CR 114490

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FLUIDIC EMERGENCY THRUSTER FOR AIRCRAFT

Contract NAS 2-5467, Task III

(NASA-CR-114490) FLUIDIC EMERGENCY THRUSTER FOR AIRCRAFT T.S. Honda (General Electric Co.) Nov. 1972 44 p CSCL 01B

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Prepared for

National Aeronautics and Space Administration
Ames Research Center
Moffett Field, California

Prepared by

T. S. Honda
Specialty Fluidics Operation
Schenectady, New York

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FOREWORD

This final report was prepared by the General Electric Company for the System Engineering Facility of the Ames Research Center, National Aeronautics and Space Administration, Moffett Field, California, under Task III Contract NAS 2-5467. The Ames Project Engineer was Mr. D. M. Chisel.

The authors wish to acknowledge the contribution of Messrs. D. M. Chisel and J. P. Murphy of NASA/ARC for their assistance in providing high pressure and hot gas test facilities and in the conduct of analog simulations during the design and evaluation phases of the program.

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INTRODUCTION

This report summarizes the work performed under Task III of Contract NAS 2-5467. The program included the design, development, fabrication and test evaluation of two prototype fluidic emergency thrusters (FET) for aircraft stabilization. The fluidic control units were designed to provide, between two diametrically opposed nozzles, a thrust differential proportional to an input voltage signal. The emergency roll control requirements of the X-14 VTOL research aircraft were defined as typical design goals. Two control units, one on each wing tip, are intended to provide a maximum thrust of 224 pounds per unit. The units are designed to operate with 2500 psig, 2000°F gas from a solid propellent gas generator. The emergency system including the gas generator was designed to add less than 11 pounds per wing tip. The operating time under emergency conditions was specified as five seconds. The fluidic emergency thruster is similar in concept to a JATO system but has the added feature of controllable thrust.

The fluidic emergency thruster system developed in the program is shown in a typical conceptual package installation in Figure 1. The control package consists of a solid propellant gas generator, two diametrically opposed vortex valve modulated thrust nozzles, and an electro-magnetic torque motor. The gas generator is ignited on an emergency command signal from the flight control logic and the control modulates differential thrust output proportionately to the electrical signal to the torque motor from the flight control computer.

The specific program objective was to design, fabricate and deliver two FET units which were designed for hot gas evaluation in a thrust stand. Orderly accomplishment of the program goals was achieved by pursuing the following program plan.

- Fluidic emergency thruster design analysis and system study including the specification of performance requirements for the thruster and the gas generator.
- Design, fabrication and test evaluation of breadboard components to obtain design data and to demonstrate compliance with the design requirements.
- Fabrication of two prototype control units for hot gas evaluation by NASA/ARC.
- Hot gas test evaluation at NASA/ARC.

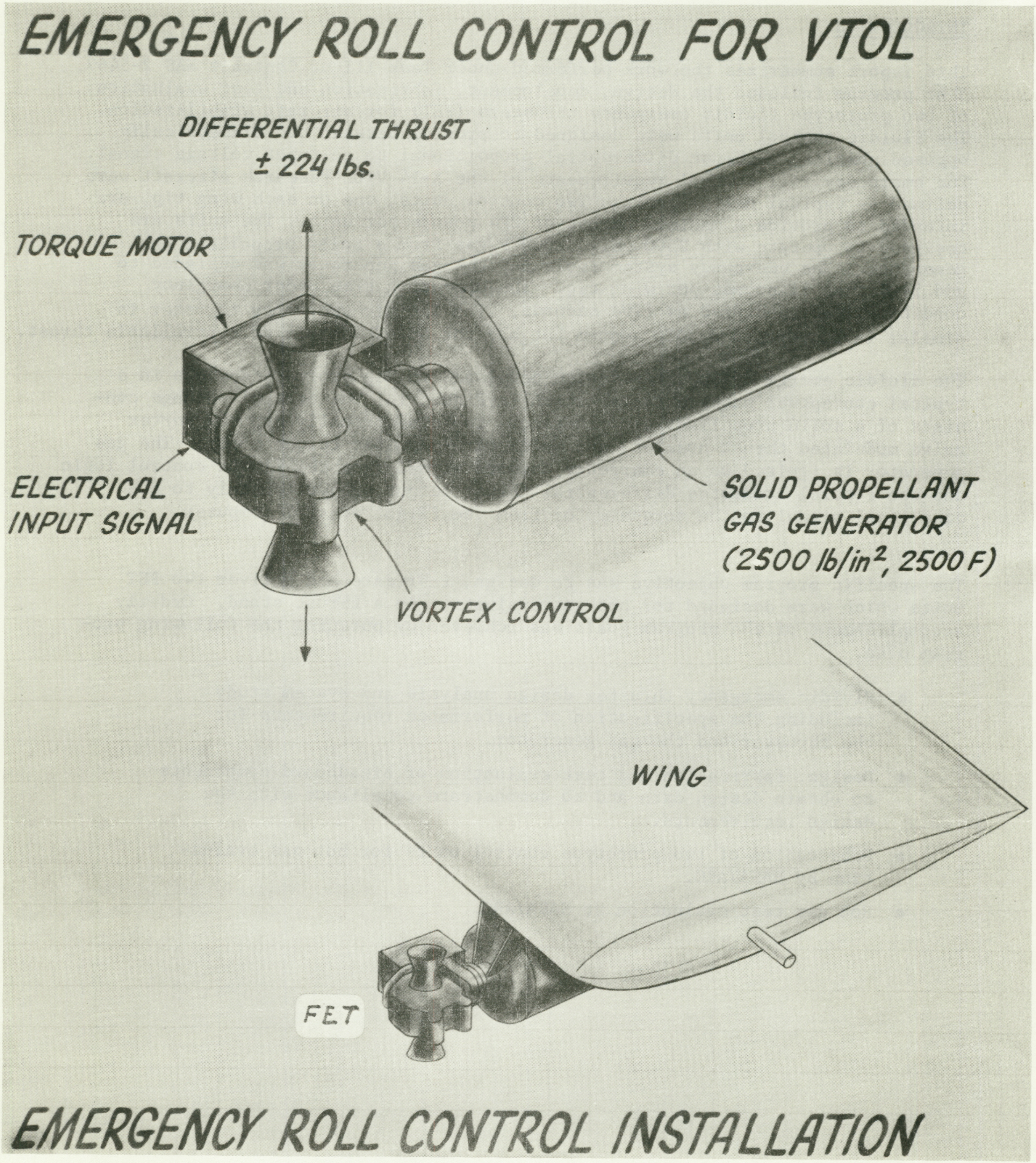


Figure 1
Fluidic Emergency Thruster System Typical Installation

SYNOPSIS

Control System Concept

The requirements of a specific VTOL aircraft were selected by NASA/Ames as typical design goals in this development program. The pertinent characteristics af a typical vehicle (based on the X-14 research aircraft) are:

Roll inertia - 2340 ft-lb sec^2

Roll radius - 16.7 ft.

The functional requirements of the emergency roll control system are based on a probable worst case roll control maneuver for a VTOL. The emergency roll control is activated by the flight control computer when the sum of the roll angle and angular rate exceed a predetermined value. The regime in which the emergency condition is assumed to exist is denoted by "fire" in Figure 2. The control "activate" signal is given based on a simple combination of rate and attitude, which if allowed to persist would permit the aircraft to fall into an unsafe flight regime.

The control maneuver is assumed to be comprised of theee phases as shown in Figure 3. During Phase I a hardover thrust command reduces the aircraft roll rate to zero at a wing attitude angle, 0, no greater than 30 degrees. During the second control phase the aircraft is torqued back to an approximate wings level, zero rate condition. Phases I and II are assumed to be preprogrammed into the flight control computer such that no action is required by the pilot. During Phase III the pilot controls the aircraft and trims the wings to the desired level attitude. The emergency roll control is assumed to be active for five seconds after initiation.

Gas Generator Design Study

The maximum available thrust vs time schedule delineated in Figure 3 is to be preprogrammed into the hot gas generator design. The gas generator design was investigated by Thiokol Chemical Corporation during the course of the program. This study indicates that a gas generator to provide the three step pressure profile over a burn time of 5 seconds by proper shaping of the propellant charge is feasible. The calculated weight of the propellant is 3.6 lbs. and the inert generator weight is 3.6 lbs. The gas generator weight estimates are compatible with the overall system design goals.

Fluidic Emergency Thruster Development

The fluidic emergency thruster hardware developed on the program is shown in Figure 4. The package consists of an electro-magnetic torque motor driven flapper nozzle stage controlling two vortex valves in push-pull. The primary development effort was directed toward the achievement of a vortex valve turndown ratio of at least 5.0. This turndown ratio was detemmined by system analysis as being essential to keep the hot gas propellant weight within design goals. Compactness and light weight packaging of the control unit were also major design objectives.

