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(6) IMPROVED JET TAB THRUST VECTOR CONTROL FOR THE BGM-34C BOOSTER.

(9) FINAL REPORT, May 75 – Jun 77,

TRW SYSTEMS GROUP
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REDONDO BEACH, CALIFORNIA 90278

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(16) 1964 (17)

Prepared for:

AIR FORCE ROCKET PROPULSION LABORATORY
DIRECTOR OF SCIENCE AND TECHNOLOGY
AIR FORCE SYSTEMS COMMAND
EDWARDS AFB, CALIFORNIA 93523

FOREWORD

This report was prepared by the Propulsion Auxiliary Section, Propulsion and Combustion Systems Department of TRW Defense and Space Systems Group, Redondo Beach, California 90278.

The program was conducted under Contract F04611-75-C-0057, Job Order Number 196400FR, and was monitored by Lt. Michael E. Bond, Motor Applications Branch, Solid Rocket Division, Air Force Rocket Propulsion Laboratory, Edwards AFB, California 93523.

The static test firings described herein were conducted at the AFRPL under the direction of Mr. P. Butler, Test Engineer. This report describes development activity performed between May 1975 and June 1977.

Mr. Richard G. Eatough was the TRW Systems Program Manager.

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MICHAEL E. BOND, Capt., USAF
Project Manager

ROBERT C. CORLEY, Chief
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FOR THE COMMANDER

CHARLES R. COOKE, Director
Solid Rocket Division

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Electromechanically Actuated Jet Tabs
Ground Launch of Remotely Piloted Vehicles (RPV)

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Jet Tab Thrust Vector Control (TVC) is a flight demonstrated system for TVC required during ground launch of a remotely piloted vehicle (RPV). Contract F04611-75-C-0057 was initiated in May 1975 to develop an improved, low cost jet tab TVC system for use in the BGM-34C RPV flight test program. Nine static test firings were conducted. Two were of a

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configuration size used on the JBQM-34H RPV program to evaluate performance of low cost materials. These tests were conducted using a TU-752 solid rocket booster motor. Seven firings were then conducted using the smaller BGM-34C configuration size. The first three continued evaluation of low cost material and component performance. The last four tests were conducted using the low cost materials selected to determine the effect of environmental extremes on system performance and demonstrate compatibility with the BGM-34C system control components. All seven test firings were conducted using a TU-793/03 solid rocket booster motor. Finally, six jet tab TVC systems were fabricated for use in the BGM-34C RPV ground launch test program. This report contains a description of the test and flight hardware and details of the static test firings.

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1.0 INTRODUCTION

Thrust vector control (TVC) has been determined to be a requirement for the ground launching of a large remotely piloted vehicle (RPV). The ground launch of small RPV's had previously been demonstrated without TVC, but required precise and difficult to achieve system alignments prior to lift off. In a tactical situation, the possibility of asymmetrical external loads, CG shift during turbojet run up and irregular terrain for launcher mounting dictated a TVC capability to assure a successful launch. The jet tab TVC system was selected for the JBQM-34H ground launch program as the lowest risk approach to integrating a TVC system into an existing solid rocket motor. The jet tab TVC was especially attractive because of the basic fixed nozzle system and its electrical actuation system which used excess on-board power. The existing solid motor exit cone was installed at a threaded interface just aft of the nozzle throat. By replacing the simple exit cone with a jet tab system, no changes in the solid motor were needed and a minimal risk program could be accomplished.

Jet tab thrust vector control (TVC) system development by TRW with the Air Force Rocket Propulsion Laboratory (AFRPL) began in March 1970 with Contract F04611-70-C-0060. The feasibility of the concept was successfully demonstrated under that contract and development was continued in March 1971 under Contract F04611-71-C-0036 to extend the capabilities of the jet tab system to the high chamber pressure and highly aluminized propellant environments.

During those two programs, 18 test firings were conducted during which the jet tab TVC system demonstrated:

- Up to fourteen degrees thrust vector deflection.
- Structural integrity with total tab exposure time greater than 20 seconds.
- Repeatable thrust vector performance with propellant aluminum loadings up to 21.1 percent and motor chamber pressures to 2600 psi.
- Actuation torques well within the range for small electric motors.

With the maturity of jet tab TVC demonstrated during those two programs, in the fall of 1972 the Air Force initiated (under contract F04611-73-C-0013) a task to demonstrate a controlled ground launch of a large RPV using a modified off-the-shelf rocket motor and the TRW jet tab TVC. Eight static test firings were conducted to demonstrate the flight readiness of the system under environmental extremes. No difficulties were encountered in meeting the required six degrees of thrust vector and four second insertion time. Finally, five successful flight tests were conducted.

The next phase of establishing a ground launch RPV capability involves flight testing of the BGM-34C RPV. The purpose of this new program (Contract F04611-75-C-0057) was to develop a jet tab TVC system for use in the BGM-34C flight test program which would be compatible with a higher total impulse booster motor while incorporating a significant number of design and material changes to reduce cost.

The accomplishment of this program was the demonstration of flight readiness of an improved low cost configuration of the jet tab TVC system supplied for use in the BGM-34C ground launch flight test program. This final report discusses the program conducted under Contract F04611-75-C-0057 by TRW and the Air Force Rocket Propulsion Laboratory (AFRPL) and presents a description of the test hardware configurations, details of the test firings and a discussion of the performance data obtained from the tests.

2.0 SUMMARY

This final technical report summarizes the work performed under Contract F04611-75-C-0057. This program was performed by the Applied Technology Division of TRW Systems for the Air Force under the sponsorship of the AFRPL. The objectives of the program were achieved in a three phase technical effort.

Phase I consisted of two product improvement test firings of jet tab TVC systems installed on a TU-752 solid rocket motor. These tests were conducted with the motor installed on the AFRPL 40-inch Char motor six component thrust stand. These tests utilized residual refurbishable hardware from Contract F04611-73-C-0013 and incorporated material and component changes which showed promise for cost and/or performance improvement.

Using the results of Phase I, a flightweight design was made of a reduced size jet tab TVC system. This reduction in size was allowed by the higher total impulse, TU-793/03, solid rocket booster motor developed by Thiokol/Wasatch for the BGM-34C program under Contract F04611-75-C-0048. The smaller size also reduced overall system costs. The design configuration included the most promising of the low cost materials evaluated during Phase I. Seven preliminary flight readiness test (PFRT) firings were conducted to determine the performance characteristics of the system under extremes of test conditions. Due to inconclusive results of material testing during Phase I, the first three tests included additional material combination investigation. The final four test firings were of the final selected material combinations. All seven test firings were conducted at the AFRPL using the TU-793/03 motor mounted in the AFRPL Ormond six component thrust stand.

Phase III consisted of the fabrication of six jet tab TVC systems for use in the BGM-34C ground launch test program. To facilitate check-out of the TVC system prior to flight, the jet tab test set provided during Contract F04611-73-C-0013 was modified to be compatible with the BGM-34C system.

The two product improvement tests were conducted using the TU-752 rocket motor which provided a typical exhaust environment for the jet tab system. The nominal motor operating pressure of 630 psig for three seconds duration provided a limited time for material performance demonstration. However, sufficient data was accumulated to allow tentative material selections for the flight system.

The TU-793/03 rocket motor used during the seven PFRT test firings provided a nominal motor operating pressure of 750 psig for six seconds duration. The longer firing times allowed a more comprehensive evaluation of the capabilities of the low cost materials investigated. Significant low cost material changes demonstrated were the use of molybdenum for the tab facing in place of silver infiltrated tungsten, a silica phenolic nozzle liner in place of carbon phenolic, and extension of the nozzle liner to eliminate the refractory metal scraper ring at the nozzle exit plane. The seven PFRT tests provided the performance base for the flight test program. During these tests, the jet tab system demonstrated performance greater than that required.

- o Survivability during tab insertion greater than 7.5 seconds with no significant tab facing erosion. (Nozzle exit erosion had a minor impact on vector performance.)
- o Approximately 7.2 degrees of thrust vector at 42 degrees shaft rotation.
- o Insertion response of 85 milliseconds to 24 degrees of shaft rotation using a 117:1 ratio gear motor and 125 milliseconds using a 170:1 ratio gear motor.
- o No effect on thrust vector performance over motor operating temperature range of -55°F to +140°F.
- o Negligible effect on actuation response over operating temperature range.

During the last five PFRT tests, the ground launch interface control unit (GLICU) being developed by Teledyne Ryan Aeronautical (TRA) was utilized to control tab operation. Several problems were experienced in obtaining sufficient power output from the controller to achieve adequate tab rotation. The required 6 degrees of thrust vector had been demonstrated during the first two PFRT tests. However, due to the GLICU output voltage limitation, the required tab rotation was not achieved until the final PFRT test on which the electromechanical actuator gear ratio was increased. The resulting GLICU gain settings resulted in achieving a 42 degree tab shaft rotation in response to a 48 degree command with an actuator gear ratio of 170:1.

One operational difficulty which occurred on early PFRT test firings was the accumulation of aluminum oxide on the molybdenum tab face. After long duration insertions, failure of the tab to retract on command occurred near the end of motor burn tail off (chamber pressure less than 200 psig) when the aluminum oxide in the nozzle exhaust was near the solidification temperature. Increasing the gap between the tab face and the nozzle exit plane from a nominal 0.045 inches to 0.068 inches eliminated this problem.

3.0 SYSTEM CONCEPT

Thrust Vector Control (TVC) for tactical missiles and other relatively small solid rocket propulsion systems has been defined as the favored steering approach for several USAF requirements. The specific needs are usually related to severe packaging restrictions and/or maneuverability at air speeds below the threshold of conventional aerodynamic surface capabilities. Jet tab thrust vector control systems, originally developed for large booster applications, have been successfully adapted to a wide range of tactical missile and small booster propulsion system requirements. For certain applications with low actuation power requirements, severely restricted envelope length or retrofit of existing propulsion units, the jet tab TVC system has several advantages.

3.1 SYSTEM OPERATION

The jet tab system uses independently actuated tabs located around the periphery of the nozzle exit plane (normally one tab is used for each control axis). By actuating the tabs singly or in combination, the commanded direction of the thrust vector can be provided. When a tab is rotated into the exhaust stream perpendicular to the nozzle axis, a shock system is created inside the nozzle which results in a high pressure region along the nozzle wall directly upstream of the tab. The magnitude of the pressure forces on the nozzle and the resultant side load on the missile is found to increase with increasing blockage of the nozzle exit plane. The side force can also be expressed as an equivalent deflection of the thrust vector.

To characterize the performance of the tab system, a series of force relationships are established as shown in Figure 3-1. The nominal axial thrust is the thrust measured without a tab inserted. The side thrust is the thrust vector measured perpendicular to the axial thrust. However, for multiple tab insertion, the side thrust is defined as the vectorial sum of the individual side thrusts attributed to each tab. The resultant thrust vector and deflection angle for single or dual tab insertion then becomes the vectorial sum of the axial thrust during vectoring plus the side thrust as defined for single or multiple tab insertion.

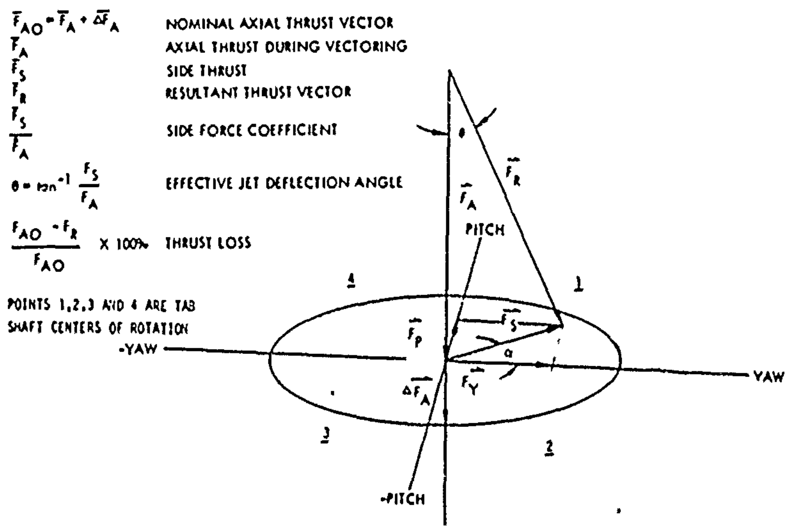


Figure 3.1. Force Relationships Used to Characterize the Performance of Jet Tab Thrust Vector Control

3.2 BACKGROUND

Development of jet tab TVC for tactical applications began with TRW obtaining license rights from Hawker Siddley Dynamics (HSD) that covered the Taildog propulsion system. The HSD program had demonstrated high vector angles, low actuation torques and adequate durability for non-aluminized solid propellants. The performance potential, if upgraded to U.S. propellant systems, was sufficient to attract AFRPL sponsorship for a small initial program whose success allowed follow-ons and expansion into more specific system applications. A brief summary of these programs follows.

3.2.1 Contract F04611-70-C-0060

The first program sponsored by AFRPL had as its objective the verification of Taildog data for higher energy USAF propellants. A total of six tests were conducted on the AFRPL Char motor using zero percent and five percent aluminum content uncured solid propellant. The testing verified thrust vector deflection angle capabilities of 10 degrees for a single tab and 14 degrees for dual tab insertion. Tab survivability greater than eight seconds was demonstrated using a silicide coated molybdenum faceplate. An illustration of the basic test unit is shown in Figure 3-2. Omniaxis TVC and very low actuation torques were also demonstrated. Details are in Reference 1.

3.2.2 Contract F04611-71-C-0036

Based upon the successful completion of the first program, a subsequent effort was sponsored by AFRPL to continue the tab system demonstration for more severe rocket motor environments. One major task in the program consisted of upgrading the existing nozzle design (Reference 1) for a 21 percent aluminum solid propellant.

The primary changes in design approach were first, to use silver infiltrated tungsten for tab facings and scraper ring, and second, to use carbon cloth phenolic material for all ablatives. Five test firings were conducted on the AFRPL Char motor using a 21 percent aluminum uncured propellant. The maximum single tab thrust vector deflection was 13 degrees. Tab survivability in the high temperature aluminized exhaust was demonstrated for extremely long insertion times. The nozzle configuration was extended to allow demonstration of electromechanical actuation as shown in Figure 3-3.

The second major task was to develop a nozzle/jet tab TVC system capable of successful operation with highly aluminized solid propellants at chamber pressures of 2500 psi. A new nozzle design compatible with the AFRPL HIPPO test motor was developed. The basic nozzle and tab materials were the same as before, except a low erosion rate pyrolytic graphite washer throat and moderate Mach number carbon phenolic blast tube were added. Five test firings were conducted on the AFRPL HIPPO motor using a 10 percent aluminum propellant. One firing was conducted with a 16 percent aluminum propellant and a boost-sustain duty cycle. Maximum chamber pressures achieved were approximately 2600 psi. Electrical actuation was demonstrated on several of the tests. Thrust vector deflection of 10.2 degrees was demonstrated. However, at equivalent nozzle exit plane blockage ratios, vector performance was lower than noted during the lower pressure tests. An illustration of the high chamber

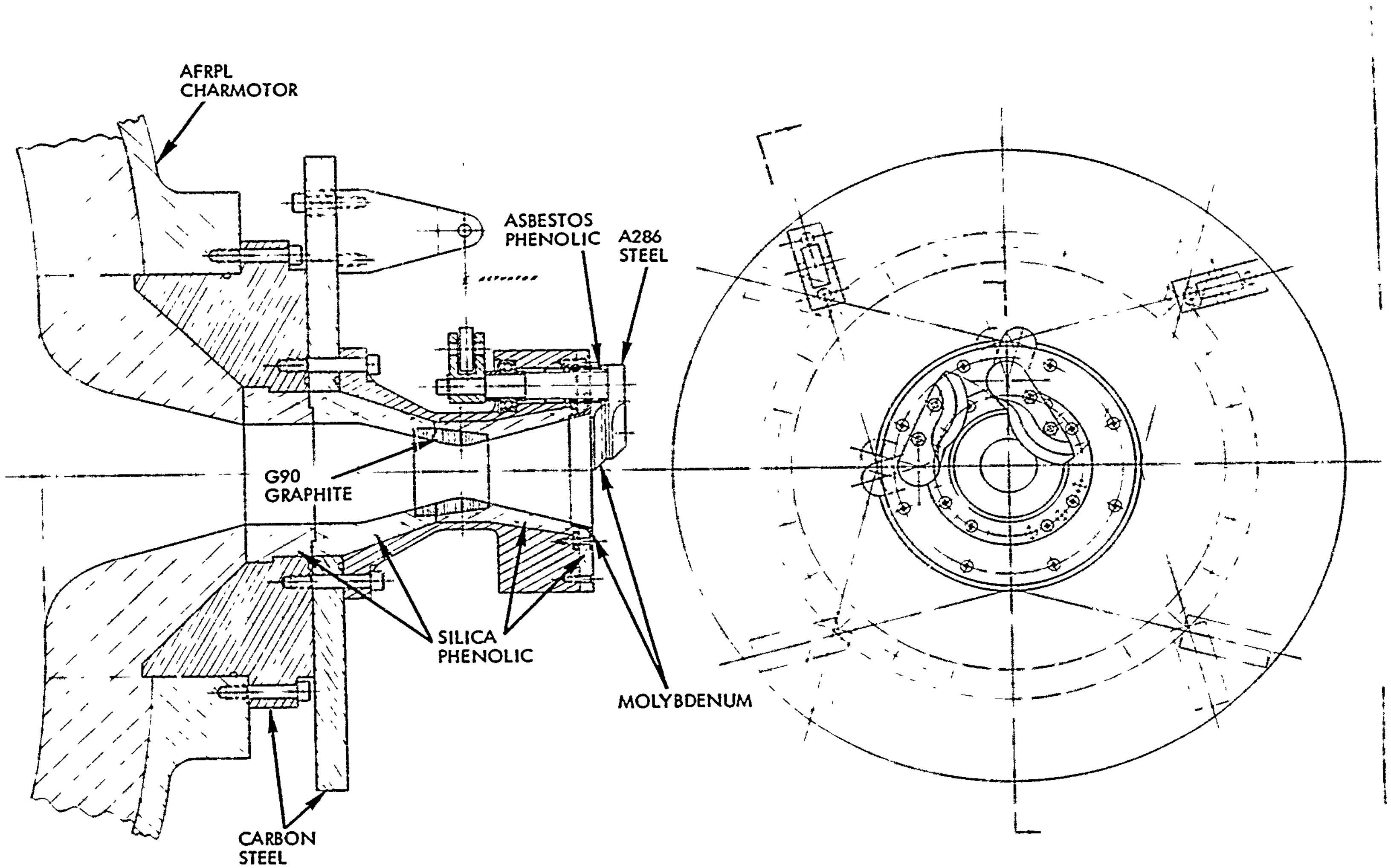


Figure 3-2. Jet Tab TVC System for Char Motor

pressure nozzle and jet tab assembly is shown in Figure 3-4. Details of the complete program are found in Reference 2.

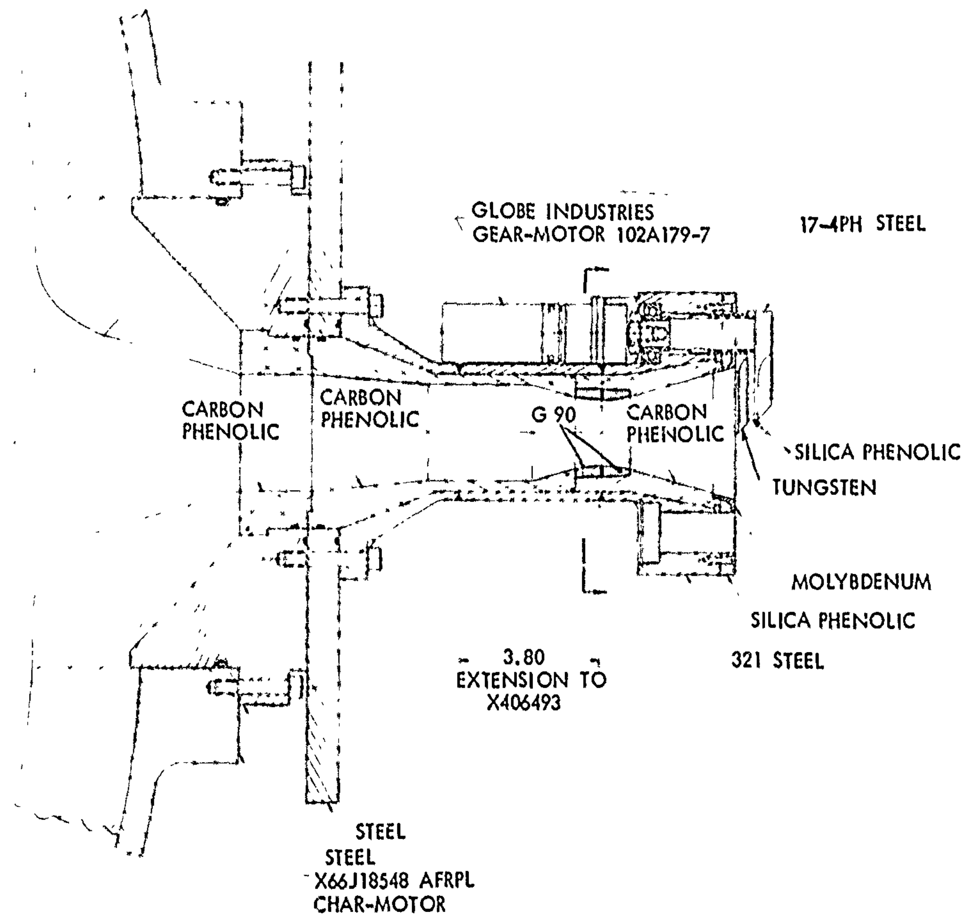


Figure 3-3. Char Motor TVC System for High Aluminum Content Propellant Tests

3.2.3 Quickturn Test Unit

Under contract to the Naval Weapons Center (NWC), a jet tab system designed and tested on the preceding contract was refurbished and test fired. The refurbishment followed a firing that experienced a nozzle housing weld failure and subsequent burn through. The Quickturn nozzle was essentially a scaled down version of the AFRPL high pressure design that used electromechanical actuation. The refurbished unit was successfully test fired at NWC on the Quickturn test motor. An illustration of the test unit is shown in Figure 3-5. Details of the firing performance were classified by NWC and are found in Reference 2.

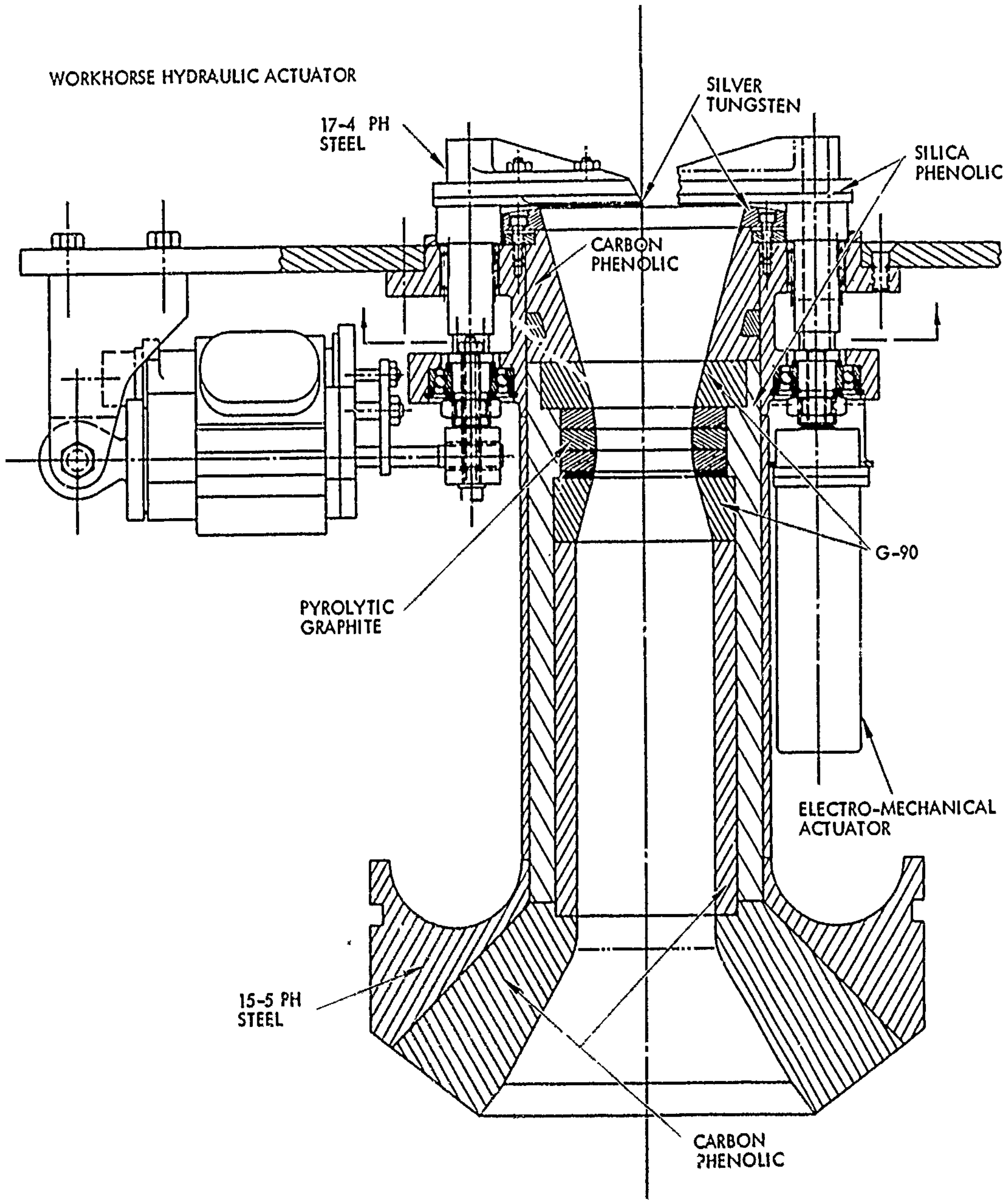


Figure 3-4. HIPPO Motor Jet Tab TVC System

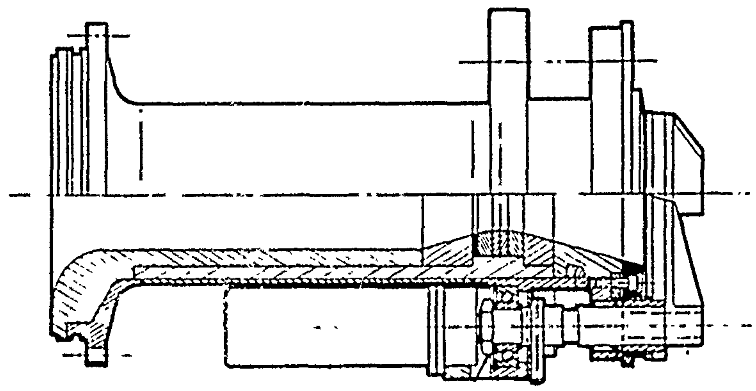


Figure 3-5. Flightweight Quickturn Test Nozzle

3.2.4 JBQM-34H Ground Launch Program

Thrust Vector Control (TVC) for remotely piloted vehicle (RPV) ground launch was determined to be a requirement by systems analysts at the USAF Aeronautical Systems Division (ASD), Wright-Patterson AFB, Ohio.

To demonstrate a large RPV ground launch capability, ASD and AFRPL personnel selected a modified Genie solid rocket motor (TU-752) due to its low cost and ready availability. The jet tab TVC system, having been well demonstrated in the previously discussed programs, was selected as the lowest risk approach to integrating a TVC system with an existing solid rocket motor. The jet tab TVC was especially attractive because of the basic fixed nozzle system and its electrical actuation system which used excess on-board power. The existing Genie exit cone was installed at a threaded interface just aft of the nozzle throat. By replacing the simple exit cone with a jet tab system, no changes in the solid motor were needed and a minimal risk program could be accomplished.

Contract F04611-73-C-0013 was initiated to demonstrate the feasibility of a controlled ground launch of a JBQM-34H RPV using a TU-752 solid rocket booster motor and a jet tab TVC system. Eight static test firings were conducted. Two were of a lightweight jet tab TVC configuration to establish performance and survivability characteristics. Six firings were then conducted with the flight configuration illustrated in Figure 3-6 to determine the effect of environmental extremes on system performance. No difficulty was experienced in providing the six degrees thrust vector and four second insertion time required. Finally, five flight tests were conducted.

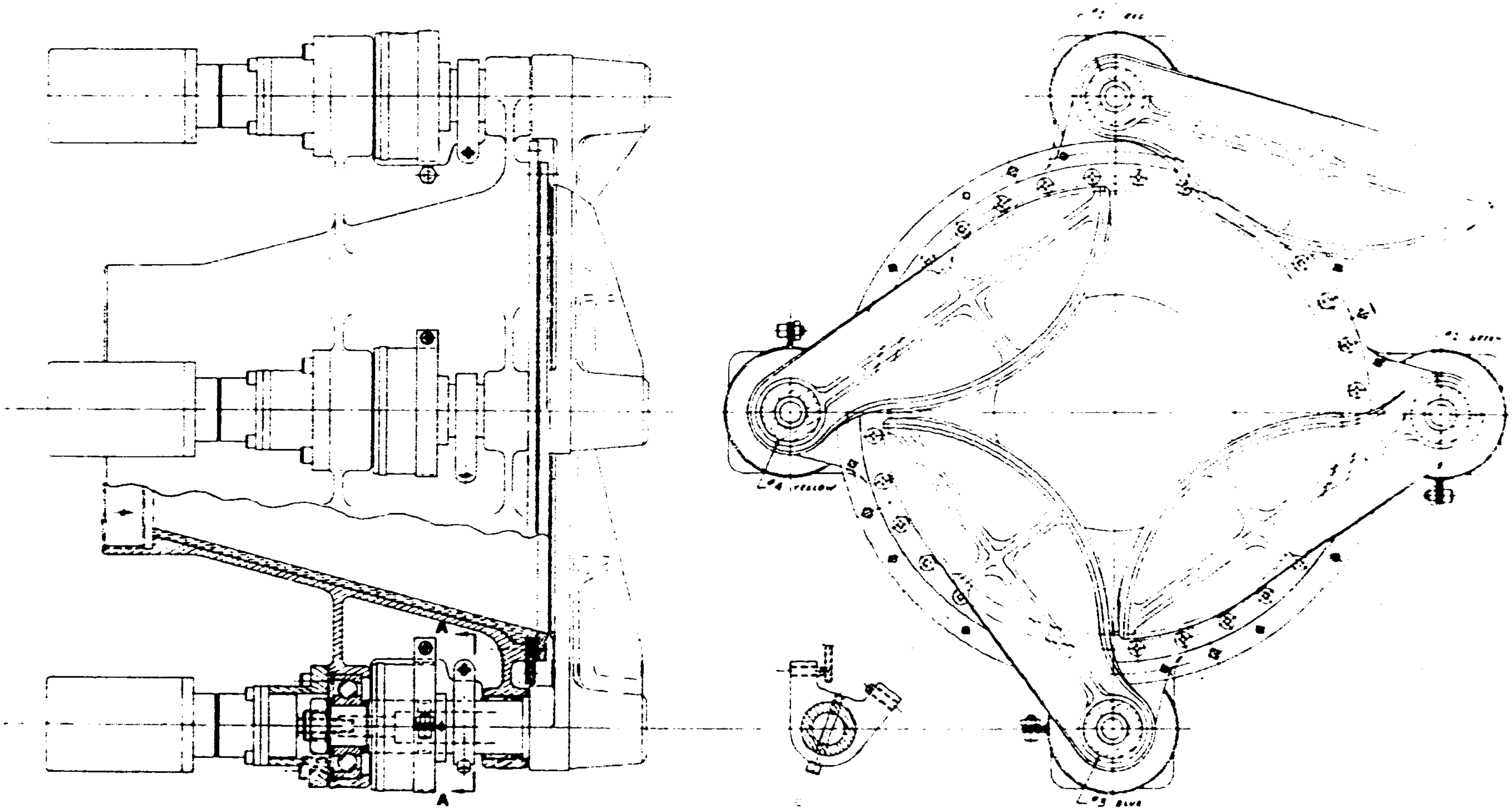


Figure 3-6. Jet Tab TVC System for JBQM-34H Ground Launch

Excellent attitude control of the vehicle was provided in both pitch and roll axes throughout the boost phase up to the time of motor separation. Program details are in luded in Reference 3.

