements were based on experimental data shown in Figure B-1. As can be seen, a wide latitude exists in bellows spring rate depending on the bellows design. A reasonable value was selected at 2200 in-lb/degree deflection. Bellows torque was thus (1.5) (2200) or <u>3300</u> in-lb.

Inertia torque was based on acceleration requirements to dither at $\pm$ 10% full deflection (.00262 radians) in a sine wave profile at 30 cps. Rotational moment of inertia about the Y or Z axis was calculated to be 3.6 ft-lb-sec^2. Angular acceleration was thus

Preceding page blank

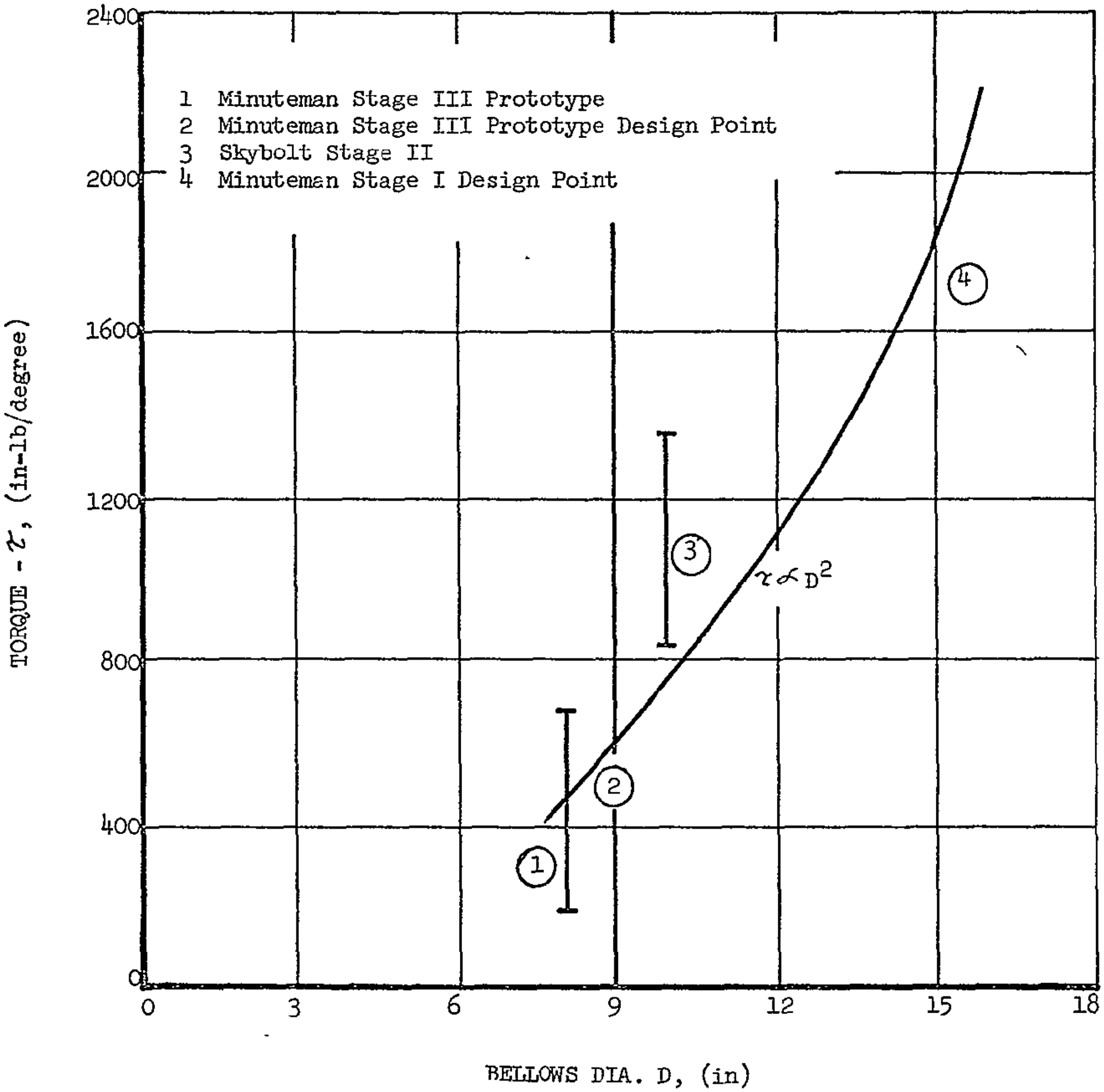


Figure B-1. Bellows Spring Torque Data

$$\alpha = (2\pi f)^2 \theta_o = (2\pi\, 30)^2(.00262) = 91.5 \text{ rad/sec}^2$$

Torque, $T = I\alpha = (3.6)(91.5) = 330$ ft-lb

or <u>3960</u> in-lb

Direction from JPL stated that the system should be capable of responding as a second order system with a natural frequency of 30 cps and a damping ratio of .7. Under these conditions, the time required to reach full deflection is defined by the relation $\zeta \omega_n t = 2.3$. Time required to first reach full deflection is $t = \frac{2.3}{(.7)(2\pi\, 30)} = \frac{.0175}{2}$ sec. Average acceleration over this time to rotate 1.5^o is 172 rad/sec^2. requiring an average torque of

$$T = I\alpha = (3.6)(172)(12) = \underline{7430} \text{ in-lb}$$

Misalignment torque is defined by the rotation axis offset from the nozzle radial center of pressure location times the ejection force. Ejection force was calculated to be 60,000 lbf as shown in Section 4.5.3. Estimated rotation axis misalignment was .01 inch.

Misalignment torque = (60,000)(.01) = 600 in-lb.

A summary of the torque requirements for Case I is given in the following table:

Torque Component	Condition 30 cps $\pm$ 10% deflection, null at 1.5^o deflection
Bellows spring torque	3300 in-lb
Inertia torque	3960 in-lb
Misalignment torque	600 in-lb
	7860 in-lb
Estimated friction torque	100
	7960
Reserve at 5%	400
	8360 in-lb

Inertial actuation forces for $\pm$ 10% deflection, $S_o = .1\ S_{max} =$ (.0256 in or .00213 ft) at 30 cps is defined $F_i = ma$

$$m = 98.4/32.2 - 3.05 \text{ slugs},$$
$$a = (2\pi f)^2 (S_o) = (60\pi)^2 (.00213) = 74.7 \text{ ft/sec}^2$$
$$F_i = (3.05)(74.7) = \underline{228} \text{ lbf}$$

Friction force is defined by

$$F_f + F_{ej}\ \mu_f$$

where:

F_{ej} = ejection force (60,000 lb)

μ_f = friction coefficient (assumed= .05)

$$F_f = (60{,}000)(.05) = 3000 \text{ lb}$$

Total actuation force is thus estimated as

$$F_i = 229$$
$$F_f = \underline{3000}$$
$$3228$$

Reserve @5% $\underline{161}$

$$F_{act} = \underline{3389} \text{ lb}$$

2.0 ACTUATION FLUID CAPACITY AND POWER REQUIREMENTS

Actuation power required was arbitrarily defined as that which permitted three full deflection cycles followed by 85 seconds of sinusoidal operation at $\pm$ 10% deflection and 30 cycles/second.

For Cases I and II, actuator displacement per degree rotation is defined as

$$\frac{\Delta V}{\beta} = \frac{\tau_{max}\ 2\pi}{360\ P_{act}}$$

P_{act} was assumed 2000 psi. (3000 psi delivery pressure with 1000 psi pressure drop across the servo valve).

$$\Delta V/\beta = (.837)(10^{-5})\gamma_{max}$$

Total rotation (β) is equal to $\sum\beta = (3)(4)(\beta_{max})$ - $(85(30)(4)(.1\ \beta_{max})$ in accordance with the assumed duty cycle.

$$\sum\beta \text{ for Case I} = 1530^\circ$$

$$\sum\beta \text{ for Case II} = 1305^\circ$$

Displacement/plane is thus

$$\text{Case I, } \Delta V = (.873)(10^{-5})(8360)(1530) \doteq 112 \text{ in}^3$$

$$\text{Case II, } \Delta V = (.873)(10^{-5})(7050)(1305) = 80.3 \text{ in}^3$$

Assuming movement in the 45° plane, Total Displacement =

$$\text{Case I } \Delta V = 112/.707 = 158 \text{ in}^3$$

$$\text{Case II } \Delta V = 80.3/.707 = 114 \text{ in}^3$$

In accordance with Appendix A , 20% reserve is required, thus total displacement is

$$\text{Case I } \quad \Delta V = (1.2)(158) = 190 \text{ in}^3$$

$$\text{Case II } \quad \Delta V = (1.2)(114) = 137 \text{ in}^3$$

Case III displacement under the same ground rules is

$$\Delta V = \frac{Fa}{P_{act}}\left(\sum S_o\right) \qquad \sum S_o = (3)(4)(.256) + (85)(30)(4)(.0250)$$

$$= 3.08 + 261 = 263 \text{ in}$$

$$\Delta V = \frac{3389}{2000} \quad 263 = 445 \text{ in}^3 \text{ per plane}$$

in the 45° plane, $\Delta V = 445/.707 = 632 \text{ in}^3$

with 20% reserve

$$\Delta V = (1.2)(632) = 758 \text{ in}^3$$

Appendix C

PERFORMANCE OF CONICAL AND CONTOURED NOZZLES FOR MOTORS WITH ALUMINIZED SOLID PROPELLANTS

A comprehensive study of the comparative performance of contoured and conical nozzles was made as part of a development program at Aerojet in 1959 and 1960. The study consisted of the firing of approximately 75 motors in an altitude facility of the AEDC in Tullahoma, Tennessee. Nozzle designs evaluated consisted of conical and contoured expansion sections of 18, 20.4, and 24 to 1 expansion ratio at various parametric values of length, initial expansion angle and throat wall radii. Propellants used were formulated of 2, 10, 17, and 19 percent aluminum by weight. The results of this program are comprehensively presented in Reference (a).

The range of parameters evaluated generally encompassed the geometrical description of the reference nozzle except that the expansion ratios did not extend beyond 24:1. Nevertheless, definite performance relationships were established, as a function of geometry, that allow reasonabl extrapolation to reference nozzle application. Representative nozzles are compared to the reference nozzle geometry for a 17.5° cone in Figure C-1.

Extrapolations of nozzle expansion ratio and nozzle length are shown in Figures C-1 and C-2. Neither of these figures stands alone as a valid extrapolation, but when considered together indicate an advantage of the contoured nozzle of slightly less than 0.5 in I_s. These data were obtained for the propellant with 19% aluminum by weight and represent only a small portion of the data obtained in the experimental program.

The primary advantage of a contoured nozzle is in the ability to achieve the performance of a standard conical design in a substantially smaller geometric envelope. Thus, in an unlimited envelope, the performance gain can often be considered negligible, particularly for small nozzles and highly aluminized propellant. However, in comparison with the reference nozzle envelope, the data of Figures C-2 and C-3 indicate that equivalent performance be be obtained using

