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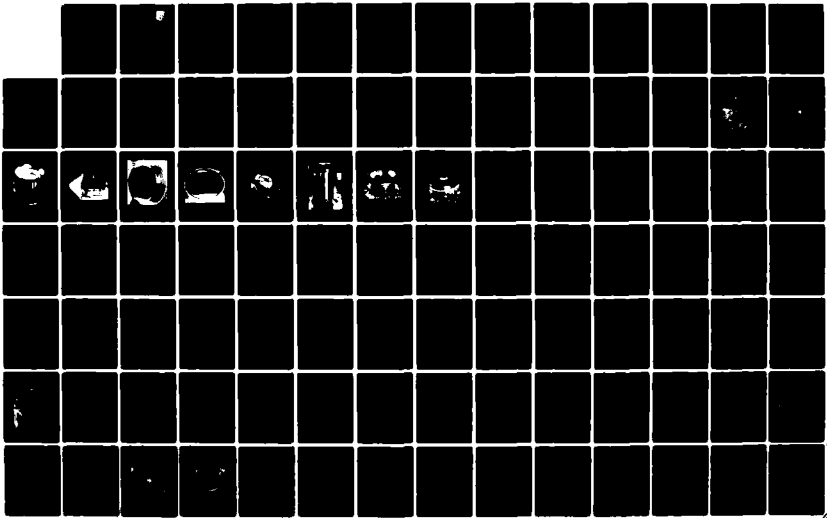

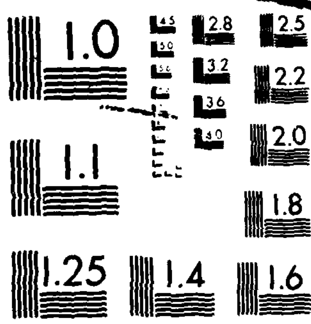
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AFWAL-TR-82-2119

RESTARTABLE HIGH POWER GAS GENERATOR

M. G. GANTS

ROCKETDYNE DIVISION/ROCKWELL INTERNATIONAL
6633 CANOGA AVENUE
CANOGA PARK, CALIFORNIA 91304

DECEMBER 1982

FINAL REPORT FOR PERIOD MAY 1979 - AUGUST 1982

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AERO PROPULSION LABORATORY
AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
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NOTICE

This technical report has been reviewed and is approved for publication.

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

A requirement exists for a means of providing large amounts of power on an intermittent basis to special airborne systems. The objective of this effort was to demonstrate the feasibility of a restartable, throttleable, LOX/JP-4 gas generator which requires no purge. Rocketdyne designed and fabricated a gas generator, capable of producing 15,000 HP when coupled with a 71% efficient turbine. Hot fire tests were performed, successfully demonstrating purgeless operation, fast start, restartability, hot gas temperature pattern factor, and required power levels.

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PREFACE

The work herein was conducted under Contract F33615-79-C-2004, for the Air Force Wright Aeronautical Laboratories from May, 1979, through August 1982 by Rocketdyne, a division of Rockwell International. At Rocketdyne, W. J. Christoff, Program Manager, and M. G. Gants, Project Engineer, were responsible for the overall direction of the Restartable High Power Gas Generator Program. Mr. P. Colegrove of the Aero Propulsion Laboratory was the Air Force Project Engineer in charge of the direction and coordination of the program between the USAF and Rocketdyne.

Important contribution to the conduct of the program and to the preparation of the report material were made by the following Rocketdyne personnel.

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Santa Susana Field Propulsion Laboratory:	Mr. D. Clarke Mr. J. Condiff

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SUMMARY

The objectives of the Restartable High Power Gas Generator Program were to design, fabricate, and perform hot fire tests on a fast start, throttlable restartable, purgeless, gas generator using LOX/JP-4 propellants. The nominal maximum power output of the gas generator is sufficient to produce 15,000 HP, when passed through a suitable turbine. It was assumed that the turbine had an overall efficiency of 71%. Overall efficiency is defined as shaft horsepower output divided by adiabatic gas horsepower input. The design used existing Lance sustainer hardware requiring a minimum of modification where possible.

The gas generator was designed to have a turndown ratio c [illegible] to 1. The gas generator consists of two major subassemblies: the inje[illegible]nd the combustion chamber, including the turbine simulator and hot gas nozz[illegible]. The injector was equipped with a movable pintle to modulate the oxidizer and fuel flow over the throttling range. Control of the pintle was achieved with a hydraulic servo valve using fuel inlet pressure as the activating media. The combustion chamber was equipped with a turbulator to enhance the hot gas temperature profile.

The unit was fabricated, water-flow calibrated, and subjected to fourteen (14) hot fire tests. During the performance of these tests, several design modifications were incorporated to compensate for deficiencies. The redesign effort included the following:

1. Improved positive face shutoff seal to eliminate leakage.

2. Improved liquid oxygen thermal liner providing increased structural integrity.

3. Nickle plating of the fuel ring exposed to hot gas to minimize erosion.

4. Improved thrust chamber-to-injector interface to enhance fuel injection ring durability.

5. Improved pintle LOX dynamic seal minimizing leakage which produced a pintle force imbalance during throttling.

6. Redesigned hot gas turbulator required to achieve the specified hot gas temperature profile.

7. Increasing the injector fuel and LOX differential pressure to eliminate a minor propellant/combustion process stability problem.

8. Copper plating the tip of the pintle to eliminate minor erosion.

As a result of the hot fire test program, the following key operating features were demonstrated:

Fast Start - Ignition and transition to full power level within 500 milliseconds.

Throttlable - 5 to 1 turndown ratio demonstrated.

Restartable - Repeatable restart capability three seconds following complete shutdown.

Purgeless Operation - Successful operation without oxidizer and fuel propellant system purges.

Hot Gas Temperature -	Distribution temperature profile demonstrated to be less than 100°F, the maximum allowable specified value.
Combustion Stability -	Combustion process demonstrated to be stable.