3.2.5 Cont ct F04611-73-C-0036

Development of a jet tab/nozzle system for high pressure environments was continued as a follow on to the previously described high chamber pressure effort. The jet tab and nozzle system were scaled up in size. The system design provided for operation using an 18 percent aluminum content, 88 percent solids propellant operating at 3500 psig for five seconds at thrust levels five times those tested during the previous programs.

Five test firings were conducted. The first three used a test weight configuration, shown in Figure 3-7, which had a nozzle expansion ratio of 8.75. Thrust vector angles of 13.2 degrees were demonstrated. Rotary motion hydraulic actuators were used for these tests. For the short firing times involved, molybdenum proved satisfactory for the refractory materials even at the very high operating pressure.

The final two test firings were conducted using a flightweight configuration (Fig. 3-8) designed to the Air Slew packaging constraints. The nozzle inner contour was identical to the test weight configuration except the expansion ratio was reduced to 5.0. At nozzle exit plane blockage ratios equivalent to the test weight units thrust vector performance was considerably lower. A thrust vector of 9.5 degrees was demonstrated. To reduce the overall system envelope, linear motion hydraulic actuators were used to provide vector slew rates of 375 degrees per second. Details are contained in Reference 5.

3.2.6 Low Cost RPV Booster Program

In an effort to further reduce the overall RPV booster motor cost, AFRPL initiated a development program to demonstrate a more cost effective booster system. Under Contract F04611-76-C-0051, TRW is teamed with United Technology's Chemical Systems Division to demonstrate an RPV booster system which will have a unit production cost of less than $6,000. The overall concept is the use of a nozzleless rocket motor with a jet tab TVC system. The jet tab system will incorporate ablative plastic facing

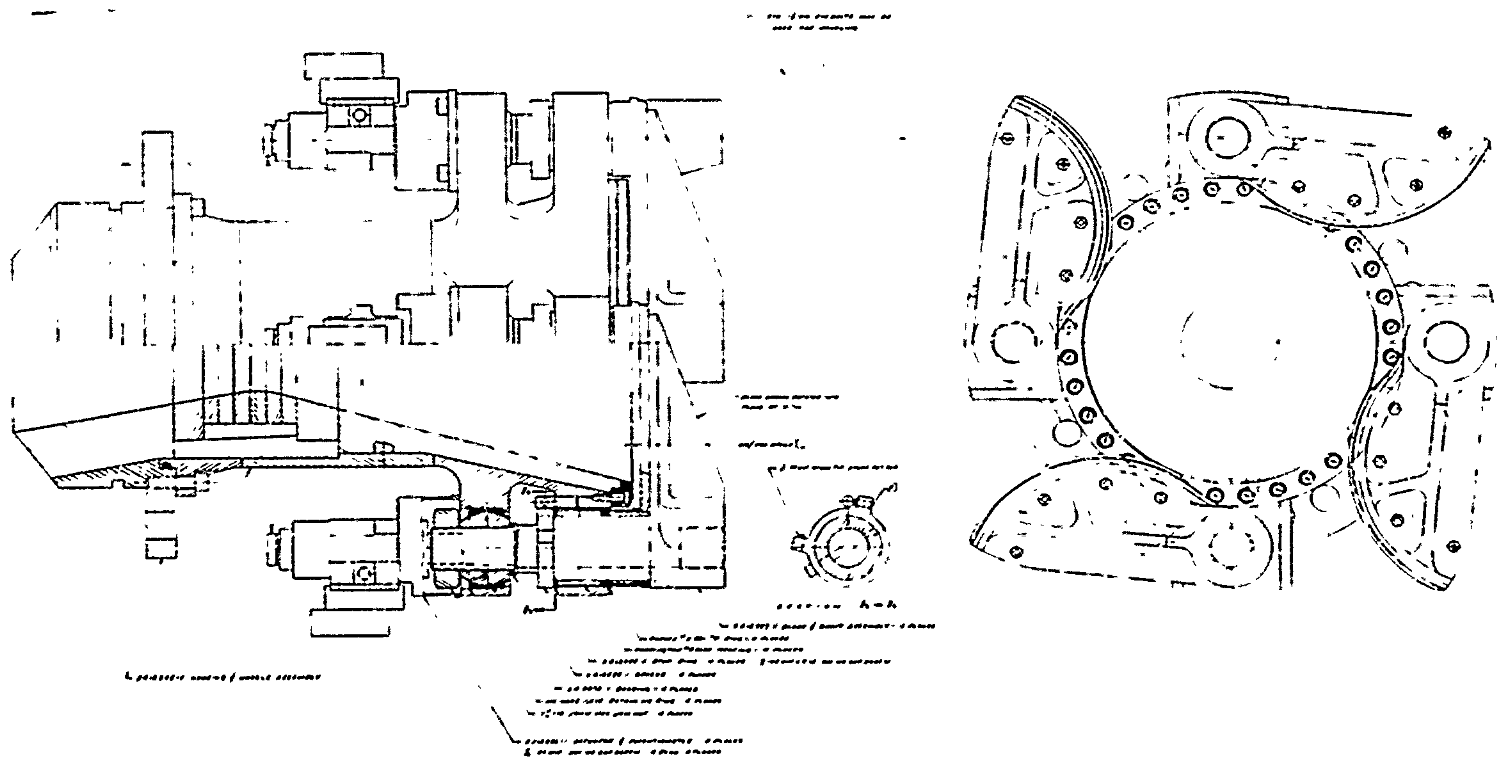


Figure 3-7. Test Weight Design Configuration

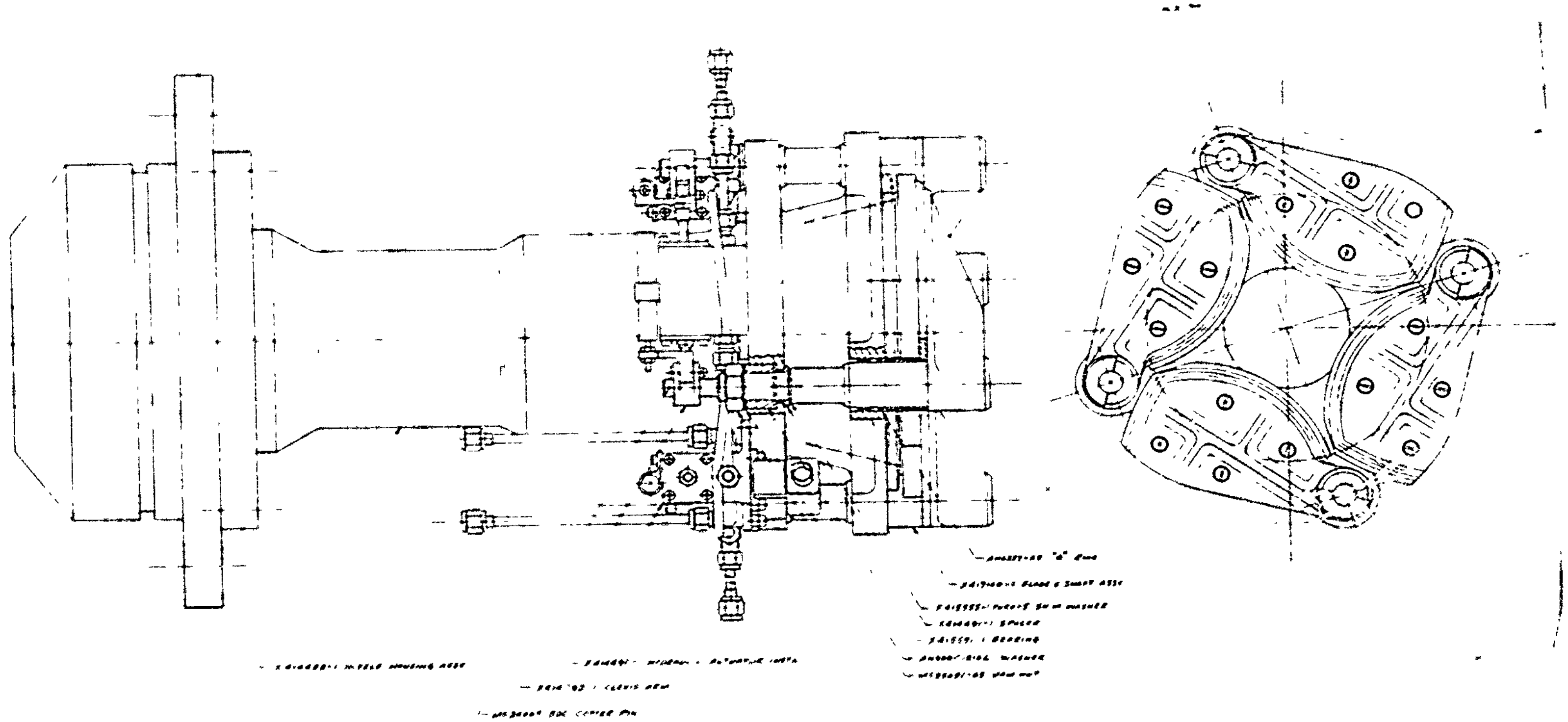


Figure 3-8. Flight Weight Design Configuration

materials and a cross-axis shaft interconnect to allow the use of only one actuator per axis. Three subscale test firings have been completed and four full scale test firings are planned. The preliminary full scale system is illustrated in Figure 3-9.

3.2.7 Tomahawk Cruise Missile

The Navy Tomahawk Cruise Missile is currently under development. Undersea launch is accomplished with a solid rocket motor equipped with a jet tab TVC system. The high pressure TVC system developed under Contract F04611-71-C-0036 was used with modifications being required only in the area of mechanical attachment to the rocket motor and the incorporation of a flightweight, pre-packaged hydraulic actuation system. The system is presented in Figure 3-10.

As of this writing, the validation and systems integration phases are complete and the full scale development phase is well under way. Twenty-four static test firings and four flight tests have been completed. The system provides ten degrees of thrust vector at insertion times of up to three seconds.

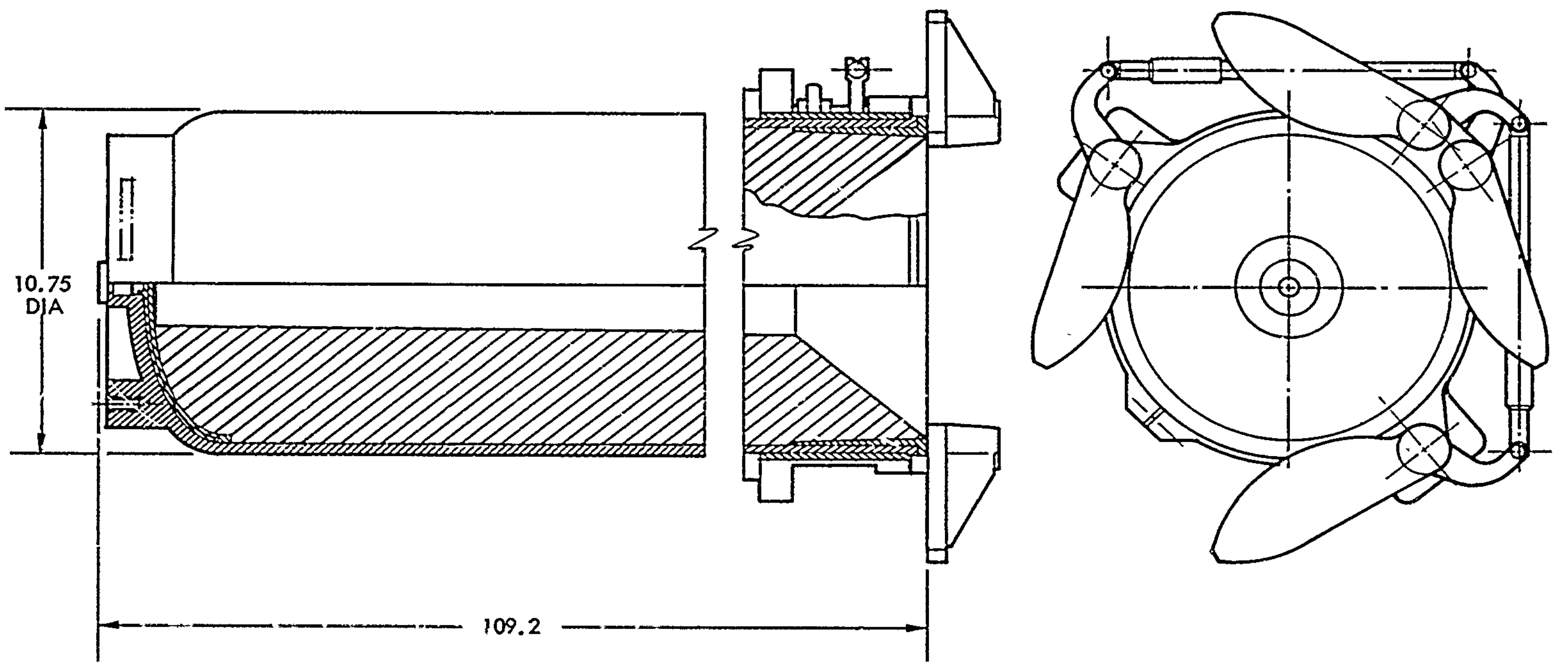


Figure 3-9. Low Cost RPV Booster

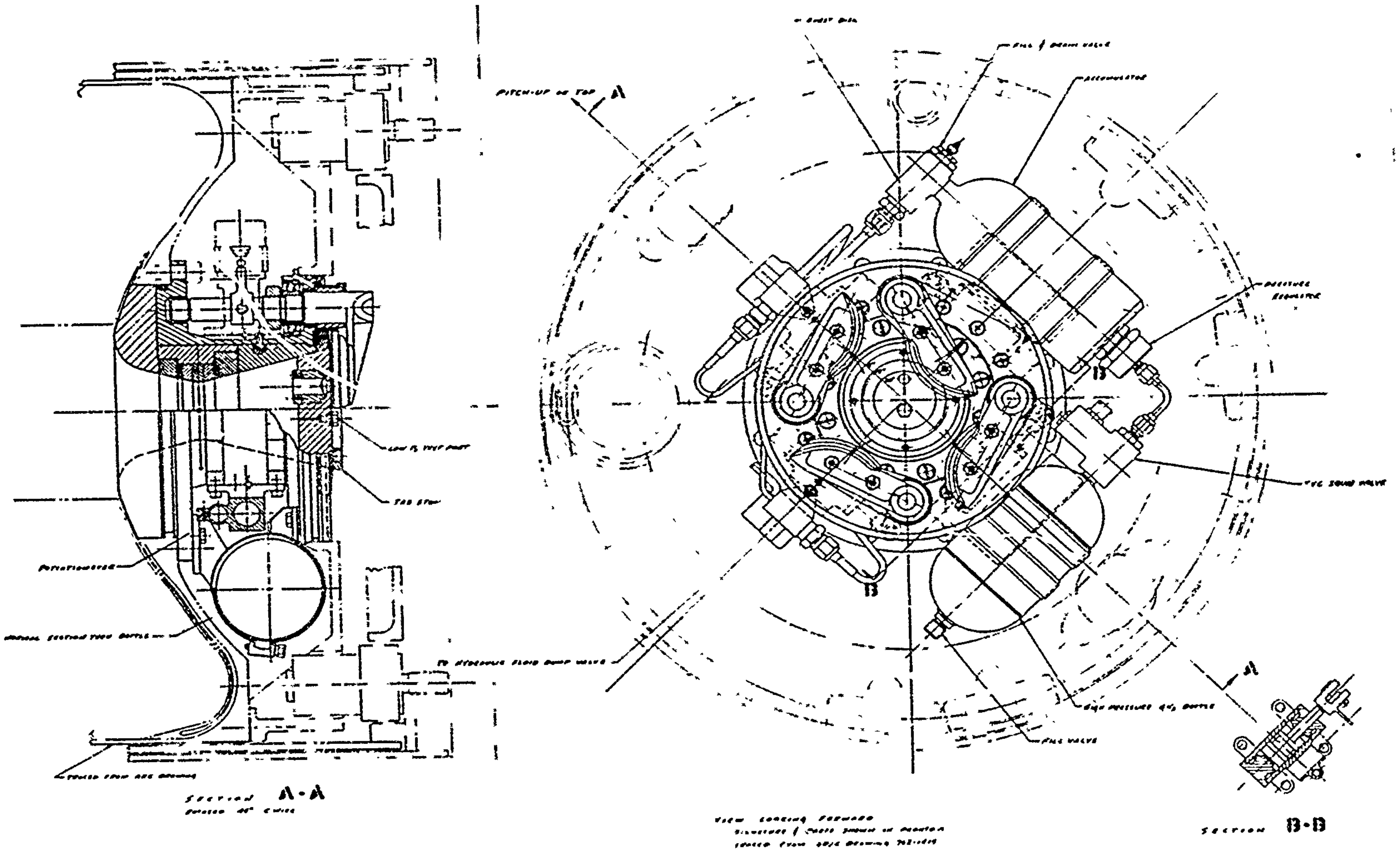


Figure 3-10. Tomahawk Cruise Missile Jet Tab TVC System

4.0 SYSTEM DESIGN

The improved, low cost jet tab TVC system which was developed on this program for the BGM-34C RPV ground launch flight testing is shown in Figure 4-1. The original intent of the program was to provide the jet tab TVC system for the BGM-34C booster in a configuration essentially identical to the proven design from Contract F04611-73-C-0013. The only changes were to be in materials and components to reduce the cost of the TVC system. The nozzle exit diameter of 10.5 inches was to remain unchanged.

During a BGM-34C design review held at TRA, just prior to initiating this effort, it was determined that the motor contractor had used a throat diameter of 4.5 inches and a nozzle expansion ratio of four (exit diameter of 9.0 inches) in determining the solid motor grain design. Using the JBQM-34H jet tab nozzle configuration would result in an excessive booster thrust level. It was necessary to either redesign the solid motor grain to reduce the thrust level or the jet tab system to provide a smaller nozzle exit diameter. As a reduction in the jet tab system size had a potential for cost reduction, the Air Force decided to have TRW redesign the jet tab system.

The resulting design described in this section incorporates both the reduction in size and low cost material changes demonstrated during the static test firings conducted. A summary of the system design criteria is listed in Table 4-1.

4.1 DESIGN DESCRIPTION

The TVC system is designed for use with the TU-793/03 booster motor, which is provided by Thiokol/Wasatch. This motor was developed from the Genie solid rocket motor and is a follow-on design to the TU-752 motor used in the JBQM-34H program. The TVC mates with the motor case aft closure at a threaded interface downstream of the throat. The jet tab thrust vector control system consists of a nozzle assembly, four blade and shaft assemblies, four needle and four thrust bearings, four TRW Globe Motors DC gear motors with integral position potentiometers, and miscellaneous hardware. A photograph of the integrated TVC system is presented in Figure 4-2. An aerodynamic shroud also provides thermal protection from RPV turbojet engine exhaust impingement during prelaunch engine start up and run. The shroud attaches to a flange on the solid motor case outer diameter.

Table 4-1. Jet Tab TVC System Design Criteria

o Solid Rocket Motor Conditions

	-55°F	+70°F	+140°F
MEOP - PSIG			965
Action Time - Sec	10.99	9.57	8.67
Propellant Aluminum Content		12%	
Flame Temperature at 1000 psig		4820°F	
Throat Diameter		4.2 in.	
Nozzle Exit Diameter		9.0 in.	
Nozzle Design Safety Factor at MEOP		1.5	

o TVC Performance

Duty Cycle - Full Insertion	6 sec.
Thrust Deflection Angle	
Pitch Axis	$\pm 6^0$
Roll Axis	$\pm 3^0$
Electrical Power- per Actuator	28 VDC @ 35 amp max
System Response (as provided by gear ratio noted)	
Pitch Axis Ratio	170:1
Roll Axis Ratio	117:1

o Environmental

Temperature	-55°F - +140°F
Vibration Spectrum	
Sinusoidal	
20-2000 Hz	0.5g
Sweep up and back 1 octave/minute	
Random (RPV)	
20-100 Hz	+6dB/octave
100-200 Hz	0.04 g^2/Hz
200-1000 Hz	+3dB/octave
1000 Hz	0.2g^2/Hz
1000-2000 Hz	-6dB/octave
Overall 14.2 G rms; Duration 30 min/axis	

Transportation: Use MIL-STD-810B (Table 514.I-VII)

a. Common carrier land and air

b. Use 6000 miles for land transportation

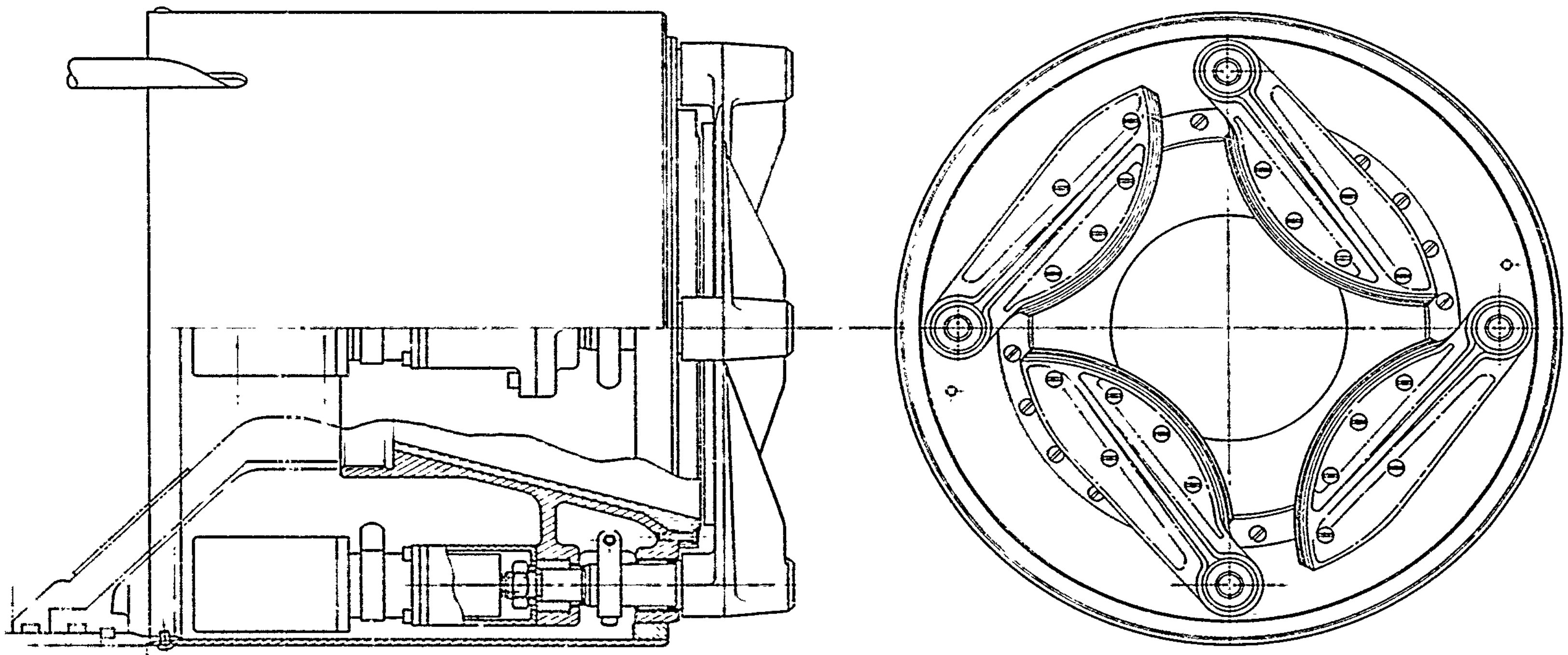


Figure 4-1. Jet Tab TVC System for BGM-34C

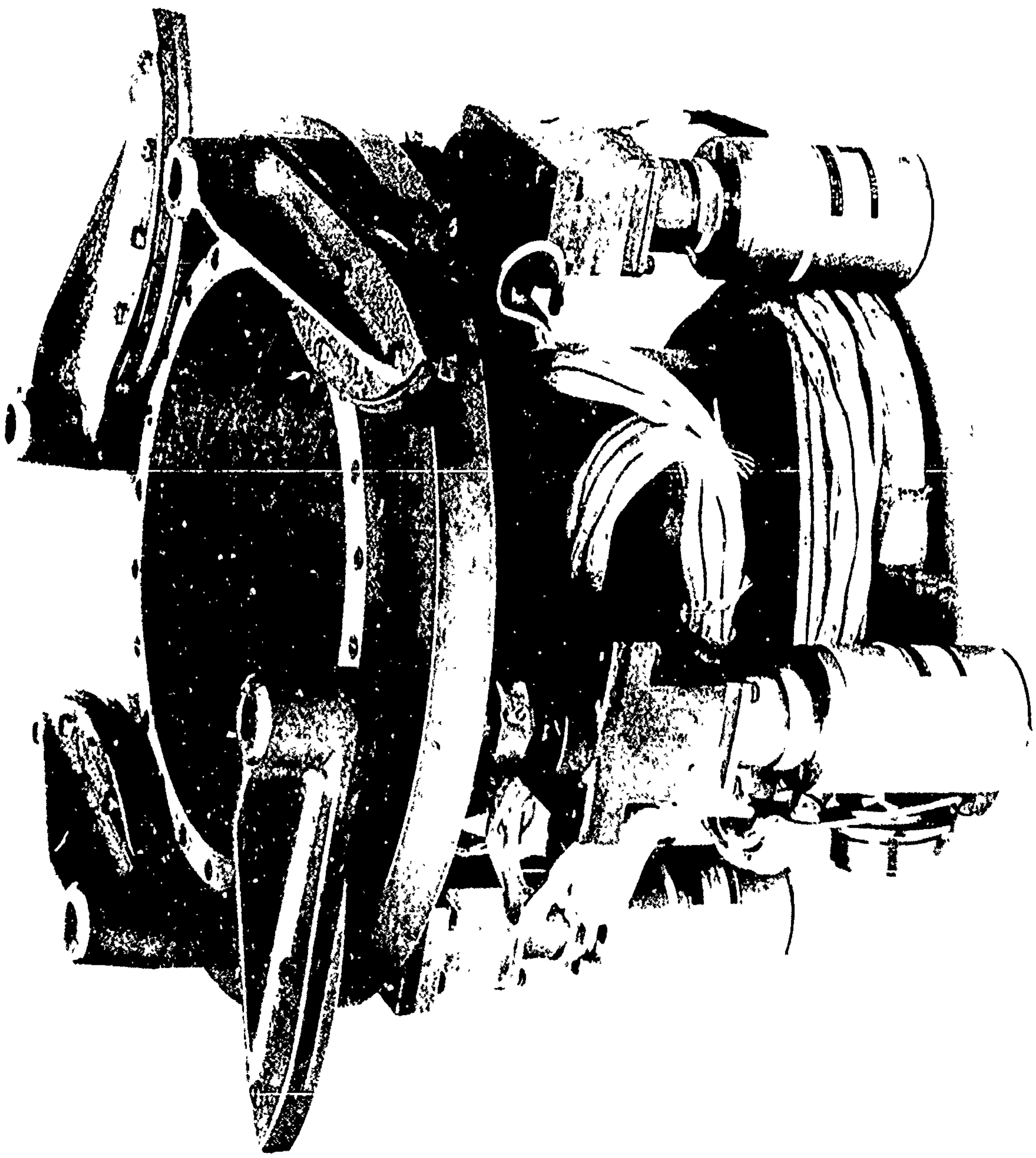


Figure 4-2. Integrated TVC System

4.1.1 Nozzle Assembly

The nozzle assembly shown in Figure 4-3 consists of a liner, housing and screws. The housing is fabricated from a 17-4 PH steel casting. Provisions for the tab shaft bearings are machined in the integrally cast lugs. The bearing races, the liner interface and mounting provisions, a bearing surface for the aerodynamic shroud, and the housing/motor aft closure thread joint are the only required machining operations.

The exit liner is tape wrapped from silica cloth tape impregnated with phenolic resin and cured at elevated temperatures and pressures. The liner is bonded to the nozzle housing using an RTV silicon rubber. In addition, the liner is attached to the nozzle housing by tantalum screws.