Preceding page blank

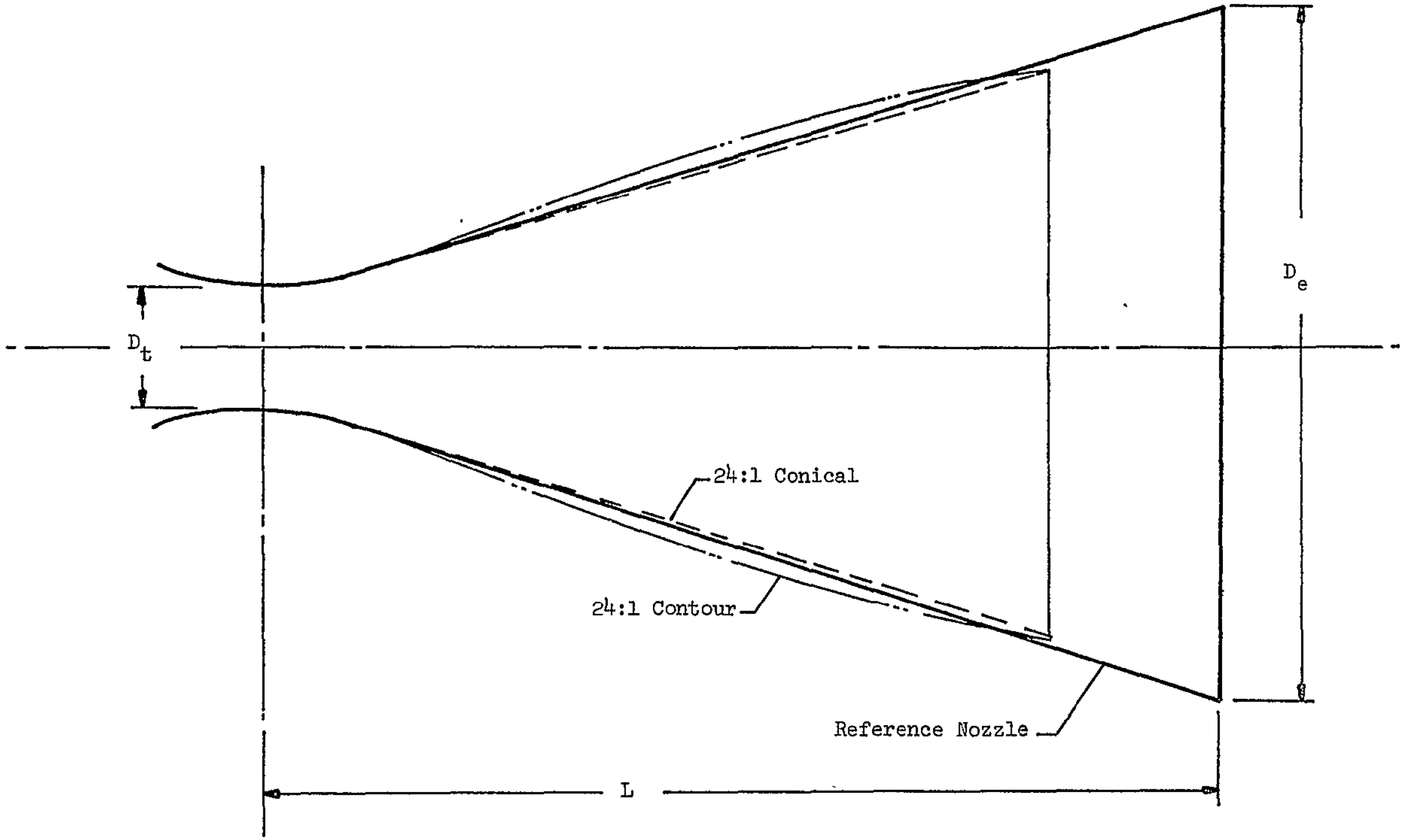


Figure C-1. Nozzle Comparisons

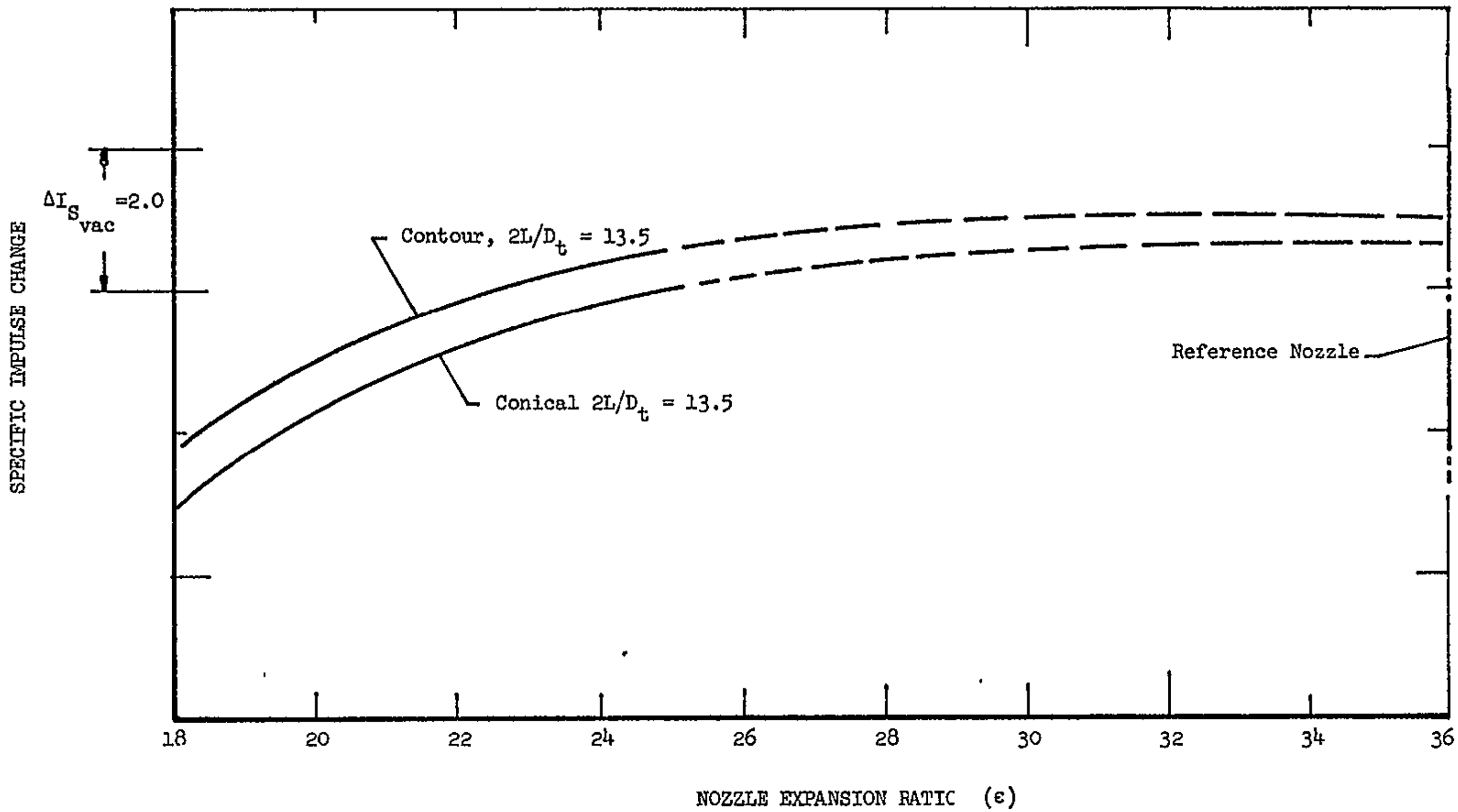


Figure C-2. Specific Impulse Charge with Nozzle Expansion Ratio

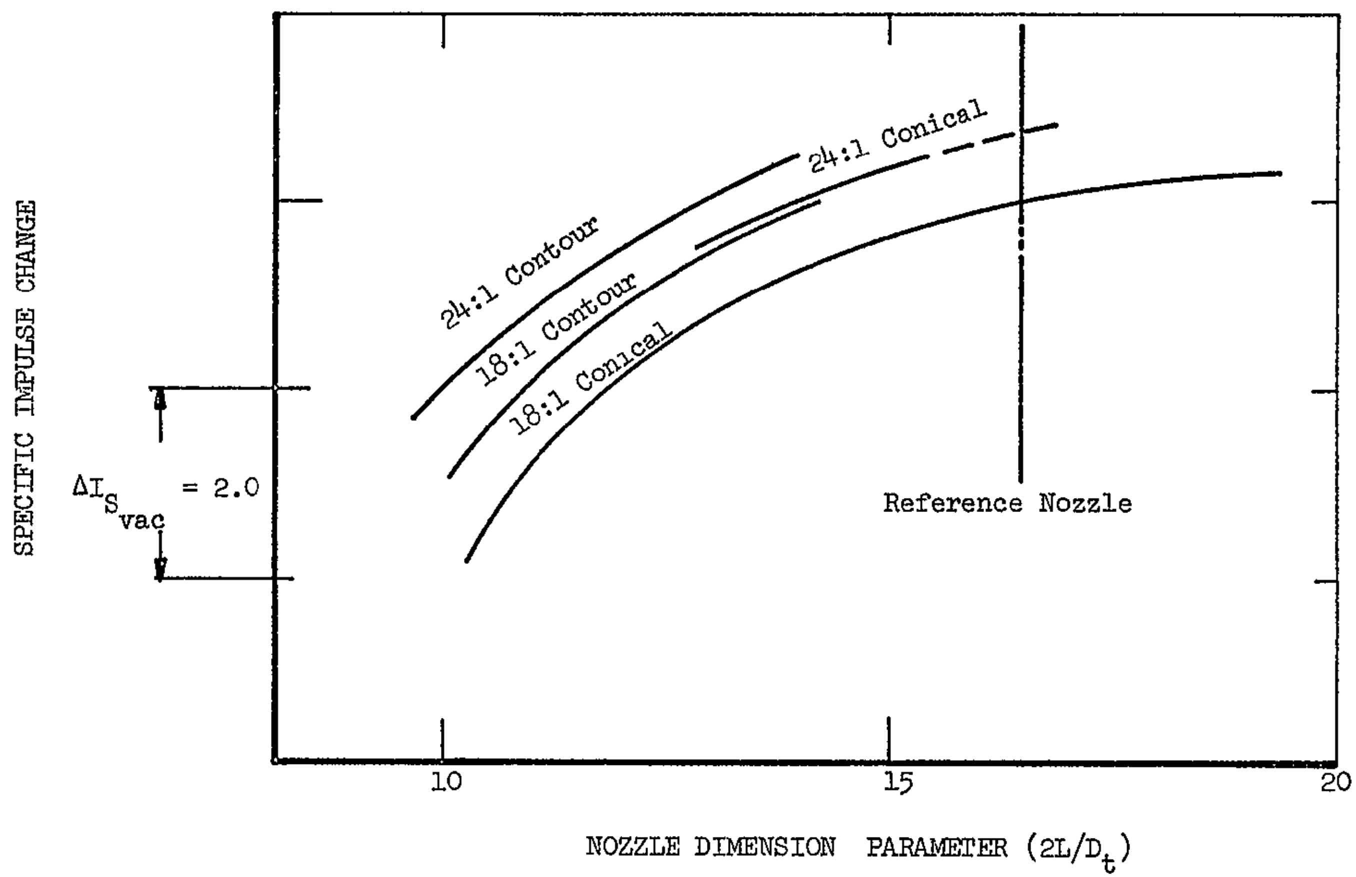


Figure C-3. Specific Impulse Charge with Nozzle Dimensions a contoured nozzle of approximately 24:1 expansion ratio and substantially reduced length ratio (from 16.5 to 15). For the same length and expansion ratio as the reference nozzle, there can still be a slight performance gain anticipated.

Reference (a): "Minuteman Nozzle Contour Development Program," Confidential Technical Memorandum No. 158 SRP by M. J. Ditore and W. S. Haigh, 27 February 1961, Aerojet-General Corporation, Solid Rocket Plant

Appendix D

PRELIMINARY STRESS AND DEFLECTION ANALYSIS

The following analyses present the methods and results of a preliminary study of gimbal ring stresses and deflections, and buckling loads in the nozzle support shell.

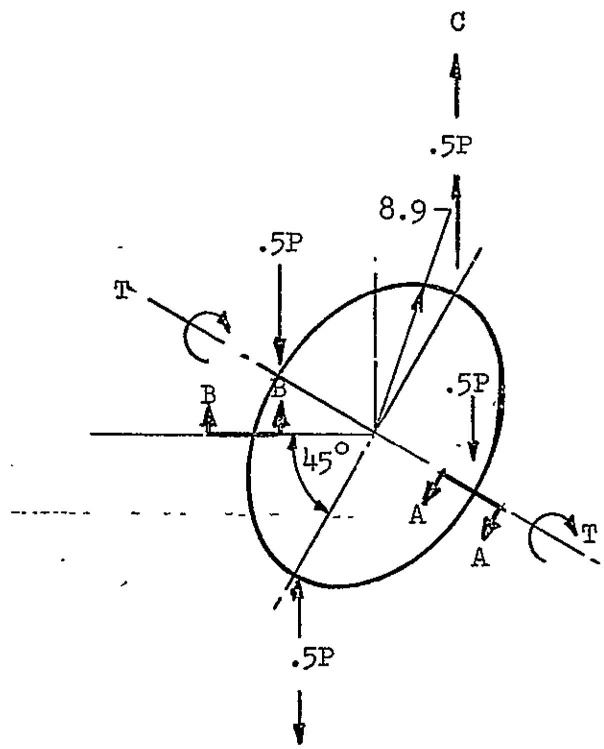
1.0 DESIGN CRITERIA

1.1 **DESIGN YIELD LOADS

Ejection Load, $P = 60{,}000^{lb\text{-}in}$

Torque per Actuator Pair, $2T = 8{,}800^{in\text{-}lb}$

1.2 GEOMETRY



Max. Gimbal Angulation = 1.5°

Figure 1

1.3 MATERIAL PROPERTIES

Titanium 6AL-4V Heatreated

F_{T_Y} = 155000 psi Tensile Yld

$F_S \cong$ 93500 psi Shear

$E = 16.4 \times 10^6$ psi Elastic Modulus*

$G = 6.2 \times 10^2$ psi Shear Modulus*

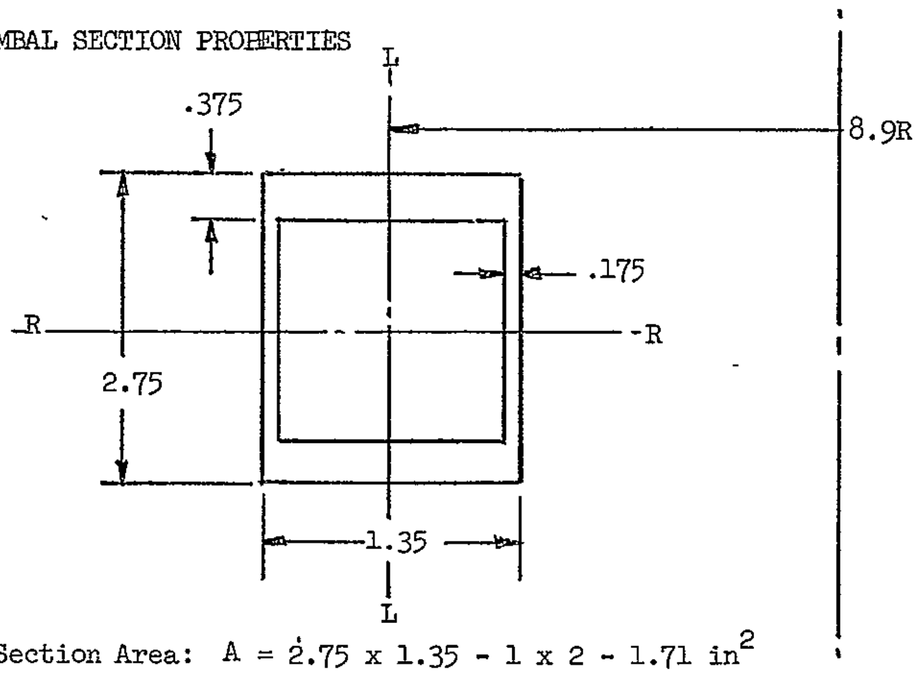
*Mil H'DB'K 5

**Supplied by N. Mittermaier

2.0 STRESS ANALYSIS

2.1 GIMBAL SECTION PROPERTIES

Figure 2



X-Section Area: $A = 2.75 \times 1.35 - 1 \times 2 - 1.71 \text{ in}^2$

Moment of Inertia

$$I_{RR} = \frac{1.35 \times 2.75^3 - 1 \times 2^3}{12} = \frac{28.4 - 8.0}{12}$$