INTRODUCTION

Requirements exist for large electrical power outputs on a rapid-start intermittent basis for specialized airborne systems. To date, approaches to meet these requirements have been directed toward the development of staged monopropellant hydrazine generators capable of driving turbo-alternators up to approximately 6000 HP. Larger power outputs are now required; and the uncertainty of further scaling the monopropellant hydrazine generators, along with logistical, safety, and environmental considerations associated with the use of hydrazine, appears to favor the use of alternate gas generator propellants.

Liquid oxygen/JP-4 was identified for investigation: this propellant combination precludes the logistical, safety, and environmental problems inherent in hydrazine, but present some new technical challenges in meeting the design and operational requirement as specified.

A program was performed to demonstrate the feasibility of a restartable high-power gas generator capable of driving turbogenerators of 15,000 HP. The restartable gas generator is capable of operating over a 5 to 1 throttle ratio using JP-4/LOX as a propellant.

The design concept makes use of existing throttling technology, and capitalizes on developed and qualified hardware concepts. To this end, the baseline gas generator design utilized the features of the production Lance Sustainer deep throttle-line injector technology, hardware and tooling.

The Restartable High Power Gas Generator design and operating requirements are presented in Table I . The effort was accomplished during the following major tasks outlined in Figure 1:

TABLE 1. RESTARTABLE HIGH-POWER GAS GENERATOR PERFORMANCE REQUIREMENTS

- Nominal Maximum Power Output (with overall turbine efficiency of 71%) - 15,000 HP

- Throttlability

  5:1 Turndown Ratio

- Nominal Average Hot-Gas Temperature

  1600 ±50 F Over Throttle Range

- Hot-Gas Uniformity at Turbine Inlet

  $$\text{Pattern Factor} = \frac{T_{max}}{T_{avg}} - 1 < 0.065$$

- Startup Time (from start signal) to Full Gas Power

  in 500 msec

- Restartability

  Full Gas Power Within 3 seconds after termination of a 10-second Run (indefinitely)

- Maximum Nominal Operating Pressure

  700 psia Chamber Pressure

- Overpressure Capability

  10% Above Nominal Pressure

- Propellants

  Satisfactory Operation with JP-4/LOX

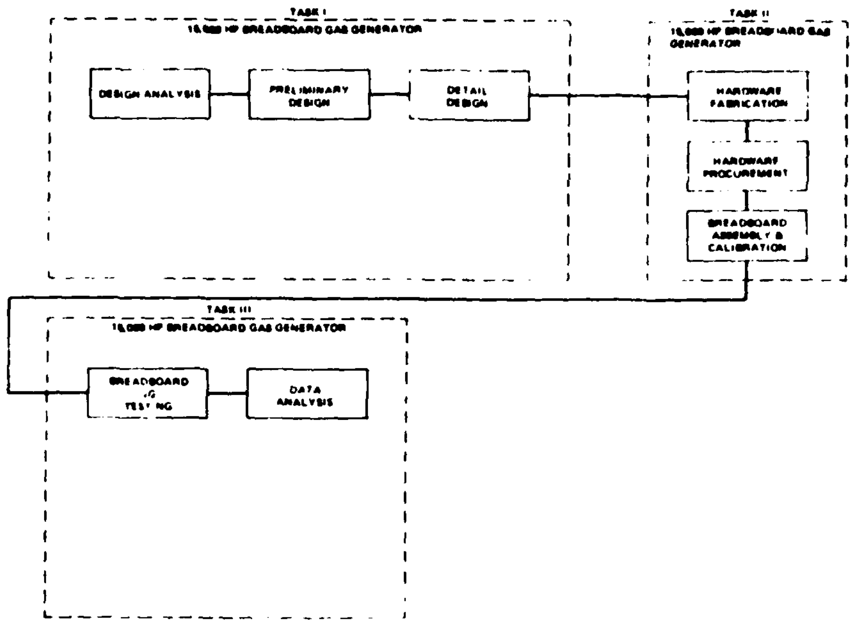


Figure 1. Program Scope

Task I - Design of Breadboard Gas Generator

Task II - Hardware Fabrication, Procurement, and Test Facility Buildup

Task III - Breadboard Gas Generator Testing

TASK I - DESIGN OF BREADBOARD GAS GENERATOR

This task addressed the design and operating requirements for the breadboard gas generator, and identified the necessary hardware modification to meet these requirements. The specific areas emphasized during this design task were: fast start-restart, throttling, purgeless operation, temperature uniformity, propellant interchangeability,servo control, propellant thermal management, combustion stability, materials compatibility, endurance and structural inte^rity.

At the conclusion of the design and analysis task, detail drawings of a 15,000 HP breadboard gas generator assembly were prepared, and a design review held with the AFAPL Project Manager for review.

TASK II - HARDWARE FABRICATION, PROCUREMENT, AND TEST FACILITY BUILDUP

The injector components were primarily fabricated from Lance Sustainer injector detail parts with modifications to achieve the operational requirements. The Lance pintle position transducer servo valve and the J-2 spark igniters were procured. The injector, combustor body, turbulator and nozzle were fabricated, using Lance program established practices whenever possible.

Following fabrication and procurement of the detail components, and prior to delivery to the hot fire test facility, the unit was assembled and subjected to a series of leakage and cold flow calibration tests to characterize the injection pattern and hydraulic behavior as a function of pintle throttle position.

TASK III - GAS GENERATOR TESTING

A detail demonstration test plan of action was prepared and submitted to the AFAPL Project Manager outlining the specific tests to be performed to demonstrate the program objectives.

A total of fourteen (14) hot fire tests were performed. A brief description of the tests performed is presented in Table II.