4.1.2 Tab Assembly

The tab assembly, shown in Figure 4-4, is comprised of a steel shaft and support, blade and shaft insulation, refractory metal blade, and refractory screws. The shaft and support weld assembly is the load carrying member and is fabricated from 17-4 stainless. The shaft is broached to mate with the spline on the DC gear motor. Close tolerance

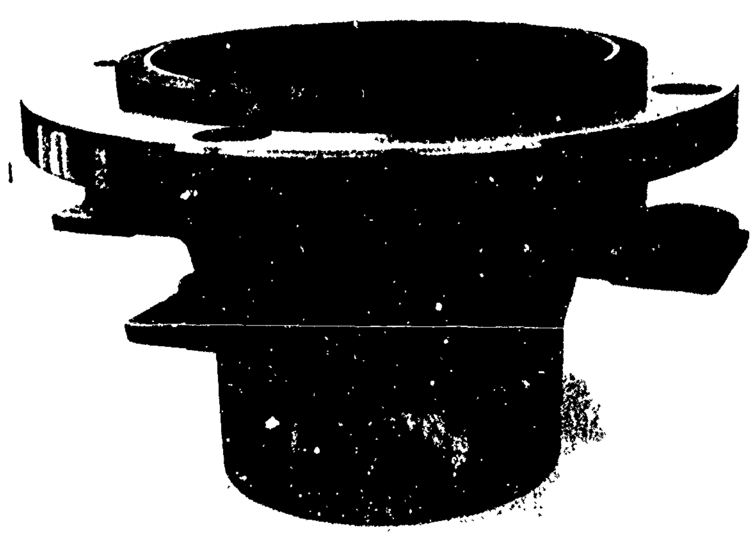


Figure 4-3. Nozzle Assembly

Figure 4-4. Tab Assembly Components

machining is required for the bearing races only. The support is cast to final dimensions with machining required only at the shaft and insulation interfaces. The blade and shaft insulation is compression molded from glass phenolic material. The success of the jet tab concept is primarily due to the function of this insulation in terms of restricting the heat flow from the blade to the shaft and connecting thermally sensitive components (bearings, gear motor, and electronics). The refractory blade is machined from molybdenum, which results in a high temperature flame deflector. Selection of the material and thickness for this part was one of the major areas of low cost material investigation conducted during the program. Tantalum screws are used to fasten the blade to the support.

4.1.3 Bearings and Miscellaneous Hardware

A shaft spacer controls the gap between the nozzle exit plane and the blade face during assembly. The required gap is determined by thermal expansion effects and aluminum oxide accumulation to assure no binding or interference during operation.

The needle roller bearing located at the aft end of the tab shaft is typical for applications where the diametrical space is limited. The rollers are relatively long compared to their diameter and as a result, the bearings can effectively carry heavy radial loads.

The thrust loads are reacted through a bronze bearing which is located at the forward end of the shaft. The radial load from the bending moment couple is also carried by this bearing. The bronze thrust bearing was selected for use on this program rather than the radial contact ball bearing used on the JBQM-34H because of its reduced size and potentially lower production cost.

A mechanical stop is provided to limit the possibility of excessive tab travel in the event of a controller malfunction. The stop is attached to the tab shaft. The relative position of the miscellaneous components in relation to the tab assembly is indicated in Figure 4-5.

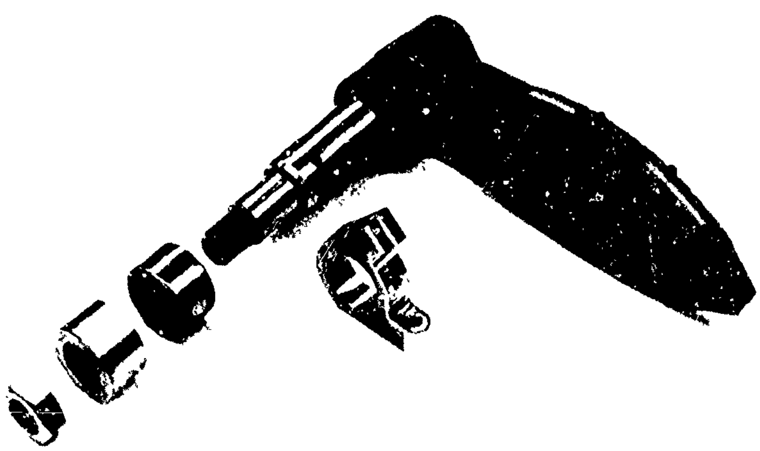


Figure 4-5. Tab Assembly and Bearings

4.1.4 Electromechanical Actuator

Tab actuation is provided by a permanent magnet DC gear motor manufactured by TRW Globe Industries. The planetary gear train provides a compact electromechanical device of minimal diameter, minimal backlash, and high efficiency. Anti-friction bearings in each planetary stage result in efficiencies of over 90 percent per stage. The high reliability and long term storage capability are similar to the requirements for the RPV on-board electronics and electrical systems. The high torque output, compact diameter, and off-the-shelf availability which led to the selection of the basic motor and gear train for the JBQM-34H program were considered applicable to the BGM-34C low cost requirements.

In a proportionally controlled system, a means of constantly monitoring tab position is required. During the JBQM-34H program a separate position potentiometer was annularly mounted on the tab shaft. To reduce overall system cost and improve reliability and performance, the potentiometer elements were incorporated into the gear head for this program. A comparison of the two actuator systems is shown in Figure 4-6. The internal gear head components, including position potentiometer feedback elements, are illustrated in Figure 4-7.

The actuator installation shown in Figure 4-8 provides for a separate motor mount which attaches to the nozzle housing. The motor mount positions the gear head such that torque is transmitted to the tab shaft on command through the gear head output splined shaft.

Performance curves for the permanent magnet motor are shown in Figure 4-9. Overall gear motor characteristics are presented in Table 4-2. Because of the TRA GLICU output limitations, it was found necessary, late in the program, to provide a higher gear ratio on the pitch axis actuators. Because of time constraints, only the pitch axis actuators were reworked. For a production program, all actuators would be identical.

4.1.5 Aerodynamic Shroud

To protect the jet tab TVC system from damage during booster motor installation on the RPV, a light weight sheet metal shroud was provided on the JBQM-34H program. The shroud also protected the TVC system from the RPV turbojet exhaust during flight. Distortion of the sheet metal

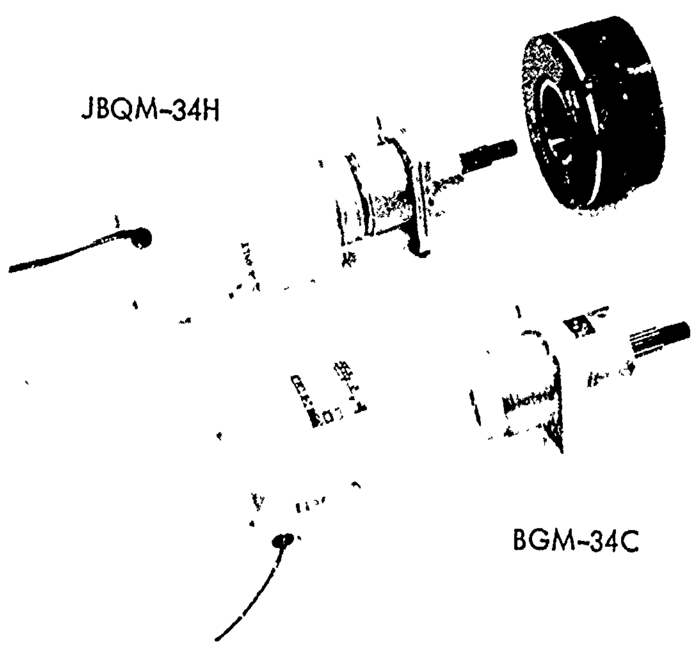


Figure 4-6. Electromechanical Actuator

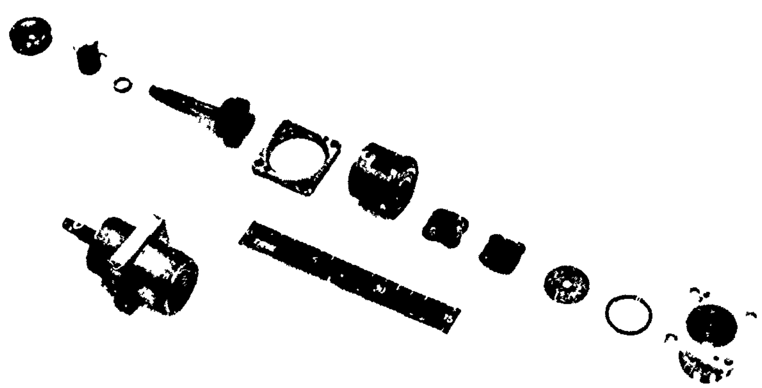


Figure 4-7. Planetary Gear Head and Potentiometer

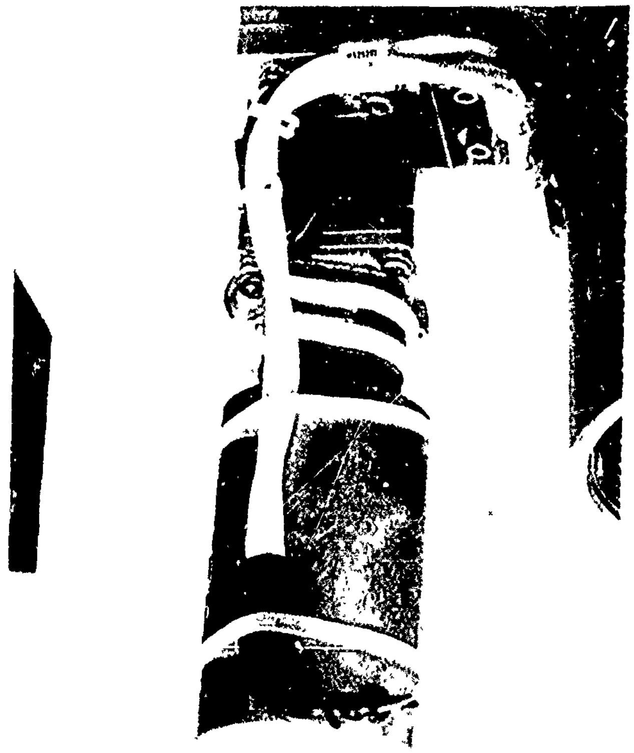


Figure 4-8. Actuator Installation

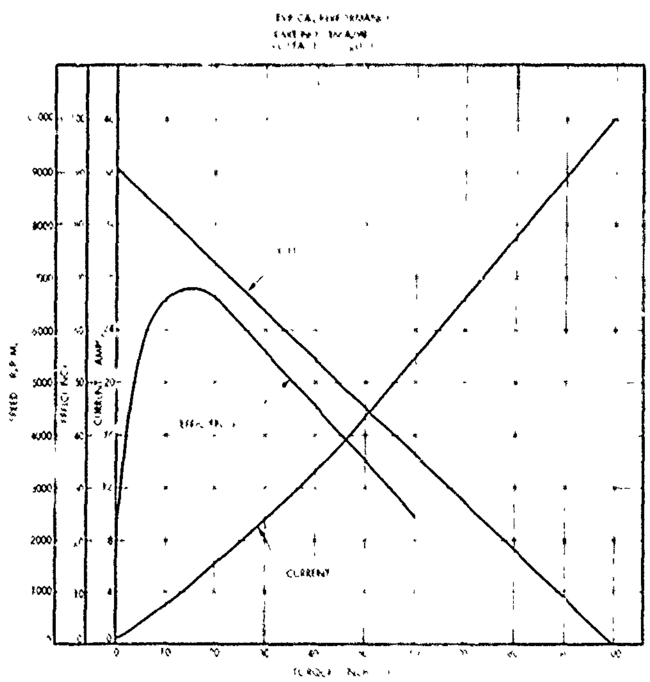


Figure 4-9. Motor Torque Speed Characteristics

Table 4-2. Gear Motor Characteristics

Voltage	27 VDC	
Motor Speed, No Load	9000 ± 500 RPM	
Torque		
Max. Rated	10 oz-in	
Nom. Stall	100 oz-in (Theoretical)	
Current		
Max. No Load	0.8 amps	
Max. Rated Load	3.4 amps	
Nom. Stall	40.0 amps	
Motor Weight	40 oz.	
Armature Inertia	165 gm cm^2	
Magnets	Alnico V	
Housing	Cadmium Plated	
Shaft	420 S. S. (Rc 45-50)	
Gear Trains	1 7/8" Flange	
	Roll Axis*	Pitch Axis
Speed Reduction Ratio	117:1	170:1
Torque Multiplier	99	144

*For a production program, roll axis actuators would be identical to pitch axis.

structure resulted in binding on the tab shaft and restriction in tab rotation during flight. To prevent the recurrence of this problem, the shroud was redesigned to avoid any potential contact.

An additional requirement imposed on the shroud was to provide thermal protection for the TVC system during a five minute turbojet engine run up prior to launch. A blast deflector, which was dropped just prior to launch, was used during the JBQM-34H program.

The reduction in the jet tab TVC size allowed the use of a simple fiberglass cylinder, the same outer diameter as the solid rocket motor, to meet the design criteria. Mandrel lay-up molding of the fiberglass part resulted in a much lower cost than the complex sheet metal structure. The shroud shown in Figure 4-10 was used during three PFRT test firings with no problems. The shroud, which connects to the rocket motor skirt, has an elastomer insert which fits to the nozzle housing outer diameter. Provisions are made for feed through of the electrical control cable which connects to the RPV.

Figure 4-10. Protective Shroud

4.2 MATERIALS SELECTION

One of the major objectives of this program was to examine potential low cost materials for incorporation into an improved, lower-cost version of the design resulting from Contract F04611-73-C-0013. The most promising areas of investigation included the tab face and insulation, scraper ring, and exit cone liner. Final selection was based on the results of the test firings.

4.2.1 Nozzle Liner

The nozzle exit liner material used in the demonstrated JBQM-34H TVC configuration was a well characterized carbon cloth phenolic (MX4926). Potential materials which offered a reduced erosion resistance at substantially lower cost were silica cloth phenolic (MX2600) and a pitch carbon fabric phenolic (Hexcel 4C1008). The two materials exhibited nearly identical erosion resistance. As the pitch carbon phenolic is not expected to be any lower in cost, the proven and well characterized silica phenolic was selected.

4.2.2 Scraper Ring

Because of the low risk approach used during the JBQM-34H program, an infiltrated tungsten scraper ring was used at the nozzle exit plane to eliminate the effects of gas wash when a tab was inserted. During that program, molybdenum had been used with no apparent difficulty. The lowest cost approach, however, would be to eliminate the refractory metal with its attendant insulator and steel retaining ring. By extending the nozzle liner to include the scraper ring function, several parts could be eliminated as shown in Figure 4-11. The only attendant problem was the extent of performance degradation associated with the eroding nozzle exit.

In addition to a molybdenum scraper ring, three ablative materials were tested. The two nozzle liner materials, MX2600 and pitch carbon fabric phenolic, were tested in addition to carbon cloth phenolic (MX4926). The erosion characteristics and resultant minimal reduction in vector performance allowed the use of a single piece of silica phenolic.

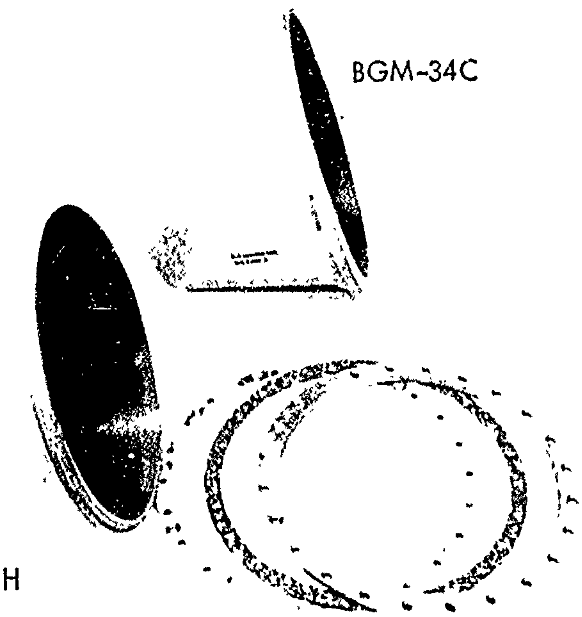


Figure 4-11. Nozzle Liner/Scraper Ring Comparison

4.2.3 Tab Insulators

The demonstrated insulator between the tab refractory face and the structural support was fabricated from compression molded chopped squares of silica cloth phenolic (MX2625). Two grades of asbestos phenolic molding compounds (RPD110 and RPD153) and a glass phenolic molding (FM16771) were evaluated. The glass phenolic provided adequate insulation properties at the minimum cost.

4.2.4 Tab Facing

The silver infiltrated tungsten tab facing was considered to be a prime item for low cost material application. Molybdenum had been used on the previous program and was considered marginally adequate. The approach used during this program was to provide a material of sufficient thickness to allow sacrificial erosion to occur in order to accomodate the long duration tab exposure duty cycles. Both carbon cloth phenolic (MX4926) and various thicknesses of molybdenum were tested. The carbon phenolic proved unsatisfactory from an erosion standpoint in the high aluminum content motor exhaust environment. Problems encountered in establishing the desired thickness of molybdenum facing were the prime reasons for extending the materials evaluation into the PFRT test hardware. The results of this investigation are discussed in detail in Section 5.

4.2.5 Tab Refractory Bolts

The bolts used to fasten the tab face to the structural support were fabricated from a tantalum-tungsten alloy (TA-10W). The material selection was satisfactory, however, a design change was made when test difficulties were encountered. During the JBQM-34H program and the early part of this program, the bolts, Figure 4-12, were installed with a countersunk head from the tab facing through clearance holes in the support. Problems were experienced with the near loss of bolt heads. This problem was eliminated by installing the bolts from the support into tapped holes in the refractory face.

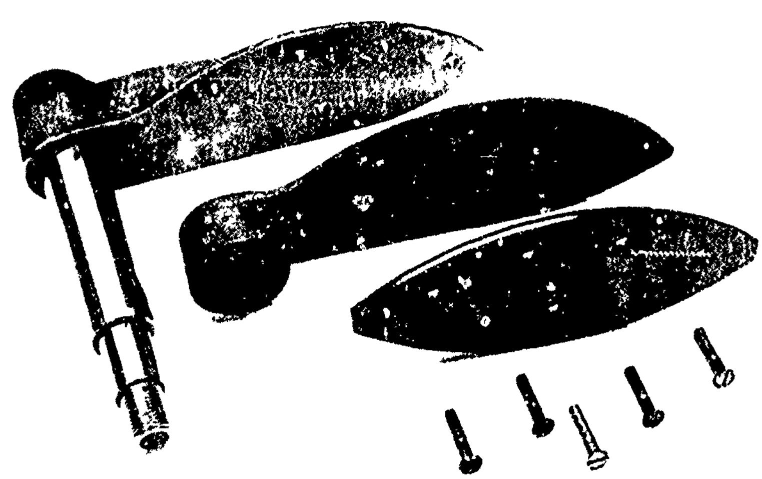


Figure 4-12. Countersunk Tab Screw Installation

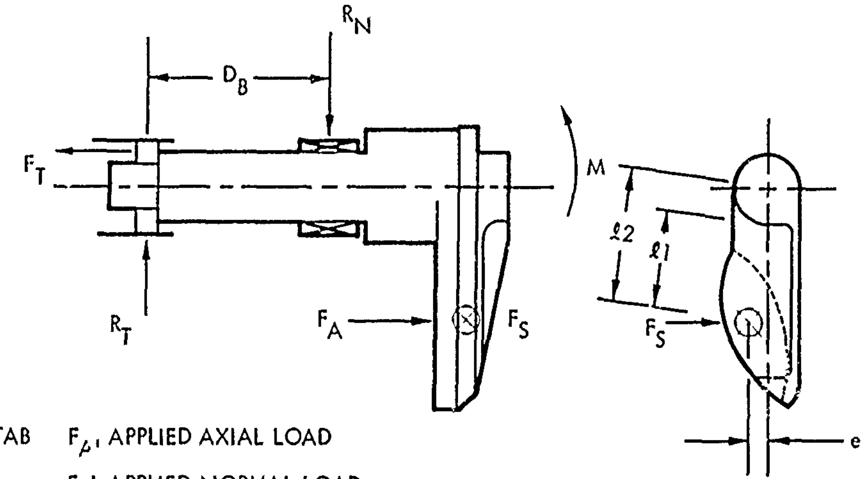
4.3 STRUCTURAL ANALYSIS

On previous programs, the jet tab assembly has been specially instrumented to determine the induced loads on the tab steel support and rotating shaft. Strain gauge data on these members showed that the axial force loads in the shaft in pressure applications of the range of this system resulted in an average of 20 percent of chamber pressure acting over the exposed area of the tab. The free body diagram presented in Figure 4-13 shows the reaction of the tab system to this applied load. The critical stress areas determined for the jet tab TVC system are shown in Figure 4-14.

The support bending stresses are dependent upon the area of the tab inserted, the moment arm to the pressure center (ℓ_1), and the applied load offset from the support's neutral axis. The shaft bending stresses are dependent upon these same parameters except for a larger moment arm (ℓ_2). The shaft torsional stresses are dependent upon the spring loads caused by the gas stream pressures and the internal frictional resistances of the bearings due to the applied loads. The radial loads on the needle bearing and thrust bearings are dependent upon the bending moment applied to the shaft and the axial distance between the bearings (d_b). The axial load on the thrust bearing is equal to the axial force applied to the system by the nozzle exhaust pressure.

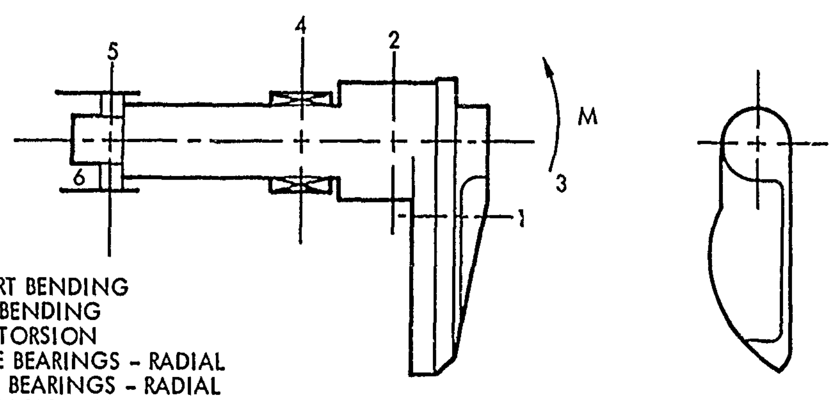
The design conditions used for the stress analysis are presented in Table 4-3. No detailed thermal analysis was conducted as a part of this program. The temperature conditions predicted during the JBQM-34H program were considered adequate for use in this application.

Because of the similarity of the nozzle configuration and the large margins present in the prior design, no analysis was required in the nozzle housing. For the tab support and bearings, positive margins of safety were indicated for all stress areas. The critical stress areas are summarized in Table 4-4.



$F_A \simeq 0.2 P_C A_{TAB}$	F_A, APPLIED AXIAL LOAD
$F_S \cong 0.06\ F_A$	F_S, APPLIED NORMAL LOAD
$M = F_S \ell_2$	M, BENDING MOMENT ON SHAFT
$R_N = R_T$	$R_{N,\ T}$, RADIAL LOADS IN BEARINGS
$R_N = \frac{M}{D_B}$	D_B, DISTANCE BETWEEN BEARINGS
$F_T = F_A$	F_T, AXIAL LOAD APPLIED TO THRUST BEARING

Figure 4-13. Free Body Force Diagram of the Tab Assembly



(1) SUPPORT BENDING
(2) SHAFT BENDING
(3) SHAFT TORSION
(4) NEEDLE BEARINGS - RADIAL
(5) THRUST BEARINGS - RADIAL
(6) THRUST BEARINGS - AXIAL

Figure 4-14. Critical Stress Areas for Jet Tab

Table 4-3. Stress Analysis Design Conditions

Nozzle	
Pressure at Throat	468 psig
Pressure at Nozzle Exit	33 psig
Temperature	100°F
Material	17-4 PH Steel
Tab Support	
Axial	1700 lb_f
Side Load	100 lb_f
Temperature	800°F
Material	17-4 PH Steel

Table 4-4. Critical Stress Areas

Station	Type of Load	Load Estimate	Safety Factor
1	Support Bending	5500 in-lb_f	2.08
2	Shaft Bending	7150 in-lb_f	1.98
3	Shaft Torsion	420 in-lb_f	4.69
4	Needle Bearing Radial	3100 lb_f	1.92
5	Thrust Bearing Radial	3100 lb_f	5.04
6	Thrust Bearing Axial	1700 lb_f	6.85

5.0 ROCKET MOTOR TESTING AND HARDWARE DESCRIPTION

As a part of this program, nine jet tab TVC systems were tested at the AFRPL on booster motors developed from the Genie solid rocket motor. The tests were designed to accomplish the following objectives.

- Two product improvement units, JBQM-34H configuration
  - Evaluate molybdenum and carbon phenolic for scraper ring and tab facings
  - Evaluate pitch carbon fabric phenolic and silica cloth phenolic as exit cone liners
- Seven PFRT units, BGM-34C configuration
  - Optimize molybdenum tab facing thickness
  - Evaluate pitch carbon fabric phenolic and silica cloth phenolic for scraper ring
  - Verify actuation system characteristics and performance
  - Demonstrate tab system performance in providing vectored thrust
  - Demonstrate compatibility with the TRA GLICU
  - Measure thrust degradation

A detailed description of all hardware is provided in this section along with a narrative discussion of material performance. Performance comparisons are in Section 7.

5.1 PRODUCT IMPROVEMENT UNITS

The first two test firings conducted during the program were designed to provide a quick evaluation of materials and/or components which had a potential for cost reduction and/or performance improvement over the design resulting from Contract F04611-73-C-0013. Of particular interest were changes to the tab facing, tab insulator, scraper ring, exit cone liner and thrust bearing materials. The various combinations of materials investigated in relation to the original configuration are shown in Table 5-1.

Table 5-1. Product Improvement Test Hardware

COMPONENT	ORIGINAL CONFIGURATION	PI-1	PI-2
Nozzle Liner	MX 4926 Carbon Phenolic	Hexcel 4C1008 Pitch Carbon	MX2600 Silica Phenolic
Scraper Ring	Silver Infiltrated Tungsten	Molybdenum	3 Quadrants-Molybdenum 1 Quadrant-Carbon Phenolic
Tab Refractory	.15 in. Silver Infiltrated Tungsten	2 Tabs-.25 in. Molybdenum 1 Tab-.375 in. Molybdenum 1 Tab-.50 in. Carbon Phenolic (No Insulator)	1 Tab-.25 in. Molybdenum 2 Tabs-.375 in. Molybdenum 1 Tab-.50 in. Carbon Phenolic (No Insulator)
Tab Insulation	.30 in. Silica Phenolic	1 Tab-.20 in. Silica Phenolic (Instrumented) 1 Tab-.20 in. Glass Phenolic 1 Tab-.20 in. Asbestos Phenolic	2 Tabs-.20 in. Silica Phenolic (Instrumented) 1 Tab-.20 in. Asbestos Phenolic
Thrust Bearing	Ball Bearing	Same as Original	1 Tab-Same as Original 3 Tabs-bronze Bushing

To provide a basis for performance comparison, the product improvement test firings were conducted using residual hardware from the JBQM-34H program. Maintaining the same hardware configuration and using the TU-752 solid motor allowed direct comparison with the prior program test results.

5.1.1 Test Unit PI-1

The most obvious cost reduction with minor changes to the existing design was the use of materials for the flame exposed components which would provide a lower thermal margin at a reduced cost. For the refractory metal components, molybdenum had been previously tested and while it met all the performance requirements, it had experienced some melting and warpage. Increasing the mass and thermal capacity were expected to alleviate excessive material degradation.

Examination of sectioned ablative components from the JBQM-34H TVC system indicated a considerable thermal margin existed in the baseline configuration. Lower cost materials could be incorporated with little or no reduction in performance.

The first test unit, shown in Figure 5-1, was assembled using residual structural parts. The specific new material combinations tested are indicated in Table 5-2. The pitch carbon nozzle liner was fabricated on a mandrel in tape wrap form using 1.125 inch straight tape woven pitch fabric. The insulators and ablative blade, except for the silica phenolic molded insulator, were machined from flat laminate moldings. All molybdenum parts were machined from powder metallurgy grade molybdenum plate. Thermocouples were installed in tab 4 to determine the thermal response of the refractory.

Actuation was provided using residual gear heads and position potentiometers. The DC permanent magnet motors were new items to avoid any possibility of degradation resulting from the demagnetization which occurs during a test firing.

5.1.2 Test Unit PI-2

The second test unit used residual hardware to the same extent as PI-1 except in the area of thrust bearings. The size of the radial contact ball bearings was not compatible with the reduced size of the BGM-34C configuration. Changing to a more compact bronze bushing would reduce the size and also provide potential for a lower production cost. No problems were anticipated as bronze bearings had been used on jet tab systems under much higher loading conditions.

The material combinations indicated in Table 5-3 provided for additional test data on the molybdenum and ablative tab facings. A second asbestos phenolic insulating material, RPD153, was also provided. The ablative facing and asbestos insulator were both machined from molded billet form material. To evaluate potential low cost materials more effectively, a carbon phenolic segment of the scraper ring contour was provided. This part was fabricated from the same MX4926 molded billet as the tab facing. The nozzle exit cone liner was tape wrapped using 1.75 inch wide silica phenolic and the same mandrel as PI-1. The carbon phenolic tab facing and scraper ring insert are indicated in Figure 5-2.

As in the first test unit, the molybdenum refractory parts were machined from powder metallurgy grade plate. The two .375 inch thick tab facings were instrumented for thermal response.

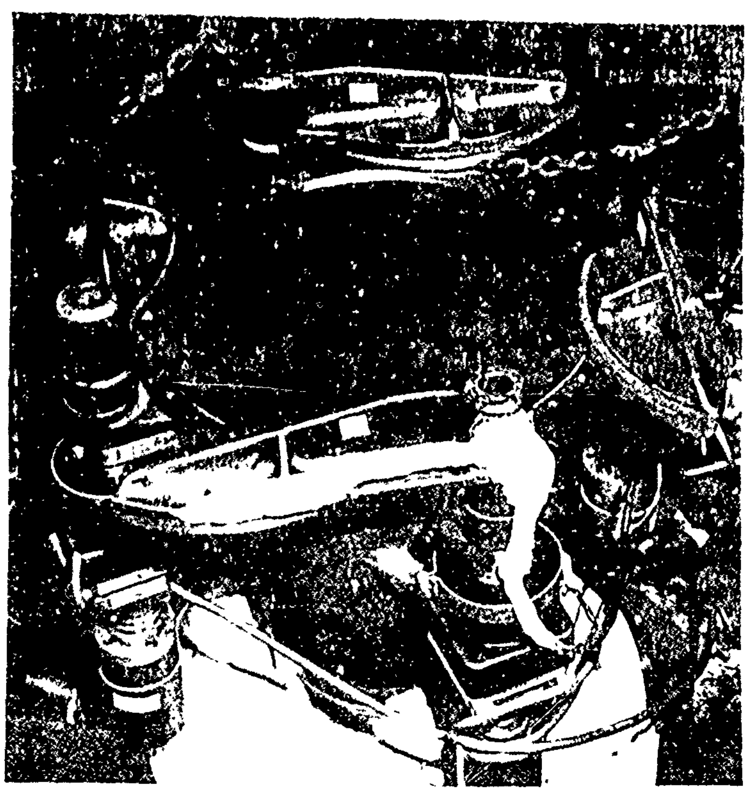


Figure 5-1. Product Improvement Test Hardware

Table 5-2. Product Improvement Unit PI-1 Material Locations

Tab No.	1	2	3	4
Tab Facing	.25 in. Molybdenum	.25 in. Molybdenum	Carbon Phenolic MX4926	.375 in. Molybdenum
Insulator	FM 16771 Glass Phenolic	RPD110 Asbestos Phenolic	None	CA2221 Silica Phenolic
Nozzle Liner	Pitch Carbon Hexel 4C1008			
Scraper Ring	Molybdenum			

Table 5-3. Product Improvement Unit PI-2 Material Locations

Tab No.	1	2	3	4
Tab Facing	.375 in. Molybdenum	.375 in. Molybdenum	.25 in. Molybdenum	MX4926 Carbon Phenolic
Insulator	CA2221 Silica Phenolic	CA2221 Silica Phenolic	RPD153 Asbestos Phenolic	None
Scraper Ring	Molybdenum	Molybdenum	Molybdenum	MX4926 Carbon Phenolic
Thrust Bearing	Bronze Bushing	Ball Bearing	Bronze Bushing	Bronze Bushing
Nozzle Liner	Silica Phenolic MX2600			

Figure 5-2. Ablative Scraper Ring Segment

5.1.3 Product Improvement Test Firings

Both product improvement test firings were successfully accomplished. The test firings were conducted at the AFRPL with the jet tab TVC system installed on a TU-752 solid rocket motor. Test unit PI-2, installed on the AFRPL 40 inch Char motor thrust stand, is shown in Figure 5-3.