$$= \frac{20.8}{12} = 1.73 \text{ in}^4$$

$$I_{LL} = \frac{2.75 \times 1.35^3 - 2 \times 1^3}{12} = \frac{6.75 - 2.0}{12}$$

$$= \frac{4.75}{12} = .395 \text{ in}^4$$

Torsion Area

$$A_T = 1.175\ (2.375) = 2.80 \text{ in}^2$$

1st moment of inertia

$$Q_{RR} = \frac{\Sigma A\ \bar{z}}{\Sigma A} = \frac{1.35\ (.375)(1.1875) + 2(.5)(.175)(1.0)}{.5\ (1.71)}$$

$$= \frac{.6 + .175}{.855} = \frac{.775}{.855} = .905 \text{ in}^3$$

2.2 BENDING at section A-A (Reference Figure I pg. D-2) normal to plane of curvature

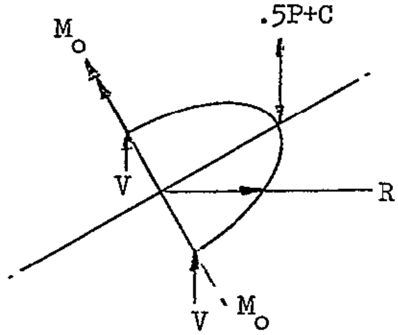


Figure 3

$$M_o - .5R \left[.5P + C \right]$$

$R = 8.9$ Reference Pg D-2

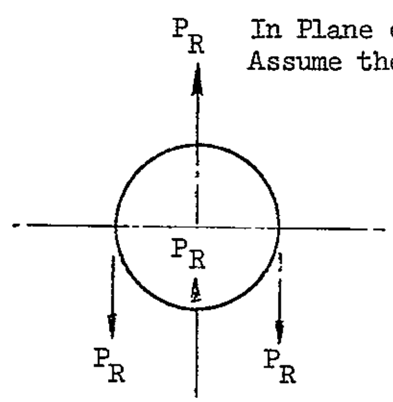
$P = 60{,}000^{\,lb}$

$$C = \frac{T}{2\ R} = \frac{8800}{2(8.9)} = 4950^{lb}$$

$$M_o = .5\ (8.9)(34950) = 155{,}000^{in\text{-}lb}$$

$$f_b = \frac{M_o C}{I_{RR}} = 155{,}000 \frac{(1.375)}{1.73} = 123{,}000 \text{ psi}$$

In Plane of Curvature
Assume the Gimbal is Angulated 1.5^o



$$P_R = (.5\ P + C) \sin 1.5^o$$
$$= 34{,}950\ (.0262) + 912^{lb}$$

$M_i = .16\ P_R\ R$ Reference: German Ring Report Case 2

$= .16\ (912)\ (8.9)$

$= 1300^{\text{in-lb}}$

$$f_{b_i} = \frac{M_L C}{I_L}$$

$$= \frac{1300\ (.675)}{.395} = 2230 \text{ psi}$$

Total Bending Stress Reference Pgs. D-4 and 5

$$\Sigma f_b = f_{b_i} + f_{b_m}$$

$$= 2230 + 123{,}000 = 125{,}230 \text{ psi}$$

$F_T = 155{,}000$ psi Tensile Yield, Reference Pg D-2

$$\text{M.S.} = \frac{155{,}000}{125{,}230} - 1 = +\ \underline{\underline{.23}}$$

2.3 SHEAR AND TORSION

Section B-B Reference Figure I Pg D-2

$$f_s = \frac{V\ Q}{2\ It} \quad \text{Shear Stress, Max}$$

$V = (.5\ P + C)\ .5 =$

$= .5(30{,}000 + 4950) = 17425^{\text{lb}}$ Ref. Pg D-4

$I_{RR} = 1.73 \text{ in}^4$ Ref. Pg D-3

$t = .175$ in Ref. Pg D-3

$Q_{RR} = .905 \text{ in}^3$

$$= \frac{17425\ (.905)}{2(.175)(1.73)} = 26200 \text{ psi}$$

$$f_{st} = \frac{T_{max}}{2\,A_T\,t}$$ Max Torsional Stress

$t = .175$ Ref. Pg. D-3

$A_T = 2.80\ in^2$ Ref. Pg. D-3

$T_{max} = .707\ M_o - 293\ (.5)R(.5\ P + C)$ Ref: Roark Pg. 153

$M_o = 155{,}000^{in-lb}$ Ref. Pg. D-4

$R = 8.9$ Ref. Pg. D-2

$(.5\ P + C) = 34{,}950\ lb$ Ref. Pg. D-4

$T_M = .707\ (155{,}000) - 8.9(.5)(.293)(34{,}950)$

$= 110{,}000 - 45500$

$= 64{,}500$ in-lb

$$f_{st} = \frac{64{,}500}{.35\ (2.80)} = 65{,}600 \text{ psi}$$

Total Shear Stress

$\sum f_s = f_s + f_{st}$ Ref. Pg. D-5 and 6

$= 26{,}200 + 65{,}600$

$= 91{,}800$ psi

$F_s = 93{,}500$ psi Ref. Pg D-2

$$\text{M.S.} = \frac{93.5}{91.8} - 1 = +\ \underline{\underline{.02}}$$

DEFLECTION

Normal to Plane of Curvature

$$*\Delta = \frac{(.5\ P + C)R^3}{4\ EI_{PR}} \left[1.14 + .28\ \frac{EI}{KG} \right]$$

$$K = 2\ tt_1\ \frac{(a-t)^2 (b-t_1)^2}{at + bt_1 - t^2 - t_1^2} \qquad \text{Torsional Stiffness Parameter}$$

$t^2 = (.375)^2 = .14$	Ref. Pg. D-3
$t_1^2 = (.175)^2 = 0.1538$	Ref. Pg. D-3
$a = 2.75$	Ref. Pg. D-3
$b = .375$	Ref. Pg. D-3

$$K = \frac{2\ (.375)(.175)(2.375)^2\ (1.175)^2}{(2.75)(.375) + 1.35(.175) - .155} = .935$$

$E = 16.4 \times 10^6$ psi	Ref. Pg. D-2
$G = 6.2 \times 10^6$ psi	Ref. Pg. D-2
$(.5\ P + C) = 34{,}950$ lb	Ref. Pg. D-4
$R^3 = (8.9)^3 = 710\ in^3$	
$I_{RR} = 1.73\ in^4$	Ref. Pg. D-3

$$\Delta = \frac{34350(710)}{4(16.4)(1.73)10^6} \left[1.14 + \frac{.28 \times 16.4 \times 1.73}{.935 \times 6.2} \right]$$

$$= .22 \times 10^{-6} \left[1.14 + 1.36 \right] = .22 \times 2.50 \times 10^{-6}$$

$$= \underline{\underline{.55\ in}}$$

*Ref: Machine Design 11/14/57, "Deflection of Circular Rings Loaded Normal to Plane of Curvature", N. D. Tabackman

2.4 BUCKLING OF SUBMERGED NOZZLE SHELL

The submerged portion of the nozzle is that portion projecting inside the pressure vessel. This section is subjected during firing to high external pressures and must, therefore, be checked for its ability to resist buckling instability collapse. All charred plastic components were ignored in this solution, and only those layers which are predicted to be unaffected by heat were used as structure. A chamber pressure of 500 psia (MEOP) was also used with an effective differential pressure approximated at 480 psi.

For ease of calculation, the truncated cone was approximated by a cone with variable wall thickness given by the expression:

$$t = \frac{R}{R_1} t_1$$

where t_1 is the actual shell thickness of 0.156 in., and R_1 is the large end normal radius (7.2 in.). The cone angle (α) is 75°, and from Timoshenko's "Theory of Elastic Stability", we have:

$$q_1 = q_{CR} \left[\frac{1 - u^2}{E} \quad \frac{R_1}{t} \right]$$

$$K_1 = \frac{t_1^2}{12R_1^2} = 3.88 \times 10^{-5}$$

From Figure 11-31 of the same reference, we obtain from this value of K_1 a value of (q_1) of 10^{-3}. Substituting this value into the above equation we obtain:

$$q_{CR} = 396 \text{ psi}$$

Surrounding this titanium core are two layers of partially uncharred insulation, the inside layer 0.125-in. thick, the outside layer 0.250-in. Using the same analytical techniques, the critical individual buckling pressures are found:

$$q_{inside} = 30 \text{ psi}$$

$$q_{outside} = 200 \text{ psi}$$

A compressive modulus of 2.7×10^6 psi and a Poisson's Ratio of 0.25 were used for these values. The total collapsing pressure may now conservatively be determined by summing the individual layer's resistance.

$$P_{CR} = (396 + 30 + 200) = 626 \text{ psi}$$

The calculated margin of safety against collapse:

$$M.S. = \frac{626}{480} - 1 = \underline{0.30}$$

The actual margin will be considerably higher due to the end rings, the constant thickness, and the interaction of the composite layers.

Appendix E

RELIABILITY ANALYSIS

1.0 INTRODUCTION

For each of the seventeen system combinations considered, a mathematical model of system reliability was formulated. In this appendix the models used are stated below and an example calculation is included for one system. In addition, the results of the calculations are tabulated in Tables E2 to E14.

2.0 MATHEMATICAL RELIABILITY MODELS

LITVC - Cold Gas Pressurized

$$R = \left[1 - (1 - R_{\substack{\text{Expl Fill} \\ \text{Valve(Leakage)}}}) (1 - R_{\substack{\text{Fill Q.D.} \\ \text{(Leakage)}}}) \right] e^{-\sum t.FR} \times R_{\substack{\text{Press.} \\ \text{Regulator} \\ \text{(Operational)}}} \times R_{\substack{\text{Compon.} \\ \text{from} \\ \text{MM-LITVC} \\ \text{Test Data}}} \times R_{\text{pyrotechnics}}$$

where

$$\sum t.FR = t_{1-1}FR_{\substack{\text{1st 10 sec} \\ \text{Boost}}} + t_1 FR_{\substack{\text{1st} \\ \text{Stg.}}} + t_2 FR_{\substack{\text{2nd} \\ \text{Stg.}}} + t_3 FR_{\substack{\text{Interplan.} \\ \text{Injection}}} + t_4 FR_{\text{Transit}} + t_5 FR_{\text{Retro}}$$

A sample calculation for this system is shown in Table E-1

LITVC - Hot Gas Pressurized

$$R = e^{-\sum t.FR} \times R_{\text{Pyrotechnics}} \times R_{\substack{\text{Components} \\ \text{from MM-LITVC} \\ \text{Test Data}}}$$

Cold Gas Reaction Jet ACS

$$R = \left[1 - (1 - R_{\substack{\text{Explosive} \\ \text{Fill Valve} \\ \text{(Leakage)}}}) (1 - R_{\substack{\text{Fill Q.D.} \\ \text{(Leakage)}}}) \right] e^{-\sum t.FR} \times R_{\substack{\text{Pressure} \\ \text{Regulator} \\ \text{(Operational)}}} \times R_{\text{Pyrotechnics}}$$

Solid Propellant Gas Generator Reaction Jet ACS

$$R = e^{-\sum t.FR} \times R_{\text{Pyrotechnics}} \times R_{\substack{\text{Components}\\ \text{from MM-LITVC}\\ \text{Test Data}}}$$

Monopropellant Reaction Jet ACS

$$R = \left[1 - \left(1-R_{\substack{\text{Explosive}\\ \text{Fill Valve}\\ \text{(Leakage)}}}\right)\left(1 - R_{\substack{\text{Fill Q.D.}\\ \text{(Leakage)}}}\right)\right] e^{-\sum t.FR} \times R_{\substack{\text{Pressure}\\ \text{Regulator}\\ \text{(Operational)}}} \times R^4_{\substack{\text{Thrust}\\ \text{Chamber}}}$$

$$\times R_{\text{Pyrotechnics}} \times R_{\substack{\text{Components}\\ \text{from MM-LITVC}\\ \text{Test Data}}}$$

Bi-Propellant Reaction Jet ACS

$$R = \left[1 - \left(1-R_{\substack{\text{Explosive}\\ \text{Fill Valve}\\ \text{(Leakage)}}}\right)\left(1-R_{\substack{\text{Fill Q.D.}\\ \text{(Leakage)}}}\right)\right]\left[1 - \left(1-R_{\substack{\text{Fuel,Oxid.}\\ \text{Ck. Valve}}}\right)\left(1-R_{\substack{\text{Fuel,Oxid.}\\ \text{Inlet Burst}\\ \text{Diaphragm}}}\right)\right]^2 e^{-\sum t.}$$

$$\times R_{\substack{\text{Pressure}\\ \text{Regulator}\\ \text{(Operational)}}} \times R_{\text{Pyrotechnics}} \times R^4_{\substack{\text{Thrust Chamber}\\ \text{Solenoid}}} \times R_{\substack{\text{Components}\\ \text{from}\\ \text{MM-LITVC}\\ \text{Test Data}}}$$