The performance data obtained for the outlet, radial in-flow vortex valve

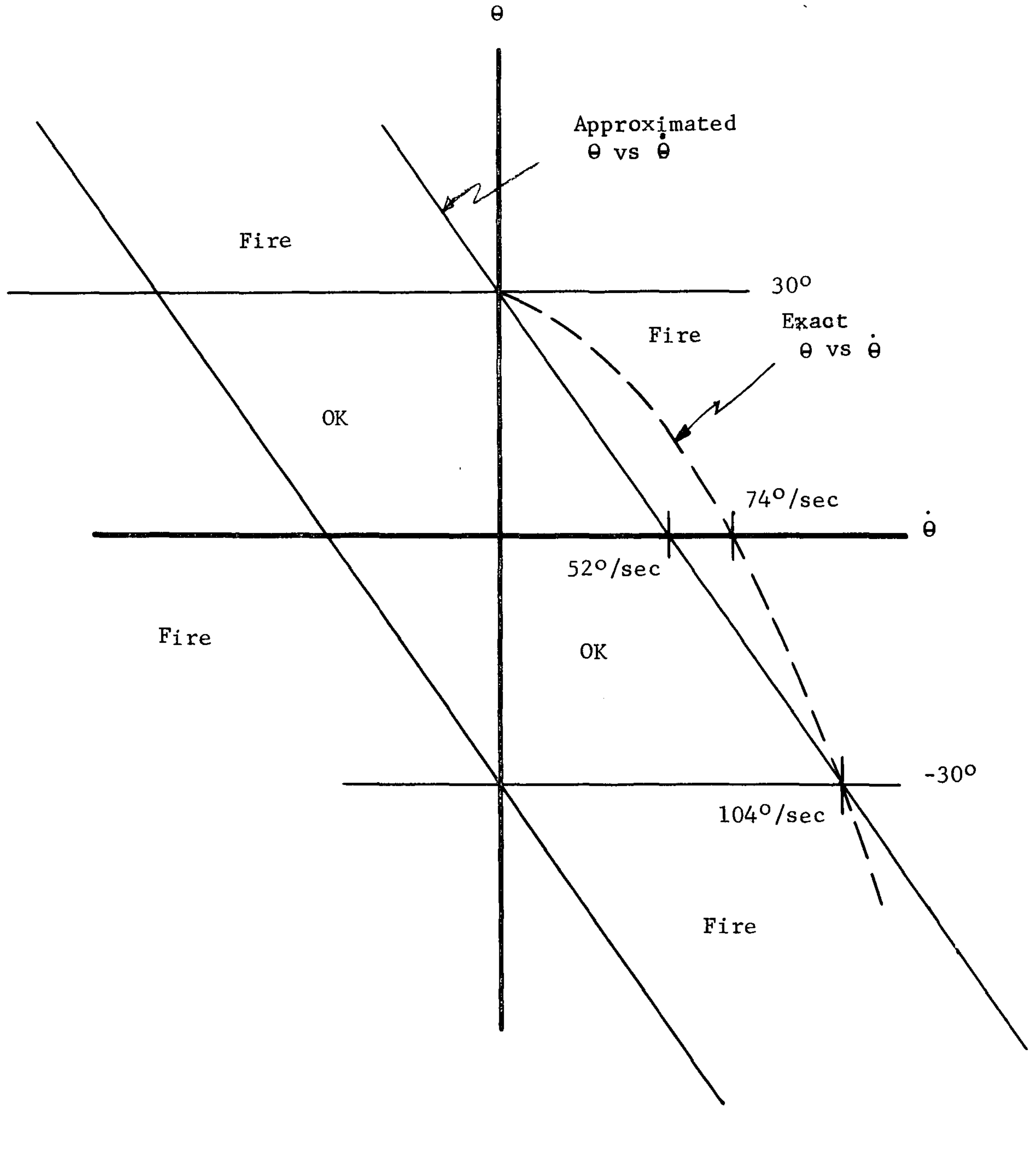


Figure 2

VTOL Emergency Flight Conditions

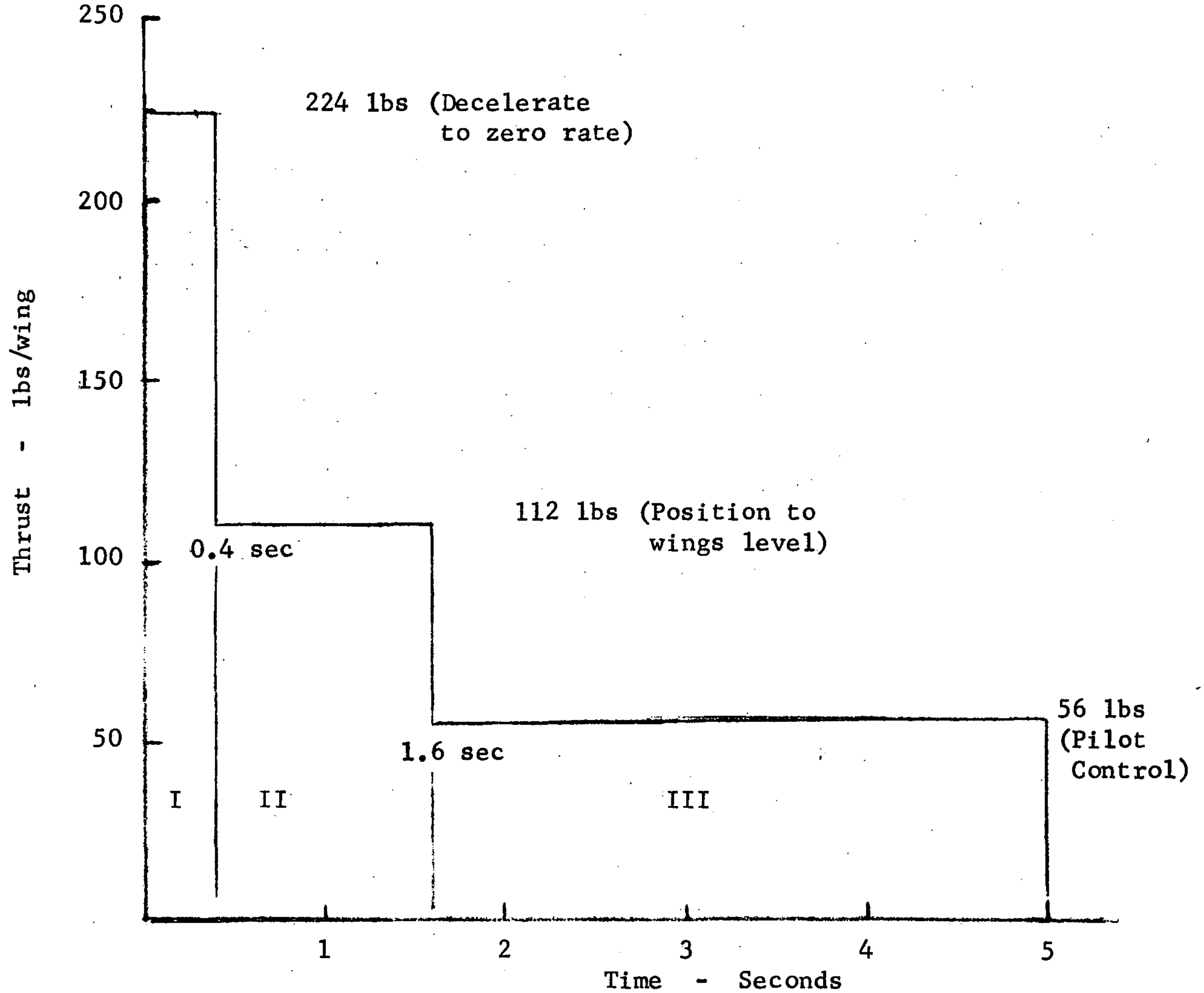


Figure 3

VTOL Emergency Thrust Schedule

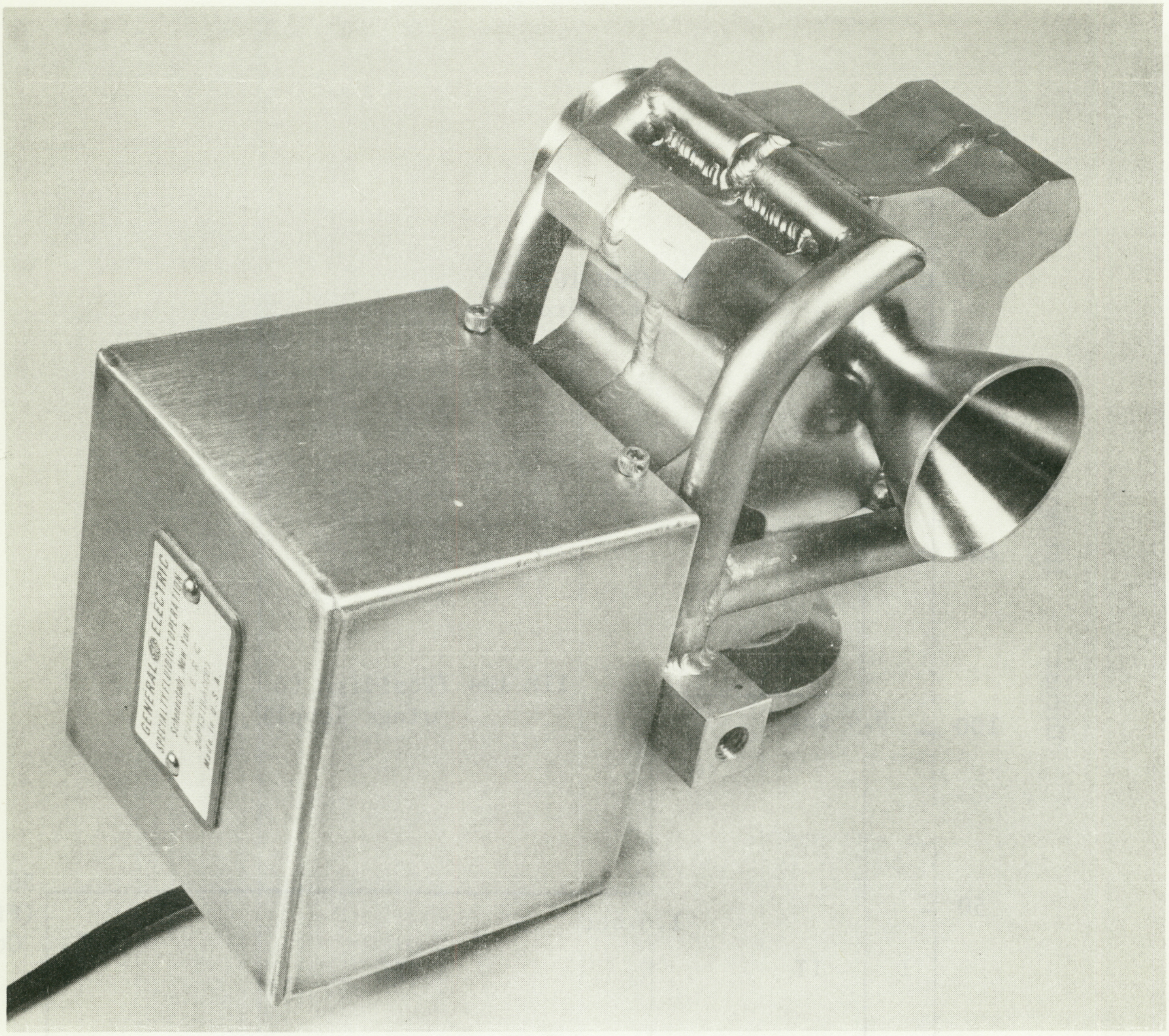


Figure 4

Fluidic Emergency Thruster

developed is shown in the non-dimensionalized characteristic turndown curve in Figure 5. It shows that the objective of obtaining a turndown ratio of 5.0 was achieved.

Two fluidic emergency thrusters, as shown in Figure 4, were fabricated and delivered to NASA/ARC for evaluation. The unit, except for the torque motor, is an all-welded assembly. The parts are machined from A.I.S.I. Type 347 stainless steel.

The FET units as fabricated weighed 4.7 pounds which met the design weight goal.

Performance Evaluation Results

Performance evaluation of the fluidic emergency thrusters consisted of the acceptance checkout procedure using shop air as delineated in specification No. ES-FERCI in Appendix A, and high pressure cold gas and hydrazine hot gas tests conducted at NASA/ARC.

The units met all of the specified requirements for static gain, saturation, hysteresis and null offset in the acceptance checkout using air at 70 psig. The high pressure tests at NASA/ARC, however, indicated the need for design refinement to correct marginal performance experienced in two specific areas. These are:

- Torque motor flapper instability at supply pressure above 500 psig.
- Thrust vs supply pressure characteristic low by approximately 30%.

Hot gas tests using a hydrazine hot gas generator were conducted. These tests were limited to 1000°F and 1300 psig by the generator design. The temperature rise data taken, nevertheless, indicates that the limitations for stainless steel are not exceeded. With gas supplied at 1000°F, the maximum unit surface temperature recorded was 630°F at the end of 5 seconds operation. Functional performance of the unit was also satisfactory during and after the hot gas tests.

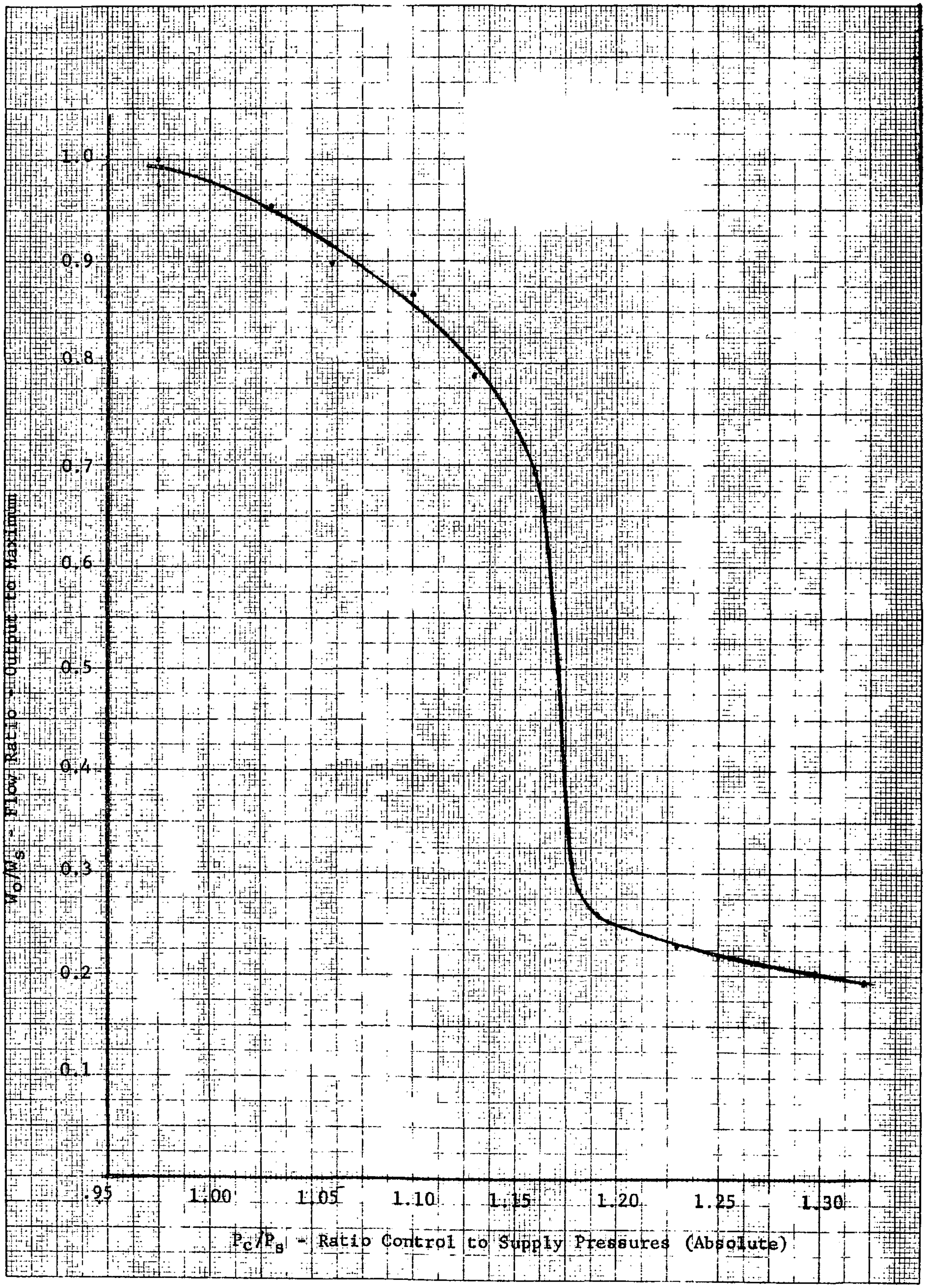


Figure 5
Vortex Valve Turndown Characteristic with Air

CONCLUSIONS

The results of Task III effort of the program described in this report demonstrate hardware feasibility of a fluidic emergency thrust control concept to provide the roll stabilization torques required in VTOL aircraft. The specific conclusions resulting from these investigations and development work are as follows.