For test firing PI-1, the tab operation sequence indicated in Figure 5-4 provided a maximum of 1.6 seconds exposure on the instrumented tab.

The post test condition of the hardware was excellent. Only minimal erosion was experienced on the molybdenum tab faces. The most extreme erosion experienced was with a 0.25 inch thick facing, Figure 5-5, inserted for a total accumulated time of just over one second. Approximately .032 inch of material removal was experienced. The performance of the carbon phenolic face during one-half second of insertion was very encouraging. The erosion of the pitch fabric nozzle liner was well within acceptable limits. The material performance in all areas indicated no required changes in the parts for PI-2.

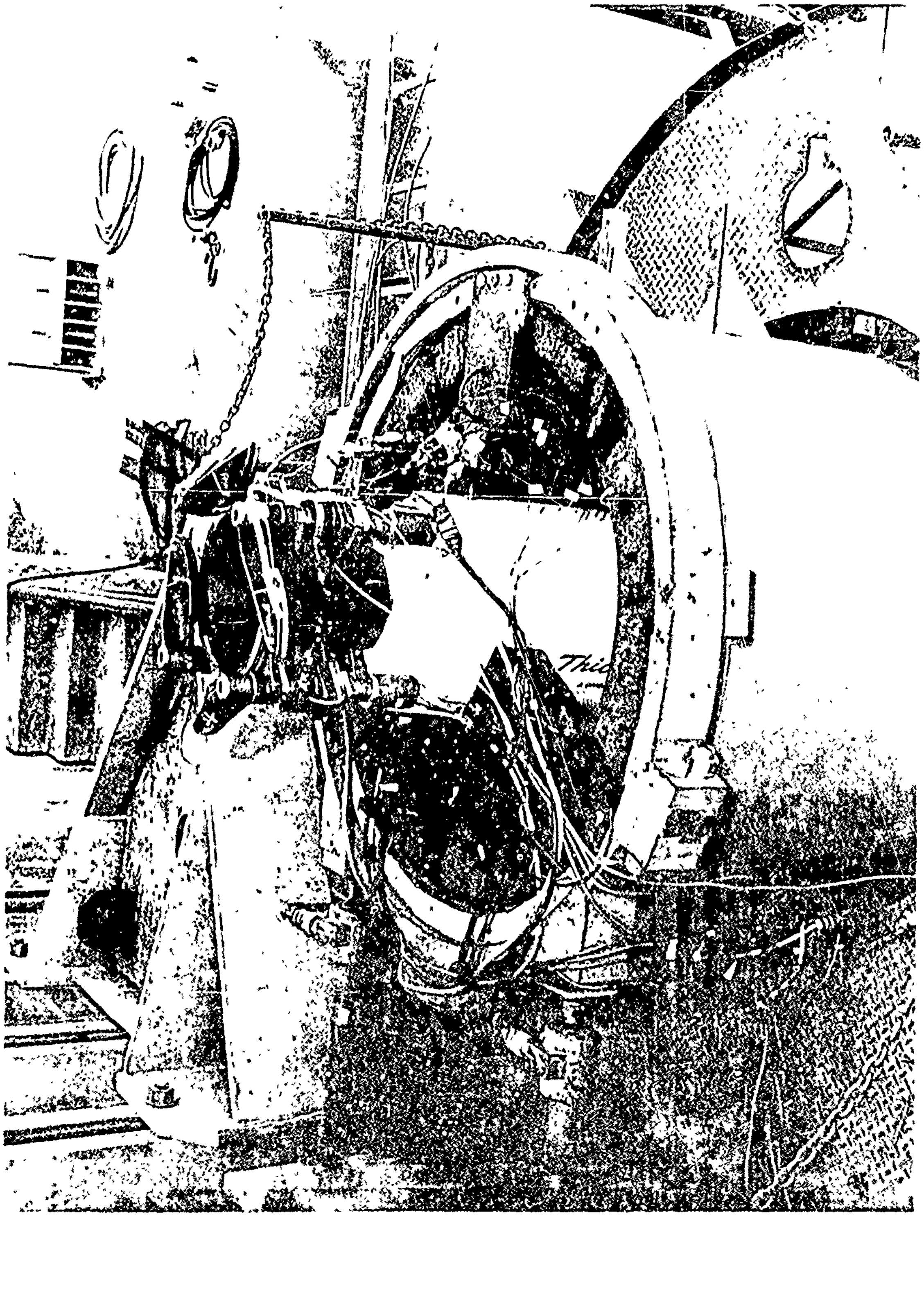


Figure 5-3. Test Unit PI-2 Installed on AFRPL Char Motor Stand

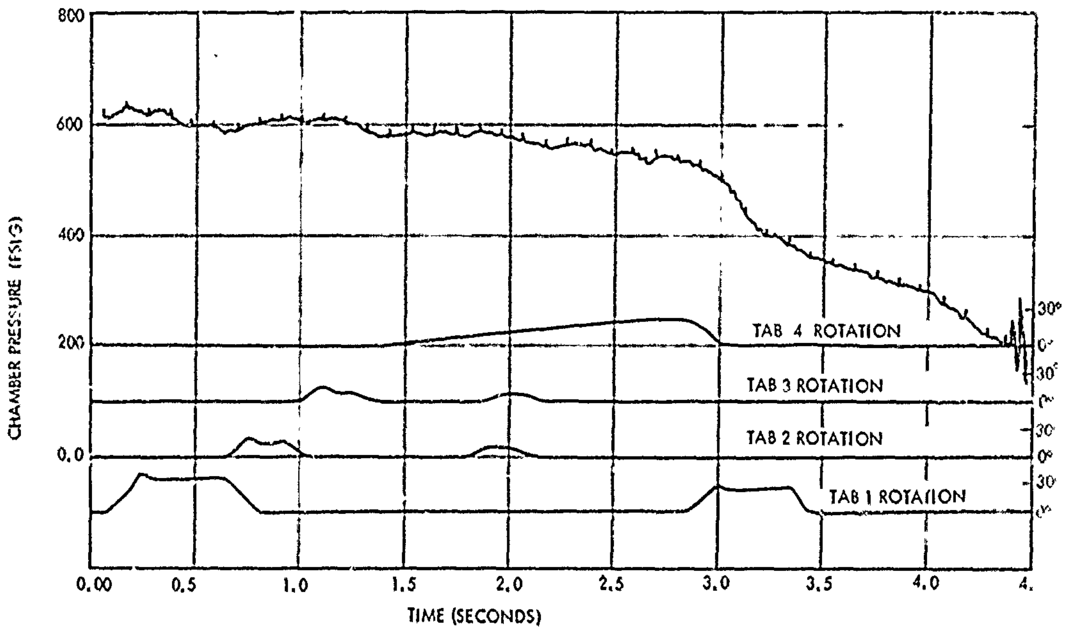


Figure 5-4. Motor Chamber Pressure and Tab Actuation, PI-1

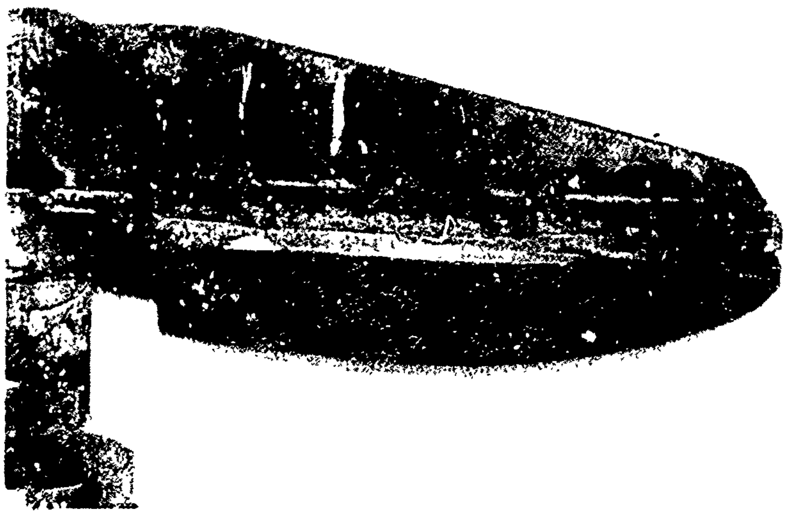


Figure 5-5. PI-1 Tab 1 Post Test

PI-2 subjected the tab system to a more extensive duration to determine the capability of meeting the longer duration firings during PFRT. As indicated in Figure 5-6, the duty cycle used during test firing PI-2 provided 2.2 seconds of insertion time on the carbon phenolic tab and on two of the three molybdenum tabs, and 2.6 seconds on the third molybdenum tab. With the exception of the carbon phenolic tab, the post test condition of the unit as shown in Figure 5-7 was excellent. The maximum amount of erosion experienced on the three refractory tabs was nearly identical and amounted to .10 inch. However, material erosion occurred over a larger area on the .25 inch thick tab than was experienced with the two .375 inch thick parts. Erosion of the carbon phenolic tab face was severe over the entire exposed area (Figure 5-8).

Performance of the silica phenolic liner was very good with the maximum erosion, which occurred directly under the tab, being nearly equal to the pitch carbon part tested on PI-1.

The performance of the molybdenum scraper ring was excellent with no noticeable erosion occurring. The carbon phenolic exit ring installed in one quadrant exhibited very little material loss. In fact, post test char swell between the exit ring and the carbon phenolic tab face reduced the gap to nearly zero.

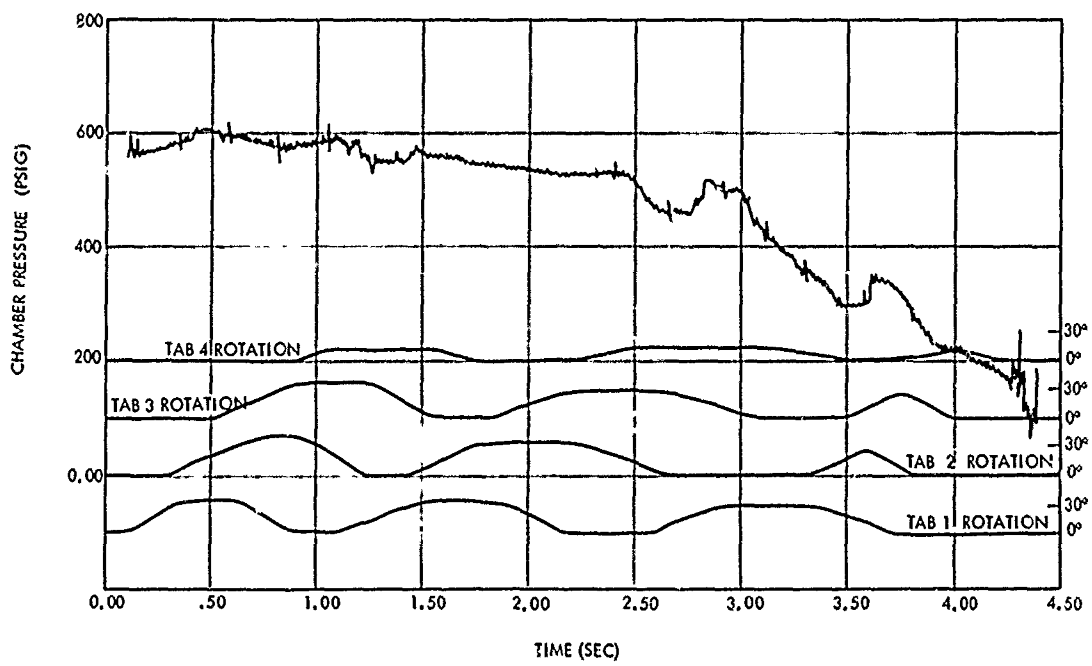


Figure 5-6. Motor Chamber Pressure and Tab Actuation, PI-2

Figure 5-7. PI-2 Post Test

Figure 5-8. Carbon Phenolic Tab Facing-Post Test

The only problem experienced during the firing was a reduction in the amount of tab insertion achieved in relation to the input command. Subsequent data review indicated that a reduction in the voltage level applied to the DC motor had occurred in both product improvement test firings in relation to a firing conducted with a TRW IR&D unit prior to the initiation of this contract.

An extensive test program was implemented at AFRPL to determine the reason. It was subsequently found that the new power supplies used on the product improvement test firings were current limiting, thus causing a drop in output voltage when the tab motor was under load during firing.

5.1.4 Product Improvement Test Summary

In evaluating the results of the product improvement tests, with the exception of the carbon phenolic tab facing, all low cost materials provided satisfactory performance in the solid motor exhaust environment.

Both nozzle exit liner materials exhibited equal erosion under the tab for equivalent duty cycles (Figure 5-9). For the scraper ring material, no appreciable erosion was measured. As can be seen in Figure 5-10, the erosion experienced on the carbon phenolic insert was minor (tab insertion angles, however, were low).

The three low cost insulating materials all exhibited adequate thermal margins. The relative char depth for equivalent exposure time is shown in Figure 5-11. An equivalent amount of erosion was experienced on both thicknesses of molybdenum tested. A relative comparison of the four tab facings used during test PI-2 is shown in Figure 5-12. A summary of thermal response of the instrumented tab facings is shown in Table 5-4.

The bronze bushings exhibited no problems in functioning as the major thrust bearing.

5.2 PRELIMINARY FLIGHT RATING TEST (PFRT) UNITS

On the basis of the two product improvement test firings, the safe, conservative design approach included a silica phenolic nozzle liner, molybdenum scraper ring, a tab assembly with a .375 inch thick molybdenum tab face, and an FM16771 glass phenolic insulator.

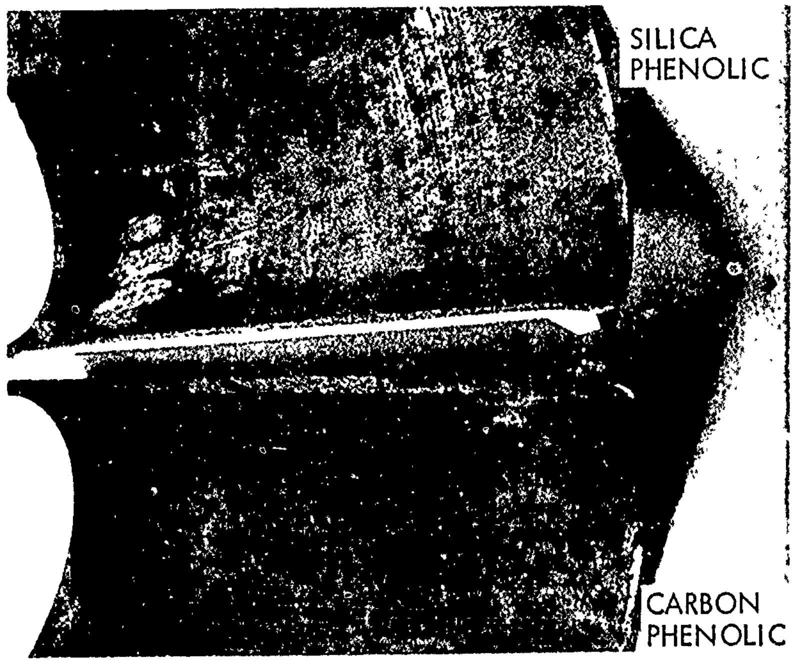


Figure 5-9. Nozzle Liner Erosion Comparison

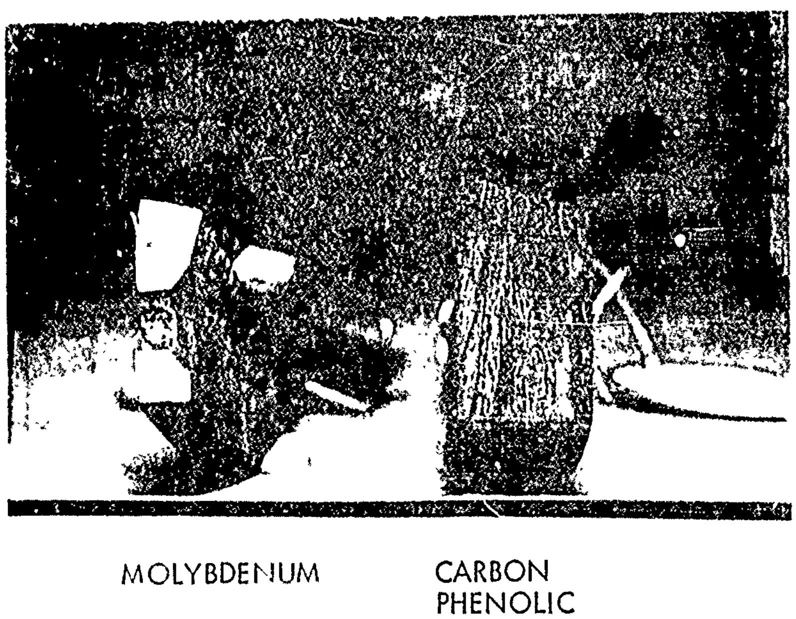


Figure 5-10. Scraper Ring Materials

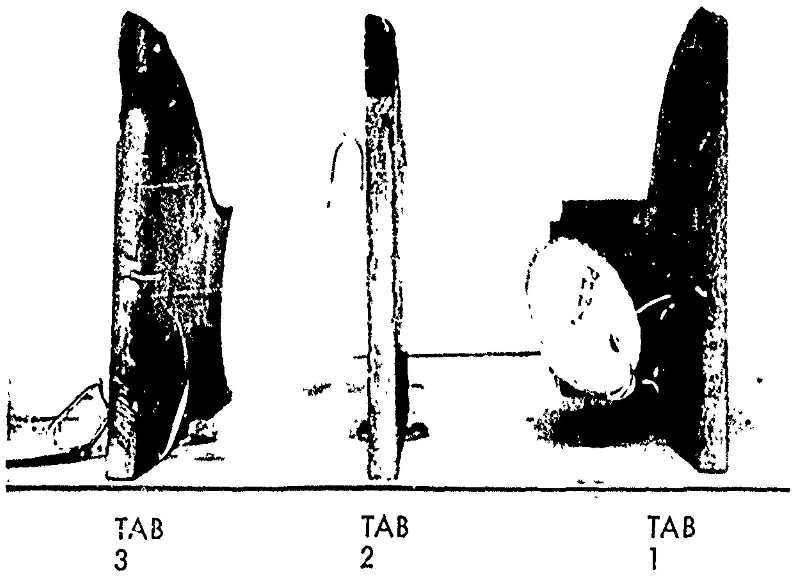


Figure 5-11. Blade Insulator Test PI-2

Figure 5-12. Tab Facing Erosion Test PI-2

Table 5-4. Thermal Summary-Refractory Thermocouples

TEST	TAB NO.	TOTAL INSERTION (SEC)	MAXIMUM TEMP. (°F)
PI-1	4	1.6	2350
PI-2	1	2.6	3000
PI-2	2	2.2	3000

There were, however, two major potential design changes which would have a significant impact on production unit costs: changing the scraper ring to an ablative integral with the nozzle liner and reducing the thickness of the tab refractory face. Both of these changes were tested during the product improvement program and showed considerable promise. However, there was insufficient test data to assure satisfactory performance with the longer duration firings of the TU-793/03 motor.

Because of the large potential for cost savings in a production program, it was agreed that additional material investigation testing during the PFRT program was desirable.

A technical program approach was outlined based on the first three PFRT test units being used for additional material testing in the area of nozzle liner material and molybdenum tab facing thickness.

A description of the hardware configuration agreed upon for each of the special PFRT test units is summarized below:

PFRT Unit Number One:

1. Two tabs to be supplied with .375 inch molybdenum face.
2. Two tabs to be supplied with .19 inch molybdenum face.
3. A pitch carbon phenolic nozzle liner/scraper ring.

PFRT Unit Number Two:

1. Two tabs to be supplied with .25 inch molybdenum face.
2. Two tabs to be supplied with .19 inch molybdenum face.
3. A silica phenolic nozzle liner/scraper ring.

PFRT Unit Number Three:

1. Two tabs to be supplied with .25 inch molybdenum face.
2. Two tabs to be supplied with .375 inch molybdenum face.
3. A silica phenolic nozzle liner to be used.
4. To have a molybdenum scraper ring.

5.2.1 Test Unit PFRT-01

The first unit of the smaller (9.0 inch exit diameter) BGM-34C configuration is shown in Figure 5-13. The nozzle exit liner was fabricated from an annealed 17-4 PH stainless steel casting. The nozzle exit liner was fabricated from Hexcel 4C1008 pitch carbon fabric tape wrapped parallel to the nozzle centerline. The nozzle exit was extended to provide sufficient thickness to withstand expected erosion during tab insertion. The liner was bonded to the housing using RTV 560. As a back up the extended flange was attached to the housing using Ta/10W screws.

The tab assembly configuration was similar to that used on the product improvement units. The support structure was machined from bar stock and welded to the support and heat treated to condition H900. The tab facing was machined from molybdenum powder metallurgy plate of the proper thicknesses noted above. The insulator between the refractory face and the support was compression molded from FM16771 glass phenolic and included an increased section thickness around the shaft to provide protection from the effects of gas wash during tab insertion. The components of the tab assembly were fastened together using Ta/10W screws. A potential problem of erosion of the refractory screw heads with face material loss was indicated on the product improvement units. As an alternative to using countersunk screws installed from the refractory side, the molybdenum was tapped and the screws installed from the support side. Both configurations were incorporated and are shown in Figure 5-14.

The thrust vector requirements for the system were established at six degrees in pitch and three degrees in roll. The use of smaller tabs, and possibly actuators, in the roll axis would provide a cost reduction on a production basis. However, cost estimates for the quantities involved on this program indicate that the two sizes of tabs would be more expensive. As only one set of casting and mold tooling was provided, the cost of

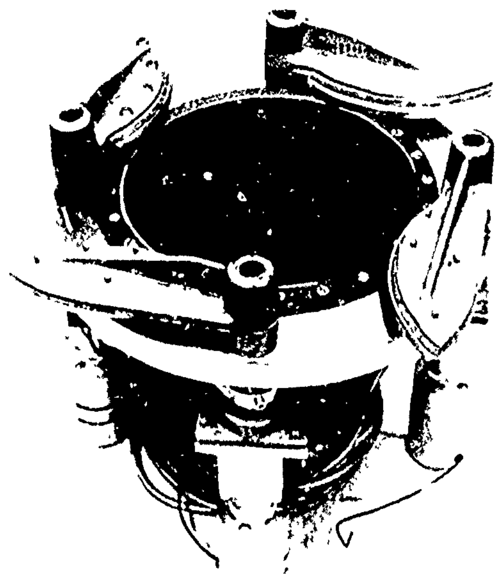


Figure 5-13. Test Hardware PFRT-01

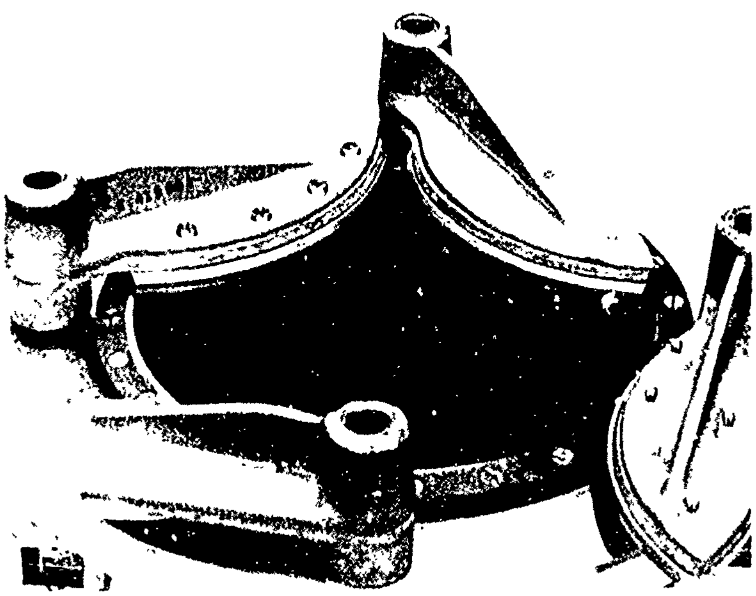


Figure 5-14. Tab Assembly Fasteners

machining the smaller units was not offset by the reduced refractory material. In fact, to provide all PFRT and flight hardware with two sizes of tabs would have increased costs by approximately $2,000 per unit. Accordingly, hardware was fabricated to provide all tabs the same size.

The actuation system used in the previous program was considered satisfactory for use. However, the gear head was modified to allow incorporation of the feedback potentiometer integral with the gear head housing (Figure 5-15). This allowed elimination of several separate detail parts and simplified the critical potentiometer "zero" adjustment experienced on the previous flight program (Reference 4). The basic 117:1 ratio double planetary gear system and the TRW Globe Motors type GRP DC permanent magnet motor were unchanged.

Tab position control during the product improvement tests was provided by using the electrical motor controller originally developed during Contract F04611-71-C-0036. An inter-circuit oscillation which occurred on one channel during the first firing resulted in excessive current drain on the test facility power supply. This was reduced on the second test by isolation matching of circuit boards. However, while it was still possible to control tab actuation, the AFRPL instrumentation system picked up the noise level from the controller and amplified it to the point where data accuracy became questionable.

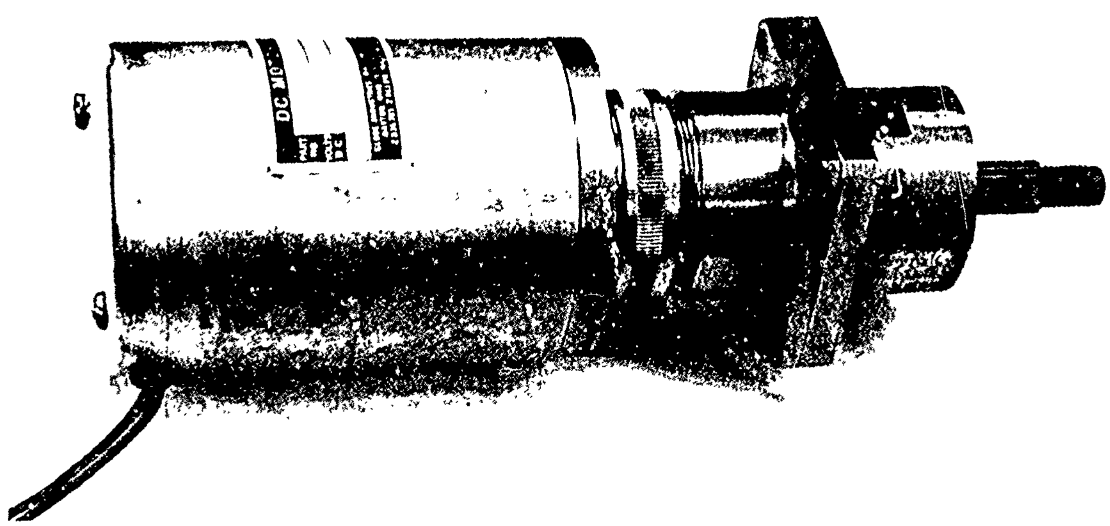


Figure 5-15. Electromechanical Actuator

In order to resolve this problem area, two action items were established. The controllers used on the product improvement tests had to be used on the first two PFRT test firings due to unavailability of the TRA GLICU. The controllers were returned to TRW for examination in an attempt to eliminate the oscillation output noted. A combination of faulty parts were found on one output stage board. The parts were replaced and the oscillation sensitivity was greatly reduced. There remained, however, a very high (.15 megahertz) frequency present during operation that was not expected to create problems with the instrumentation system.

The other action item was a decision by AFRPL to relocate the DC power supplies and controllers from the instrumentation room (approximately 250 feet from the test stand) to an area adjacent (20 feet) to the test stand. It was felt that reducing the length of lines between the controller and the test unit would minimize the noise problem previously encountered.

The net result of relocation was to transfer the long lead sensitivity from the feedback circuit to the command input. The controller was more susceptible to oscillation in this condition than had been experienced during the product improvement tests. Location of isolation (gain of one) amplifiers next to the controllers changed the circuit impedance and eliminated the instability and noise problems. However, before this solution was determined, some of the power amplifier and control circuit cards in the controller had apparently been damaged. Only two channels of control could be provided without further check-out and repair of the controllers.

As the primary purpose of the first PFRT tests was to provide additional data on material durability, the duty cycle had been selected to provide the maximum amount of insertion time on two tabs during the motor firing time The other two tabs, with much thinner (.19 inch) molybdenum facing, were only to be partially inserted for very short time periods. It was decided to proceed with the test firings operating only the two critical tabs.

The first test firing (Figure 5-16) was successfully conducted at the AFRPL with the jet tab TVC unit mounted on a TU-793/03 solid rocket motor mounted in the new AFRPL Ormond six component thrust stand (Figure 5-17). The tab duty cycle tested is indicated in Figure 5-18.