Translating Nozzle TVC-Cold Gas Pressurized, Hydraulic Servo-Actuation System

$$R = e^{-\sum t.FR} \times R_{\substack{\text{Pressure}\\ \text{Regulator}\\ \text{(Operational)}}} \times R_{\substack{\text{Burst}\\ \text{Diaphragm}}} \times R_{\substack{\text{Hydraulic}\\ \text{Fluid}\\ \text{Bladder}}} \times R_{\text{Pyrotechnics}}$$

Translating Nozzle TVC-Hot Gas Pressurized, Hydraulic Servo-Actuation System

$$R = e^{-\sum t.FR} \times R_{\substack{\text{Gas Generator}\\ \text{and Igniter}}} \times R_{\substack{\text{Burst}\\ \text{Diaphragm-}\\ \text{Hydr.Tank In.}}} \times R_{\substack{\text{Burst Diaph.}\\ \text{Hydr. Tank}\\ \text{Out}}} \times R_{\substack{\text{Hydr.}\\ \text{Fluid}\\ \text{Bladder}}} \times R_{\substack{\text{Compon.}\\ \text{from MM-}\\ \text{LITVC}\\ \text{Test Data}}}$$

Translating Nozzle TVC-Recirculation Hydraulic Servo-Actuation, with Electric Motor/Pump

$$R = e^{-\sum t.FR} \times R_{\substack{\text{Hydraulic Fluid}\\ \text{Bladder}}}$$

Translating Nozzle TVC-Recirculating Hydraulic Servo-Actuation, with Turbine-driven Pump

$$R = e^{-\sum t.FR} \times R_{\substack{\text{Hydraulic Fluid}\\ \text{Bladder}}} \times R_{\substack{\text{Gas Generator}\\ \text{and Igniter}}} \times R_{\substack{\text{Compon.}\\ \text{from MM-LITVC}\\ \text{Test Data}}}$$

Translating Nozzle TVC-Electro-Mechanical Servo-Actuation System

$$R = e^{-\sum t.FR}$$

Gimballed Nozzle TVC-Cold Gas Pressurized, Hydraulic Servo-Actuation System

$$R = \left[1 - (1-R_{\substack{\text{Nozzle}\\ \text{Seal}}})(1-R_{\text{Bellows}})\right] e^{-\sum t.FR} \times R_{\substack{\text{Pressure}\\ \text{Regulator}\\ \text{(Operational)}}} \times R_{\substack{\text{Burst}\\ \text{Diaphragm}}} \times R_{\substack{\text{Hydraulic}\\ \text{Fluid Bladder}}} \times R_{\text{Pyrotechnics}}$$

SGC 884 FR-1

Gimballed Nozzle TVC-Hot Gas Pressurized,
Hydraulic Servo-Actuation System

$$R = \left[1 - (1-R_{\substack{\text{Nozzle}\\\text{Seal}}})(1-R_{\text{Bellows}})\right] e^{-\sum t.FR} \times R_{\substack{\text{Gas Generator}\\\text{and Igniter}}} \times R_{\substack{\text{Burst Diaph.}\\\text{Hydr. Tank In.}}}$$

$$\times R_{\substack{\text{Burst Diaph.}\\\text{Hydr. Tank Out}}} \times R_{\substack{\text{Hydraulic}\\\text{Fluid Bladder}}} \times R_{\substack{\text{Compon.}\\\text{from MM-LITVC}\\\text{Test Data}}}$$

Gimballed Nozzle TVC-Recirculating Hydraulic
Servo-Actuation, with Electric Motor/Pump

$$R = \left[1 - (1-R_{\substack{\text{Nozzle}\\\text{Seal}}})(1-R_{\text{Bellows}})\right] e^{-\sum t.FR} \times R_{\text{Hydraulic Tank Bladder}}$$

Gimballed Nozzle TVC-Recirculating Hydraulic
Servo-Actuation, with Turbine-driven Pump

$$R = \left[1 - (1-R_{\substack{\text{Nozzle}\\\text{Seal}}})(1-R_{\text{Bellows}})\right] e^{-\sum t.FR} \times R_{\substack{\text{Hydr.}\\\text{Fluid}\\\text{Bladder}}} \times R_{\substack{\text{Gas Generator}\\\text{and Igniter}}} \times R_{\substack{\text{Compon.}\\\text{from MM-LITV}\\\text{Test Data}}}$$

Gimballed Nozzle TVC-Electro-Mechanical Servo-
Actuation System

$$R = \left[1 - (1-R_{\substack{\text{Nozzle}\\\text{Seal}}})(1-R_{\text{Bellows}})\right] e^{-\sum t.FR}$$

Appendix E

REFERENCES

1. Report No. SGC 262/355 Rel - 26, "Development of a Liquid Injection Thrust Vector Control System for the Improved Minuteman Stage II Motor".

2. BUWEPS Failure Rate Data Program (FARADA), September 1964.

3. AD 330 024; "Compilation and Analysis of ASD-TDR-62-219 Reliability Data on Selected Flight Control Components", preapred for Flight Control Lab., Aeronautical Systems Division, Wright-Patterson AFB, by Planning Research Corporation.

4. AD 273286; "Failure Rates and Failure Modes of Small Rotary Electrical Devices", prepared for Aeronautical Systems Division, Wright-Patterson AFB, by ARINC Research Corporation.

5. WADD-TR-60-330; AD 270462; "A compilation of Component Field Reliability Data Useful in Preliminary Design", prepared for Aeronautical Systems Division, Wright-Patterson AFB, by Systems Technology, Inc.

6. Aerospace Report No. 1923-1-89, Electronic Components.

7. Conax Corp., McCormick-Selph Associates, Explosive Devices.

8. Papers published in the Proceedings of the 9th National Symposium on Reliability and Q.C., San Francisco, Calif., January 1963.

9. Ablestar-Aerobee experienced failure rates, Subsystem and Component Field Test Procedures.

$$R_{\text{LITVC System, Cold Gas Pressurized}} = \left[1 - (1-R_{\text{Expl Fill Valve Leakage}})(1-R_{\text{Fill QD -Leakage}})\right] \times e^{-\left[t_{1-1}\, \text{F.R.}_{\text{1st 10 secs. Boost}} + t_1\, \text{F}\right.}$$

From Table 4,

$$R_{\text{Expl. N. Fill Valve (Leakage)}} = e^{-\left[.002777(33.6) + .052777(3.36) + .083333(2.52) + .083333(2.5\right.}$$

$$e^{-.0003660} = .999633$$

$$R_{\text{Fill QD (Leakage)}} = e^{-\left[.002777(1112.) + .052777(111.2) + .083333(83.4) + .083333(83.4) + \right.}$$

$$e^{-.012245} = .98775$$

For a 6 month Transit Period:

$$R_{\text{LITVC Syst. Cold Gas Press.}} = \left[1 - (1-.999633)(1-.98775)\right] \times e^{-\left[.002777(4478.2) + .052777(331.2) + .\right.}$$

$$= \left[.9999955\right] \times e^{-\left[827.008 + 4380\ (1.3954)\right] 10^{-6}} \quad (.991000)$$

$$= (.9909955) \times e^{-.0069388} = (.9909955)(.9930612) = \underline{\underline{.98412}}$$

For an 8 month transit period:

$$R_{\text{LITVC Syst. Cold Gas Press.}} = (.9909955) \times e^{-\left[827.008 + 5840\ (1.3954)\right] 10^{-6}}$$

$$= (.9909955) \times e^{-.008976} = (.9909955)(.991024) = \underline{\underline{.98210}}$$

E-6-A

Table E-1

CALCULATIONS FOR LITVC SYSTEM,

OLD GAS PRESSURIZED

---

t_1 F.R. 1st Stg. + t_2 F.R. 2nd Stg. + t_3 F.R. IntrPlt. Inj. + t_4 F.R. Transit + t_5 F.R. Retro F] x $R_{\text{Press. Regulator (Operational)}}$ x $R_{\text{Compon. from MM-LITVC Test Data}}$

x $R_{\text{Pyrotechnics}}$

$$(2.52) + 8760\ (.0417) + 022222\ (3.36)\Big]\ 10^{-6}$$

$$) + 8760\ (1.395) + .022222\ (111.2)\Big]\ 10^{-6}$$

$$) + .083333(138.2) + .083333(99.45) + 4380\ (1.3954) + .022222\ (34978.)\Big]\ 10^{-6}$$

$$\times\ (.9999956)(.990)(.9916)(.99985)^4$$

E-6-B

For a 10-month Transit Period:

$$R_{\substack{\text{LITVC Syst.}\\ \text{Cold Gas}\\ \text{Press.}}} = (.9909955) \times e^{-\left[827.008 + 7300\ (1.3954)\right]\ 10^{-6}}$$

$$= (.9909955) \times e^{-.0110134} = (.9909955)(.9889866) = \underline{.98008}$$

For a 12-month Transit Period:

$$R_{\substack{\text{LITVC Syst.}\\ \text{Cold Gas}\\ \text{Press.}}} = (.9909955) \times e^{-\left[827.008 + 8760\ (1.3954)\right]\ 10^{-6}}$$

$$= (.9909955) \times e^{-.0130507} = (.9909955)(.9869493) = \underline{.97806}$$

LIQUID INJECTION TVC [illegible]

COMPONENT FAIL[illegible]

1	2	3	4	5	6	7	8		1[illegible]
TVC System Component	Qty. in Syst.	Compon. Failure Rate, Source & Stress Level $F/10^6$ Hrs.	F.R. Adjustment; Lab. to Bench Test Level $F/10^6$ Hrs.	Env. Stress Factor, K_1 & Application stress Factor, K_2; 1st Stage Boost		Failure Rate, 1st Stage Boost, $F/10^6$ Hrs.	Env. & Appl. Str[illegible] Fact[illegible], 2nd [illegible]		[illegible]ailu[illegible] Rat[illegible] [illegible] S[illegible] $F/10^6$
				K_1	K_2		K_1	[illegible]	
TVC Gas Gen. Igniter (incl. squibs)	1	1/Test Fire							
TVC Gas Generator	1	1/Test Fire							
TVC Hot Gas Manifold Assembly	1	1/							
Gas Generator Manifold Joint Seals	7	8/Lab. .02	1.2	$5-t_{1-1}$ $.2-t_1$	.1	$4.2\ t_{1-1}$ $.168\ t_1$	.2	.1	.1[illegible]
Relief Valve	1	8/Lab 32.5	9/Oper. 3850.	$4-t_{1-1}$ $.2-t_1$	.1	$1540\ t_{1-1}$ $77\ t_1$	.15	.1	57.7
Injectant Tank	1	8/Lab. 1.44 .004 Leakage fail. mode	86.4 2.64	$7-t_{1-1}$ $.3\ t_1$	.3	$5.54\ t_{1-1}$ $.237\ t_1$	.25	.[illegible]	.19
Injectant Bladder	1	8/Lab. .09 Leak fail. mode	5.4	$5-t_{1-1}$ $.3\ t_1$	.3	$8.1\ t_{1-1}$ $.486\ t_1$	.2	.[illegible]	.32
Burst Diaphragm Hot Gas, Tank Inlet	1								
Burst Diaphragm Injectant Bladder Outlet	4	2/15. Aircraft (.107 Lab) (Leakage f.m.)	6.42	$7-t_{1-1}$ $.4\ t_1$	.3	$53.9\ t_{1-1}$ $3.08\ t_1$	.2	.[illegible]	1.5[illegible]

GAS PRESSURIZATION

RELIABILITY DATA

[illegible] te, Stage Hrs.	11 Env. & Appl. Stress Factors, Interpl. Trajectory Injection K_1	12 K_2	13 Failure Rate, Inter-Plt. Inj., $F/10^6$ Hrs.	14 Env. & Appl. Stress Factors, Transit Period K_1	15 K_2	16 Fail-ure Rate, Transit Period, $F/10^6$ Hrs.	17 Env. & Appl. Stress Factors, Opera-tional (During Retro-Thrust) K_1	18 K_2	19 Fail-ure Rate, Retro-Thrust Period, $F/10^6$ Hrs.	20 Relia-bility Pyro-Technic Compon-ents	21 Relia-bility Compon. from MM-LITVC Test Data
										.99971	
										.99895	
											.999952
.168	.15	.1	.126	.03	.1	.00042	12	.9	90.72		
[illegible].75	.15	.1	57.75	.05	.1	.1625	7	.6	16170.		
.198	.25	.3	.198	.2	.2	.00176	10	.5	432.		1/ 1/.990 (Burst fail mode)
.[illegible]24	.15	.3	.243	.2	.2	.216					1/ 1/.9916
											1/ 1/.968 (Burst fail mode)
[illegible]	.15	.3	1.155	.1	.15	.00642					1/.99985/BD Burst fail mode)

1	2	3	4	5	6	7	8	9
Injectant Tank Support Assy.	1	8/Lab .55	33.	4 t_{1-1} .2 t_1	.6	79.2 t_{1-1} 3.96 t_1	.2	.5
.G.Support Assy	1	8/Lab .55	33.	4 t_{1-1} .2 t_1	.6	79.2 t_{1-1} 3.96 t_1	.2	.5
Injectant Manifold	4	8/Lab 2.02	121.2	4 t_{1-1} .3 t_1	.3	581 t_{1-1} 43.6 t_1	.2	.2
Inject. Manif. Seals	8	8/Lab .02	1.2	5 t_{1-1} .2 t_1	.1	4.8 t_{1-1} .192 t_1	.2	.1
Injector Servo Valves	4	6.21 (Lab)	3/Bench Test 372.88	4 t_{1-1} .3 t_1	.1	596.6 t_{1-1} 44.74 t_1	.2	.1
Servo Valve Hydraulic System	1		3727.	4 t_{1-1} .3 t_1	.2	2981 t_{1-1} 223.6 t_1	.2	.1
Manifold Assy.	1	8/Lab 4.85	291.	Note: Circulatory type Hydraulic Power Sys North American Spec. 5-15594 for Min				
28 VDC Motor	1	4/Aircrft 183.6	78.					
Audio Noise Filter	1	8/Lab .345	20.7					
Hydraulic Fittings	2	2.02	242.4					
Hydr. Q.D.	2	9/Oper. 146.2	292.4					
Hydr. Filter	1	8/1.62	97.	Total F.R. during t_{1-1} & t_1		5933.5 t_{1-1} 401.0 t_1	Total F.R. during t_2	
Hydr Check Valve	1	9/337.3	337.3					
Press. Transducer	1	9/860.	860.					
Press Switch	1	5/Aircft 84.	35.8					
Thermister Mtr.Fld.	1	8/ .6	36.					
Motor-Pump Shaft	1	.35	21.					
Coupling-Splined	1	.025	1.5					

E-2 Cont.