TABLE II
TEST SUMMARY

TEST NO.	TEST OBJECTIVE	POWER LEVEL	DURATION SECOND	TEMPERATURE PATTERN FACTOR	RESULTS
1	INITIAL IGNITION	55	0.2	–	• TEST CUT FAILURE TO DETECT IGNITION TEST SETUP ERROR
2	1 SECOND DURATION	77	1.0	0.058	• SUCCESSFUL TEST
3	5 SECOND MAX POWER	100	5.0	.009	• MIXTURE RATIO 0.33 • INJ EROSION • LOX LINER FAILED
4	5 SECOND MAX POWER	100	0.2	–	• IGNITION DETECT SYSTEM FAILURE
5	5 SECOND MAX POWER	100	5.0	0.068	• NO ANOMALIES
6	10 SECOND THROTTLING	100	10.0	0.134	• PINTLE DID NOT THROTTLE • SLIGHT PINTLE EROSION • SLIGHT TURBULATOR EROSION
7	3 CYCLE THROTTLING	100	0.9	–	• HOT GAS TEMP REDLINE CUT M.R. 0.49
8	10 SECOND THROTTLING NO TURBULATOR	100	1.3	–	• HOT GAS TEMP REDLINE, HIGH M.R. • FUEL POSITIVE FACE SEAL FAILED RESTRICTING FUEL SLOTS
9	THROTTLING RESTART CU PLATE PINTLE	100–30	20.0	0.27→.038	• FUEL RING DISTORTION • TURBULATOR EROSION

TABLE II (CONTINUED)

TEST NO.	DURATION SEC	PINTLE POSITION	POWER LEVEL	FUEL RING CONFIGURATION	HOT GAS MIXER	FUEL RING RESULTS	TEMPERATURE PATTERN FACTOR	COMMENTS
10	10	100%	FULL	347 CRES Ni PLATED THERMAL SHIELDING	TURBULATOR TURBULENCE RING	NO ANOMALIES	0.23	TURBULENCE RING NOT EFFECTIVE IN IMPROVING TEMP/ DISTRIBUTION
11	10	90%	FULL	347 CRES Ni PLATED THERMAL SHIELDING	NONE	NO ANOMALIES	0.13	REMOVING TURBULATOR AND OPERATION AT INCREASED ΔP, IMPROVED TEMPERATURE PATTERN FACTOR
12	10	80%	FULL	347 CRES Ni PLATED THERMAL SHIELDING	NONE	NO ANOMALIES	0.11	NO CHANGE IN PATTERN FACTOR
13	10	90%	FULL	SOLID NICKEL THERMAL SHIELDING	NONE	EROSION	.12	CORE AND FUEL RING EROSION
14	THREE 10 SECOND TESTS BACK TO BACK	90%	FULL	347 CRES Ni PLATED THERMAL SHIELDING	RIGHT ANGLE TURBULATOR	EROSION	.033	CORE AND FUEL RING EROSION EXCELLENT TEMPERATURE DISTRIBUTION

GAS GENERATOR DESIGN

This section presents the basic design of the gas generator and a detailed discussion of the significant analyses associated with the design. As the hot fire program progressed, reevaluation and redesign efforts were initiated to eliminate problem areas for subsequent hot fire evaluation. These analyses and redesign descriptions are presented and discussed in the detail test results section.

GAS GENERATOR DESIGN CONCEPT

The design of the gas generator was based on the Lance Sustainer injector with those changes incorporated to accommodate the cryogenic oxidizer. A section view of the gas generator is shown in Figure 2. The assembly consisted of:

1. Pintle-type throttling injector using a hydraulic servo valve to control throttling;

2. Two injector face-mounted spark plugs for ignition;

3. Combustion chamber equipped with a nickel liner to dissipate localized chamber wall streaks;

4. Hot gas turbulator to enhance hot gas mixing;

5. Chamber extension equipped with a hot gas temperature rake;

6. Hot gas nozzle, simulating turbine inlet area.

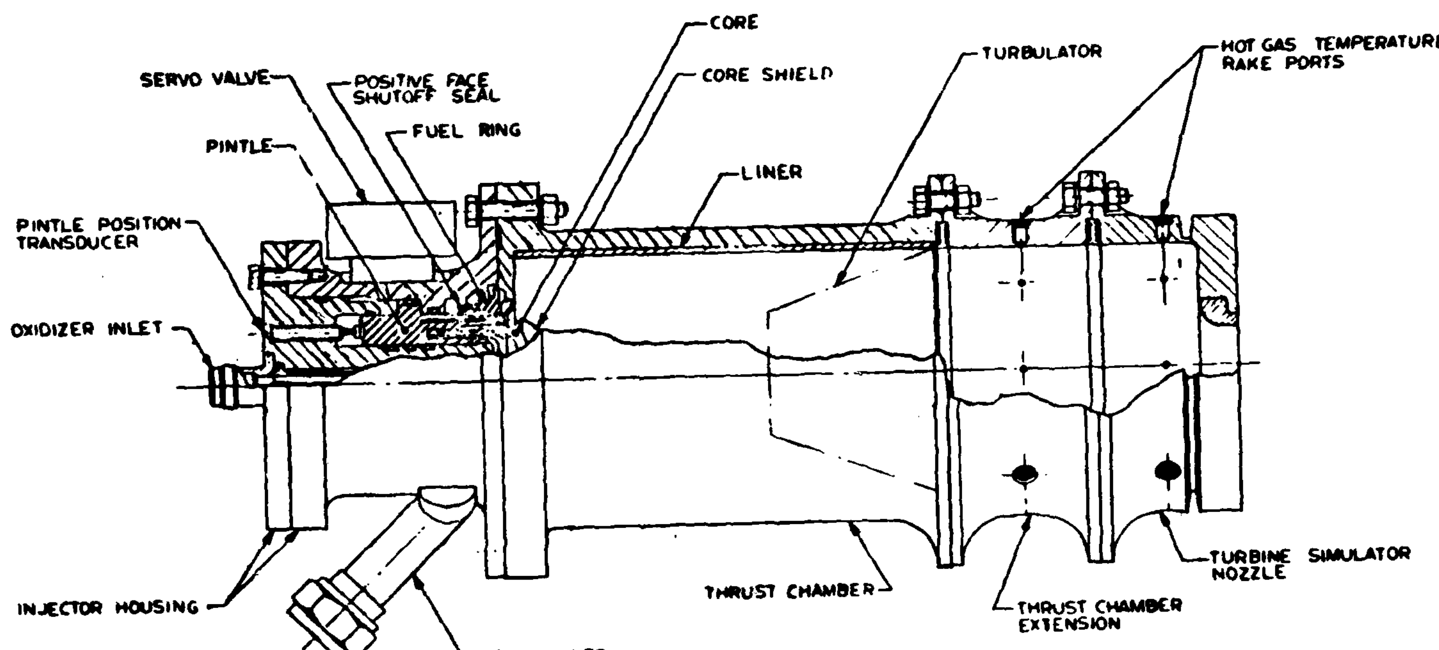


Figure 2. Gas Generator Assembly

INJECTOR CONCEPT

A section view of the injector is presented in Figure 3. The key design features are as follows. The injector consists of a 347 Cres housing, fitted with moveable pintle to modulate the propellant at a constant mixture ratio. The pintle is equipped with a hollow section, providing a thermal barrier between the cryogenic liquid oxygen and the relatively high freezing point JP-4 fuel.

Pintle position control is achieved by a four-way hydraulic servo valve using JP-4 as a working media. A pintle position transducer is used for servo feedback.

Liquid oxygen is introduced into the injector from the LOX shutoff valve through the centerline transfer tube. The tube is fitted with a thermal liner designed to minimize chilldown of the hardware by the cryogenic oxidizer. The original thermal liner was a teflon tube. During the initial tests, a structural failure of the tube was encountered (see Test Section). The liner was redesigned using a concentric Cres tube providing a static oxygen barrier to minimize heat transfer.

The liquid oxygen is injected into the oxidizer manifold through the core assembly. The liquid oxygen system relies on the metering rings to provide a seal. Metering ring leakage is in the order of 1000 cc/min at 400 psid. This minor leakage provides a means of preventing cryogenic lock-up following test termination.

The core assembly is equipped with a cryogenic dynamic seal between the core and the moveable pintle. The cavity downstream of the seal is vented external to the injector.

The face of the core was equipped with a Lance sustainer injector ablative core shield to provide additional hot gas thermal protection.

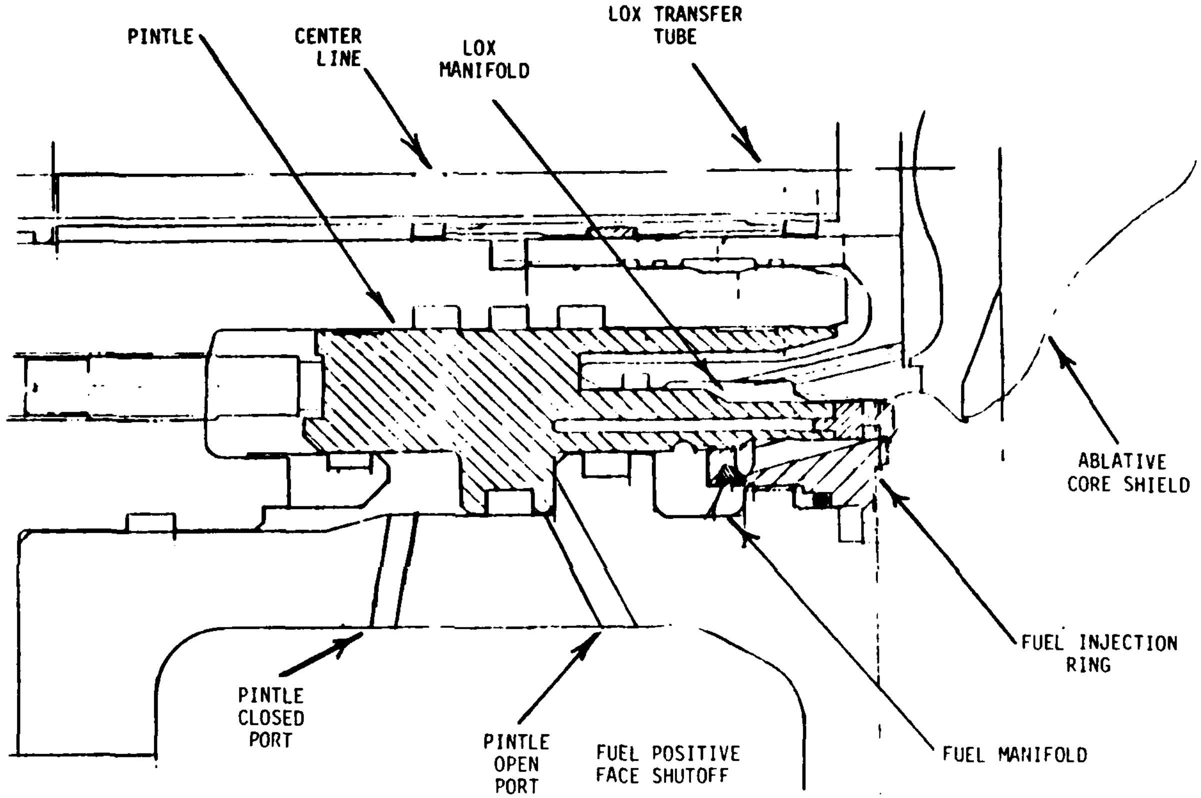


FIGURE 3. INJECTOR INTERNAL CONFIGURATION

The fuel is delivered through an outer peripheral manifold. The fuel system is equipped with a positive fact shutoff seal, with the pintle in the full closed position. The elastomeric seal attached to the pintle makes contact with the seal seat on the fuel ring, positively terminating the fuel flow at the injector face.