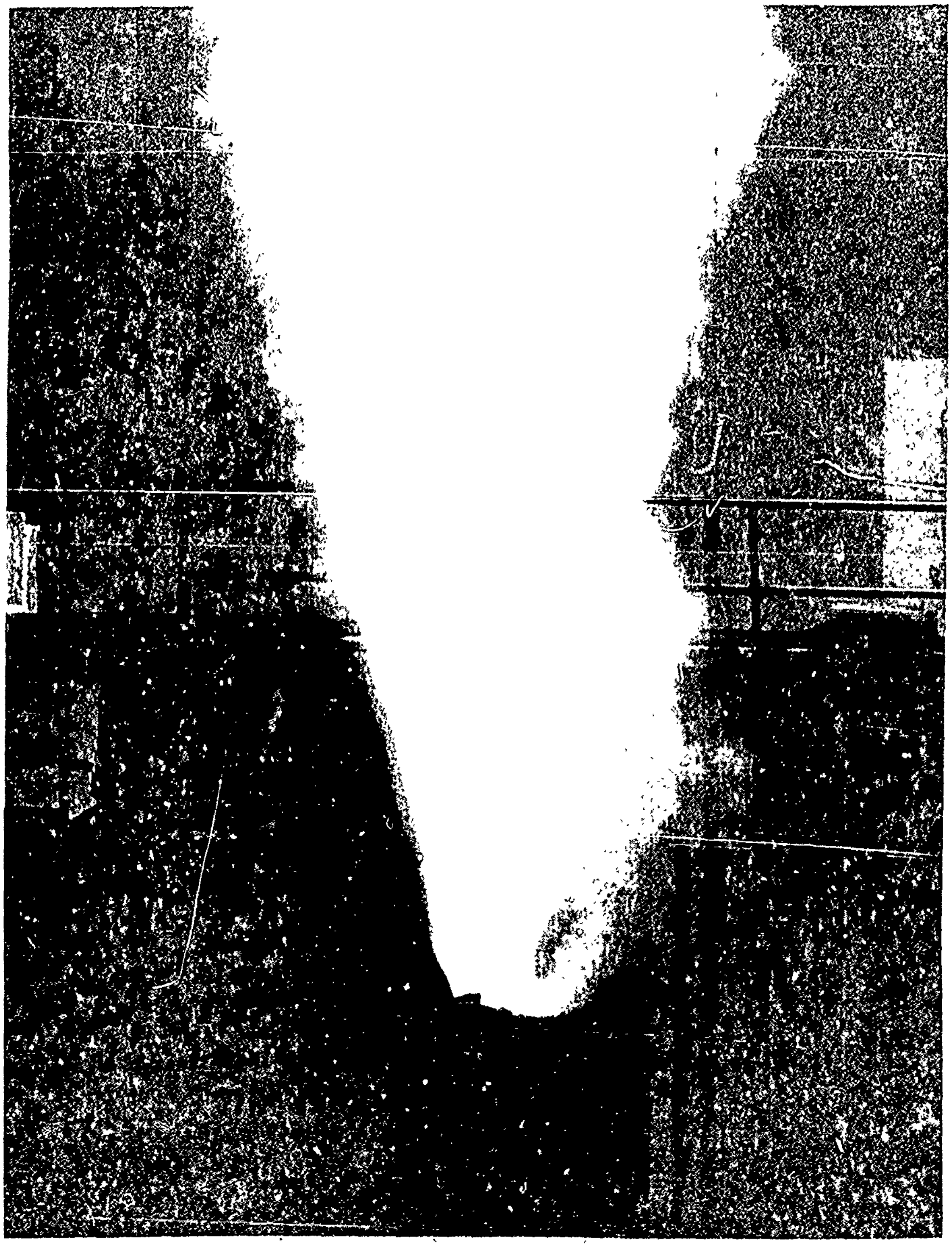


Figure 5-16. PFRT-01 Test Firing

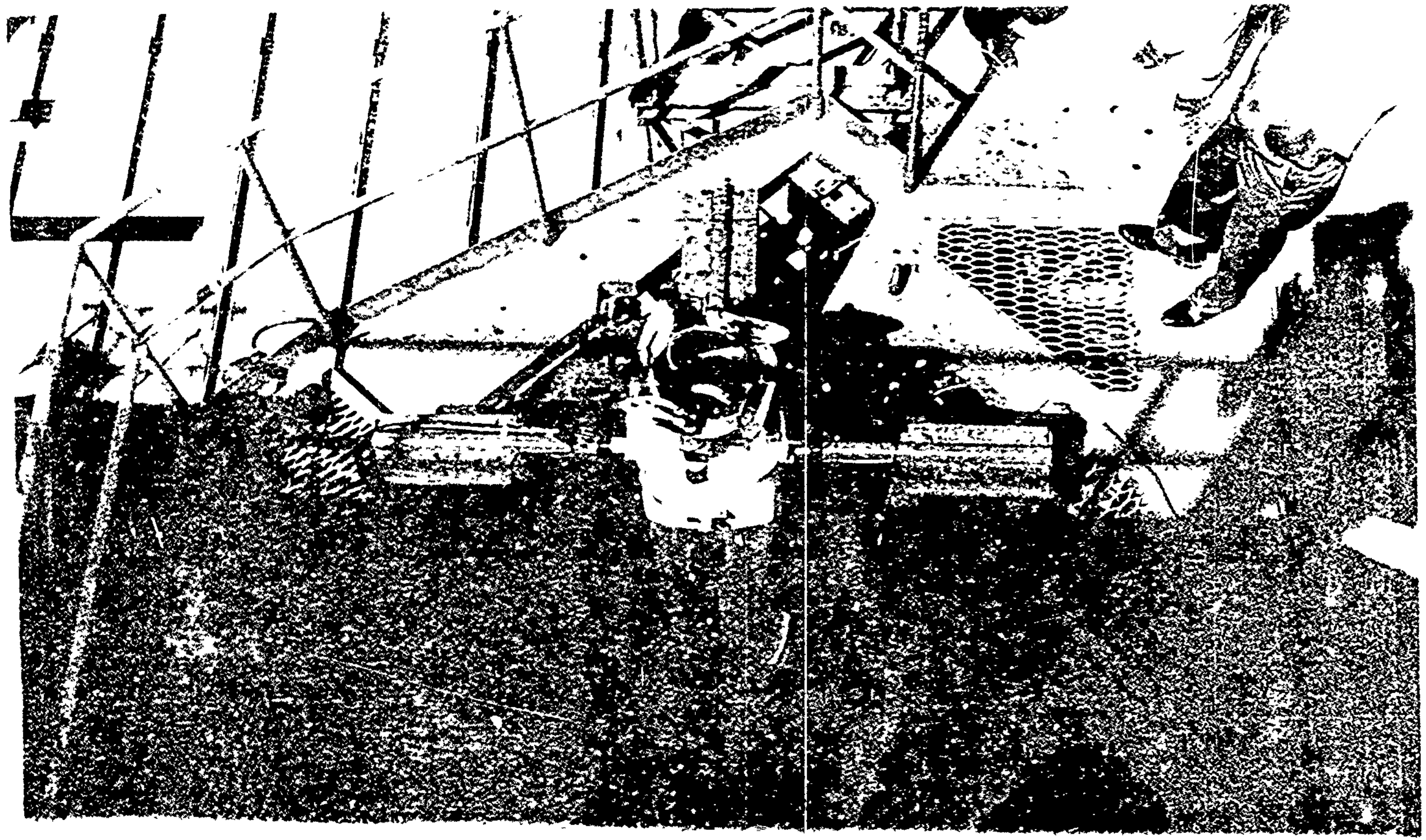


Figure 5-17. PFRT Test Unit in Six Component Thrust Stand

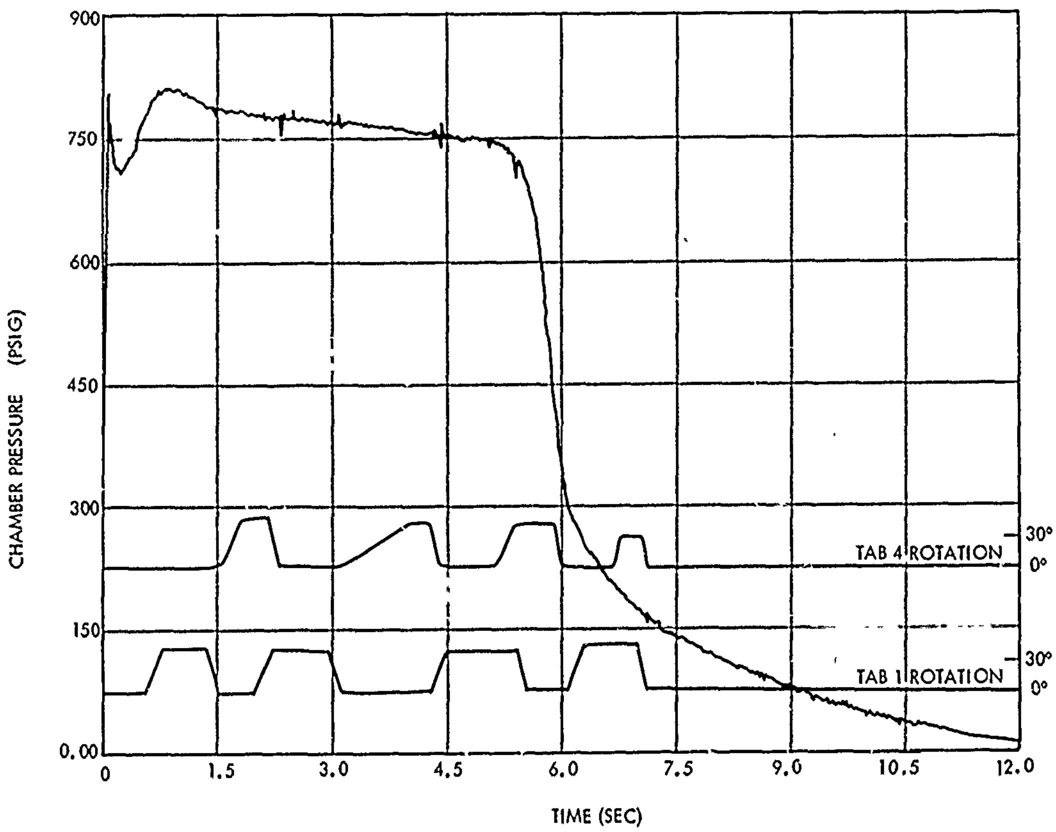


Figure 5-18. Tab Actuation and Motor Chamber Pressure, PFRT-01

5.2.2 Test Unit PFRT-02

The second PFRT test unit was identical to PFRT-01 except the nozzle exit liner was fabricated of tape wrapped MX2600 silica phenolic, and the .375 inch molybdenum tab facings were replaced by .25 inch material. Test conditions for the unit were nearly identical to PFRT-01.

The post test condition of the hardware on both test units was very satisfactory. Test unit PFRT-02 is shown in Figure 5-19. Erosion of the phenolic liners for both the silica phenolic and pitch carbon fabric phenolic materials was considered acceptable. In general, erosion of the liner immediately under the tab was equivalent in both materials and as can be seen in Figure 5-20, occurred back to the screws retaining the liner to the housing. Erosion of the molybdenum tab facings was well within acceptable limits. Total exposure time for each tab was in excess of three seconds during motor burn time with up to one additional second of exposure during tail off. The .25 inch thick molybdenum showed only minimal material loss (Figure 5-21), while the .375 inch material had a local material loss of nearly half the thickness (Figure 5-22). While

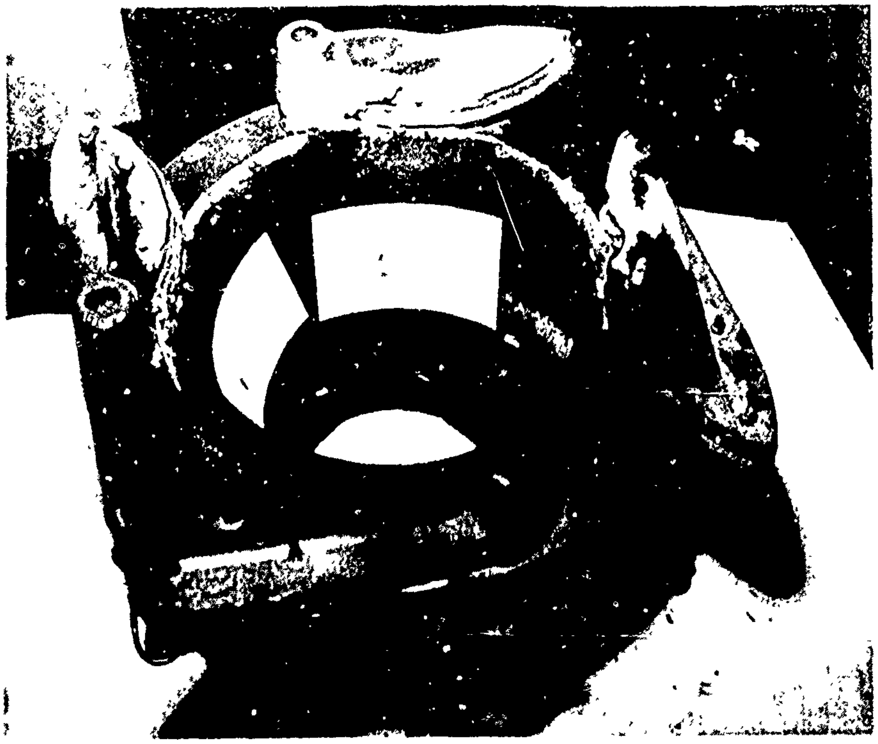


Figure 5-19. PFRT-02 Test Unit Post Test

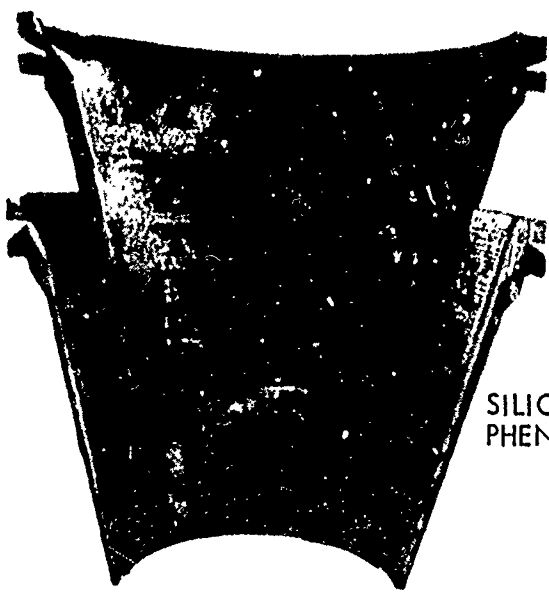


Figure 5-20. Nozzle Exit Liner Erosion Comparison

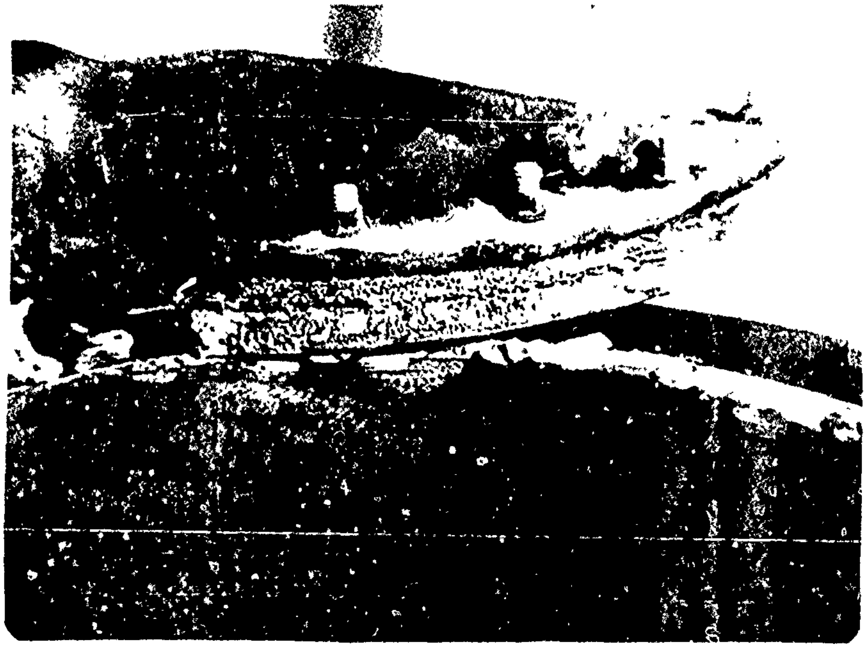


Figure 5-21. Post-Test Condition .25 Inch Tab Face

Figure 5-22. Post-Test Condition .375 Inch Tab Face

the condition was acceptable, the apparent anomaly was investigated further on PFRT-03 before a decision was made on the flight unit configuration.

The only material condition which approached marginal service during the test firing was the portion of the tab insulator which protected the tab shaft from blow-by under the tab insertion. On three of the four tab assemblies, the insulator had eroded down to the tab shaft (Figure 5-23). On one part a small area of the steel shaft had been subjected to flame impingement and melting.

During the first PFRT test firing the steady state position error (difference between commanded tab rotation and actual tab rotation) was approximately eight degrees. For a 38.5 degree command (6.5 degrees thrust vector), only 30 degrees of tab rotation occurred on one tab with a resultant thrust vector angle of four degrees. On the other tab, 31 degrees of rotation resulted in 4.5 degrees of thrust vector.

To demonstrate the system's thrust vector capability, the commanded rotation on a control tape full step input was increased to 43.5 degrees for the second test. One tab achieved 35 degrees rotation and 5.75 degrees thrust vector; the other reached 37.5 degrees rotation and 6.25 degrees thrust vector.

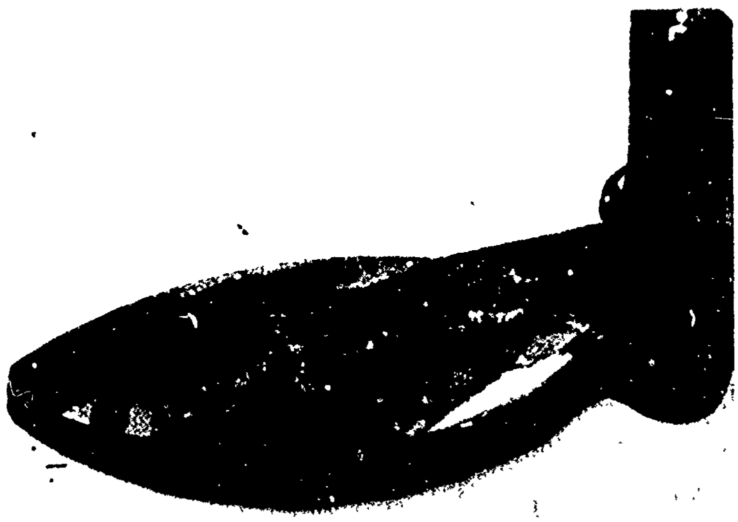


Figure 5-23. Shaft Insulator Erosion

Analysis of the results of the material performance from PFRT-01 and PFRT-02 resulted in the following conclusions:

1. The performance of the silica phenolic nozzle liner without a molybdenum scraper ring was acceptable and, as it provided the lowest production cost potential, was used for the balance of the PFRT and the flight units.

2. The glass phenolic tab insulator was acceptable for flight use. (The duty cycle tested was more severe than expected during flight test.)

3. No obvious reason for the improved erosion resistance of the thinner molybdenum material was apparent. A final decision on the molybdenum material thickness was deferred until after test firing PFRT-03, where both material thicknesses would be included in the same test firing. Analysis of the molybdenum materials included microphotographs of tested and as received conditions, chemical analysis, and amount of extruded working of the raw stock as evidenced by material hardness. In all respects, the as-received material for both 1/4 inch and 3/8 inch thicknesses appeared essentially identical.

As can be seen in Figure 5-24, differences were found in the post-test microstructure. The extremely large grain growth found in the thinner material is indicative of a much higher temperature, which would be expected to result in an increase in erosion rate. Thin material from product improvement test 2 was also sectioned. The large grain structure, Figure 5-25, was again evident. However, in the product improvement tests, the erosion of the .25 inch material, while not excessive, was greater than that experienced with the .375 inch part. This apparent inconsistent performance of the thin molybdenum material was evaluated further on the next PFRT test unit prior to final material selection.

Considerable subsurface cracking was noted in the .375 inch material. Cracks of this nature, occurring during the firing, could result in spallation, and explain the high erosion on the PFRT test.

5.2.3 Test Unit PFRT-03

The last of the materials evaluation PFRT units was similar to the first two except that the exit area of the nozzle exit liner was modified to provide for a molybdenum scraper ring as shown in Figure 5-26. This approach was the back-up configuration in the event that the all ablative configurations had not been successful. To provide additional test data on the molybdenum tab face thickness, two tabs were provided with .25 inch material and two with .375.

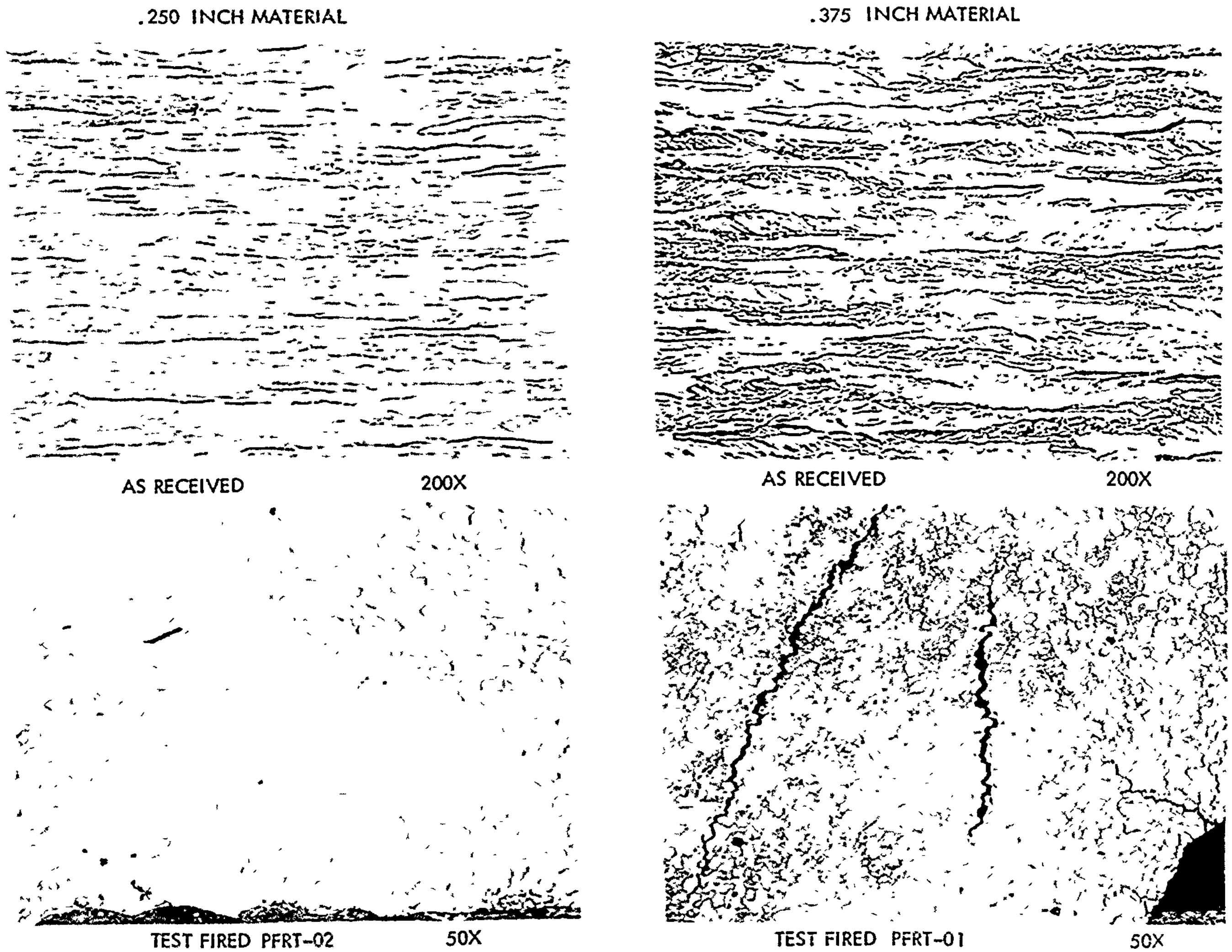


Figure 5-24. Tab Materials Grain Structure PFRT Test

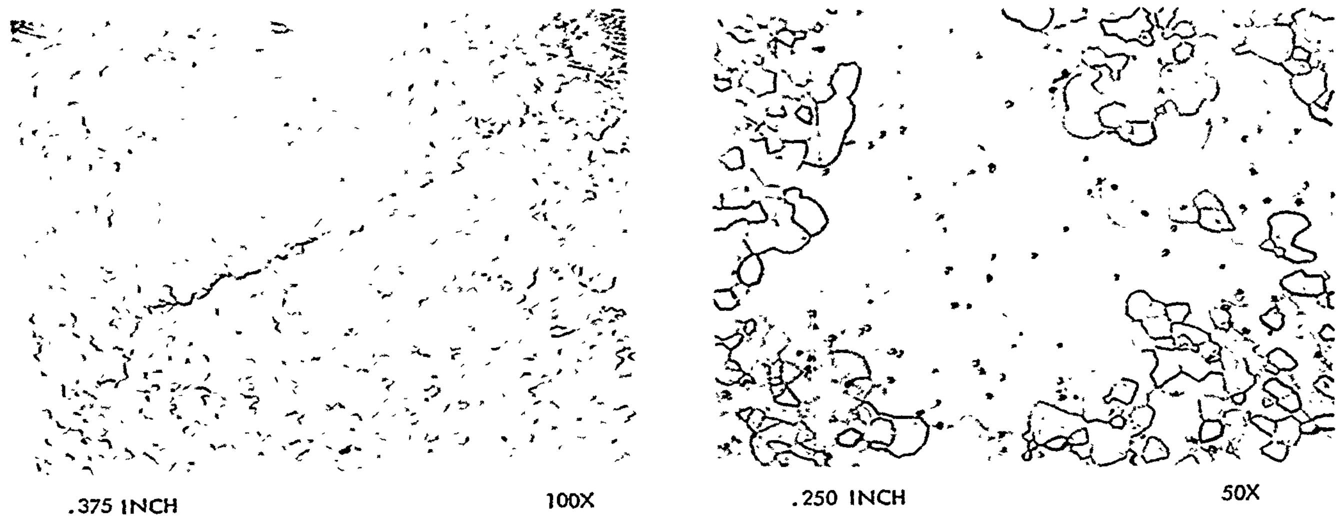


Figure 5-25. Tab Grain Structure Product Improvement Tests

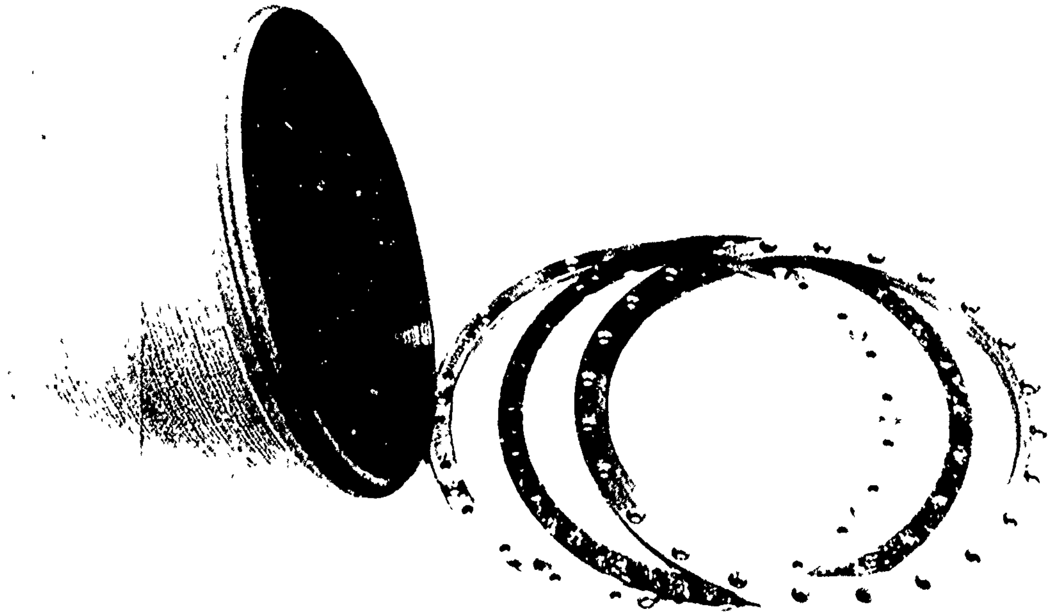


Figure 5-26. PFRT-3 Nozzle Liner

This test firing was the first to be made using the TRA GLICU. At the request of TRA, to allow the GLICU to be characterized, only the pitch tabs were actuated during the test. This, however, allowed data on only one tab of each material thickness. Two problems were encountered during pre-test check-out which could not be resolved prior to the test. The controller had been designed using the gain information from the potentiometers used on the JBQM-34H program. As that system had a higher voltage output per degree of rotation, the PFRT unit tabs would not drive in as far as desired on command. In addition, the controller had a built-in limitation for maximum command rotation angle of 33 degrees. As approximately 37 degrees of shaft rotation is required for six degrees of vector, the maximum thrust vector could not be demonstrated during this test. The test firing was conducted operating the pitch axis tabs to the duty cycle shown in Figure 5-27. Material performance throughout the tab system was excellent. The erosion of both tabs was minimal because of the low actuation angles achieved. The maximum rotation angle achieved was 28 degrees with a resulting 3.5 degrees of thrust vector. The post test appearance of the unit is shown in Figure 5-28.