	8	9	10	11	12	13	14	15	16	17	18	19
1	.2	.5	3.3	.17	.5	2.80	.06	.15	.00495	6	.7	138.6
ɩ	.2	.5	3.3	.17	.5	2.80	.06	.15	.00495	5	.7	115.5
	.2	.2	19.39	.17	.1	8.24	.03	.1	.02424	10	.8	3878
	.2	.1	.192	.15	.1	.144	.03	.1	.00048	12	.8	92.16
	.2	.1	29.83	.15	.1	22.37	.1	.15	.3726	10	.5	7457.
	.2	.1	74.54	.15	.1	55.9	.12	.1	.7452	6	.95	21243.

..ic Power System is based on
15594 for Minuteman, Stages I-II.

Total F.R. during t_2	190.53	Total F.R. during t_3	151.72	Total F.R. during t_4	1.535	Total F.R. during t_5	49617.

Total TVC System Failure Rates

Table E-2

1	2	3	4	5	6	7	8
Pump Shaft Seal	1	8/2.9	174.				
Hyd. Reservoir	1	3.37	202.2				
O-ring Seal	1	.035	2.1				
Elec. Connector		.245	14.7				
Hydraulic Pump							
Pump pistons	9	.35	189.				
Cam Drive	1	.004	.24				
Press. Compensating Valve	1	6.6	396.				
Pump Valve Plate	1	.2	12.				
Bearings - Pump Shaft & Motor Shaft	2	3.6	424.				
		62.1	3727.				

E-10-A

:r E-2 Cont.

8	9	10	11	12	13	14	15	16	17	18	19

Table E-3

SOLID PROPELLANT GAS GENERATO[R]

ACS FOR PITCH, YAW OR R[OLL]

COMPONENT FAILURE RATE AND REL[IABILITY]

1	2	3	4	5	6	7	8	9	10
R.C. System Component									
R.C. Gas Gen. Igniter (include squibs)	1	1/ Test Fire							
R.C. Gas Generator	1	1/ Test Fire							
R.C. Hot Gas Manifold Assembly	1	1/							
Gas Gen. Manif. Joint Seals	7	8/ Lab .02	1.2	5 t_{1-1} .2 t_1	.1	4.2 t_{1-1} .168 t_1	.2	.1	.168
R.C. Valve Assy. (Solenoid)	1	2/ 5/ Aircft 24 (.48 Lab)	10.2	4 t_{1-1} .2 t_1	.1	4.08 t_{1-1} .204 t_1	.15	.1	.153
G.G. Suppt. Assy.	1	8/ Lab .55	33.	4 t_{1-1} .2 t_1	.6	79.2 t_{1-1} 3.96 t_1	.2	.5	3.30
R.C. Nozzle	4	8/ Lab .05	3.	4 t_{1-1} .2 t_1	.1	4.8 t_{1-1} .24 t_1	.15	.1	.18
R.C. Nozzle Seals	4	8/ Lab .02	1.2	5 t_{1-1} .2 t_1	.1	2.4 t_{1-1} .096 t_1	.2	.1	.096
				Total F.R. during t_{1-1} & t_1		94.68 t_{1-1} 4.67 t_1	Total F.R. during t_2		3.89 Tot

3

RATOR REACTION JET

OR ROLL

D RELIABILITY DATA

10	11	12	13	14	15	16	17	18	19	20	21
										.99971	
										.9972	
											.999952
.168	.15	.1	.126	.03	.1	.00042	14	.9	105.8		
.153	.15	.1	.153	.1	.1	.0048	30	.7	214.2		1/ .999958 (Slow Response)
3.30	.17	.5	2.80	.06	.15	.00495	5	.7	115.5		
.18	.15	.1	.18	.03	.1	.0006	10	.5	60		
.096	.15	.1	.072	.03	.1	.00024	14	.8	53.7		
3.897	Total F.R.- during t_3		3.331	Total F.R.- during t_4		.0110	Total F.R.- during t_5		54.92		
- Total R.C. System Failure Rates →											

1	2	3	4	5	6	7	8	9	10
TVC System Component									
Explosive Valve, N. Fill, N.O.	1	8/ Lab .56 Leakage fail mode	(redundant) 33.6	2 t_{1-1} .2 t_1	.5	33.6 t_{1-1} 3.36 t_1	.15	.5	2.52
Quick Disconnect Valve N. Fill	1	9/ 31 (Lab)	1854	2 t_{1-1} .2 t_1	.3	1112. t_{1-1} 111.2 t_1	.15	.3	83.4
High Press. N. Tank	1	8/ Lab. .08 (Leakage f.m.)	4.8	4 t_{1-1} .2 t_1	.5	9.6 t_{1-1} .48 t_1	.15	.5	.36
N. Lines & Fittings	7	8/ Lab. .71 .05 (passive)	426	2 t_{1-1} .2 t_1	.1	59.6 t_{1-1} 5.96 t_1	.15	.1	4.47
Explosive Valve, N.C.	1	7/ Oper.							
		8/ Lab. .224 Leak f.m.	13.4	2 t_{1-1} .1 t_1	.1	2.68 t_{1-1} .134 t_1	.1	.1	.134
Pressure Regulator Valve	1	3/ Flt. Test, Final Stg. Boost to Orbit 4.4 per cycle of Oper.							
		2/ Aircft 100. .71 Lab.	42.6	4 t_{1-1} .2 t_1	.1	17.0 t_{1-1} .852 t_1	.15	.1	.64
Injectant Tank	1	Same as Table 2 →				5.54 t_{1-1} .237 t_1			.198
Injectant Bladder	1	Same as Table 2 →				8.1 t_{1-1} .486 t_1			.324
Burst Diaphragm-Injectant Bladder Outlet	4	Same as Table 2 →				53.9 t_{1-1} 3.08 t_1			1.54

STEM WITH COLD GAS PRESSURIZATION

E AND RELIABILITY DATA

10	11	12	13	14	15	16	17	18	19	20	21
2.52	.15	.5	2.52	.15	.5	.0417	.2	.5	3.36	R_{Expl} Valve (Leak-age .999633	
83.4	.15	.3	83.4	.15	.3	1.395	.2	.3	111.2	R_{QD} (Leak-age) .98775	
.36	.15	.5	.36	.15	.5	.006	5	.5	12.0		
4.47	.15	.1	4.47	.03	.1	.00105	6	.9	1610.		
										.999996	
.134	.1	.1	.134	.1	.1	.00224					
									4.4/cyc R = 5956		
.64	.15	.1	.64	.1	.1	.0071					
.198			.198			.00176			432.		1/ .990 (Burst fail mode)
.324			.243			.216					1/.9916
1.54			1.155			.00642					1/.99985/ BD (Burst fail mode)

Table E-4 C.

1	2	3	4	5	6	7	8	9	10
Injectant Tank Suppt. Assy.	1	Same as Table 2 →				$79.2\ t_{1-1}$ $3.96\ t_1$			3.3
Pressure Tank (N) Suppt Assy.	1	Same as Table 2 →				$79.2\ t_{1-1}$ $3.96\ t_1$			3.3
Injectant Manifold	4	Same as Table 2 →				$581.\ t_{1-1}$ $43.6\ t_1$			19.3
Injectant Manifold Seals	8	Same as Table 2 →				$4.8\ t_{1-1}$ $.192\ t_1$			.19
Injector Servo Valves	4	Same as Table 2 →				$596.6\ t_{1-1}$ $44.74\ t_1$			29.
Servo-Valve Hydraulic Syst.	1	Same as Table 2 →				$2981.\ t_{1-1}$ $223.6\ t_1$			74.5
				Total F.R. during t_{1-1} & t_1		$4478.2\ t_{1-1}$ $331.2\ t_1$	Total F.R. during t_2		138.2

E-13-A

able E-4 Cont.

9	10	11	12	13	14	15	16	17	18	19	20	21
	3.3			2.8			.00495			138.6		
	3.3			2.8			.00495			115.5		
	19.39			8.24			.02424			3878.		
	.192			..144			.00048			92.16		
	29.83			22.37			.3726			7457.		
	74.54			55.9			.7452			21243.		
R. 2	138.2	Total F.R. during t_3		99.45	Total F.R. during t_4		1.3954	Total F.R. during t_5		34978.		

COLD GAS (NITROGEN) PITCH OR YAW ATTIT

CONFIGURATION 1A-COMPONENT FAILURE RATE .

1	2	3	4	5	6	7	8	9	10
Configuration 1A Component									
Explosive Valve, Fill, N.O.	1	Same as Table 4 → Redundant Leakage							
Quick Disconnect N. Fill	1	Same as Table 4 →							
Nitrogen Press. Tank	1	8/ Lab. .08 (Leakage f.m.)	4.8	4 t_{1-1} .2 t_1	.5	9.6 t_{1-1} .48 t_1	.12	.3	.173
N. Tank Support Assy.	1	8/ Lab. .55	33.	4 t_{1-1} .2 t_1	.6	79.2 t_{1-1} 3.96 t_1	.15	.4	1.98
Nitrogen Lines & Fittings	5	8/ Lab. .71 .05 (Passive)	42.6	2 t_{1-1} .2 t_1	.1	42.6 t_{1-1} 4.26 t_1	.15	.1	3.195
Explosive Valve N.C.	1	7/Oper 8/ Lab. .224, Leak f.m.	13.4	2 t_{1-1} .1 t_1	.1	2.68 t_{1-1} .134 t_1	.1	.1	.134
Pressure Regulator Valve	1	3/ Flt Test, Final Stg. Boost to Orbit: 4.4 per 10^6 cycles of operation							
		2/ Aircft 100 .71, Lab.	42.6	4 t_{1-1} .2 t_1	.1	17. t_{1-1} .852 t_1	.15	.1	.64
3-Position Solenoid Valve	1	2/ 5/ Aircft 24 (.48 Lab)	10.2	4 t_{1-1} .2 t_1	.1	4.08 t_{1-1} .204 t_1	.15	.1	.153
Nozzles	2	8/ Lab .05	3.	4 t_{1-1} .2 t_1	.1	2.4 t_{1-1} .12 t_1	.15	.1	.09
Nozzle Seals	2	8/ Lab. .02	1.2	5 t_{1-1} .2 t_1	.1	1.2 t_{1-1} .048 t_1	.2	.1	.048
				Total F.R. during t_{1-1} & t_1		158.76 t_{1-1} 10.06 t_1	Total F.R. during t_2		6.413

10	11	12	13	14	15	16	17	18	19	20	21
										R_{EX} Vlv (Leak-age) .999633	
										R_{QD} (Leak) .98775	
.173	.12	.3	.173	.12	.3	.00288	4	.5	9.6		
1.98	.15	.4	1.98	.03	.15	.00247	5	.7	115.5		
3.195	.15	.1	3.195	.03	.1	.00075	6	.7	894.5		
.134	.1	.1	.134	.1	.1	.0024				.999996	
									$R_{Reg.}$ = .956		
.64	.15	.1	.64	.1	.1	.0071					
.153	.15	.1	.153	.1	.1	.0048	8	.7	57.12		
.09	.15	.1	.09	.03	.1	.0003	5	.5	15.0		
.048	.15	.1	.036	.03	.1	.00012	5	.7	8.4		
6.413	Total F.R. during t_3		6.401	Total F.R. during t_4		.02082	Total F.R. during t_5		1100.12		

1	2	3	4	5	6	7	8	9	10
Configuration 1B Component									
Explosive Valve N. Fill, N.O.	1	Same as Table 4 → Redundant in Leakage							
Quick Disconnect N. Fill	1	Same as Table 4 →							
Nitrogen Press. Tank	1	Same as Table 5 →				9.6 t_{1-1} .48 t_1			.173
N. Tank Suppt Assy	1	Same as Table 5 →				79.2 t_{1-1} 3.96 t_1			1.98
Nitrogen Lines Fittings	9	8/ Lab .71 .05 (Passive)	42.6	2 t_{1-1} .2 t_1	.1	76.7 t_{1-1} 7.67 t_1	.15	.1	5.75
Explosive Valve N.C.	1	Same as Table 5 →							
		Same as Table 5 →				2.68 t_{1-1} .134 t_1			.134
Pressure Regulator Valve	2	3/ Same as Table 5 →							
		2/ Aircft 100 Lab. .71	42.6	4 t_{1-1} .2 t_1	.1	34. t_{1-1} 1.704 t_1	.15	.1	1.28
2-Positive Solenoid Valve	2	2/ 5/ Aircft 67 (.48 Lab)	28.6	4 t_{1-1} .2 t_1	.1	22.88 t_{1-1} 1.144 t_1	.15	.1	.858
Nozzles	4	8/ Lab .05	3.	4 t_{1-1} .2 t_1	.1	4.8 t_{1-1} .24 t_1	.15	.1	.18
Nozzle Seals	4	8/ Lab .02	1.2	5 t_{1-1} .2 t_1	.1	2.4 t_{1-1} .096 t_1	.2	.1	.096
				Total F.R. during t_{1-1} & t_1		232.2 t_{1-1} 11.47 t_1	Total F.R. during t_2		10.451