The combustor chamber assembly consists of the chamber, hot gas turbulator, removeable variable length section, and nozzle section. The chamber is fitted with a nickel 200 liner to distribute localized hot streaks. Temperature and pressure bosses and two high frequency chamber pressure bosses were provided.

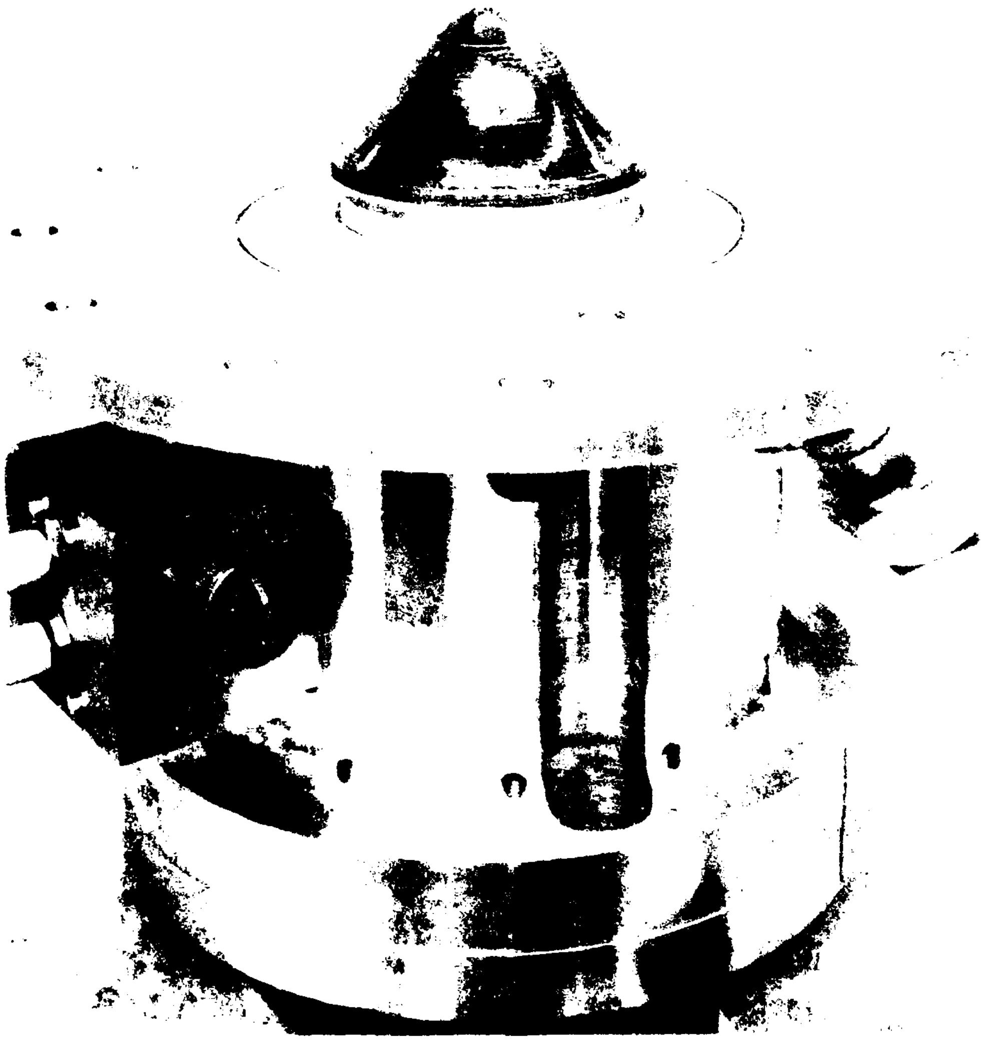
Photographs of the injector detail injector components and combustion chamber components are presented in Figures 4 through 13.

INJECTOR ELEMENT DESIGN

The fuel and oxidizer injection element configuration is basically the same as the Lance Sustainer. The injection element configuration consists of 72 each oxidizer and fuel slots as shown in Figure 14. Throttling is accomplished by axial positioning of the pintle metering rings, which varies the slot height. and consequently the flow area. The 0.060 inch wide slots are aligned to form an unlike impingement pattern. The resulting impinging fuel and oxidizer is directed into a splash plate which further enhances mixing.

Both the LOX and fuel injection configurations employ primary and secondary slots. Figure 15 indicated the plan view of the slot configuration. The secondary slots differ from the primary slots in that the slot run out for the secondary slots is 0.110 less than the primary slots. The secondary slots were employed to reduce the sensitivity of pintle position during deep throttling.