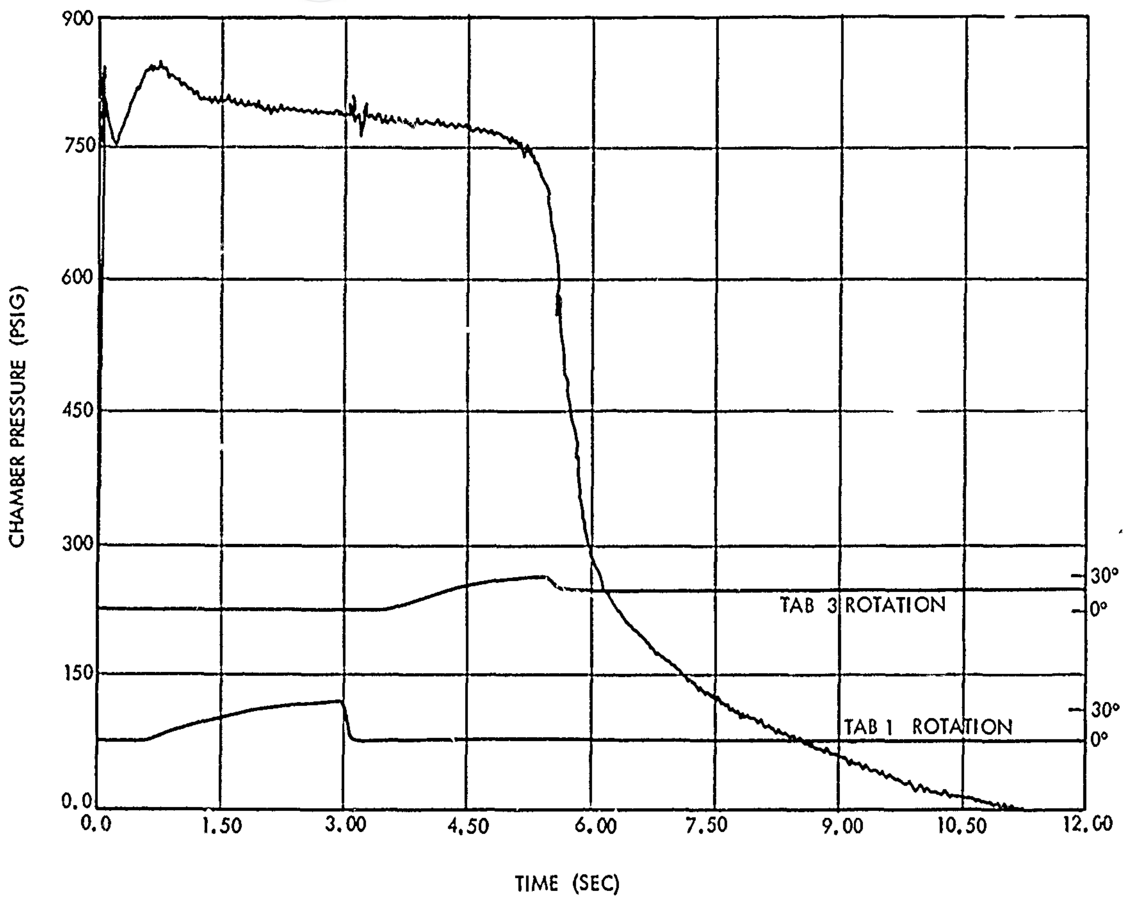


Figure 5-27. Tab Actuation and Motor Chamber Pressure, PFRT-03

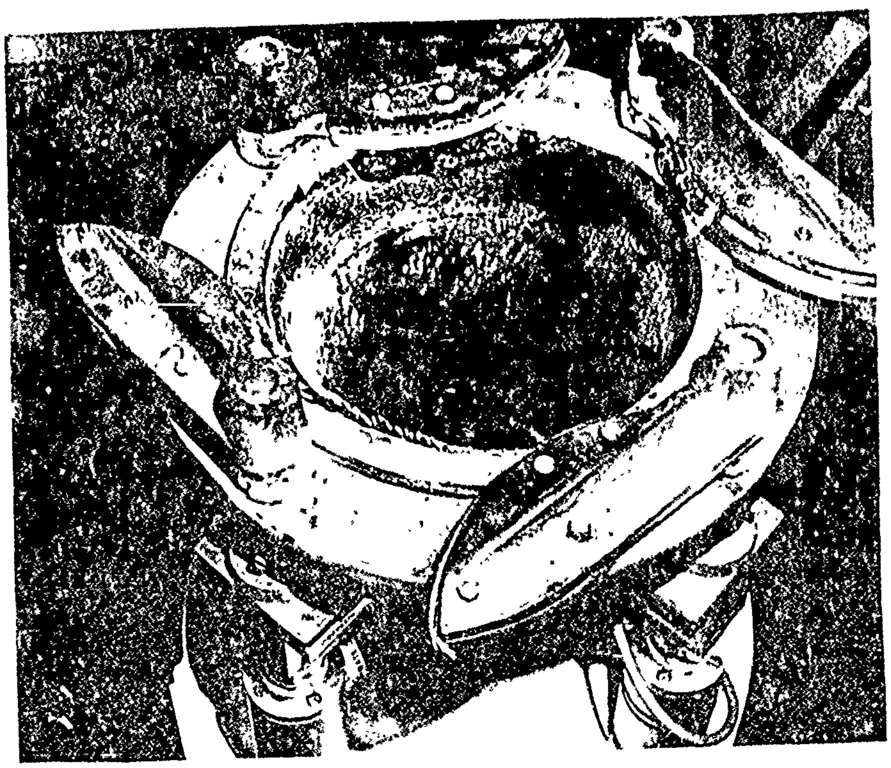


Figure 5-28. PFRT-3 Post Test

The two molybdenum tabs from test PFRT-3 were sectioned. Examination of the microstructure indicated essentially the same characteristics as noted previously. The thicker molybdenum exhibited some subsurface cracking and the thinner section indicated a large amount of recrystallization. One area which was noted was the orientation of the raw stock grain in the fabricated part. For the .25 inch material, the long tab dimension appeared to be oriented in the direction of raw stock rolling while in the .375 inch thick part it was perpendicular to the rolling direction. The tested parts from previous firings were examined to determine if this condition was common to those parts in which subsurface cracking was noted.

A comparison of the results is presented in Table 5-5 below.

Table 5-5. Microstructure Comparison of Molybdenum Tabs

Test No.	Tab No.	Thickness (in)	Direction of Rolling	Visible Microscopic Cracks
PI2	2	.375	Parallel to length	Yes (Minor)
PI2	3	.25	Parallel to width	No
PFRT-01	1	.375	Parallel to length	No
PFRT-01	4	.375	Parallel to width	Yes
PFRT-02	1	.25	Unknown*	No
PFRT-02	4	.25	Unknown*	No
PFRT-03	1	.25	Parallel to length	No
PFRT-03	4	.375	Parallel to width	Yes

*Complete recrystallization

In general, the major cracks were observed to run parallel to the width of the tab facing. . It also appeared that the propagation of cracks, when occurring, is coincident with the elongated grains along the rolling direction. It should also be noted that the thicker (.375 inch) tabs are more susceptible to cracking. It was concluded, therefore, that there were two contributing factors to the cracking and high erosion noted: material thickness and grain orientation. The probable influence of material thickness was assumed to be the degree of recrystallization present in the as-received material.

As a result of this evaluation, the .25 inch thickness was selected for the balance of the PFRT units and the flight hardware. In addition to the thickness selection, a requirement was added to have the length of the part parallel to the raw stock rolling direction. As there was some indication of bolt head melting occurring, the installation of the tab refractory bolts into threaded holes in the facing was selected.

5.2.4 Test Units PFRT-04 through PFRT-06

With the material configuration established, the hardware for the balance of the scheduled PFRT tests was identical. The only two changes made were the addition of the flight configured electrical wiring harness and the fiberglass shroud. The firings were conducted with no major problems being encountered with the TVC system. Difficulties, however, were experienced in achieving the desired test results with the GLICU. A brief outline of each test is provided below. A summary of some of the pertinent test conditions and test results are indicated in Table 5-6.

Table 5-6. PFRT Environmental Test Conditions

Test Number	PFRT-04	PFRT-05	PFRT-06
Ambient Conditioning Temperature (^{o}F)	+140	-55	+70
Maximum Chamber Pressure (psig)	935	630	796
Motor Burn Time (Seconds)	4.6	7.0	5.6
Maximum Tab Rotation (Degrees)	24.0	36.5	31.5
Thrust Vector (Degrees)	2.9	5.75	4.4
Maximum Insertion Time (Seconds)	4.5	7.5	5.7

- Test PFRT-04 - The actuation duty cycle for the pitch axis was identical to test PFRT-03. The imposed actuation for the roll axis is indicated in Figure 5-29. Prior to conducting the test firing the motor and the TVC system were conditioned to +140^{o}F. Only minimal material loss was experienced with any of the molybdenum facings. Erosion of the liner exit under the pitch tabs was approximately .125 inch. No problems were experienced with the shroud as noted in Figure 5-30. This same shroud was reused without refurbishment in tests PFRT-05 and PFRT-06.

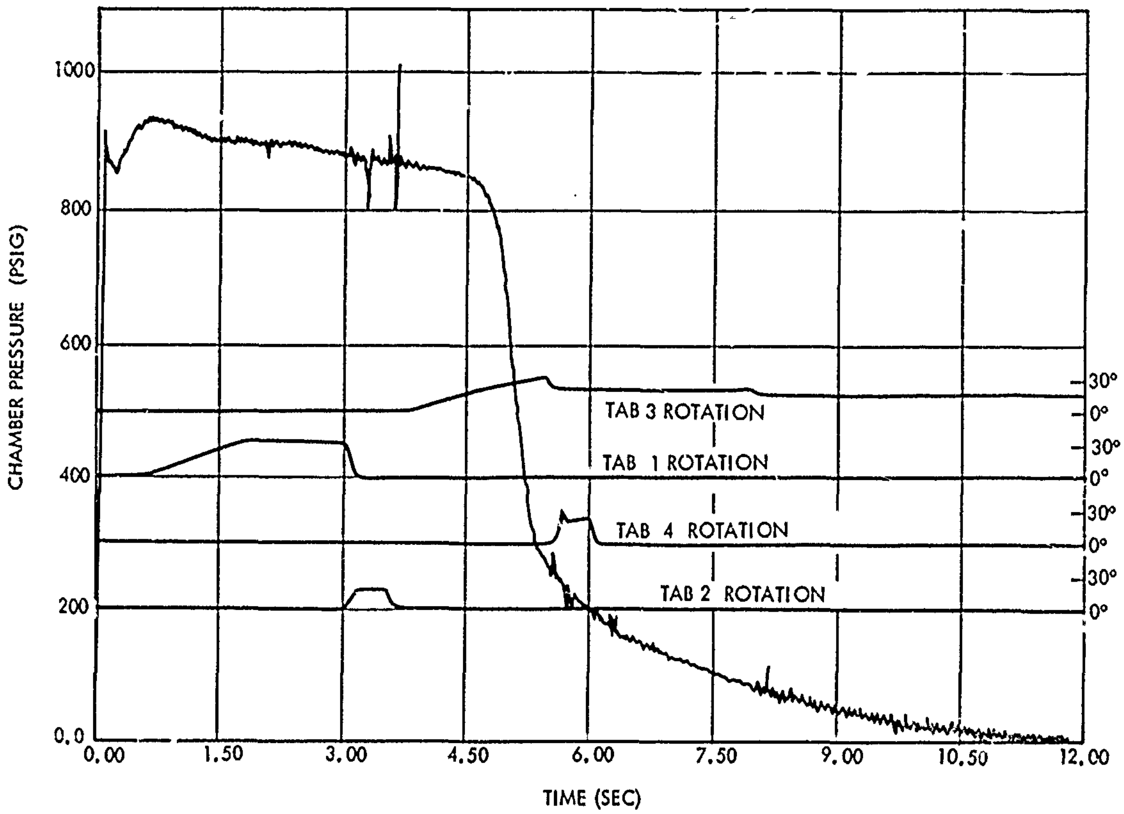


Figure 5-29 Tab Actuation and Motor Chamber Pressure PFRT-04

One actuation problem which occurred was the failure of tab 3 to retract when commanded during tail off. This resulted from an accumulation of aluminum oxide adhering to the tab face (Figure 5-31) during the cooling portion of tail off. A review of test data indicated this same problem had occurred during test PFRT-03. For tests PFRT-05 and PFRT-06, the gap between the tab face and the nozzle exit plane was increased to 0.060 inch. No further problems were encountered with tab retraction during motor tail off.

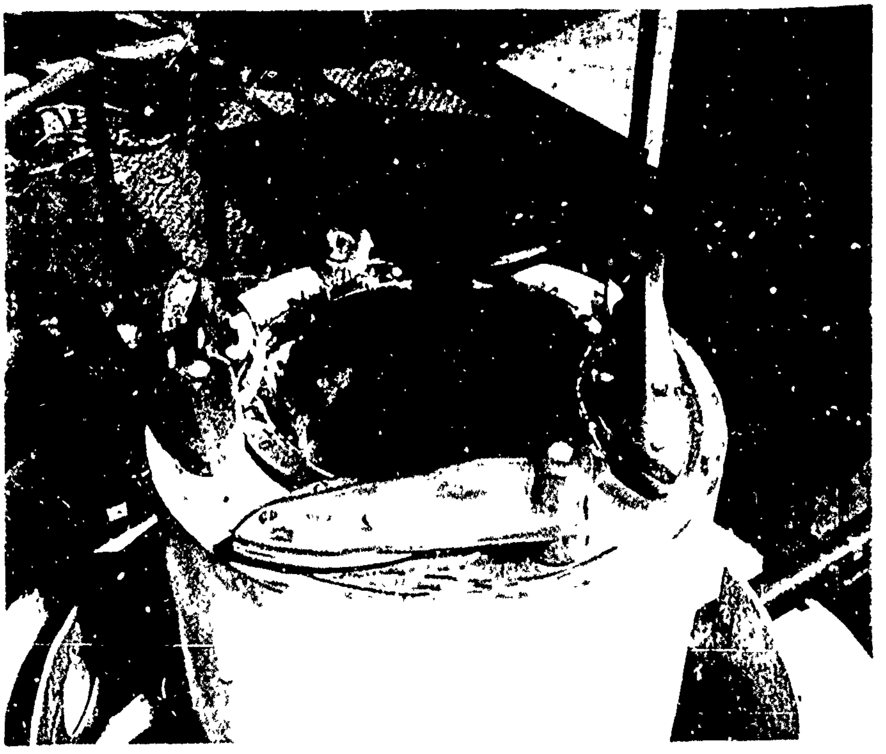


Figure 5-30. Test Unit PFRT-04 Post Test

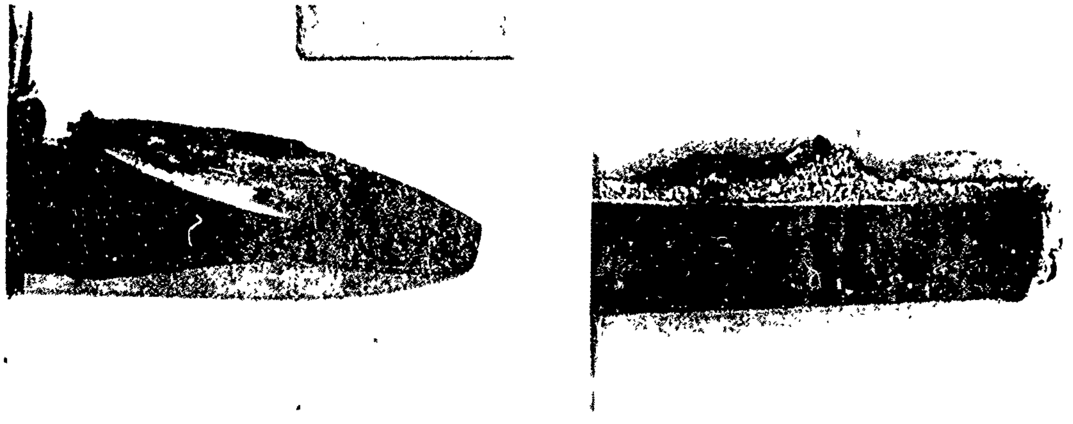


Figure 5-31. Aluminum Oxide Accumulation

The TRA GLICU had been modified in an attempt to match the potentiometer feedback characteristics. However, the internal limit which ignored commands in excess of 33 degrees of tab rotation was still present. The result was the low thrust vector demonstrated.

- Test PFRT-05 - For this test firing, the tab actuation duty cycle indicated in Figure 5-32 was modified from the PFRT-04 duty cycle to be more representative of expected typical flight requirements. The motor and TVC system were conditioned to -55^{O}F (Figure 5-33). The only apparent effect of the modified duty cycle on tab material performance was an increase in the amount of erosion of the nozzle liner under the longer duration tab (tab 1) to .25 inch.

  The TRA GLICU was used again. The internal electrical limit had been increased to accept commands of up to 43 degrees of tab rotation. The amount of tab rotation achieved, in view of the reduced operating pressure, was still inadequate.

- Test PFRT-06 - Prior to conducting the next PFRT test firing, a coordination meeting was held at TRA to resolve questions regarding the interface between the jet tab TVC system and the GLICU.

  The electrical characteristics of the TVC system position potentiometer were reviewed. Based on test data from PFRT-04 and PFRT-05, a new gain factor of feedback voltage to tab rotation was

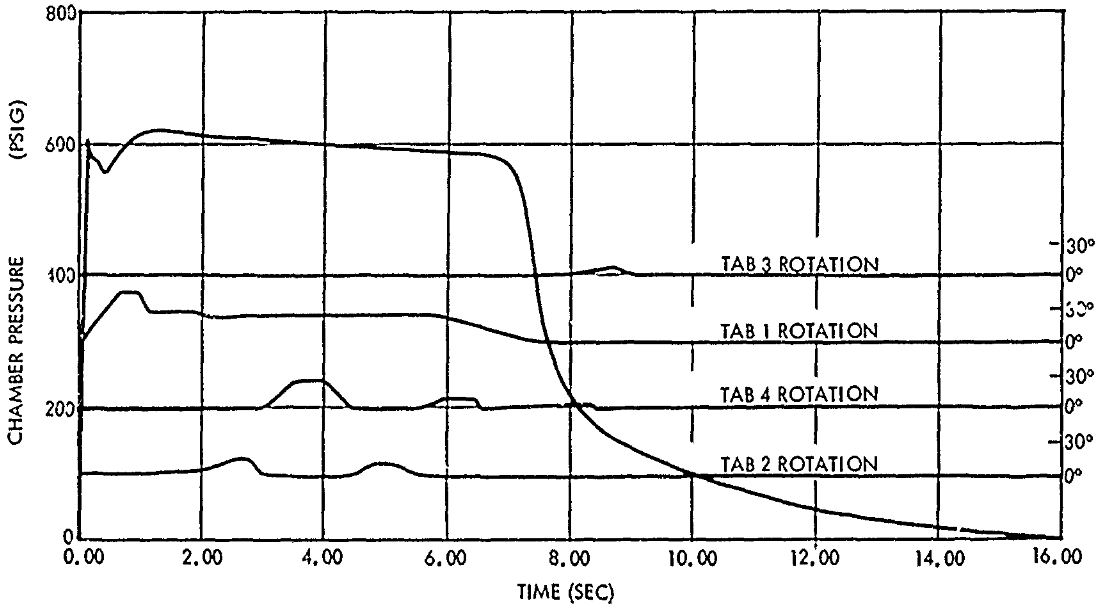


Figure 5-32. Tab Actuation and Motor Chamber Pressure, PFRT-05

Figure 5-33. TVC and Motor Conditioned to $-55^{0}F$

defined. In order to provide sufficient tab rotation under motor firing conditions, the GLICU was modified to accept commands of up to 48 degrees tab rotation.

Overall system gains relating to the change in the TVC system size from the JBQM-34H program to the BGM-34C configuration were supplied by the Air Force.

With the changes required in the controller, additional bench tests needed to be conducted using a BGM TVC unit. Test unit PFRT-06 was used to support the additional bench tests conducted by TRA using their modified GLICU. Items which were characterized included the relationship of tab position potentiometer output to the GLICU telemetry output, tab position in relation to command input signals for both pitch and roll axes, and no-load hysteresis.

One overall system anomoly which was noted during pitch axis testing was the difference between positive and negative axis action. The variation in tab feedback potentiometer output was less than two percent while the actual closed loop control position difference was five percent. Conversely, for the roll axis individual feedback potentiometers, the difference in output versus position was as high as three percent; the closed loop control difference was less than one percent.

The test firing was conducted with the motor and TVC system conditioned to +70^{o}F. The actuation duty cycle shown in Figure 5-34 was identical to PFRT-05 except for the addition of two actuations of the pitch tab to zero to allow characterization of the thrust reduction during thrust vectoring. The problem which was encountered was still in the area of total amount of insertion achieved. This test firing was conducted at an ambient temperature of 70^{o}F which resulted in an average motor chamber pressure of 760 psig. At this load condition the 49 degree command to the TRA GLICU resulted in only 31.7 degrees tab rotation and 4.2 degrees thrust vector. In reviewing the expected torque at the insertion position, it appeared that the output of the DC pulse from the controller had dropped to an equivalent 22 volts DC steady state. With this level of output available, when operating the motor at the maximum temperature the tab may be limited to providing only 2.5 degrees of thrust vector. As this level of performance was inadequate, a review was conducted by TRA of potential modifications to the TVC unit to provide a higher torque capability at the reduced power input level.

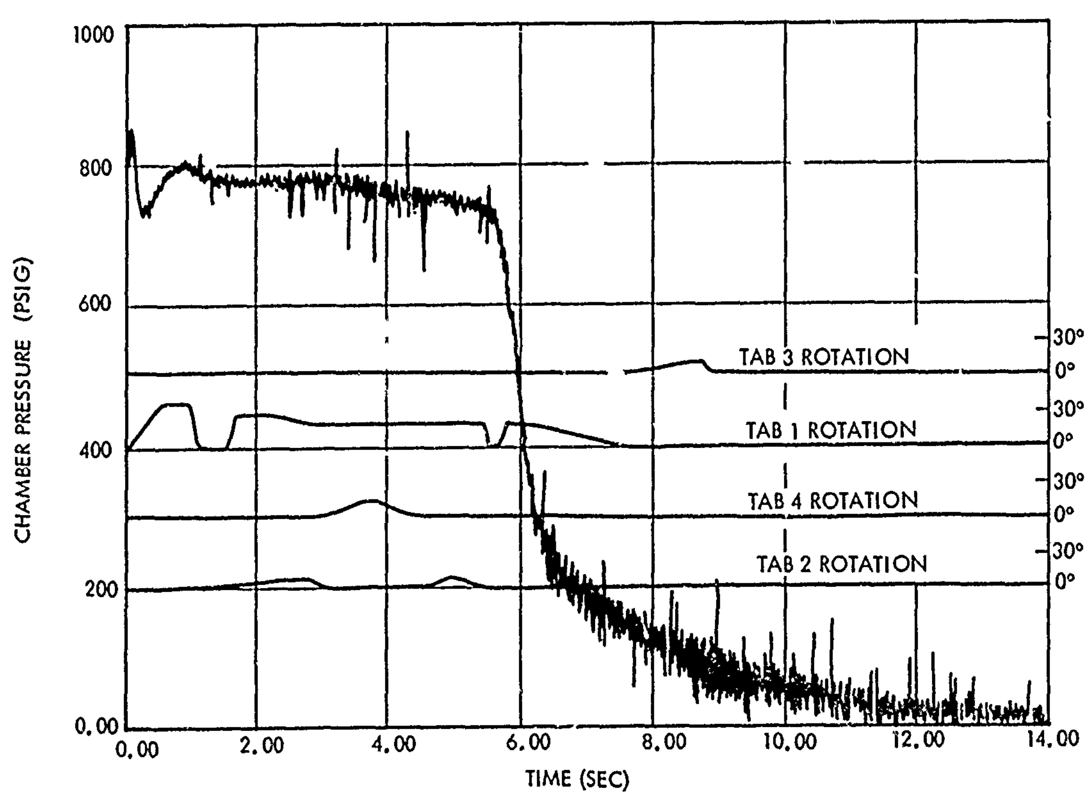


Figure 5-34. Tab Actuation and Motor Chamber Pressure, PFRT-06

5.2.5 Test Unit PFRT-07

The program had originally been planned for six PFRT test firings. However, because of the incompatibility between the TRA GLICU power output and the TVC system actuation system, an additional test firing was added.

As a part of the review of the GLICU low power output problem encountered during the sixth PFRT test firing, the feasibility of modifying the electromechanical actuator gear ratio was determined. The existing gear head had an output ratio of 117:1. Within the limits of the gear head housing, the ratio could be increased to 170:1. Higher gear ratios would require a new housing configuration and an extended procurement lead time.

Based on the above and the apparent difficulty in modifying the TRA GLICU, the Air Force decided to proceed with the modification of the gear heads in the pitch axes of all flight units. The first flight unit was modified to incorporate the higher gear ratio on the pitch axis actuators. This unit was then diverted for use in a PFRT test firing. The unit was subjected to a series of gain characterization tests with the TRA GLICU. These tests were similar to those which were conducted prior to PFRT test number 6. In addition, a series of load tests were made to determine the relationship between the output of the tab actuators and overall system position error. At a sufficient position error to result in a motor current requirement of 23 amperes, a sixty percent increase in output torque was measured in the pitch axis over the roll axis.

The unit was then taken to AFRPL and a test firing was conducted. The motor was fired at an ambient temperature of +65^{o}F. The maximum motor chamber pressure was 756 psig compared to 796 achieved on PFRT test number 6. The tab actuation duty cycle was identical to that used during the sixth firing.

The thrust vector performance achieved was considerably improved. For a 48 degree tab rotation command during the sixth test, 31.5 degrees of rotation was achieved with a resulting thrust vector of 4.4 degrees. For the seventh test, with the higher gear ratio, for the 48 degrees of command 42 degrees of tab rotation occurred and the corresponding thrust vector was 7.2 degrees. This level of vector performance demonstrated the TVC/GLICU was ready to proceed into the ground launch.

The post test appearance of the TVC system was comparable to previous firings except for an increase in the amount of erosion of the nozzle liner directly under the tab inserted for nearly ninety percent of the total motor firing time (Figure 5-35). A slight reduction in thrust vector at the constant blockage position was noted late in the firing. This reduction, which resulted from the larger gap under the tab with the increased liner erosion, was not considered detrimental.

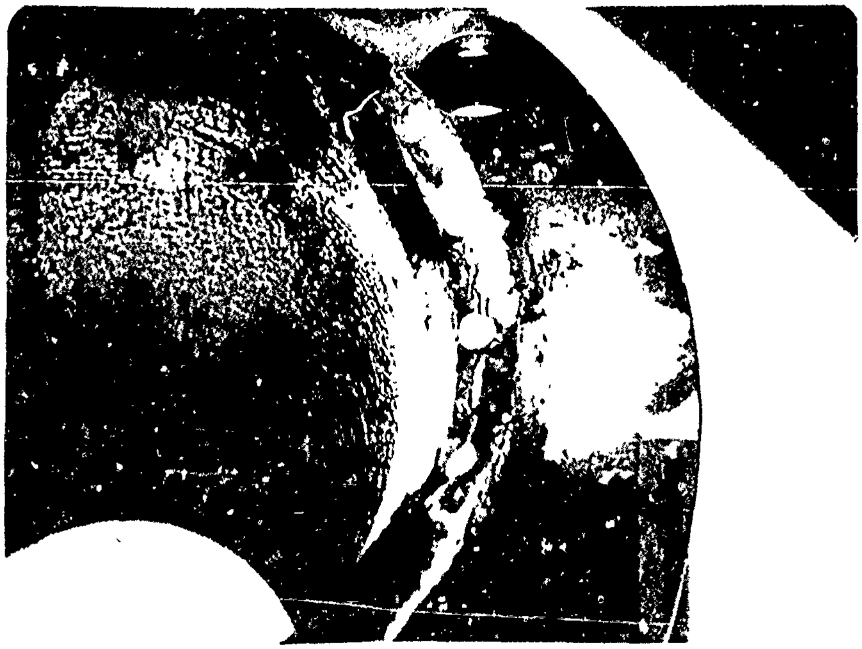


Figure 5-35. Nozzle Liner Erosion

5.3 SOLID ROCKET MOTOR

The solid rocket motors used with the TRW jet tab TVC system were developed from the Genie motor. The motors are manufactured by Thiokol Corporation/Wasatch Division. The motor used on the JBQM-34H program and for the product improvement tests on this program is designated the TU-752. For the higher total impulse requirement of the BGM-34C RPV the motor length was increased and the propellant burning rate and nozzle throat diameter decreased. For the BGM-34C application the solid motor is designated TU-793/03.

Based upon performance requirements and ready availability, the standard Genie solid rocket motor was selected as the baseline item for development to the booster ground launch requirements. The primary modification was to decrease thrust and total impulse by reducing the case length and increasing the throat diameter. The interface between the jet tab system and the booster is immediately aft of the nozzle throat, which is an integral part of the aft closure subassembly. An external thread on the aft closure is used to mechanically link the components and anti-rotation is provided by three cup point set screws in the jet tab nozzle housing. Gas sealing is provided by a precisely controlled interface. An illustration of the booster motor with an artist's conception of the jet tab TVC unit installed is shown in Figure 5-36.

The motors use a Thiokol Corporation solid propellant containing 12 percent aluminum, ammonium perchlorate oxidizer and a ferric oxide burn rate catalyst. Total solids is 82 percent and the binder fuel is carboxyl terminated polybutadiene (CTPB). Approximate theoretical flame temperature is 5400^{o}F. The mechanical properties of the propellant as cast with the basic five point star base are adequate to allow operation over the -55^{o}F to +140^{o}F temperature range. A performance summary of the TU-793/03 motor is shown in Table 5-7.

The motor case is fabricated from rolled and welded 4132 steel. Internal case insulation is provided by a glass fiber phenolic in the aft end and an asbestos filled CTPB polymer in the case and forward dome. A pyrogen igniter with a star point grain of Genie propellant is installed in a threaded boss in the motor forward dome.

Additional information on the TU-793/03 motor can be found in Reference 6.

Table 5-7. Performance Summary TU-793/03

Temperature, °F	-55	60	140
Time, sec.			
Web Burn	6.63	5.72	5.24
Action Time	10.99	9.57	8.67
Pressure, psia			
Maximum (@ +140°F)			965*
Web Time Average	648	752	830
Action Time Average	460	533	587
Thrust, lbf			
Maximum	13,400	15,690	17,450
Web Time Average	12,870	15,070	16,740
Action Time Average	8,940	10,490	11,660
Impulse, lbf-sec (without TVC)			
Action Time	98,320	100,400	101,280
Initial Throat Diamaeter, in.	4.20	4.20	4.20
Initial Expansion Ratio	4.6:1	4.6:1	4.6:1
Propellant Weight, lbm	455	455	455

*MEOP at +140°F only

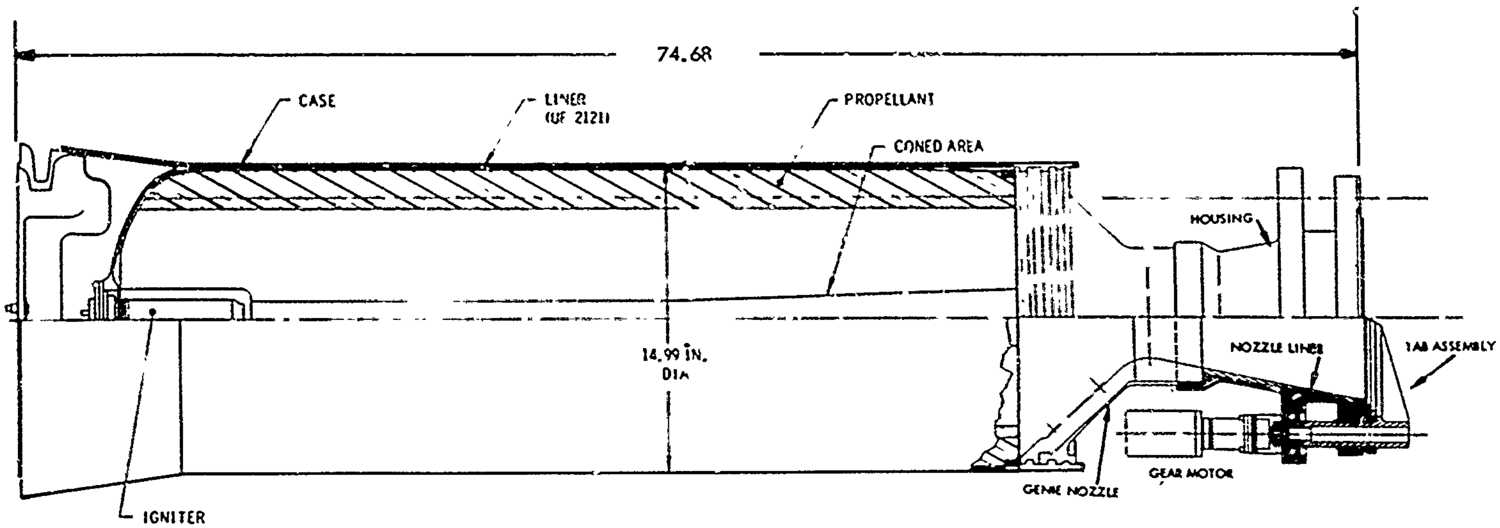


Figure 5-36. Booster Motor and Jet Tab TVC System

6.0 FLIGHT TEST UNITS

The final phase of the program will involve the flight testing of the jet tab system in conjunction with the TU-793/03 motor as the booster for ground launching of the BGM-34C RPV. Flight testing will be performed by the 6514th Test Squadron, Hill AFB, Utah at Dugway Proving Grounds, Utah. The following paragraph describes the hardware involved. Flight testing is scheduled to begin in the fall of 1977.