- Vortex valves having no moving parts are ideally suited for proportional thrust control using propellant hot gases.

- A thrust to weight ratio of 20 for the fluidic emergency thruster system (including the gas generator and propellant) is achievable.

- The desired maximum available thrust schedule can be pre-programmed by shaping the propellant charge.

- Further design refinement and optimization of the FET is required to eliminate the torque motor flapper instability and to obtain full design thrust capability.

- Simple control laws can be used.

RECOMMENDATIONS

On the basis of the conclusions reached, the following recommendations are made to advance the concepts developed.

- Refine and optimize design of the FET to achieve specific performance goals not attained is the present program.
- Fabricate gas generator designed and test evaluate the complete FET system.
- Conduct vehicle analog simulation with FET hardware in the loop.
- Define hardware test program to establish pilot confidence in the system and ultimately lead to flight test evaluation.

VTOL EMERGENCY ROLL CONTROL REQUIREMENTS

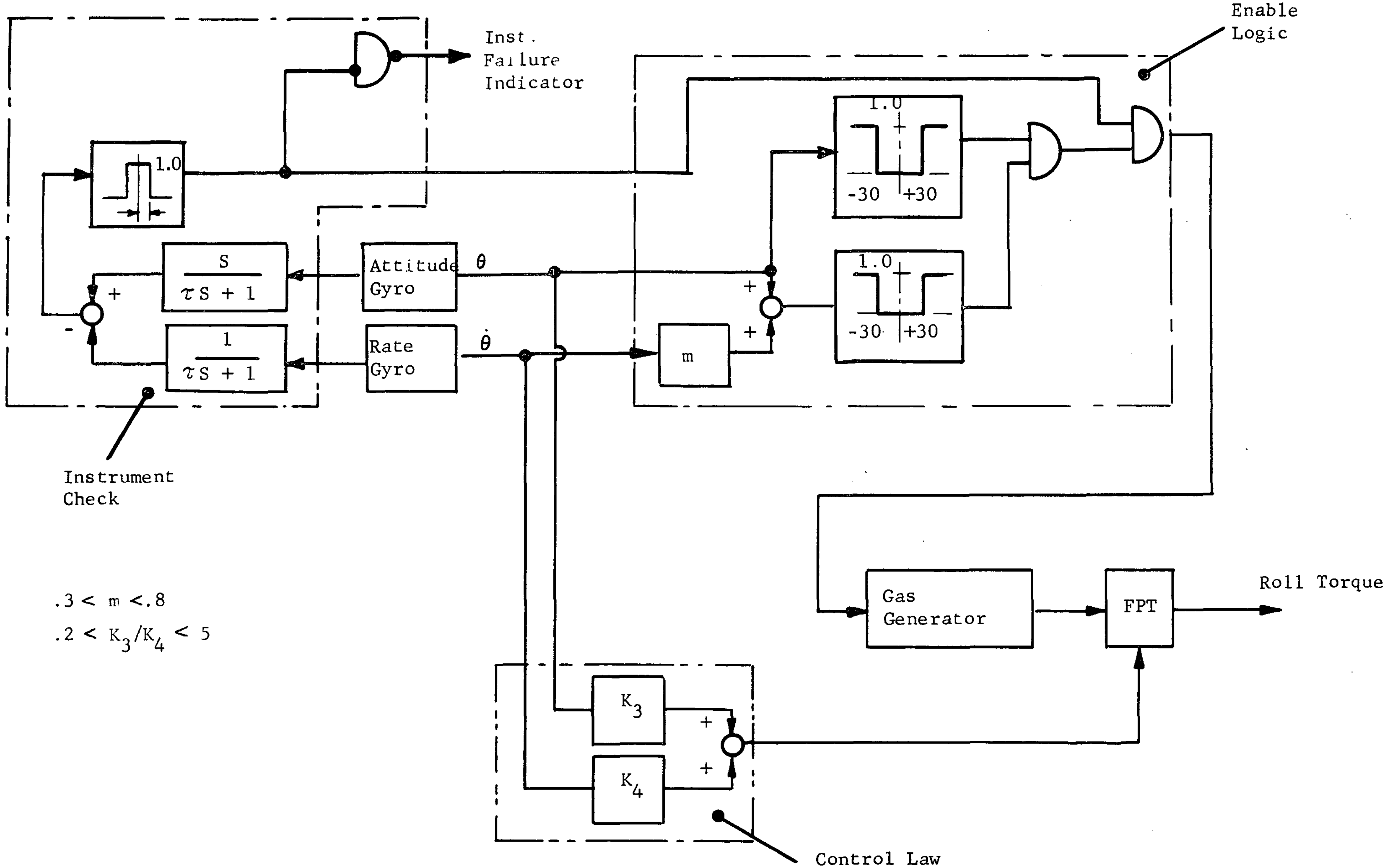
The control system in which the fluidic emergency thrusters are to operate is depicted in the block diagram representation of Figure 6. The fluidic thruster is driven by a hot gas source and electrically commanded to provide the roll torques. Cross-checked rate and attitude gyro signals are compared in an electronic logic circuit and combustion of a solid propellant in the gas generator is initiated when the rate and attitude signals exceed the limits (i.e. $\pm$ 30 degree roll attitude at zero roll rate) set in the logic. These limits correspond to the approximate θ vs $\dot{\theta}$ defined in Figure 2. The cross-checked values of rate and attitude are obtained by crudely differentiating and integrating the aircraft attitude and rate gyros. A control law is preprogrammed into the automatic control system which brings the aircraft to a wings level zero rate condition and the system operates in an automatic mode without benefit of pilot interaction in the loop. The system is to have proportional control characteristics.

Two separate gas generator thruster packages are used to provide redundancy. If one of the gas generators fails to fire, a couple is not achieved; however, control torque at one-half the normal level is still available. The use of solid propellant gas generators in conjunction with fluidic control components provide a reliability level approaching that of JATO systems.

The control maneuver is assumed to be comprised of three phases as shown in Figure 3 and previously described (in the Synopis). The total impulse required for the three control phases is shown in Figure 7. The total impulse is the value required at each wing tip and this total is plotted as a function of the acceleration level α_1. On the avárage, 21% of the total impulse is required in Phase I, 30% in Phase II, and 49% is required for Phase III maneuver. The three thrust levels are preprogrammed on an open loop basis by proper design of the burning surfaces of the gas generator grain. The capability of performing the required aircraft maneuver by a simple control and a preprogrammed thrust schedule is planned to be demonstrated later by operation of the FET in conjunction with an analog simulation of the aircraft system.

For conservatism, the emergency system is assumed to supply all of the impulse required for vehicle stabilization and that no torque is available from the normal reaction control system. Further conservatism is injected by the large amount of total impulse programmed for Phase III of the control sequence (49%). To obtain a weight estimate, it is assumed that twice the normal roll torque to inertia ratio, $\alpha_1 = 3.2$ rad/sec^2 is utilized under emergency conditions; thus, requiring a total impulse (from Figure 7) of 430 lb-sec. A thrust during control Phase I of 224 lbs (shown on Figure 3) is required at each wing tip for the typical aircraft inertia of 2340 slug-ft^2 and lever arm of 16.7 ft. For a representative gas generator propellant, an average delivered specific impulse of 139 seconds is available with the fluidic system dictating a total propellant load of 3.1 lbs at each wing tip. The case weight associated with the propellant weight is also estimated at 3.1 lbs and the fluidic thruster weight is 4.7 lbs. The total fluidic thruster system design weight goal is therefore established to be 11.9 lbs at each wing tip.

For a VTOL aircraft roll inertia of 2340 ft-lb sec^2 and torque radius of 16.7 ft, it was determined that theoretical impulse requirements from 300 to 800 seconds are required over a range of zero to 60 degrees per second. The theoretical required impulse values determined are shown in Figure 8. In generating the data of



$.3 < m < .8$

$.2 < K_3/K_4 < 5$

Figure 6
Emergency Roll Control System Block Diagram

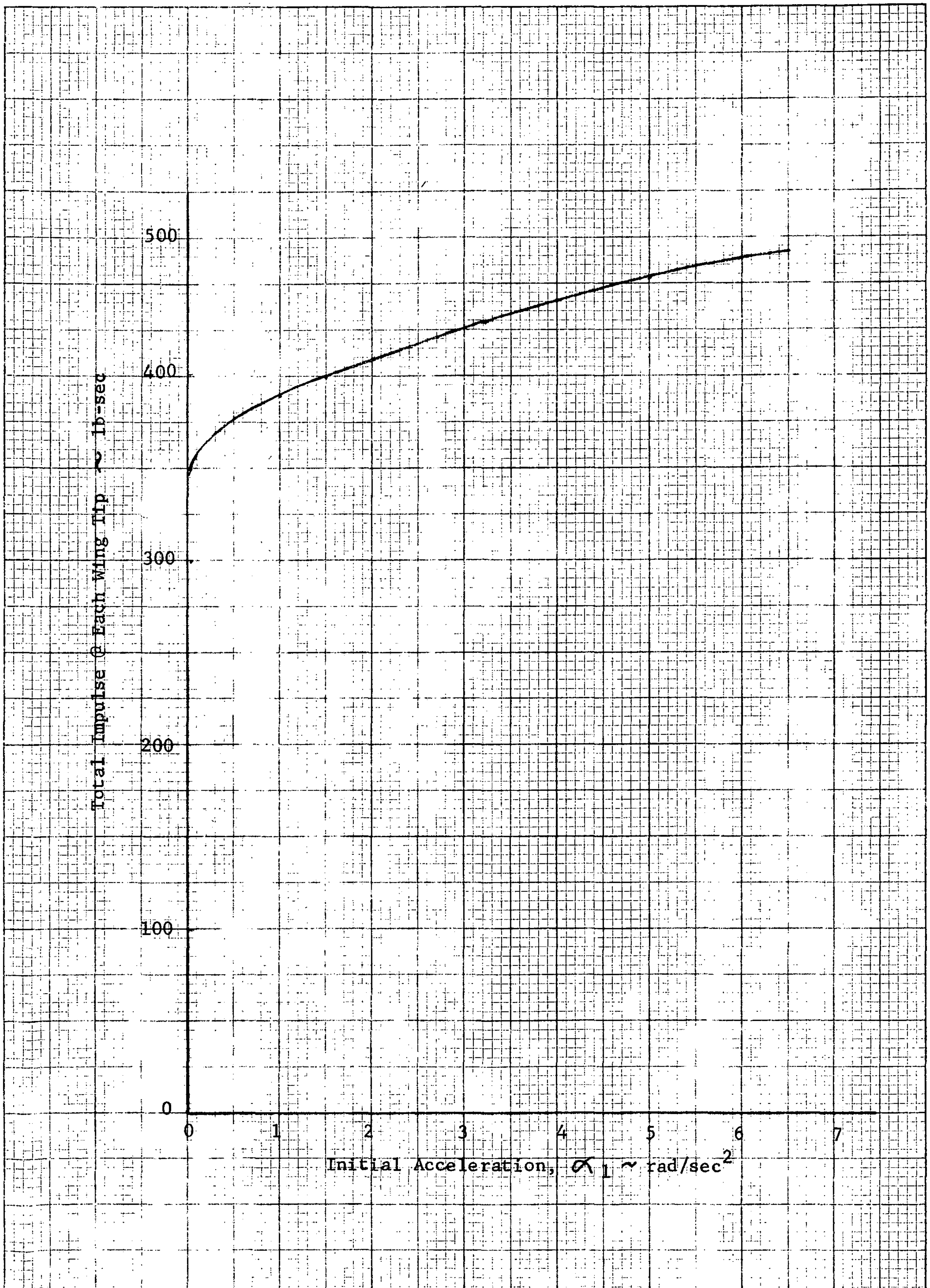


Figure 7
Total Impulse vs Acceleration

Figure 8 it was assumed that the emergency maneuver would be initiated at various roll attitude angles from zero to 20° at various roll rates ranging from zero upward. The roll rates are in a direction to increase the attitude angle. A further parameter in the analysis was the torque to inertia ratio applied by the emergency system. The emergency system could be activated either when an excess roll torque is required or on loss of control power either by malfunction or by an engine-out condition. In all of the calculations it was assumed that a roll attitude angle no greater than 45° could be tolerated.

Figure 9 shows the optimum (i.e. minimum in this case) control time to complete the emergency maneuver. The assumptions applicable to Figure 8 also apply to Figure 9. This figure shows that control time increases as available control acceleration decreases. The time also decreases as the initial roll angle is increased since it requires less time to reach the maximum roll angle of 30 degrees.