During throttling at a constant propellant inlet pressure and diminishing



1XZ52-2/28/80 - CIC

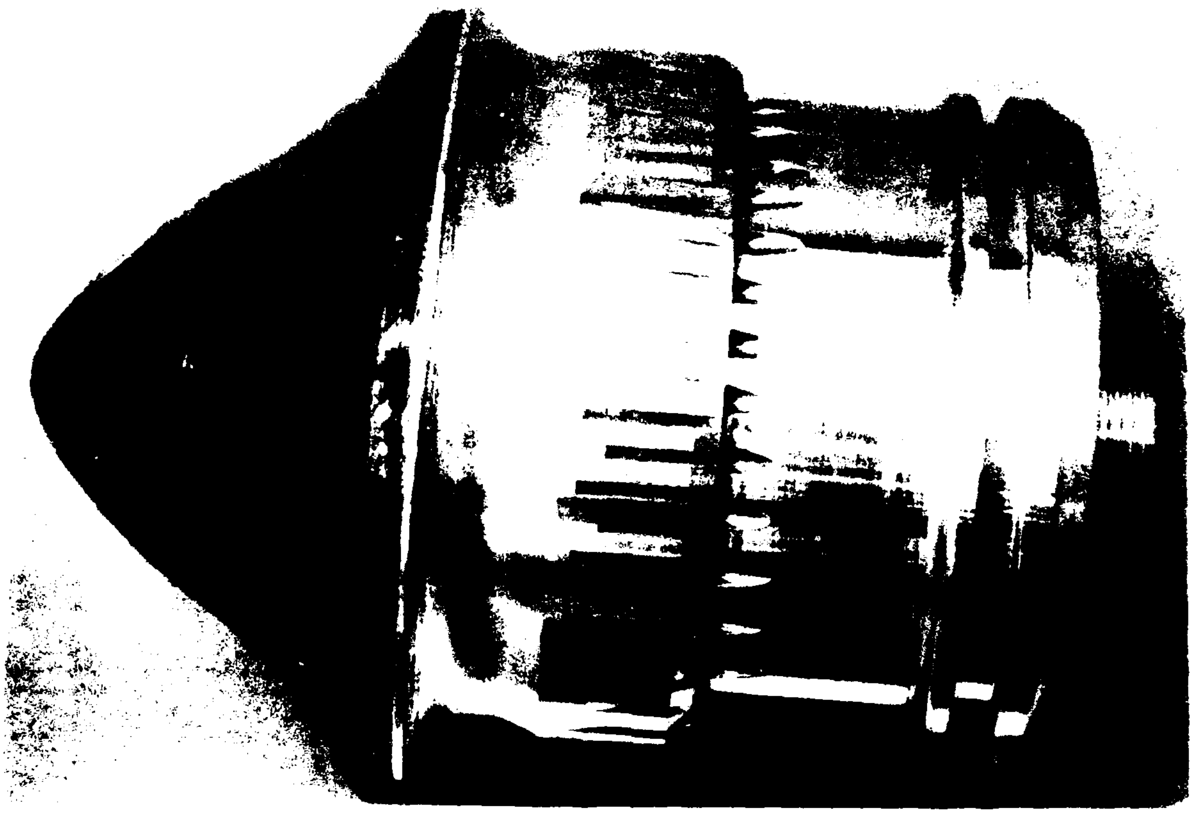
Figure 4. Injector Assembly

4EX55-2/27/80 - CIA

Figure 5. Injector Housing

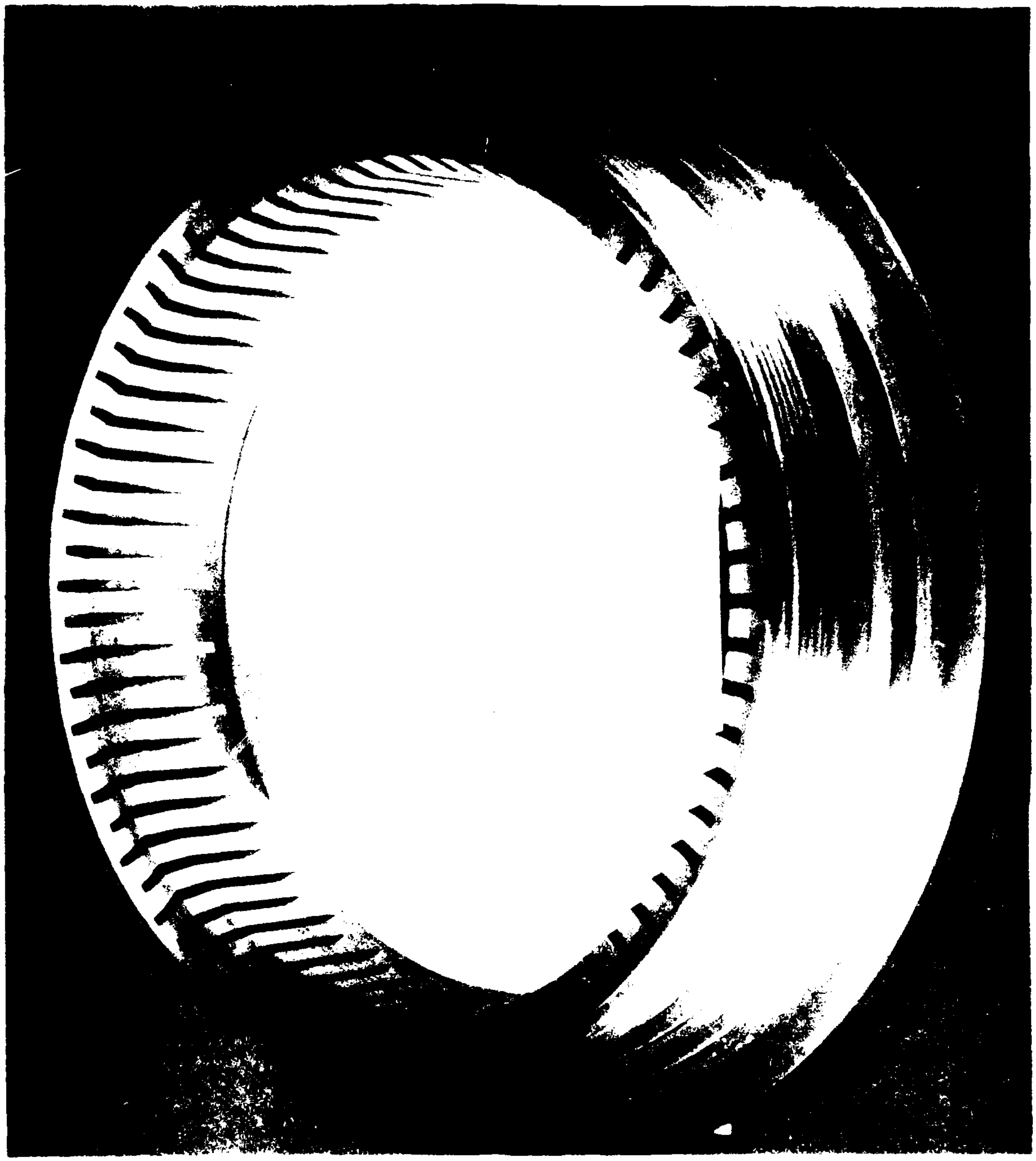