6.1 FLIGHT TEST HARDWARE

After completion of the seventh PFRT unit test firing (PFRT-07), six flight test units, shown in Figure 6-1, were fabricated. The flight test units were identical to the final PFRT unit described in Section 5. System weight was approximately 74 lbm. A weight break-out is presented in Table 6-1. The flight test units were delivered to Hill AFB. They will be integrated with the TU-793/03 booster at the flight test site at Dugway Proving Ground, Utah, prior to installation on the BGM-34C.

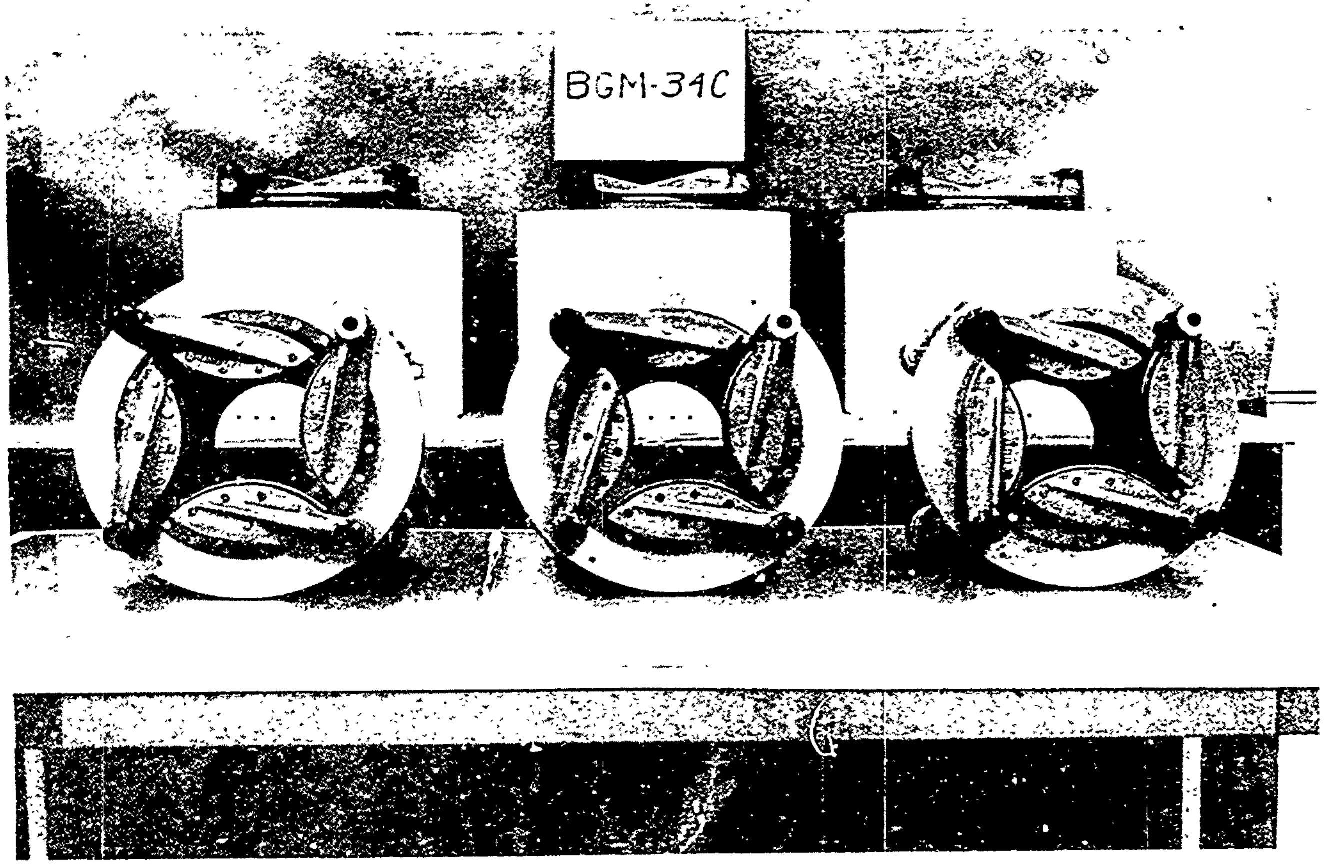


Figure 6-1. BGM-34C Jet Tab TVC Flight Systems

Table 6-1. Weight and Center of Gravity

	Weight (lbs)	Estimated Center of Gravity* (in)
Jet Tab TVC Installation	73.48	95.23
Jet Tab TVC Assembly	68.00	95.37
Housing	29.30	97.03
Exit Liner	2.20	96.61
Shaft and Support (4)	7.88	100.07
Blade Insulator (4)	0.86	100.43
Blade (4)	4.16	100.24
Tantalum Screws (44)	0.45	100.02
Limit Stops (4)	0.85	97.97
Motor Mounts (4)	3.72	95.07
Gear Motor (4)	11.88	92.23
Bearing B1612 (4)	0.27	98.92
Thrust Bearing (4)	0.69	96.72
Spacers (8)	0.15	96.71
Nuts and Bolts	0.54	95.00
Wiring Harness	4.84	65.25
Bonding Adhesive	0.21	96.61
Shroud Installation	5.48	93.45
Shroud	5.31	93.62
Bolts	0.17	88.00

*Based on assumption nozzle exit plane at 100.00

7.0 PERFORMANCE ANALYSES

The objective of the PFRT static test program was to determine the jet tab TVC system performance with the TU-793/03 booster motor. Items of specific interest were all components of thrust, thrust vector deflection rate and basic structural and thermal response of the system under motor firing conditions. The capability of the jet tab system to provide the required thrust vector control was well demonstrated. Tab vectoring performance, actuation characteristics and thermal performance are discussed in the following paragraphs.

7.1 VECTOR PERFORMANCE

The experimentally determined relationship between exit area blockage and thrust deflection angle (θ) for a single tab is shown in Figure 7-1. The percent degradation of the magnitude of thrust during thrust vectoring is shown in Figure 7-2 as a function of nozzle exit area blockage. These relationships can be extended to omniaxial conditions through the proper trigonometric equations.

Excellent repeatability of thrust vector performance was obtained during the static test program between different tabs and various tests. For equivalent shaft rotation angles shown in Figure 7-3, a total data variance of one-half degree thrust vector was measured.

Thrust loss correlation between tests, as shown in Figure 7-4, was found to be more susceptible to configuration variation than was noted for thrust vector performance. Thrust loss variation in excess of two percent thrust loss was encountered at high rotation angles.

On previous tab programs, performance trends have been shown to be relatively insensitive to small changes in chamber pressure, expansion ratio, and propellant properties of the magnitude experienced over the temperature range of the program. The thrust loss is largely dependent upon the spacing between the tab surface and the nozzle exit plane. Increasing the gap increases the thrust loss and decreases the actuation torques.

One side effect of using the jet tab TVC system is the cross coupling effect due to the small change in the actual direction of thrust vector as

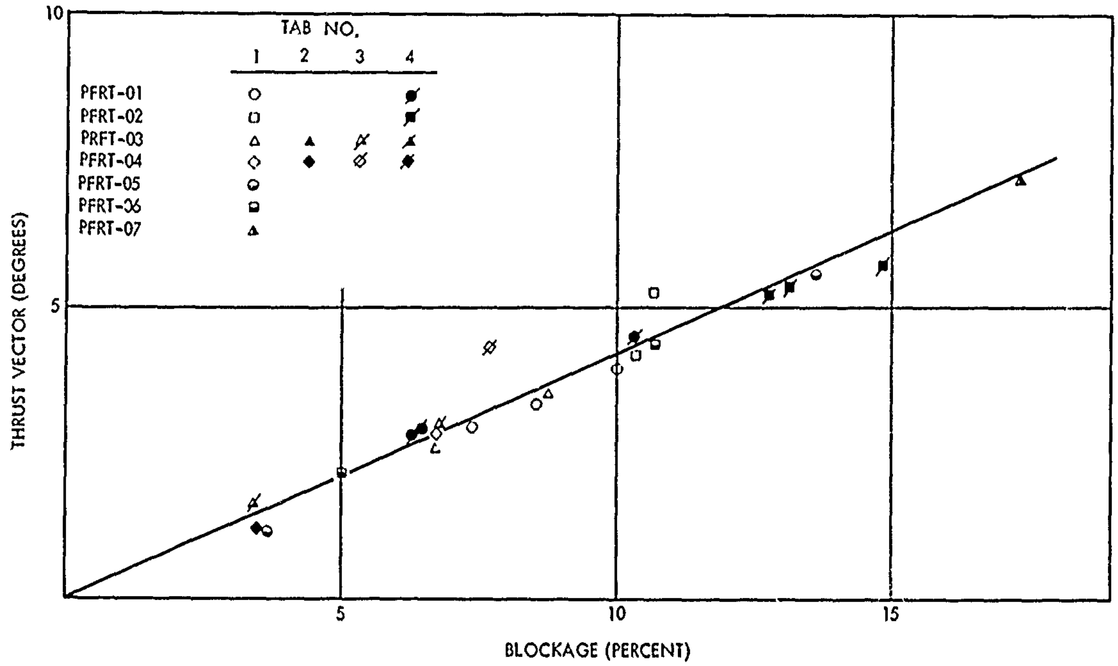


Figure 7-1. Thrust Vector Angle vs. Nozzle Exit Area Blockage

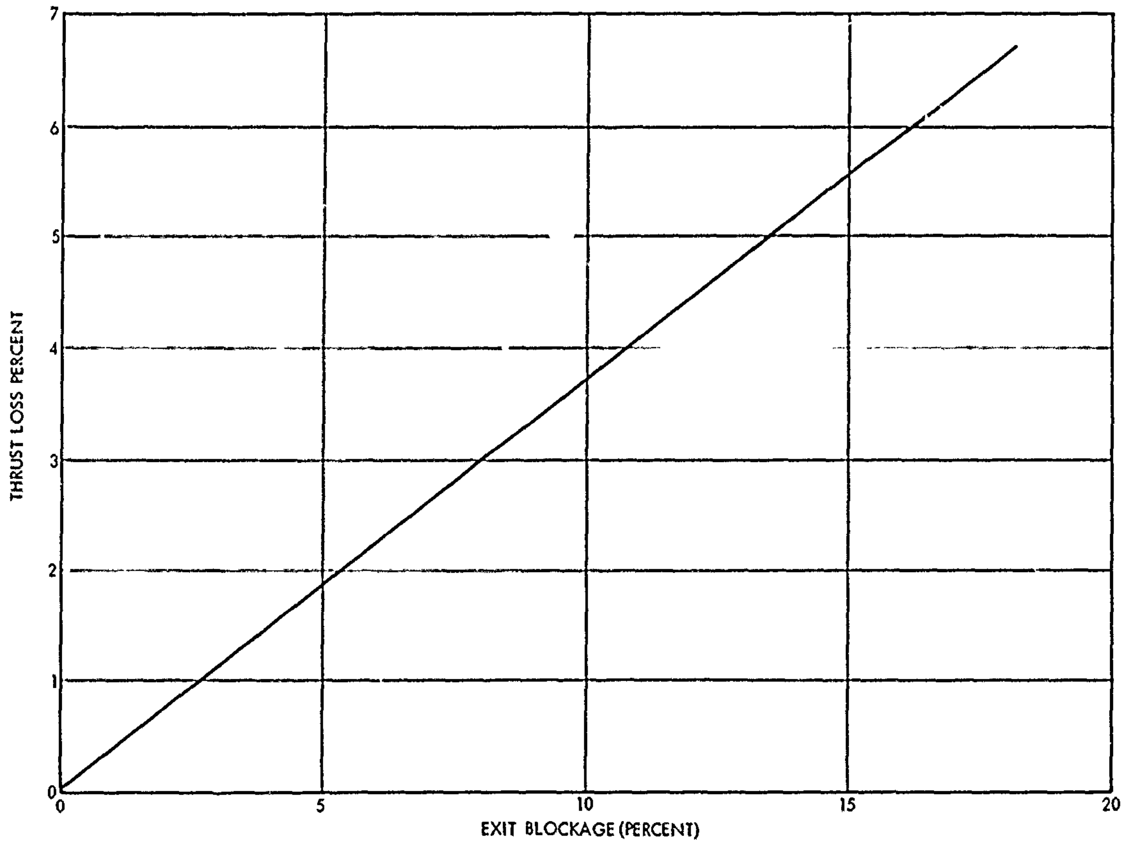


Figure 7-2. Thrust Loss as a Function of Nozzle Exit Area Blockage

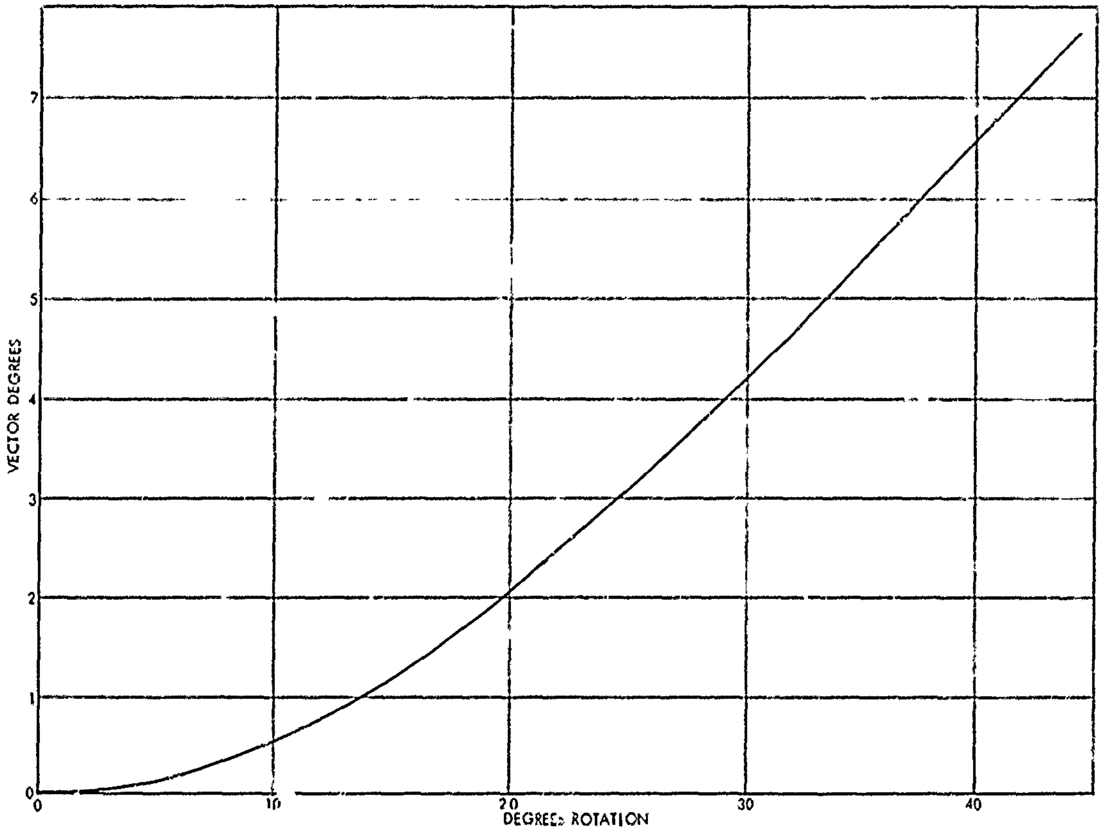


Figure 7-3. Thrust Vector vs. Shaft Rotation

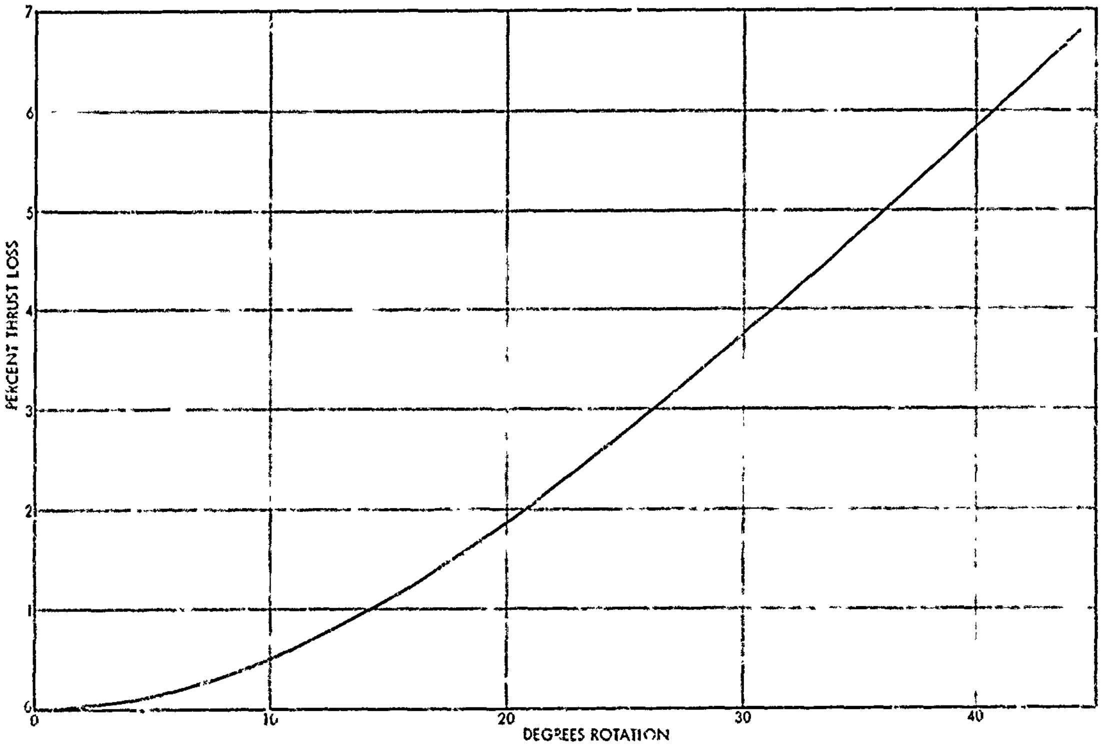


Figure 7-4. Thrust Loss as a Function of Shaft Rotation

the tab is inserted. As can be seen from Figure 7-5, the direction of thrust vector progresses nearly linearly from approximately 1.5 degrees to six degrees. The tab shaft was located to provide the thrust vector on the RPV axis at 3.5 degrees of thrust vector. The total vector progression over the maximum vector range is 14 degrees.

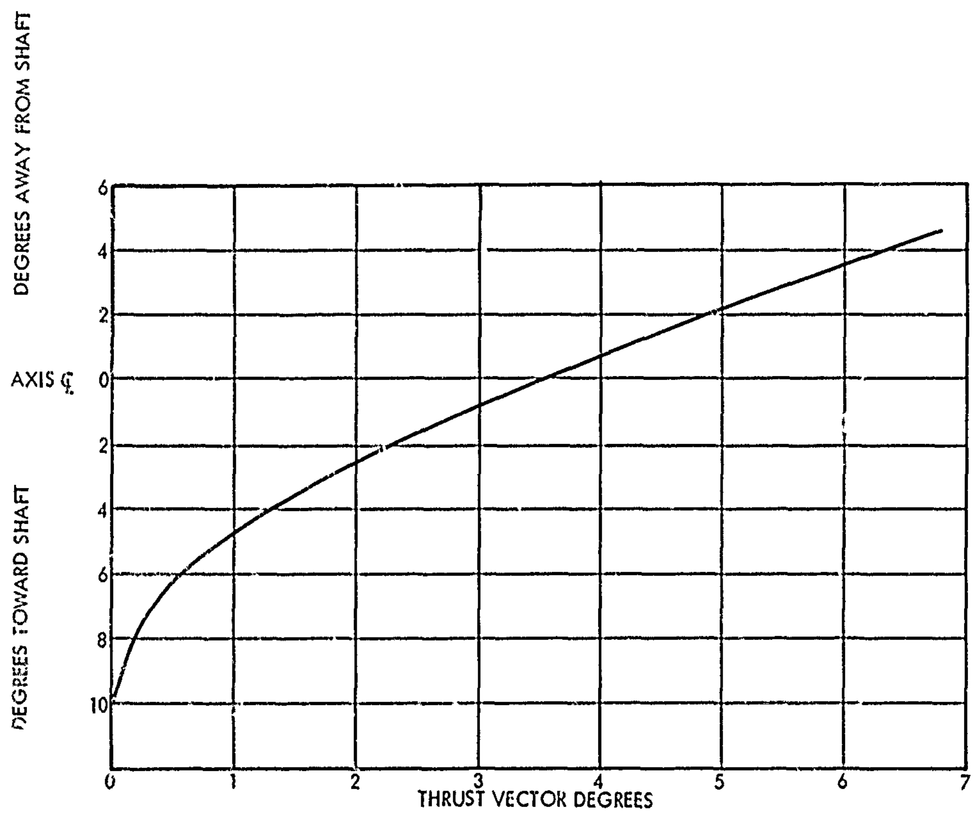


Figure 7-5. Thrust Vector Progression

7.2 ACTUATION CHARACTERISTICS

An attractive feature of the jet tab thrust vector control system is the low actuation torque required. Low torque allows the use of simple low-cost electromechanical actuators. This is particularly attractive in the BGM-34C where a surplus of electrical power is available. Measurement of the level of actuation forces during motor firing allows optimization of the selection of electric gear motor actuators.

Because of the power output problems encountered when operating the TVC system using the TRA GLICU, it was necessary to utilize different gear head ratios on the pitch and roll axes. Typical actuation response to step input commands for the two gear ratios is shown in Figure 7-6.

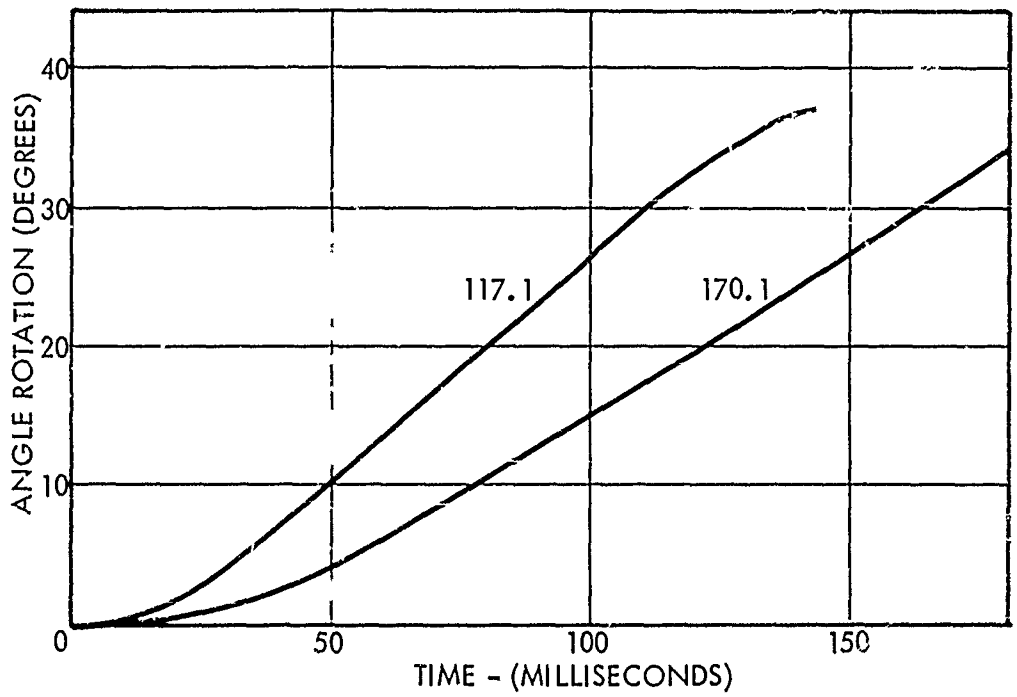


Figure 7-6. Actuation Responses

7.3 THERMAL CHARACTERISTICS

The thermal capability characteristics of the BGM-34C jet tab TVC system are typified by the charring and ablation of the exit liner, the charring of the blade insulator and the resistance to degradation of the tab face refractory.

The predicted thermal margin of the liner is quite substantial as was discussed elsewhere in the report. A sectioned liner was examined to determine in-depth charring and surface ablation. Figure 7-7 illustrates the condition of the liner that was fired in unit PFRT-5. The section was taken at the location of maximum erosion underneath tab 1 (which had the longest insertion time). Since the char and erosion depths were much less than the material thickness, it can be concluded that the existing design is extremely conservative. Char depth data was determined by visual observation as well as qualitative changes in material hardness that are indicative of the heat affected zone in the resin system. No corrections were made for char swell or post test heat soak.

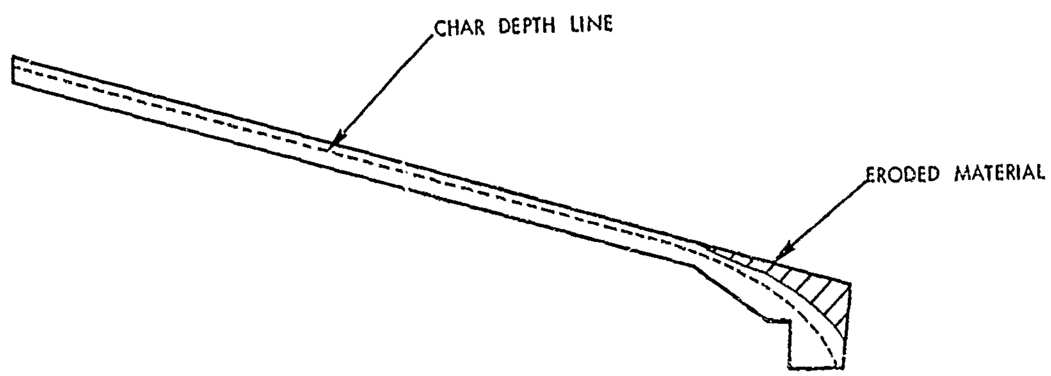


Figure 7-7. Nozzle Liner Char Depth

The blade insulator thickness and material was selected on the basis of TRW experience and the results of the product improvement tests. Configurations similar to the tab unit cross section used have survived for over 20 seconds of tab insertion time. To confirm the thermal margin for the tab system, the insulator from tab 1 of unit PFRT-05 was sectioned in four locations to allow measurement of in-depth charring. The insulator survived with the major portions being unaffected by heating. Erosion was experienced around the shaft insulator due to impingement of alumina contained in the exhaust products. The char and erosion characteristics are shown in Figure 7-8. The relatively deep char at the insulator leading edge is attributed to the constant exposure to the axial flow exhaust. The shallow char depth on the face of the insulator results from thermal conduction from the blade.

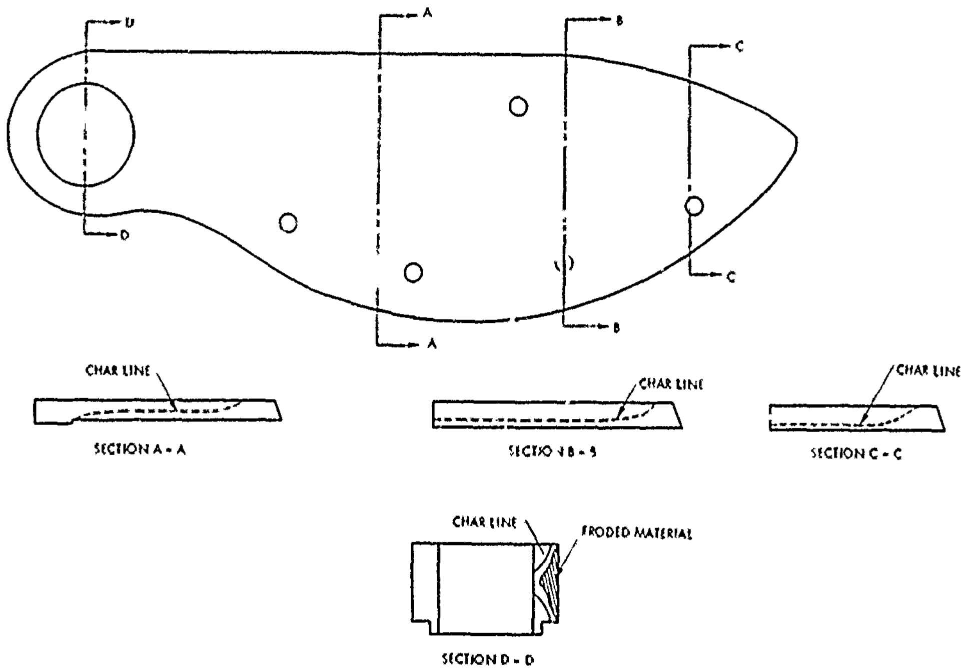


Figure 7-8. Tab Insulator Char Depth

The resulting tab facing material and thickness resulted from the extensive test demonstration on the product improvement test units and the first three PFRT units as discussed in Section 5.0. After the final material selection, because of problems with the TRA GLICU unit, a significant duty cycle with maximum insertion depths was not achieved until the final test. Previous programs and the temperature data obtained during the product improvement tests indicated that the refractory material temperature can approach the propellant flame temperature under extended exposure conditions. Tab 1 from test PFRT-07 was sectioned and examined.