The equations which describe the curves in Figures 8 and 9 are:

$$\text{Total Impulse} = \frac{I}{R}\left[\sqrt{\frac{2\phi_m}{\phi_m - \phi_o}} + 1\right]\dot{\phi}_o$$

$$= \frac{2I}{R}\sqrt{\alpha\phi_m} + \frac{I}{R}\dot{\phi}_o$$

$$\text{Total Time} = 2(\phi_m - \phi_o)\left[\sqrt{\frac{2\phi_m}{\phi_m - \phi_o}} + 1\right]\frac{1}{\dot{\phi}_o}$$

$$= 2\sqrt{\frac{\phi_m}{\alpha}} + \frac{1}{\alpha}\dot{\phi}_o$$

where: I = roll moment of inertia = 2340 ftlbsec^2

R = roll radius = 16.7 ft

α = torque to inertia ratio

ϕ_m = maximum roll angle = 30 deg

ϕ_o = initial roll angle

$\dot{\phi}_o$ = initial roll rate

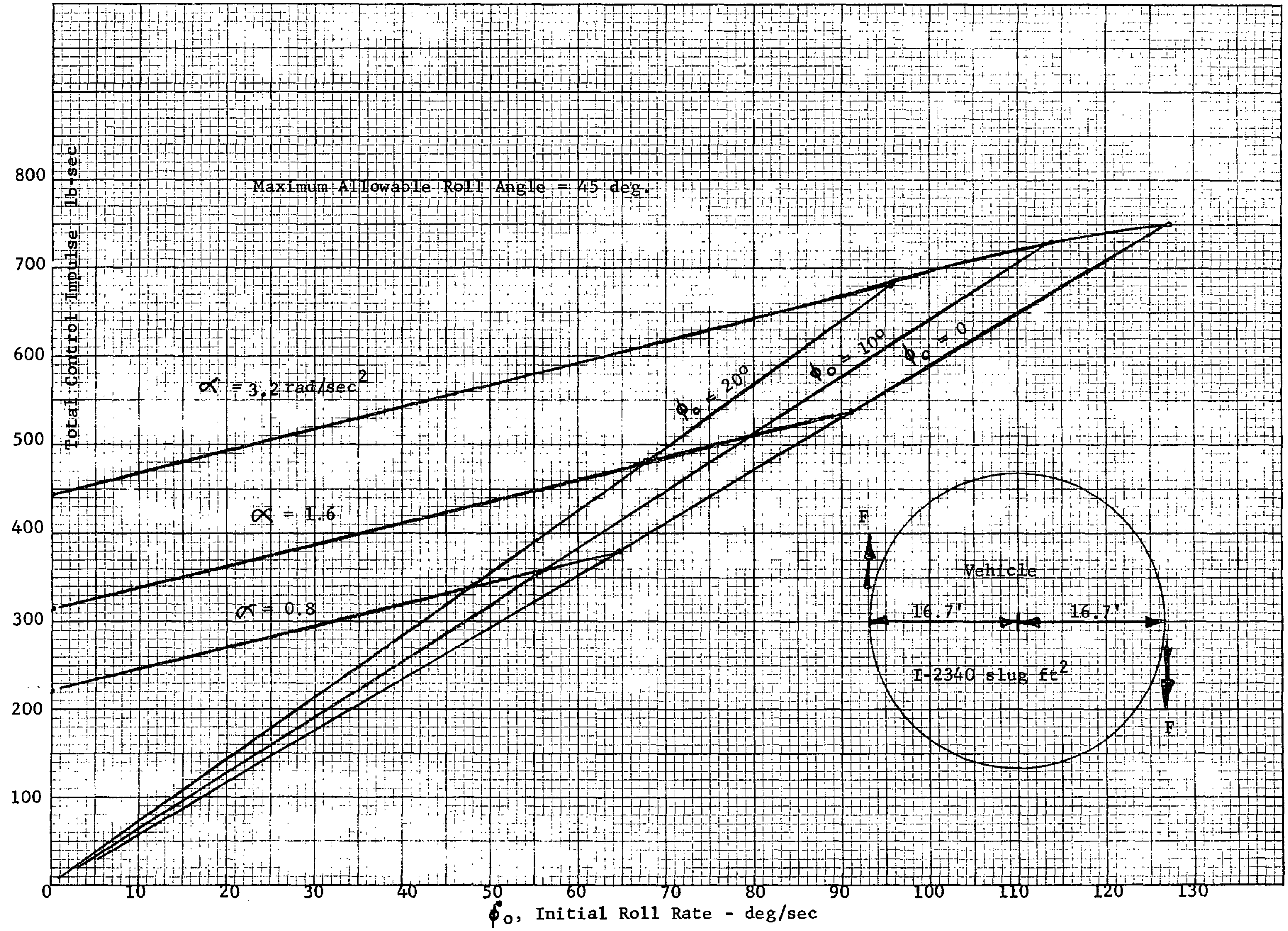


Figure 8 Optimal Control Impulse vs Initial Roll Rate

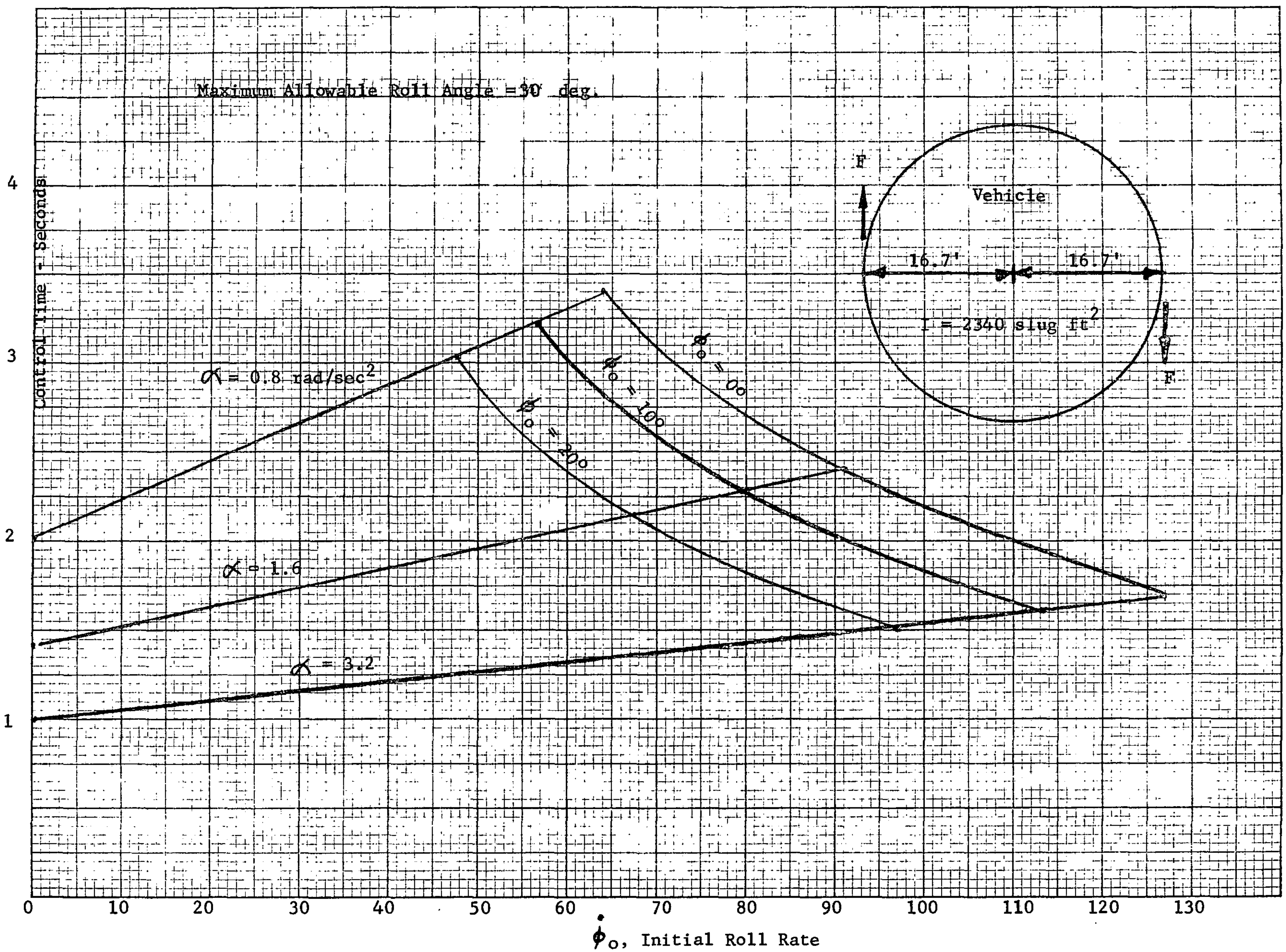


Figure 9 Optimum Control Time vs Initial Roll Rate

PRELIMINARY GAS GENERATOR DESIGN

A preliminary gas generator design for the fluidic emergency thruster was established. The gas generator design is 4.5 inches in diameter (maximum) and 9.9 inches long from the initiator interface to the thruster interface. The nominal calculated weight to provide the specified impulse requirements is 7.2 pounds, of which the estimated propellant weight is 3.6 pounds. The generator meets the three step pressure profile specified by system requirements and is shown in Figure 10. The maximum operating pressure at 70°F is 2500 psia and the burn time is 5 seconds. The gas generator design is based on an effective throat area of 0.0765 in^2 and an assumed discharge coefficient of 1.0.

A Thiokol Q-series propellant is the basis for the gas generator design. This propellant is based on an oxygenated polyster binder cured with an epoxide. The oxidizer is ammonium perchorate, which is used with a unique coolant, Thiokol LL-521. The propellant exhibits low flame temperature, clean exhaust products and a wide range of burning rate characteristics. This type of propellant also has excellent mechanical properties, is resistant to moisture and has excellent aging capability. It has no phase changes, has a high cure density, and is easily ignited. The specific designation of the propellant is TP-Q-3074A-01.

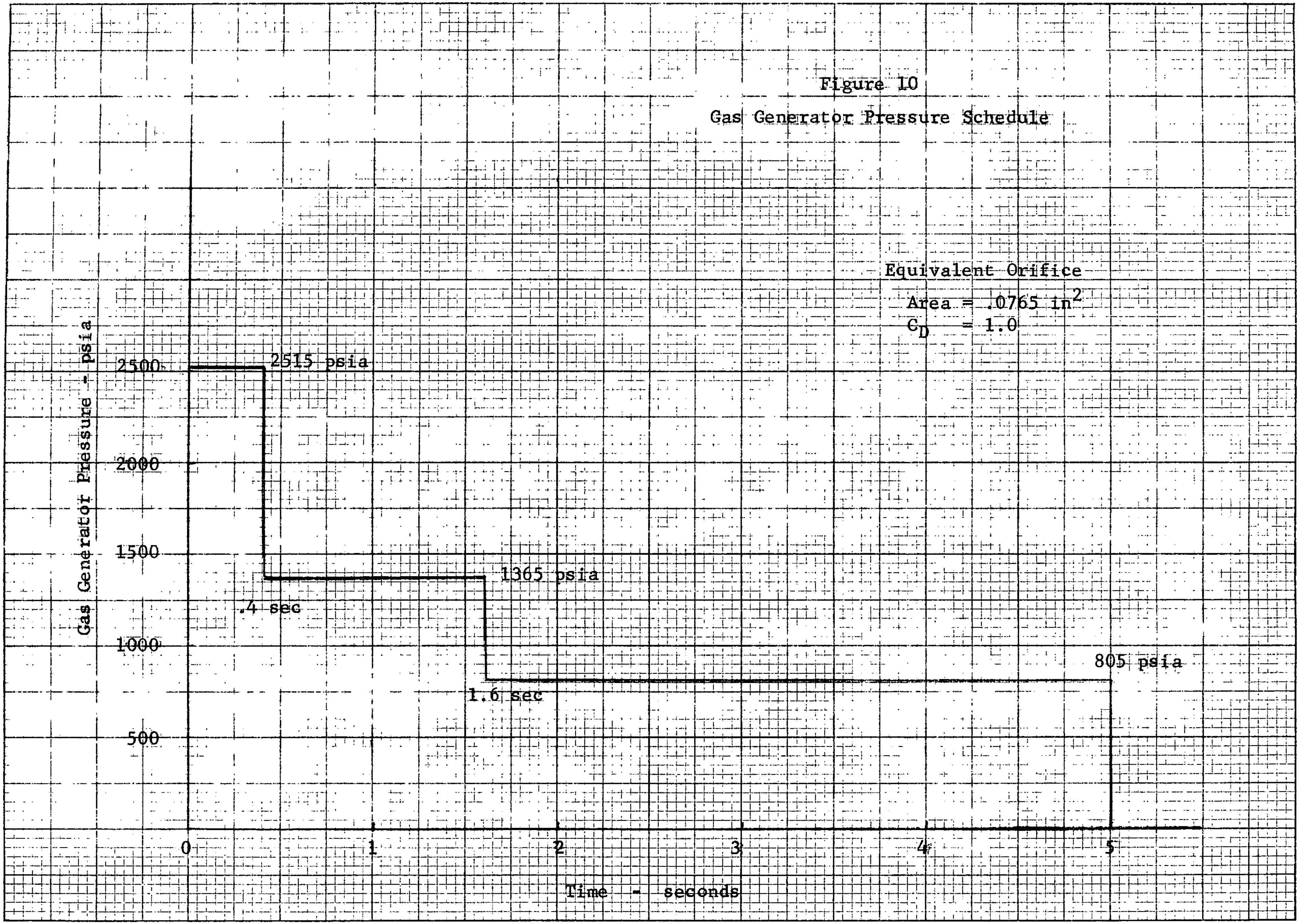


Figure 10

Gas Generator Pressure Schedule

FLUIDIC EMERGENCY THRUSTER DESIGN

The final thruster design selected is shown schematically in Figure 11. It consists simply of two vortex valves controlled differentially by an electromagnetic torque motor driven flapper nozzle. The inputs to the thruster are the high pressure supply gas from the generator and the electrical command signal from the flight control computer. The output is a differential thrust proportional to the voltage input to the torque motor. The transfer function from voltage input to thrust output is derived and defined in Appendix C.