4EX55-2/27/80 - CIG

Figure 6. Pintle



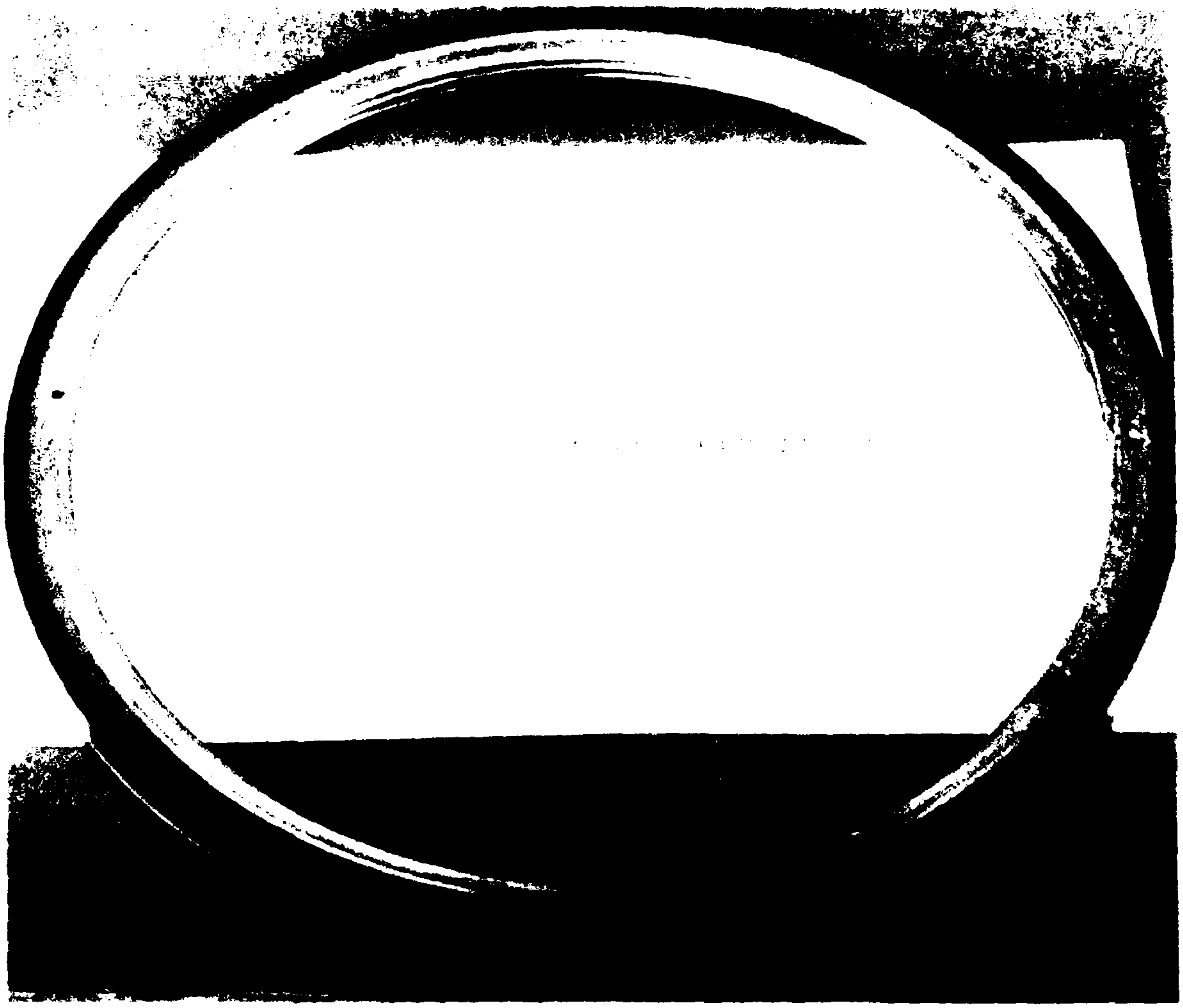
4EX55-2/27/80 - CIC

Figure 7. Core



4EX55-2/27/9- - CIF

Figure 8. Fuel Injection Ring



4EX55-2/27/80 - CIB

Figure 9. Fuel Positive Face Shutoff Seal