As can be seen from Figure 7-9, complete recrystallization of the structure had occurred. The larger grain sizes nearer to the flame surface are typical for extended exposure. The absence of subsurface cracks noted in the .25 inch material tested, is a typical condition found in the thinner grain oriented material. A small amount (0.03 inch) of surface regression experienced resulted from the loss of single large grain crystals (Figure 7-10) rather than subsurface cracking and spallation.

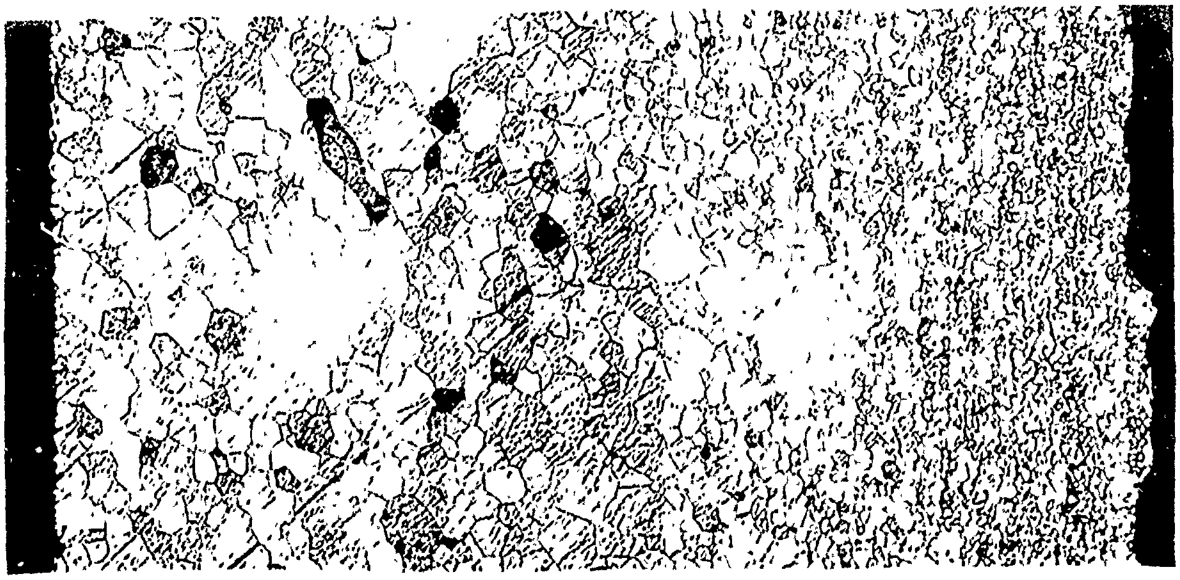


Figure 7-9. Tab Facing Microstructure - 27X - Tab 1 - Test PFRT-07

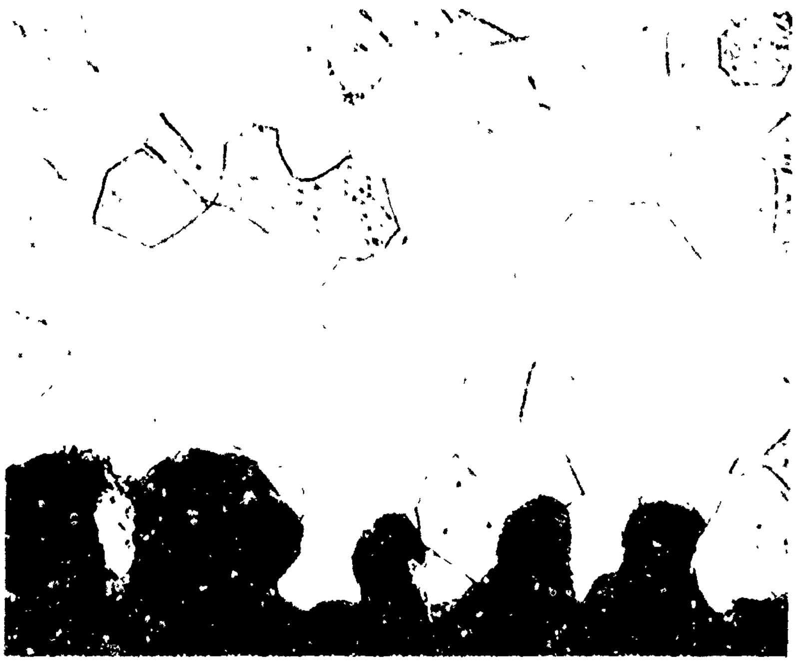


Figure 7-10. Surface Grain Loss - 50X - Tab 1 - Test PFRT-07

8.0 INSTRUMENTATION

To measure the performance of the jet tab thrust vector control capability, all tests were conducted with the motor fired vertically upward in a six component thrust stand. Limited temperature measurements were also conducted on the first two product improvement test firings. Based upon the prior experience with jet tabs as described in Section 3.2, the need for more extensive determinations of environmental characteristics was of minor importance.

8.1 THRUST MEASUREMENT

Two AFRPL six-component thrust stands were used during the course of the program. The product improvement tests were accomplished using the AFRPL Char motor test stand located on Pad 1 in the 1-32 Test Area. The 40-inch diameter Char motor case was modified to mechanically interface with the TU-752 rocket motor. A schematic of the six component Char motor thrust stand is shown in Figure 8-1. The test data obtained from the Char motor stand exhibited substantial dynamic ringing.

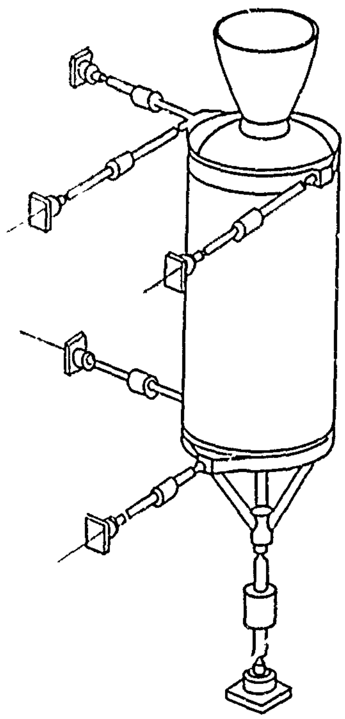


Figure 8-1. AFRPL Six-Component Char Motor Thrust Stand

A new six component thrust stand fabricated by Ormond Inc. was installed on Pad 1 of the AFRPL 1-32 Test Area. The new test stand was used for all PFRT test firings. A schematic of the stand is shown in Figure 8-2. The thrust data from this stand was considerably improved over the Char motor test data. The thrust stand was provided with a built in calibration system to allow periodic accuracy verification.

8.2 THERMAL MEASUREMENTS

The thermal capability of the jet tab system was not of major concern because of the relatively mild environment provided by the short duration, conventional chamber pressure characteristics of the TU-752 and TU-793/03 rocket motors. Temperature measurements were limited to those sufficient to confirm this assumption. On test PI-1, one tab was instrumented with W/Re thermocouples located within the molybdenum tab facing. Figure 8-3 illustrates the thermocouple installation schematic. On test PI-2, two tabs were provided with the same thermocouple instrumentation. The configuration of the buried thermocouple is shown in Figure 8-4. Maximum temperature levels of approximately 3200^{o}F were observed. Thermocouple installation was not performed on any of the PFRT unit tests since the product improvement test unit results did not warrant the expenditure required for additional measurements.

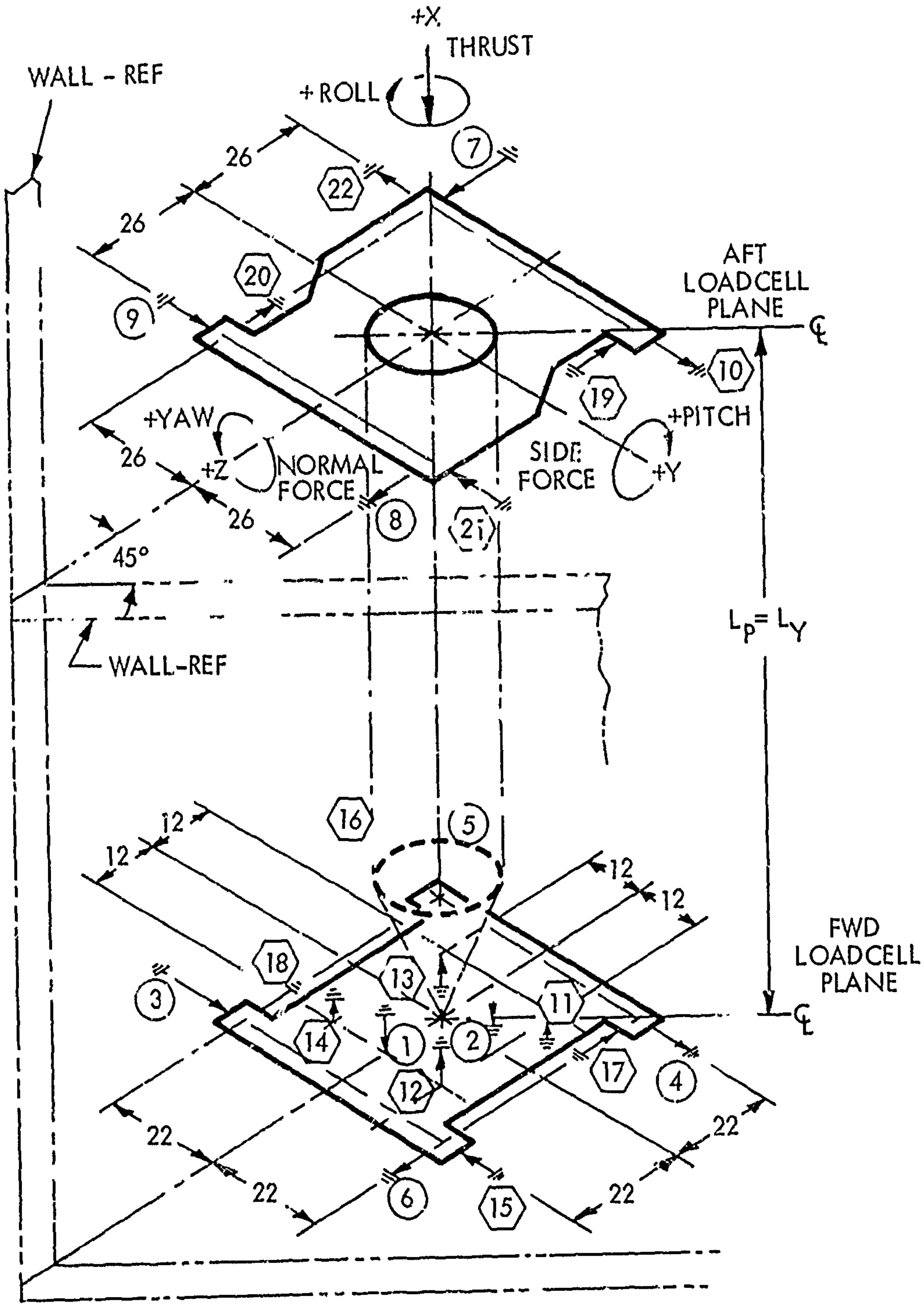


Figure 8-2. Test Stand Schematic

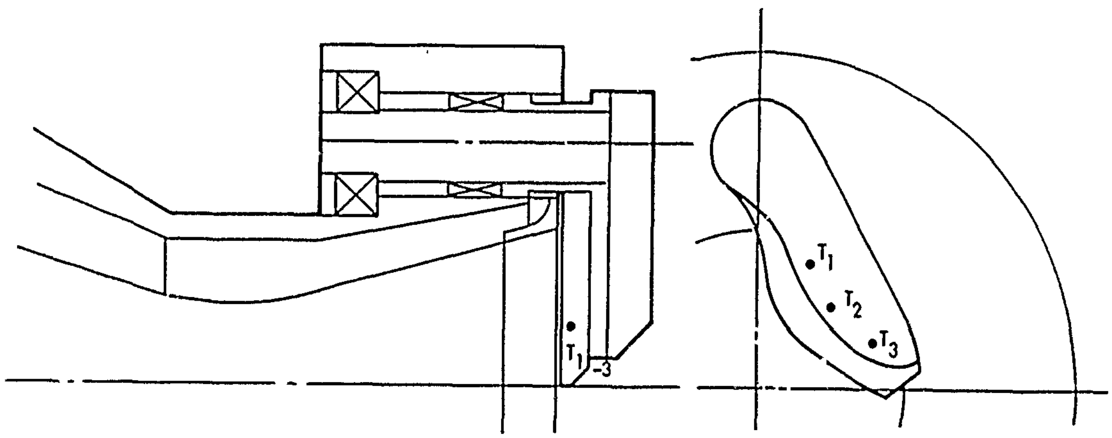


Figure 8-3. Thermocouple Location

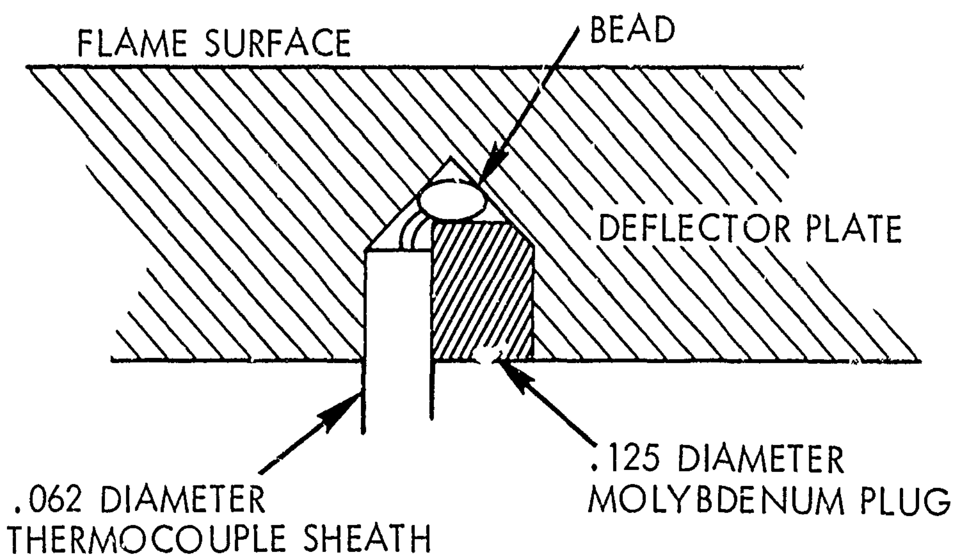


Figure 8-4. Buried Thermocouple

9.0 SYSTEM SAFETY

During the design and fabrication phase of this program a system safety analysis was conducted. This study was made in accordance with the outline for preliminary hazard analysis contained in Paragraph 5.8.2.1 of MIL-STD-882.

A list of potential hazards relating to operation of the jet tab TVC system was compiled. Each item was categorized as to the level definitions of MIL-STD-882. All items were considered to be of either category I - negligible or category II - marginal. The results of the analysis are presented in Table 9-1 together with specified preventive measures and possible corrective measures for each item.

TABLE 9-1. SYSTEM SAFETY ANALYSIS

HAZARD CLASSI-FICATION	POTENTIAL HAZARD	HAZARD EFFECT	SPECIFIED PREVENTIVE MEASURES	POSSIBLE CORRECTIVE MEASURES
II	Rotation of jet tab TVC system relative to solid rocket motor closure. For example, during an extended prelaunch hold, system vibration causes above-mentioned rotation that mis-aligns TVC system pitch/yaw axes with RPV axes. (4)	Upon actuation, pure pitch or yaw commands will generate a component of force in the orthogonal axis. Maximum rotation is estimated as a 1" circumferential displacement at the nozzle/motor interface. The spurious component will be approximately 22.5% of the command level while the desired force is reduced to 96% of the programmed value	Set screws at the interface will be torqued in accordance with maximum allowable values during the initial assembly operations.	Torque procedure could be re-checked at integration of booster/RPV.
II	Rotation of gear head housing containing tab position feed-back potentiometer relative to nozzle housing or tab shaft. (4)	Spurious feedback signal will cause controller to be incapable of performing in a closed-loop operation sequence. Tab over-actuation may damage TVC power train	TVC system manufacturing planning includes empirical check of motor mounting screws, which clamp gear head housing on installation, and safety wiring to prevent any loose condition. Prior to flight, use of actuation check out kit will allow measurement of potentiometer feedback values.	Redundant check of motor mounting screws could be performed prior to flight.
I	Loose condition between DC actuation motor and gear reduction unit. (4)	Tab control response rate capability will degrade somewhat. Reversal of actuation directions will result in a lag (estimated <.1 sec) as armature inertia causes limited counterrotation of motor body.	Plastic clamps are installed over the knurled motor/gear box attachment to prevent loosening. Prior to clamp installation the knurled ring is torqued in accordance with manufacturers instructions.	Redundant check of motor/gear box tightness prior to flight.
II	Tab face (refractory) failure allows impingement of rocket exhaust on unshielded TVC components.	Tab operation as a predictable TVC device for that component of force will be eliminated. Possible requirements for control forces will not be achieved.	System design with multiple fasteners, low blade deflection and adequate refractory dimensions minimize the probability of occurrence. Inspection of components for proper dimensions and material properties prior to assembly insures that design factors apply to the actual unit.	NONE
II	Tab support shaft failure (1)	Same as directly above.	Structural margin in the support shaft are very high (above 3.0) for test conditions. Quality control requirements prevent acceptance of a defective component.	NONE
II	Bearing failure for either thrust bearing or radial load needle bearing.	Bearing failures would result in greatly increased actuation power requirements and/or expulsion of the tab shaft. Either occurrence would eliminate predictable and effective control in the affected quadrant.	Design margins for both bearings are extremely high (above 4.0) for all projected modes of operation. Defective bearings are eliminated by quality control. Correct bearing function is proven by tab actuation checkout prior to flight.	Redundant checkouts of bearings by physical movement of tabs can be accomplished at any time prior to energizing the TVC system before RPV launch.
II	Gear train failure flight (3) checkout (5)	Any gear train failure effectively locks up the actuation system in the approximate position of failure. The likelihood of failure during flight is very low. During pretest checkout, due to the no load tab condition, likelihood of failure is higher. Flight failure would result in the loss of that axis of control with a possible introduction of a spurious and unchangeable force. A checkout failure has no mission success implications	Since gear head failures result from impact loading, the physical actuation stops are both padded and adjusted for a wide clearance from desired control point. Also, the power available from the checkout unit is low enough to reduce rate and power capability of the actuation system.	During checkout, the technician may apply a slight load to the tab by grasping the aft stiffening rib of the tab. This will limit actuation rates and reduce the possibility of impact loads

TABLE 9-1. SYSTEM SAFETY ANALYSIS (CONTINUED)

HAZARD CLASSI-FICATION	POTENTIAL HAZARD	HAZARD EFFECT	SPECIFIED PREVENTIVE MEASURES	POSSIBLE CORRECTIVE MEASURES
II	Potentiometer failure such that tab position feedback to the controller is not possible (3)	The lack of feedback will halt proper closed loop control system function. Resultant TVC commands may be spurious and not related to flight requirements.	The manufacturing and quality controls eliminate defective pots prior to installation. Functional checks prior to system shipment verify correct operation. The preflight checkout confirms acceptable potentiometer function.	NONE
II	Exit liner failure such that rocket motor exhaust products have paths to the nozzle housing (2)	An early liner failure could result in a TVC system failure to function in any manner. The exhaust gasses would burn through the steel housing and damage the actuation system, potentiometers, and wiring almost certainly beyond a continued functional ability.	Exit liner manufacturing and quality controls eliminate defective components. Installation procedures include bonding with an RTV adhesive that provides some insulation and sealing capability. The exit liner design margins, structural and thermal are very high.	Visual inspection of the liner surface prior to launch would reveal any handling or environmental damage.
II	Housing failure such that structural or thermal margins are exceeded (2)	A housing failure will result in a catastrophic failure of the TVC system with a complete lack of functional capability.	The manufacturing and quality controls prevent use of defective housings the structural margins are very high and the annealed housing material is not overly sensitive to handling or environmental effects. Static testing of housings with carefully selected defects has defined the limits of acceptable variance.	Visual inspection of the housing prior to flight would reveal any unforeseen damage due to transportation, etc.
II	Damaged wiring, either internal to shroud or in external umbilical (3)	The TVC system will cease to function predictably with a detrimental effect on flight performance.	Damage will be prevented by careful handling and use of redundant cable changes. Preflight checkout will verify proper wiring functions.	Visual inspection for damage prior to flight.
II	Noisy command signal (2)	The thrust vector will tend to follow the command signal within the limits of its response rate capability. If the noise is of extreme amplitudes, durations, etc., detrimental flight performance may result.	Cable connectors will be cleared and installed in accordance with appropriate procedures. Shielded wiring is used where needed.	NONE
II	Loss of actuation power. (2)	Thrust vector orientation will be determined by the installation alignments. Unpowered tabs will be forced to an out (no vector) position by aerodynamics loads in the rocket exhaust.	Power connectors will be installed in accordance with appropriate procedures.	NONE
I	Crumpling, deformation or tearing away of the aerodynamic shroud. (2)	The loss of the shroud should not affect performance of the TVC system.	The shroud was designed for reasonable stiffness and structural integrity. Assembly is in accordance with an approved procedure.	Visual inspection of the shroud prior to flight should detect damage or improper assembly.

10.0 RELIABILITY AND MAINTAINABILITY PREDICTION

One of the program requirements was to conduct a qualitative analysis and numerical prediction of potential system maintainability and reliability. The limited number of tests coupled with the random failures experienced do not provide a significant confidence level at this time in the predicted reliability assessment.

10.1 RELIABILITY ANALYSIS

A preliminary analytical reliability estimate of the flight jet tab TVC system was completed through an examination of the hardware included in the configuration and a comparison with characteristics associated with similar (generic) hardware. A listing of hardware used in the TVC system is shown in Table 10-1. The table indicates that among the components, the DC gear motor is considered to exhibit potentially the highest probability of failure. This component is inactive during the storage and pre-firing periods and is required to survive to operate functionally only during the short (∿8 second) mission phase. The generic failure rates shown for other components represent estimates based on their complexity relative to the gear motor. The total failure rate (representing a series - non-redundant - system) for what are considered potentially the most failure prone components is estimated to be approximately 90.0×10^{-5} failures/hour. This failure rate applied to an 8 second function mission plus allowance for RPV turbojet engine start-up indicated an estimated mission reliability of ∿0.999. Allowing for some failure rate growth and error, a reliability estimate of 0.998 success probability per test is realistic and potentially attainable for the system.

The high reliability is a direct result of the design simplicity and lack of hydraulic components which can have relatively high failure rates. The DC gear motor is assumed to have the lowest reliability conditions. Limited laboratory bench tests have indicated that the gear motor can be subjected to stall torque requirements more than 25 times without a failure.

Table 10-1. Predicted Reliability for Jet Tab TVC System

	Component/Assembly	Estimated Reliability
1.	Gear Motor	0.99950
2.	Control Circuit	0.99958
3.	Potentiometer	0.99964
4.	Power Supply	0.99972
5.	Blade and Shaft Assembly	0.99978
6.	Nozzle Assembly	0.99986
7.	Shaft Bearings	0.99992

10.2 MAINTENANCE

The jet tab TVC and nozzle assembly can be handled completely separate from the remaining RPV components. The design lends itself quite well to periodic bench tests to check out the TVC actuation system. Operational tests may be required for each gear motor prior to deployment. An auxiliary power source (12 volts DC) would be used to provide power to the motors to avoid activating the RPV power supply.

During storage no special maintenance is envisioned since no hydraulic systems with potential leakage problems are present. The gear motors are sealed such that the armature contacts will not oxidize, even when exposed to environmental extremes. The gear trains and bearings are life lubricated. Therefore, the jet tab TVC system can be maintained in a ready-for-operation state for as long as ten years.

11.0 PRODUCTION COST STUDY

A cost analysis was conducted on the flight jet tab TVC system. An analysis was made for assumed production quantities of 500, 1000 and 5000 units. The analysis consisted of three principal phases. First, detailed production flow diagrams were developed. The fabrication process was laid out for each component. Figure 11-1 typifies the level of detail used in this portion of the analysis. The associate production plan identified the most cost effective methods for fabricating the various number of units, and indicated those areas of trade-off where the amortization of new equipment, higher quality tooling, etc., is cost effective.

Second, Operation Worksheets were completed for each operation identified in the diagram. Each worksheet contained a brief description of the operation analyzed. This analysis resulted in the labor, materials, and tooling requirements for the operation. Integration and test costs were based on the statistical base being generated on the Tomahawk Cruise Missile program. This data base also provided estimates of quality control, supervision, engineering support and other direct costs required per unit. Material costs were obtained from supporting information from potential material suppliers and parts fabricators.

Finally, Item Unit Cost Summary Sheets were prepared for each principal component. These sheets summarized the requirements identified on the Operations Worksheets, and using appropriate labor and overhead rates, the requirements were converted to dollars per production unit. The results of the production cost analysis is presented in Table 11-1. A summary of the key material item costs is presented in Table 11-2.

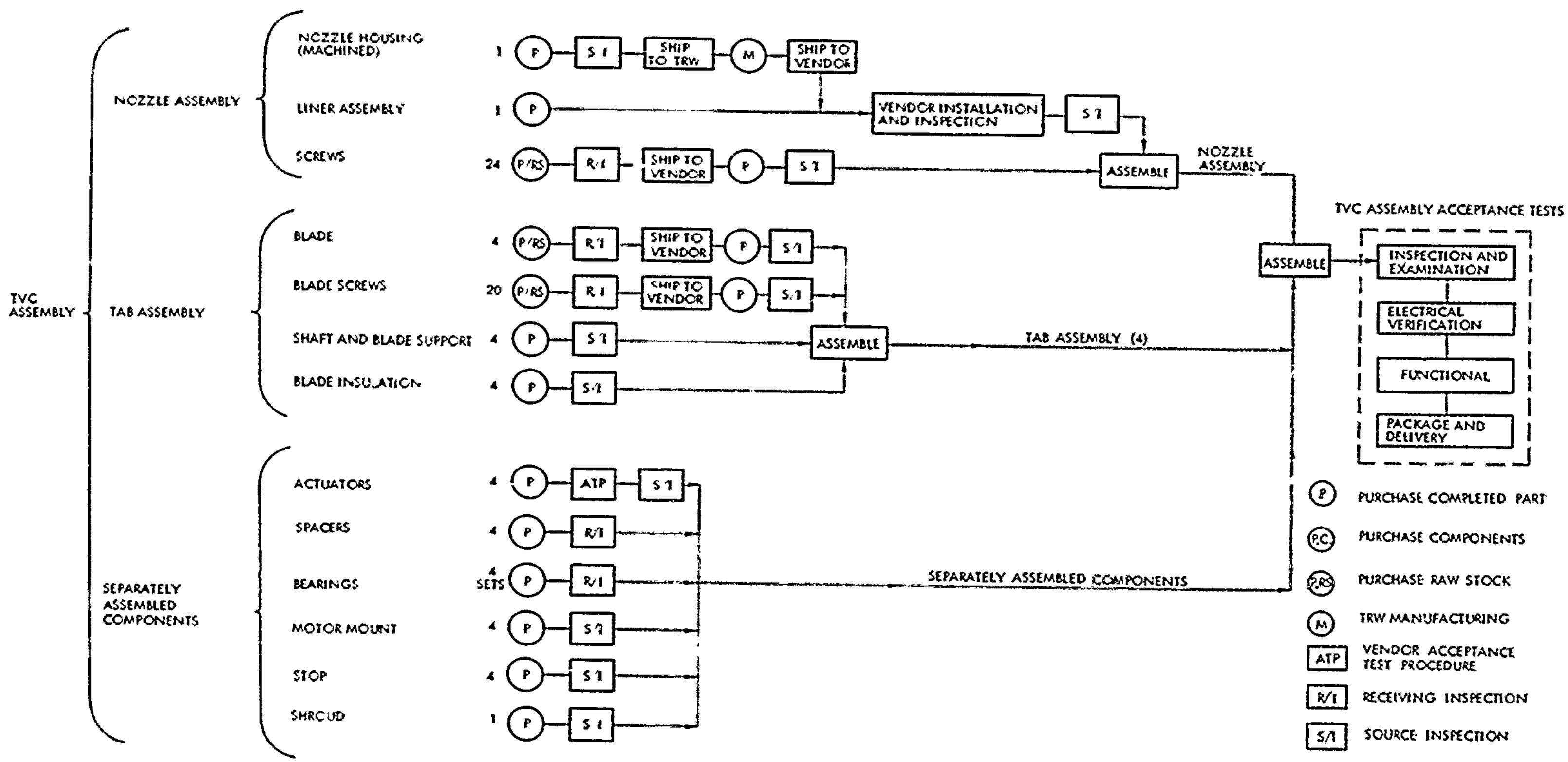


Figure 11-1. Jet Tab TVC System Production Flow Diagram

Table 11-1. Jet Tab TVC System Production Cost Summary

Item	- QUANTITY - 500	1000	5000
Program Management	$ 400	$ 300	$ 300
Integration and Test	750	600	600
Materials Engineering	40	30	30
Material	4,545	4,115	3,890
Reliability	30	20	20
Quality Assurance	250	200	200
Material Control	50	40	40
Other Direct Costs	40	30	30
Total Cost	$6,105	$5,335	$5,110

Table 11-2. Jet Tab TVC System Material Costs

	- QUANTITY - 500	1000	5000
Key Materials			
Nozzle Housing	$1,295	$1,160	$1,102
Nozzle Liner	650	527	505
Tab Support	340	300	275
Actuator	1,060	1,011	960
Shroud	249	210	188
Tab Face	376	357	335
Low Value Materials	575	550	525
Total Material	$4,545	$4,115	$3,890

12.0 CONCLUSIONS AND RECOMMENDATIONS

In line with the objective of this program, which was to demonstrate a thrust vector control system for a solid rocket booster motor, the following conclusions can be stated:

A. The BGM-34C jet tab TVC system provides thrust vector performance equivalent to the baseline JBQM-34H configuration.

B. The low cost material changes implemented have demonstrated adequate durability.

C. The jet tab TVC/GLICU have been demonstrated in test firings and are ready for commitment to ground launching of the BGM-34C RPV.

Additional development effort is warranted to achieve a minimum production cost system by investigation of the following areas:

A. The ablative materials used provided a significant thermal margin over that required. Changing processes to allow in-place molding will reduce overall unit cost.

B. The thrust vector capability of the jet tab system is greater than that required for the launch envelope. At a minimum, the size of the roll tabs should be reduced to be compatible with the electrical limits imposed by the control unit.

C. Thrust vector response rate should be reviewed. Changing to a higher ratio gear motor with higher output torque at slower vector response rate, particularly in the roll axis, may allow the use of a smaller lower cost electric motor and lower amperage electronic equipment in the controller.

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