The sizing of the flow controlling orifices and passages is based upon providing 224 pounds differential thrust with a gas supply pressure of 2500 psig. A vortex valve turndown ratio (TDR) of 5.0 is also assumed in the design. Since half of the supply pressure will be available up-stream of the thrust nozzles which are the outlets of the vortex valves, the nozzle throat on the vortex outlet diameter required is 0.4 inch for an optimum nozzle expansion ratio of 10. The calculated thrust vs supply pressure is shown in Figure 12.

A single outlet radial-in-flow vortex valve with the outlet configured as a divergent thrust nozzle was selected and developed as the primary thrust controller. The pertinent dimensions of the vortex valve and thrust nozzle are:

Outlet (nozzle throat) diameter (D_o) = 0.4 in.

Nozzle expansion ratio = 10

Spin chamber diameter (D_s) = 2.0 in.

Control nozzle area (A_c) = 0.031 in^2

Spin chamber height (h) = 0.30 in.

The vortex valve control nozzle area flapper-nozzle dimensions and torque motor characteristics presented are derived from the vortex outlet size. The initial design is defined by scaling from prior work done on the SPARCS fluidic proportional thruster program (NASA Contracts NAS 2-4490 and NAS 2-5466) and other General Electric vortex valve development programs. The final design is based upon refinement through breadboard evaluation.

Alternative techniques for the conversion of the electrical to fluidic command signals and the amplification of the fluidic signal to enable control of the vortex valve were investigated. The approach finally selected and implemented was that using the largest commercially available electromagnetic torque motor driving a flapper nozzle first stage transducer-amplifier to directly modulate the vortex valve control pressures. The alternative approach of using a small electromagnetic torque motor flapper nozzle with three stages of fluidic amplifiers was investigated. It was, however, not developed because it proved to be more complex and offered nosignificant size and weight advantage. The need to collect the amplifier vents at a pressure level of approximately one-half supply pressure was the primary factor resulting in a significantly larger amplifier than originally conceived.

The torque motor and flapper nozzle design were finalized to conform to the vortex valve control requirements. The flapper nozzle requirements based on providing

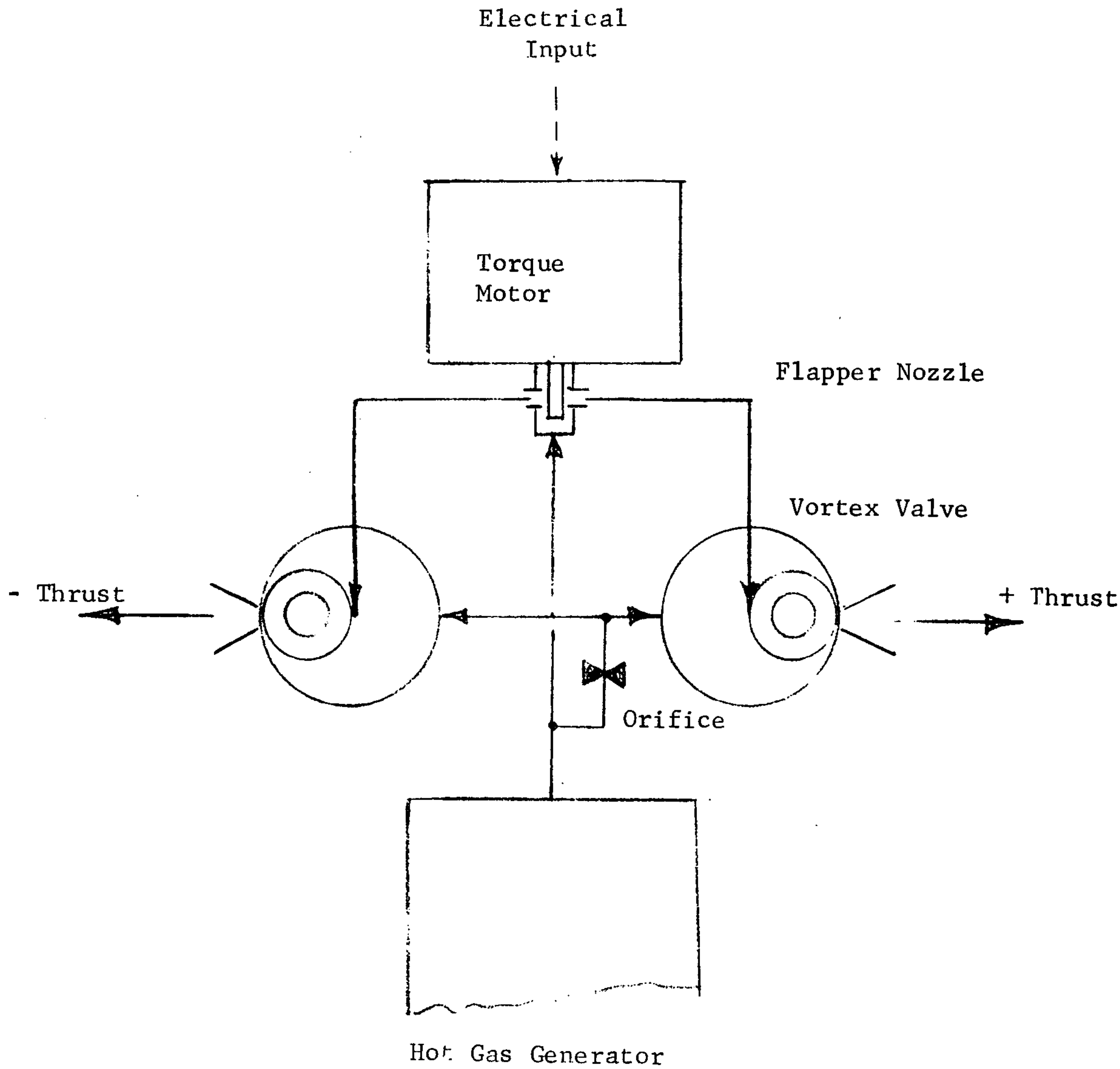


Figure 11
Fluidic Emergency Thruster Schematic

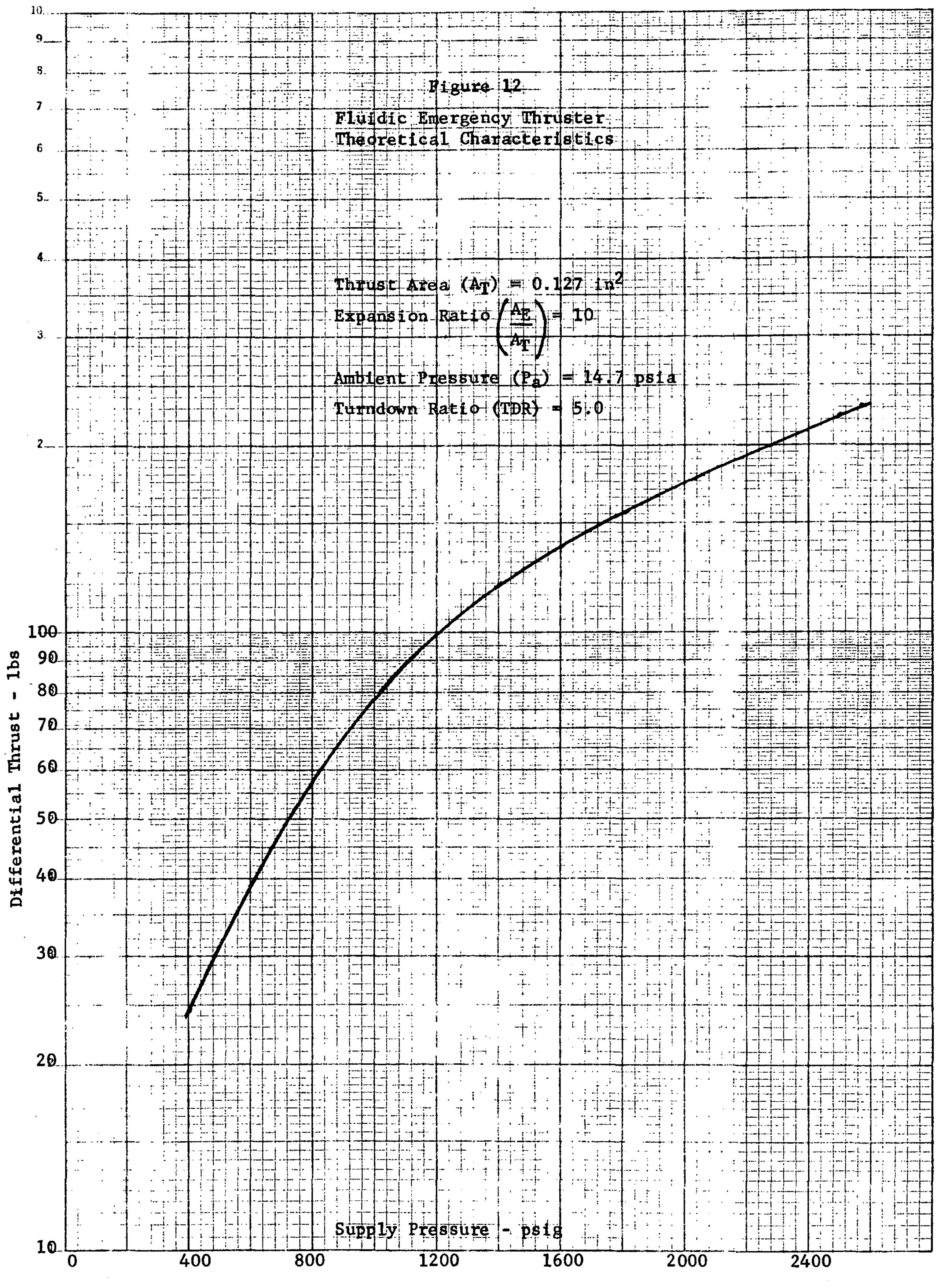


Figure 12
Fluidic Emergency Thruster
Theoretical Characteristics
Thrust Area (A_T) = 0.127 in^2
Expansion Ratio $\left(\frac{A_E}{A_T}\right)$ = 10
Ambient Pressure (P_a) = 14.7 psia
Turndown Ratio (TDR) = 5.0
Differential Thrust - lbs
10
20
30
40
50
60
70
80
90
100
Supply Pressure - psig
0
400
800
1200
1600
2000
2400

a maximum ratio of control to vortex valve supply pressure of 1.4 are:

nozzle diameter (D_N) = 0.186 in.

flapper travel (X) = $\pm$0.015 in.

A D. G. O'Brien Model 124 dry coil toruqe motor was selected to provide the required flapper stroke and force. Some of the significant torque motor characteristics specified are:

Model	124
Stroke	$\pm$0.15 in.
Mid-Position Force at Rated Current and Stroking Position	12 lbs.
End-of-Stroke Force at Rated Current and Stroking Position	0.5 lb
Stroking Position Below Base	0.50 in.
Hysteresis % of Rated Current	less than 2%
Resonant Frequency	Greater than 250 Hz
Proof Pressure of Flexure Member	5000 psi
Maximum Operation Temperature at Flapper for 5 seconds	2000°F
Net Spring Constant at Stroking Position	Maximum possible
Weight	24 oz.
Resistance per coil	80 ohms
Dimensions	As specified in Standard Specification
Gain (parallel coil)	6×10^{-5} in/ma

Heat transfer and stress analysis were performed to determine the most suitable material for the control fabrication. Strength and weight were the criteria for selection. The short time (5 seconds) during which the control is exposed to 2000°F and the fact that the highest pressures are experienced when the unit is cool alleviates the material high temperature strength problem so that super alloys are not required. The material selected is A.I.S.I. Type 347 stainless steel to be compatible with the welded assembly design.

FET TEST EVALUATION

Typical test data obtained during the performance evaluation of the FET units are presented in this section.