FAILURE RATE AND RELIABILITY DATA

10	11	12	13	14	15	16	17	18	19	20	21
										R_{EX}Vlv (Leakage) .999633	
										R_{QD}(Leak) .98775	
.173			.173			.00288			9.6		
1.98			1.98			.00247			115.5		
5.75	.15	.1	5.75	.03	.1	.00135	6	.7	1610.3		
										.999996	
.134			.134			.0024					
									5.956 per Regulator		
1.[illegible]8	.15	.1	1.28	.1	.1	.0142					
.858	.15	.1	.858	.1	.1	.0096	8	.7	160.16		
.13	.15	.1	.18	.03	.1	.0006	5	.5	30.0		
.[illegible]6	.15	.1	.072	.03	.1	.00024	5	.7	16.8		
[illegible]	Total F.R. during t_3		10.427	Total F.R. during t_4		.03374	Total T.R. during t_5		1942.3		

1	2	3	4	5	6	7	8	9	1
Monopropellant ACS Component									
Explosive Valve N. Fill, N.O.	1	Same as Table 4 →				$33.6\ t_{1-1}$ $3.36\ t_1$			2.5
		Redundant in Leakage							
Quick Disconnect Valve N. Fill	1	Same as Table 4 →				$1112.\ t_{1-1}$ $111.2\ t_1$			83.
Nitrogen Press. Tank	1	Same as Table 5 →				$9.6\ t_{1-1}$ $.48\ t_1$			.1
N. Tank Suppt. Assy	1	Same as Table 5 →				$79.2\ t_{1-1}$ $3.96\ t_1$			1.9
Nitrogen Lines & Fittings	6	8/ Lab .71 (.05 passive)	42.6	$2\ t_{1-1}$ $.2\ t_1$	.1	$51.1\ t_{1-1}$ $5.11\ t_1$	.15	.1	3.8
Explosive Valve N.C.	1	7/ Same as Table 5 8/ Same as Table 5 →				$2.68\ t_{1-1}$ $.134\ t_1$			.1
Pressure Regulator Valve	1	3/ Same as Table 5 2/ Same as Table 5 →				$17.\ t_{1-1}$ $.852\ t_1$			.6
Propellant Tank	1	6.3 (Lab)	2/ Hydrazine) 886.	$6\ t_{1-1}$ $.3\ t_1$	.3	$1595.\ t_{1-1}$ $79.7\ t_1$	.25	.3	66.45
Propellant Tank Suppt. Assembly	1	8/ Lab .55	33.	$4\ t_{1-1}$ $.2\ t_1$	.6	$79.2\ t_{1-1}$ $3.96\ t_1$	.2	.5	3.3
Propellant Pos. Displ. Bladder	1	8/ Lab .09 (Leak f.m.)	5.4	$5\ t_{1-1}$ $.3\ t_1$	.3	$8.1\ t_{1-1}$ $.486\ t_1$	.2	.3	.3
Burst Diaphragm Tank Inlet	1								
Burst Diaphragm Propellant Bladder Outlet	1	2/ aircft. .15 .107 Lab. (Leakage f.m.)	6.42	$7\ t_{1-1}$ $.4\ t_1$	.3	$13.48\ t_{1-1}$ $.77\ t_1$	.2	.3	.3

10	11	12	13	14	15	16	17	18	19	20	21
2.52			2.52			.0417			3.36	$R_{Expl\ Vlv.}$ (Leakage) .999633	
83.4			83.4			1.395			111.2	R_{QD} (Leakage) .98775	
.173			.173			.00288			9.6		
1.98			1.98			.00247			115.5		
3.83	.15	.1	3.83	.03	.1	.0128	6	.7	1073.4		
.134			.134			.0024				.999996	
.64			.64			.0071			5 .956		
66.45	.25	.3	66.45	.2	.2	.252	6	.5	2658.		
3.3	.17	.5	2.8	.06	.15	.00495	6	.7	138.6		
.324	.15	.3	.243	.1	.2	.108					1/ .9916
											1/8 .968 (Burst f.m.)
.335	.15	.3	.289	.1	.15	.0016					1/ .99985 (Burst f.m.)

Table E-7

1	2	3	4	5	6	7	8	9	
Propellant Lines & Fittings	12	8/ Lab. 2.02	121.2	4 t_{1-1} .3 t_1	.3	1744. t_{1-1} 130. t_1	.2	.2	55
N_2H_4 Servo Control Valves	4	6.21 (Lab)	3/ Oper. 373.	4 t_{1-1} .3 t_1	.1	597. t_{1-1} 448.8 t_1	.2	.1	25
Thrust Chamber & Catalyst	4	.1	2/ Oper 50/cyc 6	→ (at~20 cyc/chamber, 4 t_{1-1} .2 t_1	.1	9.6 t_{1-1} .48 t_1	.15	.1	
Expansion Nozzle	4	8/ Lab .05	3.	4 t_{1-1} .2 t_1	.1	4.8 t_{1-1} .24 t_1	.15	.1	
				Total F.R. during t_{1-1} & t_1		4210.t_{1-1} 271.t_1	Total F.R during t_2		165

E-17-A

A

-7 Cont.

10	11	12	13	14	15	16	17	18	19	20	
58.17	.17	.1	24.72	.03	.1	.0727	7	.8	8144.		
29.83	.15	.1	22.37	.1	.15	.3726	14	.5	10444.	—	
.36	.15	.1	.36	.05	.1	.002		$e^{-20(50)10^6} = .999/TC$			
.18	.15	.1	.18	.03	.1	.0006	10	.7	84.		
.65.75	Total F.R. during t_3		124.17	Total F.R. during t_4		.8401	Total F.R. during t_5		22667.		

B

1	2	3	4	5	6	7	8	9	10
Bi-Propellant ACS Component									
Explosive Valve, He, Fill, N.O.	1	Same as Table 4 → (Redundant in Leakage)				$33.6\ t_{1-1}$ $3.36\ t_1$			2.52
Quick Disconnect Valve He, Fill	1	Same as Table 4 →				$1112.t_{1-1}$ $111.2t_1$			83.4
Fuel Check Valve	1	2/ Aircft. 230 (Redundant in Fuel Leakage)	98	$7\ t_{1-1}$ $.4\ t_1$	.2	$137.\ t_{1-1}$ $7.84\ t_1$	.15	.2	2.94
Burst Diaphragm Fuel Tank Inlet	1	2/ Aircft 15. (Leakage f.m.)	6.42	$7\ t_{1-1}$ $.4\ t_1$	.3	$13.48\ t_{1-1}$ $.77\ t_1$	.2	.3	.385
Oxid. Check Valve	1	(Same as Fuel C.V.) → (Redundant in Oxid. Leakage)							
Burst Diaphragm Oxid. Tank Inlet	1	(Same as Fuel BD) →							
Helium Press. Tank	1	8/ Lab. .126	7.56	$4.\ t_{1-1}$ $.2\ t_1$	.5	$15.1\ t_{1-1}$ $.756\ t_1$	.12	.3	.045
He. Tank Suppt Assy.	1	(Table 5) →				$79.2\ t_{1-1}$ $3.96\ t_1$			1.98
He. Lines & Fitings	13	8/ Lab .71 (.05 passive)	42.6	$2\ t_{1-1}$ $.2\ t_1$	.1	$110.7\ t_{1-1}$ $11.07\ t_1$	.15	.1	8.30
Explosive Valve, N.C.	1	7/ 8/	Same as Table 5 Same as Table 5 →			$2.68\ t_{1-1}$ $.134\ t_1$			.134
Pressure Regulator Valve	1	3/ 2/	Same as Table 5 Same as Table 5 →			$17.\ t_{1-1}$ $.852\ t_1$			.64

CTION JET ACS (PITCH & YAW)

AND RELIABILITY DATA

10	11	12	13	14	15	16	17	18	19	20	21
2.52			2.52			.0417			3.36	R_{Expl} Vlv. (Leakage) .999633	
83.4			83.4			1.395			111.2	R_{QD} (Leakage) .98775	
2.94	.15	.2	2.94	.05	.1	.49				R_{CV} (Leakage) .995703	
.385	.15	.3	.289	.1	.15	.0963				R_{BD} (Leakage) .999156	
										R_{CV} (Leakage) .995703	
										R_{BD} (Leakage) .999156	
.045	.12	.3	.045	.12	.3	.00453	4	.5	15.12		
1.98			1.98			.00247			115.5		
8.30	.15	.1	8.30	.03	.1	.00195	7	.7	2713.		
.134			.134			.0024				5.96	
.64			.64			.0071			5.956	B	

1	2	3	4	5	6	7	8	9	10	
ropellant Tank	2	6.3	2/ 886.	6 t_{1-1} .3 t_1	.3	319. t_{1-1} 159.4 t_1	.25	.3	132.9	.
ropellant nk Suppt. sy.	2	8/ Lab .55	33.	4. t_{1-1} .2 t_1	.6	159. t_{1-1} 7.9 t_1	.2	.5	6.6	.
opellant nt.Displ. ladder	2	8/ Lab .09 (Leakage f.m.)	5.4	5 t_{1-1} .3 t_1	.3	16.2 t_{1-1} .97 t_1	.2	.3	.648	.
urst Diaphragm ropell. Tank nlet	2									
urst Diaphragm ropellant ladder Outlet	2	2/ Aircft 15 .107 Lab (Leakage f.m.)	6.42	7 t_{1-1} .4 t_1	.3	26.9 t_{1-1} 1.54 t_1	.2	.3	.77	.
ropellant Lines ttings	30	8/ Lab 2.02	121.2	4 t_{1-1} .3 t_1	.3	4363. t_{1-1} 327. t_1	.2	.2	145.4	.
-propellant alve	4	9/ Oper. 870. 15 (Lab)	870.	4 t_{1-1} .3 t_1	.1	1392 t_{1-1} 104.4 t_1	.2	.1	69.6	.
olenoid	8	5/ Aircft 33. .24 (Lab)	3/ Sat. Oper. 7.6/cyc	7 t_{1-1} .4 t_1	.1	185. t_{1-1} 10.5 t_1	.25	.1	6.6	.
cro-switch for Oxid. Lead)	4	2/ Aircft 13. .093(Lab)		7 t_{1-1} .5 t_1	.1	36.4 t_{1-1} 2.6 t_1	.25	.1	1.3	.
rust Chamber njector	4	2/ Aircft 200 1.5 Lab	86.	4 t_{1-1} .2 t_1	.1	137.6 t_{1-1} 6.88 t_1	.15	.1	5.16	.
pansion ozzle	4	8/ Lab .05	3.	4 t_{1-1} .2 t_1	.1	4.8 t_{1-1} .24 t_1	.15	.1	.18	.
				Total F.R. during t_{1-1} & t_1		6864.5 t_{1-1} 638. t_1	Total F.R. during t_2		380.25	T d

A

E-19-A

8 Cont.

10	11	12	13	14	15	16	17	18	19	20	21
132.9	.25	.3	132.9	.2	.2	.504	6	.5	5316.		
6.6	.17	.5	5.6	.06	.15	.0099	6	.7	277.2		
.648	.15	.3	.486	.1	.2	.216					1/.9916/ Bldr.
											1/8 .968/ BD. (Burst f.m.)
.77	.15	.3	.578	.1	.15	.0032					1/.99985/ BD (Burst f.m.)
.4 .	.17	.1	61.8	.03	.1	.1818	7	.8	20361.		
9.6	.15	.1	52.2	.07	.1	.42	12	.5	20880		
6.6	.2	.1	5.28	.05	.1	.0096	At 20 cyc/chamber x 2 Sol/Chamber, $e^{-20(7.6)(2)10^{-6}}$ = .9996/Chamber				
1.3	.2	.1	1.04	.05	.1	.00186	10	.9	468.		
5.16	.15	.1	5.16	.05	.1	.03	10	.5	1720.		
.18	.15	.1	.18	.03	.1	.0006	12	.7	100.8		
30.25	Total F.R.276.32 during t_3			Total F.R.1.3954 during t_4			Total F.R. during t_5		51966.		