Figure 13 shows the FET voltage input vs output flow characteristics measured at a supply pressure of 70 psig. These x-y plots also indicate that the magnitude of hysteresis is less than 3 % of the peak to peak input. The null drift characteristic of the FET was also obtained during low pressure bench checkout. A typical null drift trace from 0 to 70 psig supply pressure is shown in Figure 14.

The FET was evaluated with high pressure air and with a hydrazine hot gas generator. The maximum differential thrust developed at supply pressures to 600 psig is shown in Figure 15. The actual thrust developed is approximately 2/3 of that predicted. The test results indicate that further optimization of the FET design is required to achieve the design thrust goals. In the design analysis, the thrust developed was based on the assumption that the vortex valves would be supplied with one-half of the supply pressure to the FET. The actual thrust was 2/3 of design value because the vortex valve supply pressure was dropped to approximately one third of the system supply pressure. This was the result of optimization of the available torque motor-flapper nozzle vortex combination for maximum turn down capability. For a given system pressure, the possible means for increasing the thrust delivered are to increase the thrust nozzle and vortex valve supply restrictor areas. Increasing the first stage size will also increase thrust, but this approach requires the specification of a nonstandard torque motor.

The relationship between differential control pressure of the first stage and thrust developed was determined as shown in Figure 16. The test results show that relationship is a simple proportionality factor of 0.2 lbs/psi. This gain was established to eliminate the need for thrust measurement in aircraft system simulation with the FET hardware.

Two hot gas runs using a hydrazine generator were conducted to determine the functional performance and temperature rise characteristics of the FET. The maximum pressure at the generator was 1300 psig and the maximum generator nozzle temperature attained was 1000 degrees F. The hydrazine tests indicated an insufficient generator capacity for operation of the FET at maximum design conditions. The functional performance of the FET during and after the hot runs was satisfactory The temperature rise at various parts of the unit was monitored during the test run and for several minutes after shutdown. The temperature rise due to heat soaking after shutdown is the significant factor. However, the temperature at the torque motor base which is the most critical area did not exceed 200 degrees F after shutdown.

Instability of the torque motor flapper at supply pressures above 500 psig became evident during the high pressure tests. The stable range of operating pressure was increased to 850 psig by decreasing the torque motor gain. The torque motor gain was reduced by shorting out part of the magnetic path. Assurance of flapper stability throughout the ultimate range of operating pressure requires torque motor redesign. A net mechanical spring rate which is greater than the equivalent pneumatic spring rate must be provided.

Figure 13

FET Serial No. 24PT31AA0001
Static Test Characteristic
Upper Vortex Valve
P_s = 70 psig

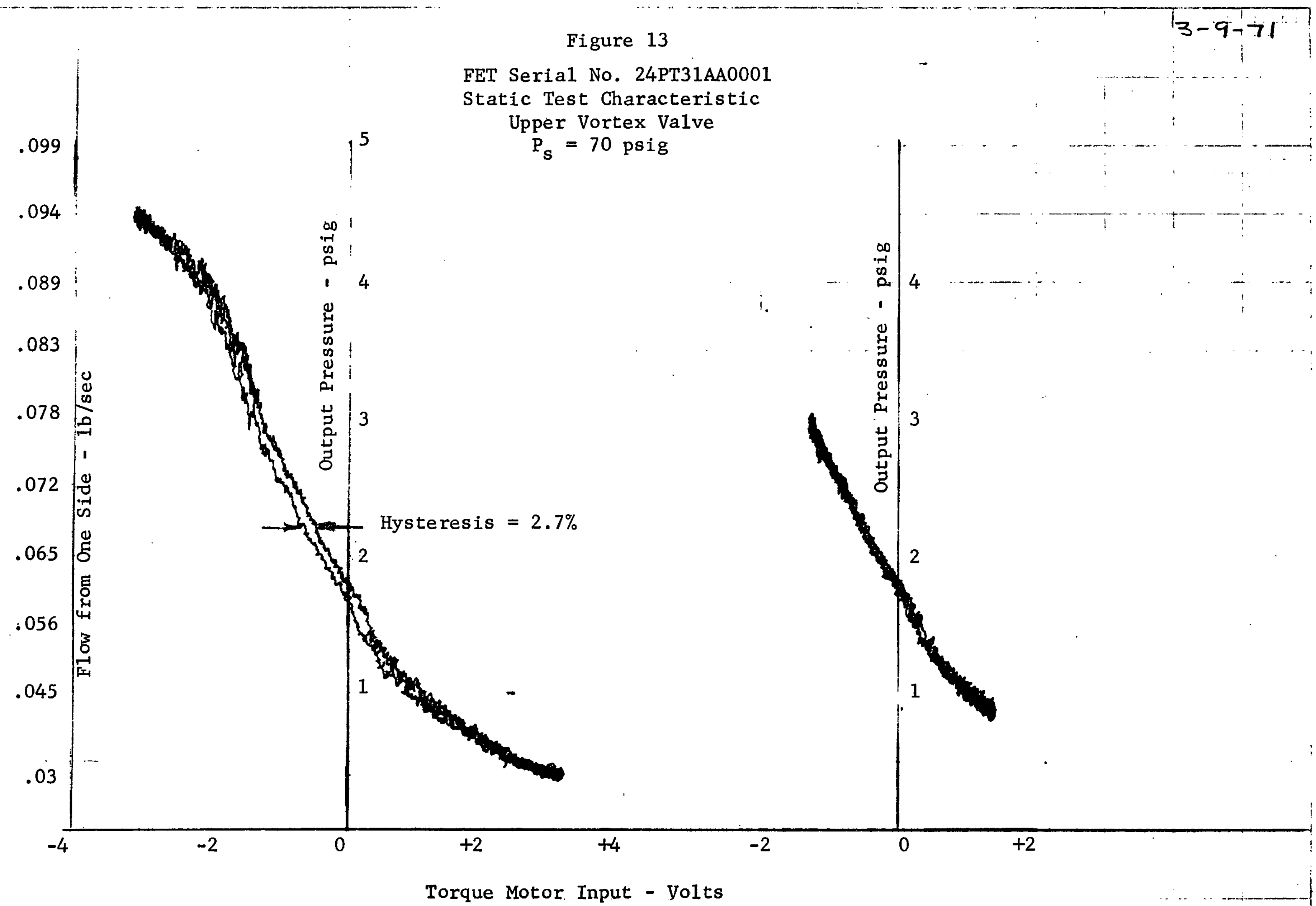


Figure 14

FET Serial No. 24PT31AA0001
Null Offset Test

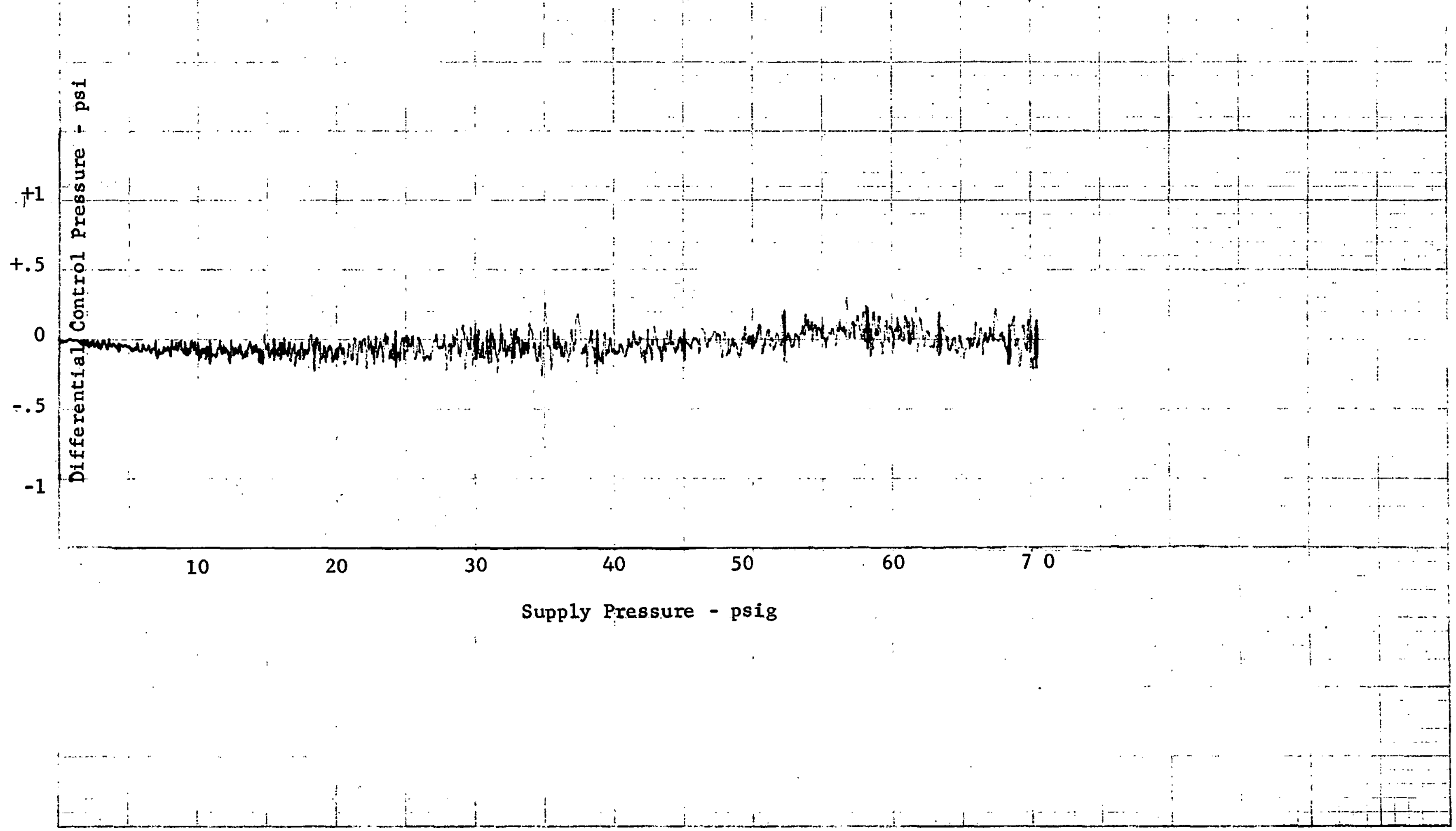
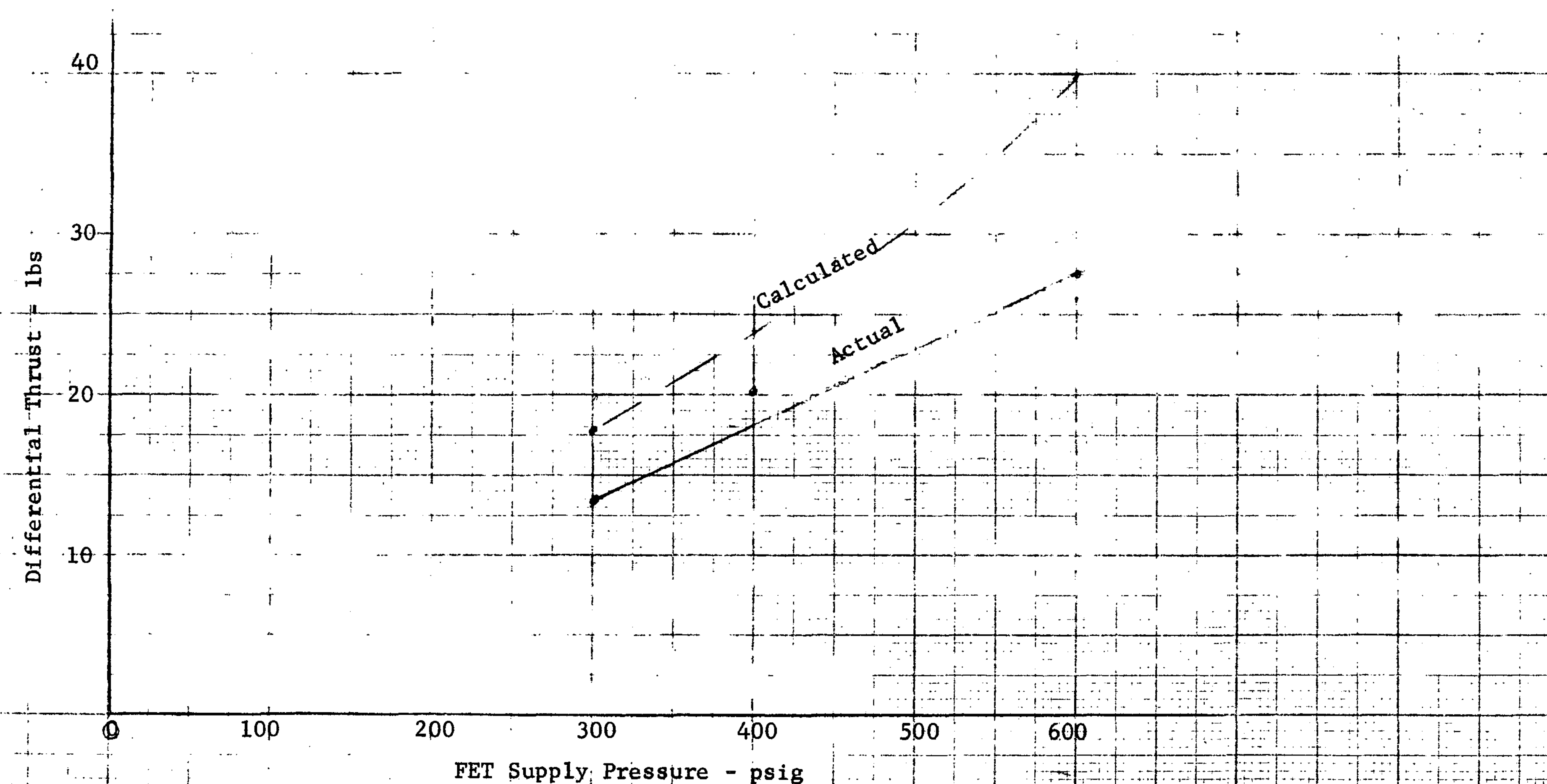


Figure 15

Fluidic Emergency Thruster
Thrust Test Data



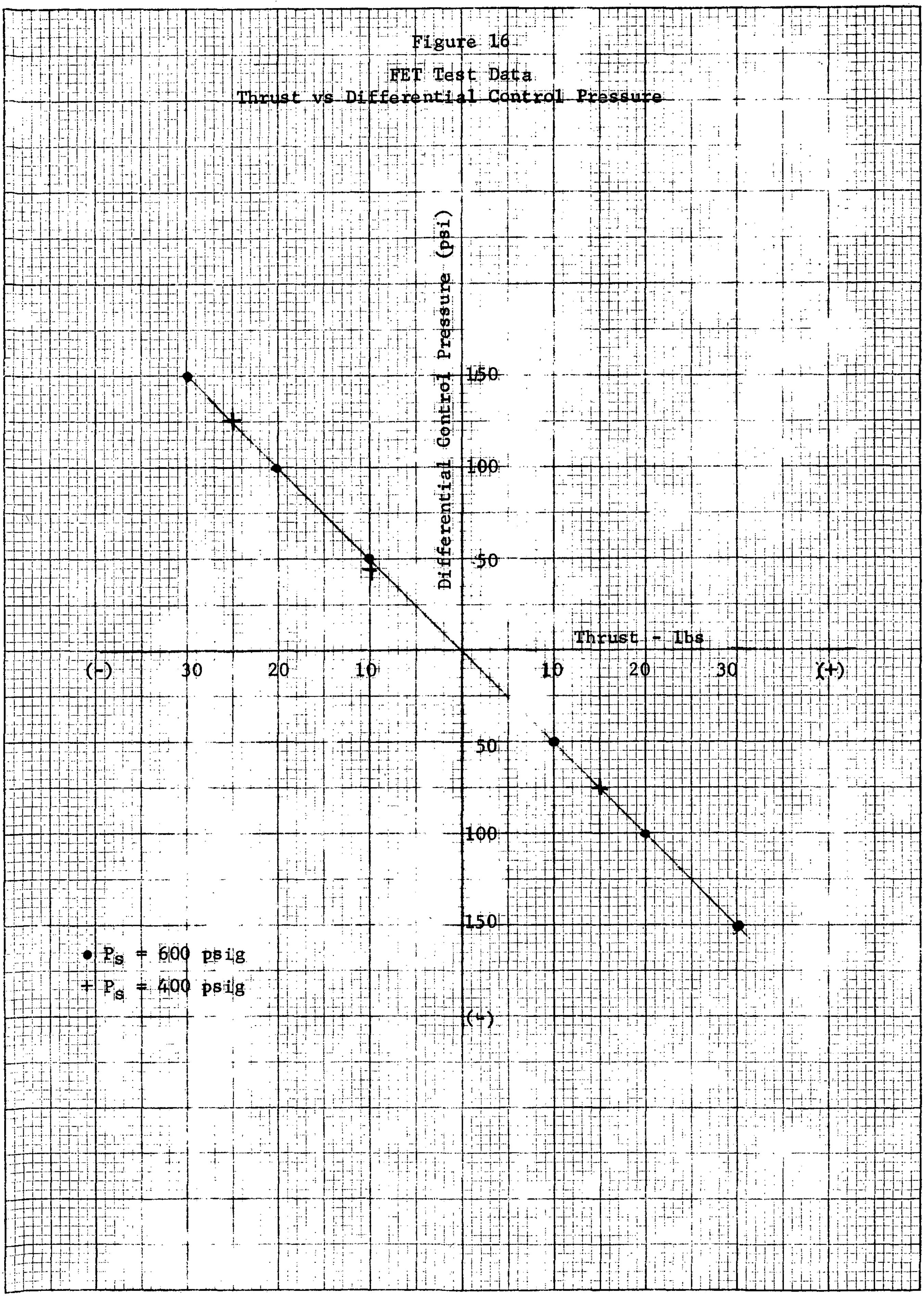


Figure 16
FET Test Data
Thrust vs Differential Control Pressure
Differential Control Pressure (psi)
150
100
50
Thrust - lbs
(-)
30
20
10
10
20
30
(+)
50
100
150
(-)
● P_s = 600 psig
+ P_s = 400 psig

Appendix A

FET Outline Drawing 543C314

GENERAL ELECTRIC

543C314

UNLESS OTHERWISE SPECIFIED USE THE FOLLOWING:—

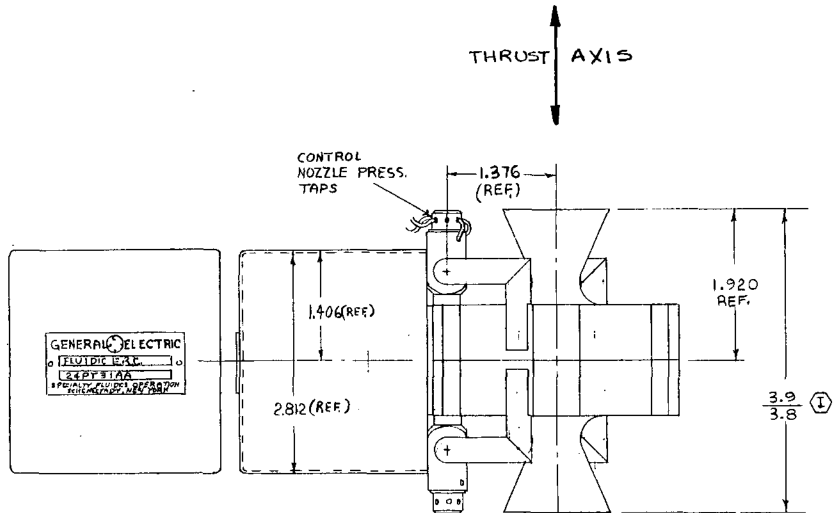
APPLIED PRACTICES	SURFACES	TOLERANCES ON MACHINED DIMENSIONS FRACTIONS	DECIMALS	ANGLES
	✓	+ −	+ −	+ −

TITLE

OUTLINE (EMERGENCY ROLL CONTROL)

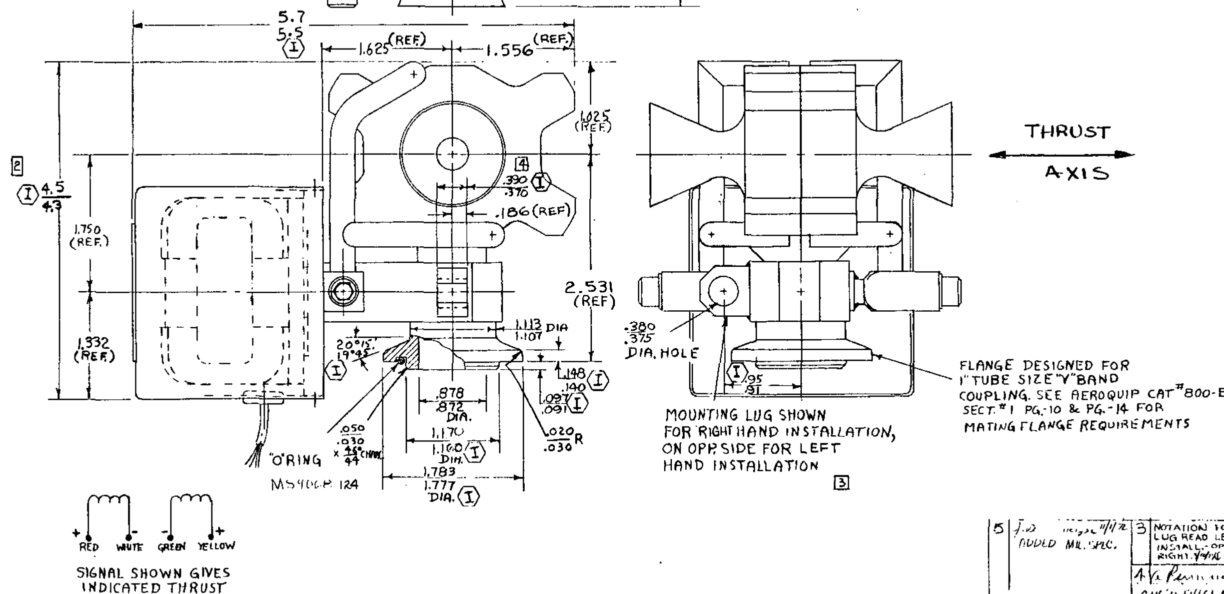
FIRST MADE FOR X-14 VTOL RESEARCH AIRCRAFT

FOR DETAILS SEE DWG #423D181 SH-1&2



- NOTES -

1. E.R.C.'s FURNISHED LEFT & RIGHT HAND. MODEL Nº 24PT31AA DESIGNATES RIGHT HAND, 24PT31BA DESIGNATES LEFT HAND.
2. CALC. NET WT=4.82 LBS.
3. (I) DENOTES DIMENSIONS FOR GOVERNMENT AGENCY INSPECTION.



REVISIONS

1. [signature] 3/3/71 ADDED TOL. TO OVERALL & ALL CRUCIAL DIMS.
2. [signature] 2/16/71 DENOTED (I) DIMENSIONS AND REVISED TOLERANCES ON OVERALL DIM.
3. NOTATION FOR MOUNT. LUG READ LEFT HAND INSTALL. OPP. SIDE FOR RIGHT [signature]
4. [signature] 3/11/71 CHG'D THICKNESS MTG LUG AT (5-D)
5. [signature] ADDED MIL SPEC.

PRINTS TO

MADE BY [signature] Dec 4 1970 — ISSUED Dec 4, 1970 G.Y.R. — APPROVALS J.S.H. 12-4-70 — SPEC. FLUIDICS DIV. OR DEPT — SCH'DY LOCATION — 543C314

543C314 — REV NO.

PF-809-P (3-70) PRINTED IN U.S.A.

Appendix B

Engineering Performance Test Procedure

The following engineering performance test procedure was written and submitted to NASA/ARC for approval during the course of Task III work. The procedures were complied with in the conduct of FET acceptance tests.

ENGINEERING SPECIFICATION

SPECIFICATION NO.: ES-FERC-1

Title: Engineering Performance Test Procedure	**Issue Date:** 23 November 1970 **Revision:**
Product: Fluidic Emergency Roll Control **Model No.**	**Contract or Task No.** NAS 2-5467
Prepared T. S. Honda — Proj Engr **Checked** — Mfg Mgr **Approved** — Engr Mgr	**Distribution:** W. T. Rauch J. N. Shinn T. F. Conroy T. S. Honda

Reference Drawings:

GE Dwg. 423D181

REVISIONS

Ltr	Pages	Description	Date	Approved

Fluidic Emergency Roll Control

for VTOL Aircraft

Engineering Performance Test Procedure

1.0 General Instructions

1.1 Scope - This test procedure, in accordance with Attachment Q-2 paragraph 4 of Contract NAS 2-5467, provides detailed instructions for conduct of Fluidic Emergency Thruster (FET) engineering tests. The tests shall be conducted by the FET contractor.

1.2 Hardware Identification - The FET test hardware shall be designated:

Fluidic Emergency Roll Control
G.E. Part Number: 24PT31AA0001 RH; 24PT31BA0001 LH

1.3 Applicable Documents - G.E. Dwg. # 423D181 FET Asm. Q-6, 542C314 Outline Q-2.

1.4 Inspection Plan - Tests shall be witnessed by G.E. Engineering and Quality Assurance personnel. The NASA/ARC designated representative shall be notified forty-eight (48) hours in advance and four (4) hours on retest.

1.5 Inspection Verification - Prior to engineering tests, conformance to applicable drawings and specifications shall be provided by inspection personnel.