B

1	2	3	4	5	6	7	8	9	10	1
.C System .mponent										
ranslating ozzle Sliding eal	2	2/ Lab .92	55.2	7 t_{1-1} .5 t_1	.2	154.6 t_{1-1} 11.04 t_1	.15	.1	1.656	.1
-Ring Seal	1	.6 (Lab)	2/ 35	5 t_{1-1} .3 t_1	.15	26.3 t_{1-1} 1.58 t_1	.15	.1	.53	.
abyrinth Seal	1	.4 (Lab)	2/ 20	4 t_{1-1} .2 t_1	.1	8. t_{1-1} .4 t_1	.15	.1	.30	.
ozzle Flange Bearing Surface	1	8/ .42	25.2	5 t_{1-1} .2 t_1	.1	126 t_{1-1} .5 t_1	.15	.1	.38	..
		Translating Nozzle F.R. -				189. t_{1-1} 13.5 t_1			2.87	
Actuator, P & Y	4	8.8 (Lab)	3/ Aircft 531	4 t_{1-1} .2 t_1	.1	849. t_{1-1} 42.5 t_1	.15	.1	31.84	.
Actuator Support Assy.	4	8/ Lab .55	33.	4 t_{1-1} .2 t_1	.6	316.8 t_{1-1} 15.8 t_1	.2	.5	13.2	.
Actuator Conncting Rod & Yoke Assy	8	8/ Lab .35	21	3 t_{1-1} .2 t_1	.1	50.4 t_{1-1} 3.36 t_1	.1	.1	1.68	
Servo Valve	2	23.5 (Lab)	2/ Aircft 3290	4 t_{1-1} .2 t_1	.1	2632. t_{1-1} 131.6 t_1	.1	.1	65.8	
Feedback Transducer Nozzle Position	2	5 (Lab)	2/ Aircft 300	6 t_{1-1} .3 t_1	.1	360. t_{1-1} 18. t_1	.15	.1	9.0	
Hydraulic Fluid Tank	1	1.4 (Lab)	2/ Aircft 83.8	6 t_{1-1} .3 t_1	.3	150.8 t_{1-1} 7.54 t_1	.25	.3	6.28	
Hydraulic Tank Support Assy	1	8/ Lab .55	33	4 t_{1-1} .2 t_1	.6	79.2 t_{1-1} 3.96 t_1	.2	.5	3.3	

'VC - COLD GAS PRESSURIZED
SERVO-ACTUATION SYSTEM
'ATE AND RELIABILITY DATA

10	11	12	13	14	15	16	17	18	19	20	21
1.656	.15	.1	1.656	.05	.1	.0092	10	.6	662.4		
.53	.15	.1	.53	.03	.1	.0018	4	.6	84.		
.30	.15	.1	.30	.03	.1	.0012	4	.5	40.		
.38	.15	.1	.38	.05	.1	.0021	10	.6	151.2		
2.87			2.87			.0143			937.6		
31.84	.15	.1	31.84	.03	.1	.1056	6	.5	6372.		
13.2	.17	.5	11.2	.06	.15	.0198	6	.7	554.4		
1.68	.1	.1	1.68	.03	.1	.0084	4	.5	336.		
65.8	.1	.1	65.8	.03	.1	.141	4	.5	13160.		
9.0	.15	.1	9.0	.03	.1	.03	4	.5	1200.		
6.28	.25	.3	6.28	.2	.2	.056	7	.7	410.6		
3.3	.17	.5	2.8	.06	.15	.00495	6	.7	138.6	B	

1	2	3	4	5	6	7	8	9	10
Hydr Tank Suppt. Assy	1	8/ Lab .55	33	4 t_{1-1} .2 t_1	.6	79.2 t_{1-1} 3.96 t_1	.2	.5	3.3
Hydraulic Tank Positive Displ. Bladder	1	8/ Lab .09 (Leakage f.m.)	3/ Oper 200/10^6 cyc (Leakage f.m.)	5 t_{1-1} .3 t_1	.3	8.1 t_{1-1} .486 t_1	.2	.3	.324
Burst Diaphragm Hydraulic Tank Outlet	1	2/ Aircft 15 .107 Lab (Leakage f.m.)	6.42	7 t_{1-1} .4 t_1	.3	13.5 t_{1-1} .77 t_1	.2	.3	.385
N. Pressure Regulator Valve	1	3/ Flt. Test, Final Stage Boost to Orbit: 4.4 per 10^6 cycles of operation							
		2/ Aircft 100 .71 Lab	42.6	4 t_{1-1} .2 t_1	.1	17 t_{1-1} .85 t_1	.15	.1	.64
Explosive Valve, N.C.	1	7/ Oper. 8/ Lab. .224 (Leakage f.m.)	13.4	2 t_{1-1} .1 t_1	.1	2.68 t_{1-1} .134 t_1	.1	.1	.134
Nitrogen Pressure Tank	1	8/ Lab .08 (Leakage f.m.)	4.8	4 t_{1-1} .2 t_1	.5	9.6 t_{1-1} .48 t_1	.12	.3	.173
N. Tank Suppt Assy.	1	8/ Lab .55	33	4 t_{1-1} .2 t_1	.6	79.2 t_{1-1} 3.96 t_1	.15	.4	1.98
N. Lines & Fittings	6	8/ Lab .71 (.05 passive)	42.6	2 t_{1-1} .2 t_1	.1	51.1 t_{1-1} 5.11 t_1	.15	.1	3.83
				Total F.R. during t_{1-1} & t_1		4868. t_{1-1} 252.5 t_1	Total F.R. during t_2		142.3

A

ble E-9 Cont.

9	10	11	12	13	14	15	16	17	18	19	20	21
5	3.3	.17	.5	2.8	.06	.15	.00495	.6	.7	138.6		
3	..324	.15	.3	.243	.1	.2	.108	10	.95	$1900/10^6$ cyc	$R_{Bladder} = e^{-.0019} = .9981$	
3	.385	.15	.3	.289	.1	.15	.0016					$1/.99985$ (Burst f.m.)
1	.64	.15	.1	.64	.1	.1	.0071			$R_{Reg.} = e^{-(1)(4.4)10^{-6}}$ 5 $= .956$		
-	.134	.1	.1	.134	.1	.1	.0024				5 .96	
;	.173	.12	.3	.173	.12	.3	.00288	6	.7	20.1		
	1.98	.15	.4	1.98	.03	.15	.00247	5	.7	115.5		
	3.83	.15	.1	3.83	.03	.1	.0128	6	.7	1073.4		
.	142.3	Total F.R. during t_3		139.6	Total F.R. during t_4		.6688	Total F.R. during t_5		34014.		

B

Table E-10

TRANSIATING NOZZLE TVC - HOT GAS GENER

HYDRAULIC SERVO-ACTUATION SY

COMPONENT FAILURE RATE AND RELIA

1	2	3	4	5	6	7	8	9	10
TVC System Component									
Gas Generator Igniter (incl. squibs)	1	1/Test Fire							
Gas Generator	1	1/Test Fire							
Hot Gas Manifold Assembly	1	1/							
Gas Generator Manifold Joint Seals	7	8/Lab .02	1.2	5 t_{1-1} .2 t_1	.1	4.2 t_{1-1} .168 t_1	.2	.1	.168
Relief Valve	1	6.3 (Lab)	2/Aircft 377	4 t_{1-1} .2 t_1	.1	151 t_{1-1} 7.54 t_1	.15	.1	5.655
Burst Diaphragm Hydraulic Tank Inlet	1	1/							
Gas Generator Suppt. Assy.	1	8/Lab .55	33	4 t_{1-1} .2 t_1	.6	79.2 t_{1-1} 3.96 t_1	.2	.5	3.3
Hydraulic Fluid Tank	1	(Table 9) →				150.8 t_{1-1} 7.54 t_1			6.28
Hydraulic Tank Suppt. Assy.	1	(Table 9) →				79.2 t_{1-1} 3.96 t_1			3.3
Hydraulic Lines & Fittings	25	(Table 9) →				60.6 t_{1-1} 4.5 t_1			.86
Servo Valve	2	(Table 9) →				2632. t_{1-1} 131.6 t_1			65.8
Feedback Transducer-Nozzle Pos.	2	(Table 9) →				360 t_{1-1} 18. t_1			9.

E-10

GAS GENERATOR PRESSURIZED

TUATION SYSTEM

, AND RELIABILITY DATA

10	11	12	13	14	15	16	17	18	19	20	21
										.99971	
										.99895	
											.999952
.168	.15	.1	.126	.03	.1	.00042	12	.9	90.72		
5.655	.15	.1	5.655	.05	.1	.0315	7	.6	1584.		
											[8].968 (Burst f.m.)
3.3	.17	.5	2.8	.06	.15	.00495	5	.7	115.5		
.28			6.28			.056			410.6	——	
3.3			2.8			.00495			138.6		
.86			.86			.1515			9696.		
5.8			65.8			.141			13160.		
9.			9.			.03			1200.		

B

1	2	3	4	5	6	7	8	9	10
Hydraulic Tank Posit. Displ. Bladder	1		(Table 9) →			8.1 t_{1-1} .486 t_1			.324
Burst Diaphragm Hydr. Tank Outlet	1		(Table 9) →			13.5 t_{1-1} .77 t_1			.385
Actuator P&Y	4		(Table 9) →			849. t_{1-1} 42.5 t_1			31.84
Actuator Suppt. Assy.	4		(Table 9) →			316.8 t_{1-1} 15.8 t_1			13.2
Actuator Cnnt. Rod-Yoke Assy.	8		(Table 9) →			50.4 t_{1-1} 3.36 t_1 $\Sigma \rightarrow$	4835. t_{1-1} 244. t_1		1.68 Σ —
Translating Nozz. Assy.	1		(Table 9) →			189. t_{1-1} 13.5 t_1			2.87
				Total F.R. during t_{1-1} and t_1		4963. t_{1-1} 254. t_1	Total F.R. during t_2		144.65

A

-10 Cont.

10	11	12	13	14	15	16	17	18	19	20	21
.324			.243			.108			$1900/10^6$ cyc	$e^{-.0019}$ =.9981	
.385			.289			.0016					1/.99985 (Burst f.m.)
1.84			31.84			.1056			6372.		
3.2			11.2			.0198			554.4		
1.68 $\Sigma \rightarrow$	143.16		1.68 $\Sigma \rightarrow$	139.85		.0084 $\Sigma \rightarrow$	.668		336. $\Sigma \rightarrow$	34043.	
2.87			2.87			.0143			937.6		
4.65	Total F.R. during t_3		141.44	Total F.R. during t_4		.678	Total F.R. during t_5		34595.		

B

TRANSLATING NOZZLE TVC - HYDRAULI

RECIRCULATING SYSTEM - ELECTRIC :

COMPONENT FAILURE RATE AND R

1	2	3	4	5	6	7	8	9	10
TVC System Component									
Hydraulic Fluid Tank	1	(Table 9) →				150.8 t_{1-1} 7.54 t_1			6.28
Hydr. Tank Posit. Displ. Bladder	1	(Table 9) →				8.1 t_{1-1} .486 t_1			.324
Hydr. Tank Suppt. Assy.	1	(Table 9) →				79.2 t_{1-1} 3.96 t_1			3.3
Hydraulic Lines & Fittings	36	8/ Lab 2.02	121.2	4 t_{1-1} .3 t_1	.3	87.2 t_{1-1} 6.54 t_1	.17	.1	1.236
Electric Motor-Pump	1	28. (Lab)	3/ ICBM 3929	3 t_{1-1} .2 t_1	.1	1178. t_{1-1} 78.58 t_1	.17	.1	66.79
Hydr. Accumulator	1	12 (Lab)	3/ ICBM 1655	3 t_{1-1} .2 t_1	.1	496.5 t_{1-1} 33.1 t_1	.15	.1	24.82
Relief Valve Hydr.	1	16. (Lab)	2/ Aircft 96.4	4 t_{1-1} .2 t_1	.1	38.56 t_{1-1} 1.93 t_1	.15	.1	1.446
Check Valve	1	2/ Aircft 230	98	7 t_{1-1} .4 t_1	.2	137. t_{1-1} 7.84 t_1	.15	.2	2.94
Servo Valve	2	(Table 9) →				2632 t_{1-1} 131.6 t_1			65.8
Feedback X-ducer Nozz. Pos.	2	(Table 9) →				360 t_{1-1} 18. t_1			9.
Actuator, P & Y	4	(Table 9) →				849. t_{1-1} 42.5 t_1			31.84

A.

able E-11

- HYDRAULIC SERVO-ACTUATION

- ELECTRIC MOTOR DRIVEN PUMP

RATE AND RELIABILITY DATA

10	11	12	13	14	15	16	17	18	19	20	21
6.28			6.28			.056			410.6		
.324			.243			.108			$1900/10^6$ cyc = -.0019 = e .9981		
3.3			2.8			.00495			138.6		
1.236	.17	.1	1.236	.03	.1	.2181	4	.8	13962.		
66.79	.17	.1	66.79	.05	.1	.140	4	.5	7858		
24.82	.15	.1	24.82	.05	.1	.06	4	.5	3310		
1.446	.15	.1	1.446	.05	.1	.08	7	.6	404.9		
2.94	.15	.2	2.94	.02	.1	.196	7	.6	411.6		
65.8			65.8			.141			13160.		
9.			9.			.03			1200		
31.84			31.84			.1056			6372.		

B

Table E-11 Cont.

1	2	3	4	5	6	7	8	9	10
Actuator Suppt. Assy.	4	(Table 9)				316.8 t_{1-1} 15.8 t_1			13.2
Act. Cnnt. Rod Yoke Assy.	8	(Table 9)				50.4 t_{1-1} 3.36 t_1			1.68
Translating Nozzle Assy.	1	(Table 9)				189. t_{1-1} 13.5 t_1			2.87
				Total F.R. during t_{1-1} & t_1		6572. t_{1-1} 364.7 t_1	Total F.R. during t_2		231.5

A

E-11 Cont.

	10	11	12	13	14	15	16	17	18	19	20	21
	13.2			11.2			.0198		·	554.4		
	1.68			1.68			.0084			336.		
	2.87			2.87			.0143			937.6		
R. 2	231.5	Total F.R. during t_3		228.9	Total F.R. during t_4		1.182	Total F.R. during t_5		49055.		

Reproduced from best available copy.