1.6 Failure Report - Nonconformance reports shall be submitted in accordance with attachment Q-3 of Contract NAS 2-5467.

2.0 Test Conditions: The following test conditions apply to all tests described in Section 3.0 of this specification.

2.1 Test Fluid - The fluid used in the performance of all tests shall be shop air. The fluid temperature shall be room ambient.

2.2 Test Set-up Environment - Unless otherwise noted:

a. Ambient temperature shall be 70 $\pm$ 15^{o}F.

b. Ambient pressure shall be normal sea level (28-32 inches of mercury)

2.3 Test Measurements - Instruments shall be calibrated to commercial standards.

2.3.1 Pressure - All pressures shall be measured with gauges or pressure transducers which have been calibrated with a standard dead weight tester.

2.3.2 Temperature - Laboratory therometers or thermocouples shall be used for temperature measurement.

2.3.3 Flow Measurement - Unless otherwise specified, the flow output from the thrust nozzles shall be exhausted into a duct approximately 1 3/8 in. ID x 18 in. long with a convergent (VDI) nozzle outlet. The outlet nozzle throat diameter shall be 0.56 inch. The flow shall be computed from the duct pressure (average of at least 3 points) measured 0.6 inch upstream of the outlet.

2.4 Test Pressures - The test pressure shall be at maximum available laboratory pressure (approximately 75 psig).

3.0 Test Methods: The following tests shall be performed on each of the two (2) fluidic emergency roll controls provided under the contract containing this specification.

3.1 Examination of Product - Each FET shall be carefully examined visually and dimensionally prior to any other test to determine conformance with the requirements of specification in regard to workmanship per Q-6, identification, marking, finish and conformance to applicable drawings.

3.2 Torque Motor Resistance - The two coils in each torque motor shall be connected in parallel so that a voltage applied across the coils causes the flapper to deflect. The resistance of the coils in parallel shall not exceed 40 ohms.

3.3 Static Test - With +10 volts maximum applied to the input of the torque motor, the voltage shall be slowly cycled to -10 volts and back to +10 volts. The vortex valve control and the output differential pressures shall be recorded on the ordinate of an X-Y recorder with the torque motor input voltage recorded on the abscissa. This test shall be repeated with an input sufficient to produce a peak amplitude of 50% saturation or less.

3.3.1 Saturation - The output of the FET shall saturate at input amplitudes of less than ±10 volts.

3.3.2 Static Gain - The static gain around null shall be determined from the X-Y plot. It shall be expressed in terms of psid/volt.

3.3.3 Hysteresis - The hysteresis shall be determined from the X-Y plots and shall not exceed 3% when the input amplitude is within the saturation limits.

3.3.4 Null Offset - With no input to the torque motor, the null offset shall not exceed 5% of the peak to peak saturation limits.

Appendix C

Fluidic Emergency Thruster
Mathematical Model Derivation

Fluidic Emergency Thruster Mathematical Model

1. Torque motor equations

Volt - Current

$$\Delta I = \frac{\frac{1}{R_c}}{1 + \tau_M S} \Delta E \qquad (1)$$

Current - Force

$$\Delta F = K_M \Delta I \qquad (2)$$

2. Flapper Displacement Equation

$$\Delta F + 2A_N \Delta C = (M S^2 + D S + K_S) \Delta X \qquad (3)$$

3. Flapper-Nozzle-Vortex Valve Control Stage

Flapper Nozzle Flow

$$\Delta W = \frac{\partial W}{\partial X} \Delta X \qquad (4)$$

where $\frac{\partial W}{\partial X} = \frac{C_1 \pi D_N}{\sqrt{T}} P_s$

Control Volume Compressible Flow

$$\Delta W - \frac{\partial W}{\partial C} \Delta C = \frac{g V_c S}{\gamma RT} \Delta C \qquad (5)$$

where $\frac{\partial W}{\partial C} = C_1 \frac{A_c}{\sqrt{T}} f \left(\frac{P_v}{C}\right)_o \left[1 + \frac{\frac{\partial f}{\partial C}\left(\frac{P_v}{C}\right) \left(\frac{C}{P_s}\right)_o P_s}{f\left(\frac{P_v}{C}\right)_o} \right]$

and $f\left(\frac{P_v}{C}\right) = \frac{\left(\frac{P_v}{C}\right)^{\frac{1}{\gamma}} \left[1 - \frac{P_v}{C}^{\frac{\gamma - 1}{\gamma}} \right]^{\frac{1}{2}}}{\left(\frac{2}{\gamma+1}\right)^{\frac{1}{\gamma-1}} \left(1 - \frac{2}{\gamma+1}\right)^{\frac{1}{2}}}$

Combining equations (4) and (5) yields the transfer function from flapper displacement to control pressure as follows:

$$\frac{\Delta C}{\Delta X} = \frac{\frac{\partial C}{\partial X}}{\tau_C S+1} \qquad (6)$$

where $\tau_C = \left(\frac{\partial C}{\partial W}\right) \frac{g}{\gamma} \frac{V_C}{RT}$

4. Vortex Valve Thrust Nozzle Equation

$$\Delta T_F = \frac{-\partial T_F}{\partial C} e^{-\tau_v S} \qquad (7)$$

where $\tau_v = \frac{2g \; V_v}{C_1 \; A_V \; R \sqrt{T}}$

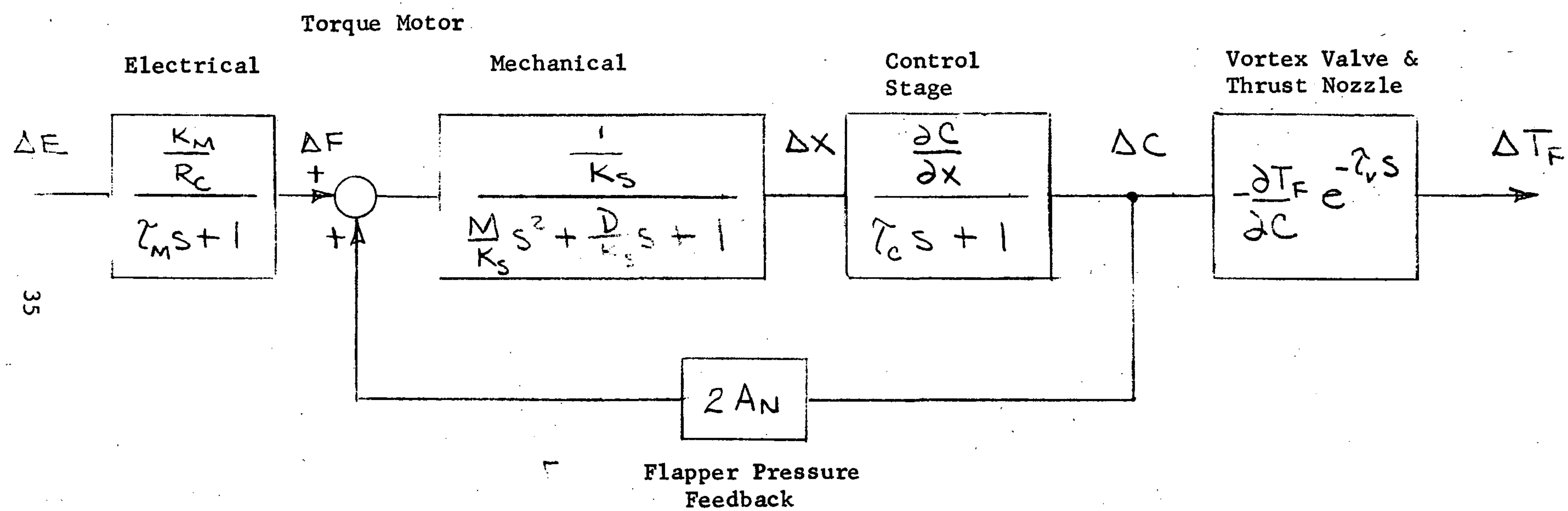


Figure 17

Fluidic Emergency Roll Control
Block Diagram

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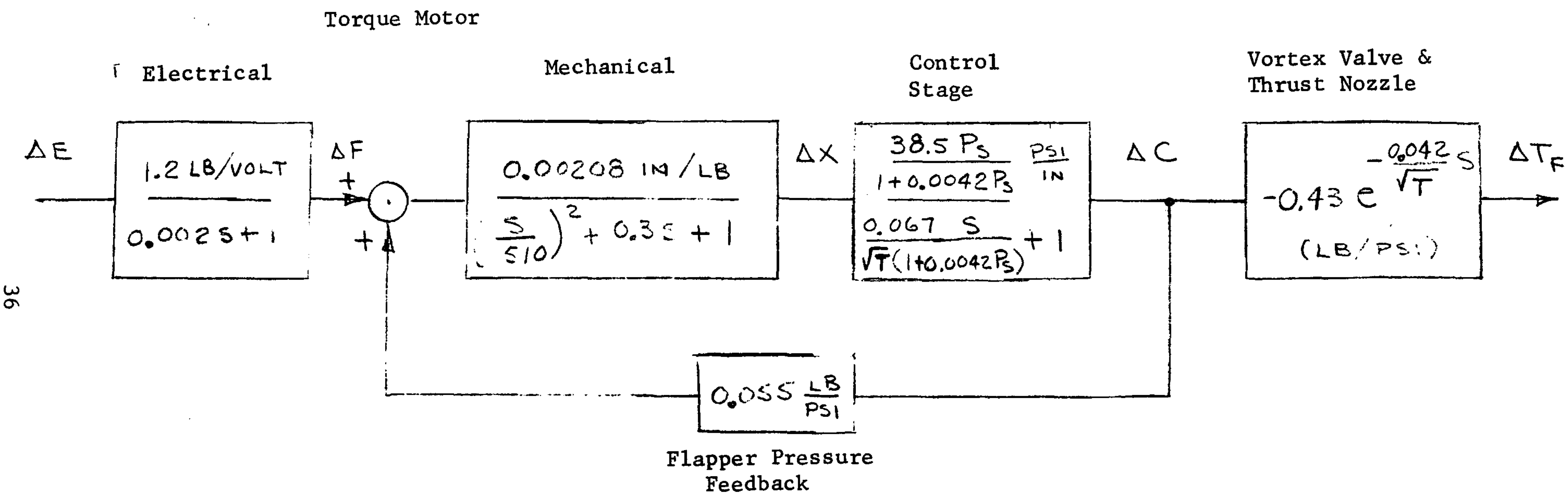

Figure 18

Transfer Function
Fluidic Emergency Roll Control

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Parameter Definition

A_c - vortex valve control nozzle area - in^2

A_N - flapper-nozzle area - in^2

A_V - vortex valve outlet area - in^2

C - vortex valve control pressure - psia

C_1 - constant - sec^{-1} $^oR^{\frac{1}{2}}$

D - flapper viscous damping - lb-sec/in

D_N - flapper-nozzle diameter - in.

E - command signal - volts

e - exponential

F - torque motor force - lbs

f - denotes function

g - gravitational acceleration - in/sec

I - current - milliamperes

K_m - torque motor current-force gain - lb/ma

K_s - torque motor spring gradient - lb/in

M - torque motor armature flapper mass - $lb\text{-}sec^2/in$

o - subscript denoting initial condition

P_s - control supply pressure - psia

P_V - vortex valve supply pressure - psia

R - gas constant - $in^2/sec^2\text{-}^oR$

R_c - torque motor coil resistance - ohm/coil

s - LaPlace operator

T - gas temperature - ^oR

T_F - thrust output - lbs

V_c - control stage entrained volume - in^3

V_V - vortex valve spin chamber volume - in^3

W - weight flow - lb/sec

x - flapper displacement - in

∂ - denotes partial derivative

Δ - denotes small incremental change

γ - gas specific heat ratio

τ_M - torque motor electrical self time constant - sec

τ_C - control stage time constant - sec

τ_v - vortex valve delay time - sec

Parameter Design Values

$A_c = 0.024\ in^2$

$A_N = 0.0275\ in^2$

$A_V = 0.127\ in^2$

$C_1 = 0.44\ sec^{-1} - {}^oR^{\frac{1}{2}}$ for hot gas
$(0.54\ sec^{-1} - {}^oR^{\frac{1}{2}}$ for air)

$D = 8.9 \times 10^{-2}$ lb-sec/in

$D_N = 0.187$ in.

$g = 386\ in/sec^2$

$K_m = 0.048$ lb/ma

$K_s = 480$ lb/in

$M = 19 \times 10^{-5}\ lb\text{-}sec^2/in$

$R = 3.33 \times 10^5\ in^2/sec^2 - {}^oR$

$R_c = 80$ ohm/coil

$T = 2460^oR$

$V_c = 0.5\ in^3$

$V_v = 1.0\ in^3$

$\gamma = 1.25$

$_m = 0.002$ sec

$$f\left(\frac{P_v}{C}\right)_o = .635$$

$$\frac{\partial f\left(\frac{P_v}{C}\right)}{\partial C} = .0048/psi$$

$$(P_v/C)_o = .9$$

$$\left(\frac{C}{P_s}\right)_o = 0.56$$