B

Table E-12

TRANSLATING NOZZLE TVC - HYDRAULIC S

RECIRCULATING SYSTEM - GAS GEN. TURB

COMPONENT FAILURE RATE AND RELI

1	2	3	4	5	6	7	8	9	10
TVC System Component									
Gas Generator Igniter (Incl. squibs)	1	1/ Test Fire							
Gas Generator	1	1/ Test Fire							
Gas Generator to Turbine Manif. Assy.	1	1/							
Gas Gen Manif. Joint Seals	7	(Table 2) →				$4.2\ t_{1-1}$ $.168\ t_1$			.168
Relief Valve, Hot Gas	1	(Table 10) →				$151.\ t_{1-1}$ $7.54\ t_1$			5.655
Gas Gen. Suppt. Assy	1	(Table 2) →				$79.2\ t_{1-1}$ $3.96\ t_1$			3.3
Turbine & Pump		17 (Lab)	3/ ICBM 2386	$3\ t_{1-1}$ $.2\ t_1$	.1	$715.\ t_{1-1}$ $47.7\ t_1$	.15	.1	35.8
Hydraulic Fluid Tank	1	(Table 11) →				$150.8\ t_{1-1}$ $7.54\ t_1$			6.28
Hydr. Tank Posit. Displ. Bladder	1	(Table 11) →				$8.1\ t_{1-1}$ $.486\ t_1$			.324
Hydr. Tank Suppt Assy.	1	(Table 11) →				$79.2\ t_{1-1}$ $3.96\ t_1$			3.3
Hydr. Lines Fittings	36	(Table 11) →				$87.2\ t_{1-1}$ $6.54\ t_1$			1.230

-12

RAULIC SERVO-ACTUATION

EN. TURBINE DRIVEN PUMP

.D RELIABILITY DATA

10	11	12	13	14	15	16	17	18	19	20	
										.99971	
										.99895	
											.999952
168			.126			.00042			90.72		
555			5.655			.0315			1584.		
3			2.8			.00495			115.5		
.8	.15	.1	35.8	.05	.1	.085	4	.7	6680.		
28			6.28			.056			410.6		
324			.243			.108			$1900/10^6$ cyc $= e^{-.0019} = .9981$		
3			2.8			.00495			138.6		
236			1.236			.2181			13962.		

B

1	2	3	4	5	6	7	8	9	10
Hydraulic Accumulator	1	(Table 11) →				$496.5\ t_{1-1}$ $33.1\ t_1$			24.82
Relief Valve Hydr.	1	(Table 11) →				$38.56\ t_{1-1}$ $1.93\ t_1$			1.446
Check Valve	1	(Table 11) →				$137.\ t_{1-1}$ $7.84\ t_1$			2.94
Servo Valve	2	(Table 11) →				$2632\ t_{1-1}$ $131.6\ t_1$			65.8
Feedback X-ducer Nozz. Pos.	2	(Table 11) →				$360\ t_{1-1}$ $18.\ t_1$			9.
Actuator P & Y	4	(Table 11) →				$849\ t_{1-1}$ $42.5\ t_1$			31.84
Actuator Suppt. Assy.	4	(Table 11) →				$316.8\ t_{1-1}$ $15.8\ t_1$			13.2
Act. Cnnt. Rod-Yoke Assy.	8	(Table 11) →				$50.4\ t_{1-1}$ $3.36\ t_1$			1.68
Translating Nozzle Assy.	1	(Table 11) →				$189.\ t_{1-1}$ $13.5\ t_1$			2.87
			Total F.R. during t_{1-1} & t_1			$6343.\ t_{1-1}$ $345.5\ t_1$	Total F.R. during t_2		235.48

A

2 Cont.

10	11	12	13	14	15	16	17	18	19	20	21
4.82			24.82			.06			3310		
1.446			1.446			.08			404.9		
2.94			2.94			.196			411.6		
5.8			65.8			.141			13160.		
9.			9.			.03			1200		
.84			31.84			.1056			6372		
.2			11.2			.0198			554.4		
.68			1.68			.0084			336.		
.87			2.87			.0143			937.6		
..	Total F.R. during t_3		206.53	Total F.R. during t_4		1.164	Total F.R. during t_5		49668.		

B

TRANSLATING NOZZLE TVC - ELECTRO-

COMPONENT FAILURE RATE AND :

1	2	3	4	5	6	7	8	9	1
TVC System Component									
Electro-mechanical Servo-Actuator Assy.	4	81.68	5059.	4 t_{1-1} .2 t_1	.15	12140. t_{1-1} 607. t_1	.17	.1	344
Gear Train(3 gears to CW Clutch	3	(Lab) 8/ .98	F 58.8	Q X F 176.4					
Gear Train(4 gears to CCW Clutch	4	8/ 1.8	108.	432					
Gear Train(2 gears to each end of worm gear shaft)	4	8/ 1.8	108.	432					
Worm Drive Gear & Sector	1	2.8	2/Aircft 167.5 5/AC	(AC) 167.5		(302.4)t_{1-1}			
Screwjack	1	2.1	126	126.		(15.1) t_1			(8.
Feedback Transducer, nozzle pos. (screwjack)	1	5.	2/ AC 300 5/ AC	300					
Rotary Solenoid	2	4.05	243	486					
Mechanical Clutch; (Tapered Coil spring end to conical cluth face & mandrel-CW,CCW)	2	2.5	2/ 150	300					
Clutch Interlock Bearing, & Solenoid Adjs't.	1	8/ 1.8	108.	108.					
Clutch Shaft	1	8/ .62	37.	37.					
Worm Drive Shaft	1	8/ .62	37.	37.					
Bearings, Ball	10	8/ 3.53	212. 3/Space	2120. Envir.					
Synchronous Motor	1	3.	337	337					
		81.68		5059					
Translating Nozzle Assy.	1	(Table 9)				189. t_{1-1} 13.5 t_1			2.37
						12329. t_{1-1} 620.5 t_1			346.87

ELECTRO-MECHANICAL SERVO-ACTUATION

TE AND RELIABILITY DATA

10	11	12	13	14	15	16	17	18	19	20	21
344.	.17	.1	344	.03	.1	.9801	3	.7	42495		
(8.57)			(8.57)			(.025)			(1058)		
2.87			2.87			.0143			937.		
346.87			346.87			.9944			43432		

B

Table [illegible]

GIMBALLED NOZZLE [illegible] COLD GAS

HYDRAULIC SE[illegible]CTUATION

COMPONENT FAILURE [illegible] AND REL

1	2	3	4	5	6	7	8	[illegible]	10
TVC System Component									
Nozzle Sliding Seal	1	2/ Lab .92	55.2	$7\ t_{1-1}$ $.5\ t_1$ (Redundant)	.2	$77.2\ t_{1-1}$ $5.5\ t_1$	.15	[illegible]	.828
Bellows	1	8/ 2.237	134.22	$6\ t_{1-1}$ $.3\ t_1$	.2	$161.\ t_{1-1}$ $8.\ t_1$	.15	[illegible]	2.013
Flexure Pivot Bearing	4	8/ Lab .21	12.6	$7\ t_{1-1}$ $.4\ t_1$	.1	$35.2\ t_{1-1}$ $2.01\ t_1$	.17	[illegible]	.857
O-Ring Seal	1	.6 (Lab)	2/ 35	(Table 9) →		$26.3\ t_{1-1}$ $1.58\ t_1$			.53
			Gimballed Nozzle F.R.			$61.5\ t_{1-1}$ $3.59\ t_1$			1.387
Rotary Hydr. Actuator P&Y	4	2.9	5/ Aircft 143	$4\ t_{1-1}$ $.2\ t_1$	.1	$228.8\ t_{1-1}$ $11.44\ t_1$	.15	[illegible]	8.58
Actuator Suppt. Assy.	4	(Table 9) →				$316.8\ t_{1-1}$ $15.8\ t_1$			[illegible]3.2
Servo Valve	2	(Table 9) →				$2632.\ t_{1-1}$ $131.6\ t_1$			65.8
Feedback Transducer (rotary)	2	(Table 9) →				$360.\ t_{1-1}$ $18\ t_1$			9.0
Hydraulic Lines & Fittings	25	(Table 9) →				$60.6\ t_{1-1}$ $4.5\ t_1$			.86
Hydraulic Fluid Tank	1	(Table 9) →				$150.8\ t_{1-1}$ $7.54\ t_1$			6.28
Hydr. Tank Suppt. Assy.	1	(Table 9) →				$79.2\ t_{1-1}$ $3.96\ t_1$			3.3

	11	12	13	14	15	16	17	18	19	20	21
-	.15	.1	.828	.05	.1	.0046	10	.6	331.2	4 .951	
[illegible]	.15	.1	2.013	.05	.1	.01118	7	.6	563.7	3 .9888	
57	.15	.1	.756	.03	.1	.0025	10	.6	302.4		
[illegible]			.53			.0018			84.		
..57			1.286			.0043			386.4		
[illegible]	.15	.1	8.58	.03	.1	.0348	6	.5	1716.		
[illegible]			11.2			.0198			554.4		
[illegible]			65.8			.141			13160.		
[illegible]			9.0			.03			1200.		
.86			.86			.1515			9696.		
..23			6.28			.056			410.6		
[illegible]			2.8			.00495			138.6		

B

Table E-14 Cont.

1	2	3	4	5	6	7	8	9	10	
Hydr. Tank Pos. Displ. Bladder	1	(Table 9) →				$8.1\ t_{1-1}$ $.486\ t_1$			.324	
Burst Diaphragm Hydr. Tank Outlet	1	(Table 9) →				$13.5\ t_{1-1}$ $.77\ t_1$			.385	
N. Pressure Regulator Valve	1	(Table 9) →				$17.\ t_{1-1}$ $.85\ t_1$			.64	
Explosive Valve N.C.	1					$2.68\ t_{1-1}$ $.134\ t_1$			.134	
Nitrogen Press Tank	1	(Table 9) →				$9.6\ t_{1-1}$ $.48\ t_1$			.173	
N. Tank Suppt. Assy.	1	(Table 9) →				$79.2\ t_{1-1}$ $3.96\ t_1$			1.98	
N. Lines & Fittings	6	(Table 9) →				$51.1\ t_{1-1}$ $5.11\ t_1$			3.83	
				Total F.R. during t_{1-1} & t_1		$4071.\ t_{1-1}$ $208.2\ t_1$	Total F.R. during t_2		115.87	To du

E-30-A

C 884 FR-1

A

14 Cont.

10	11	12	13	14	15	16	17	18	19	20	21
324			.243			.108	(Table 9) →			.9981	
385			.289			.0016					1/.99985 (Burst f.m)
.64			.64			(Table 9) → .0071			^{5}.956		
.134			.134			.0024	(Table 9) →			^{5}.96	
.173			.173			.00288			20.1		
.98			1.98			.00247			115.5		
.83			3.83			.0128			1073.4		
.67	Total F.R. during t_3		113.09	Total F.R.		.5796	Total F.R. during t_5		28471.		

B

APPENDIX F

NOMENCLATURE

ALPHABETIC SYMBOLS

a		acceleration, ft/sec^2
A		area, in^2
C_F		thrust coefficient
D		diameter, in.
F		thrust, force, lb
FR		failure rate
g		gravitational constant, 32.2 ft/sec^2
I		inertia, ft-lb-sec^2
I_{sp}		specific impulse, lbf-sec/lbm
I_{Tot}		total impulse, lbf-sec
L		length, in.
m		mass, slugs
M		mass, slugs
P	-	pressure, lb/in^2
	-	power, hp
r	-	uncertainty in c.g. location, in.
	-	radius, in.
R	-	gas constant, ft lb/lb ^oR
	-	reliability
S	-	stress, lb/in^2
	-	stroke, in.
	-	deflection, in.
t	-	time, sec
	-	thickness, in.
T	-	temperature, ^oR
	-	torque, in-lb
V		volume
$\dot{w}$		weight flow, lb/sec
W		weight, lb
W_n		natural frequency, rad/sec
X		distance parallel to motor centerline, in.
Y		distance normal to motor centerline, in.
Z		compressibility factor

GREEK SYMBOLS

α	-	th
	-	an
β		no
γ		sp
ϵ		no
ζ		da
η		li
ρ		de

SUBSCRIPTS

$\cdot$		pe
o	-	in
	-	no
1		no
2		no
a		ax
act		ac
b		pr
c	-	c
	-	c
f		f
g		g
i		i
ℓ		l
N		n
P	-	p
	-	p
PT		p
PS		p
r		r
req		r
res		r
s		
t		-
		-
T		

E-3/-A

P

APPENDIX F

NOMENCLATURE

t, 32.2 ft/sec^2

-sec/lbm

:

ocation, in.

, °R

/sec

otor centerline, in.

or centerline, in.

GREEK SYMBOLS

α	- thrust vector angular misalignment, degrees
	- angular acceleration, rad/sec^2
β	nozzle rotation, degrees
γ	specific heat ratio
ϵ	nozzle expansion ratio
ζ	damping ratio
η_ℓ	line efficiency
ρ	density, lb/in^3

SUBSCRIPTS

.	peak amplitude
o	- initial
	- nozzle bellows flange
1	nozzle inlet station
2	nozzle exit station
a	axial
act	actuation
b	pressurization tank
c	- component
	- chamber
f	final
g	gas
i	initial
ℓ	line
N	normal to roll axis
P	- parallel to roll axis
	- propellant
PT	propellant tank
PS	pressurization system
r	response
req	required, pressurization gas
res	residual, pressurization gas
s	side (injectant)
t	-throat
	-tank material
T	tank

7

E-31-B