4EX55-2/27/80 - CID

Figure 10. Servo Valve

Figure 11. Combustion Chamber

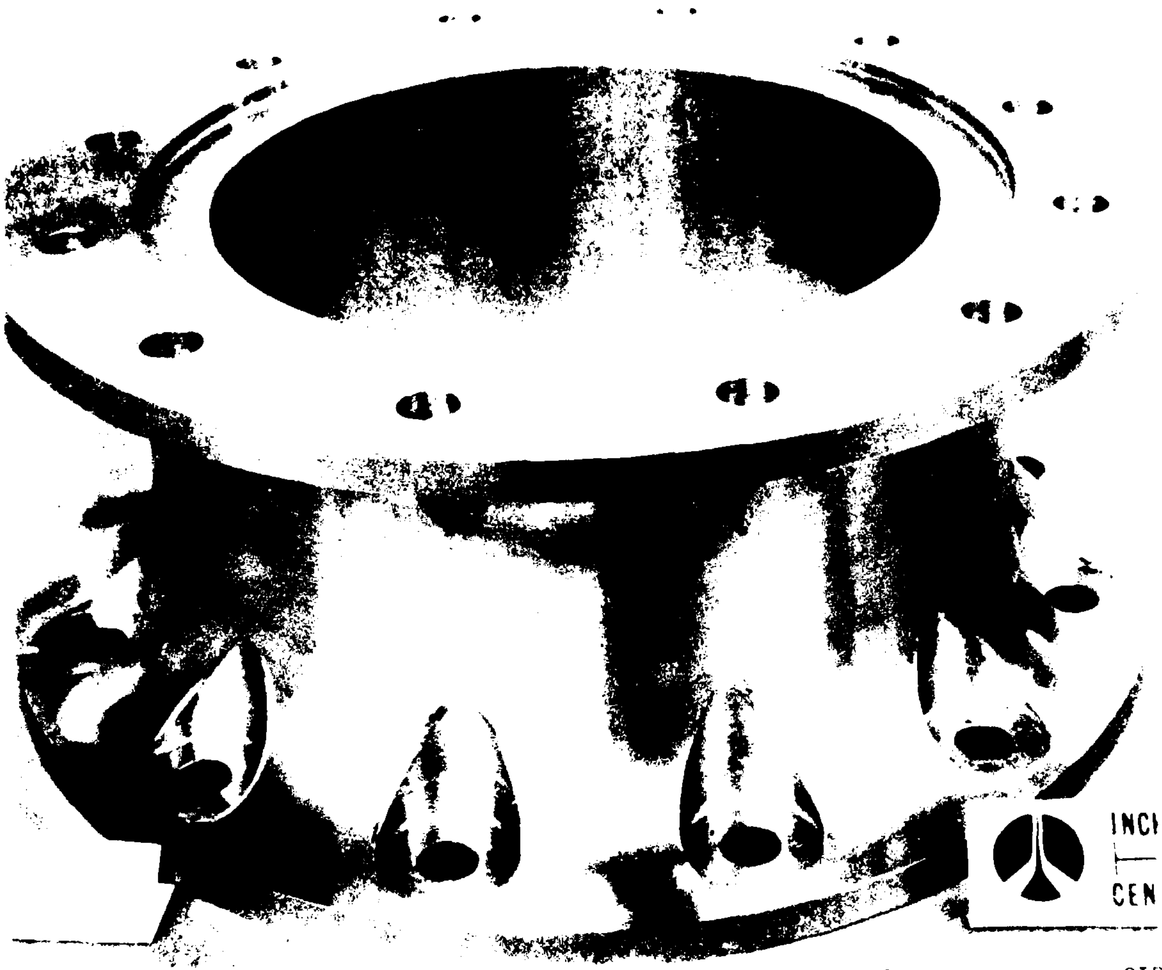


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Figure 12. Combustion Chamber Extension

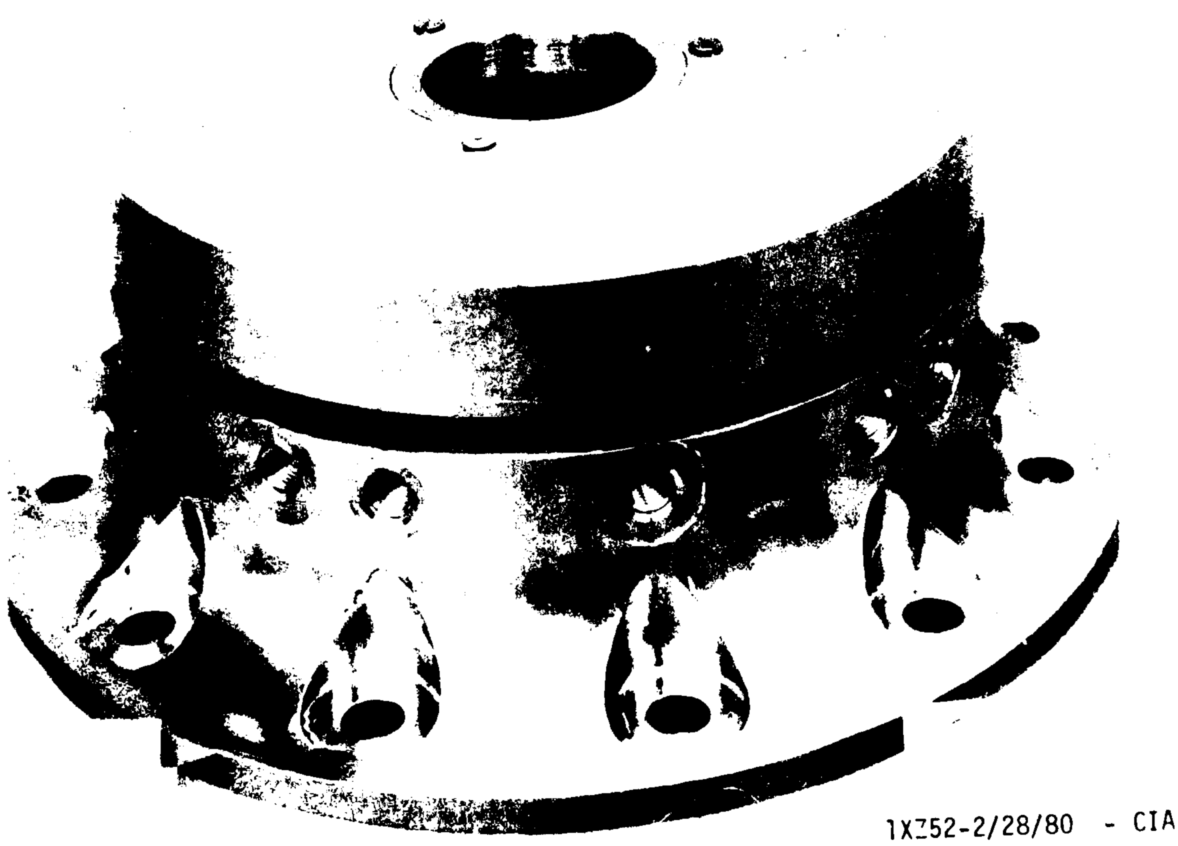
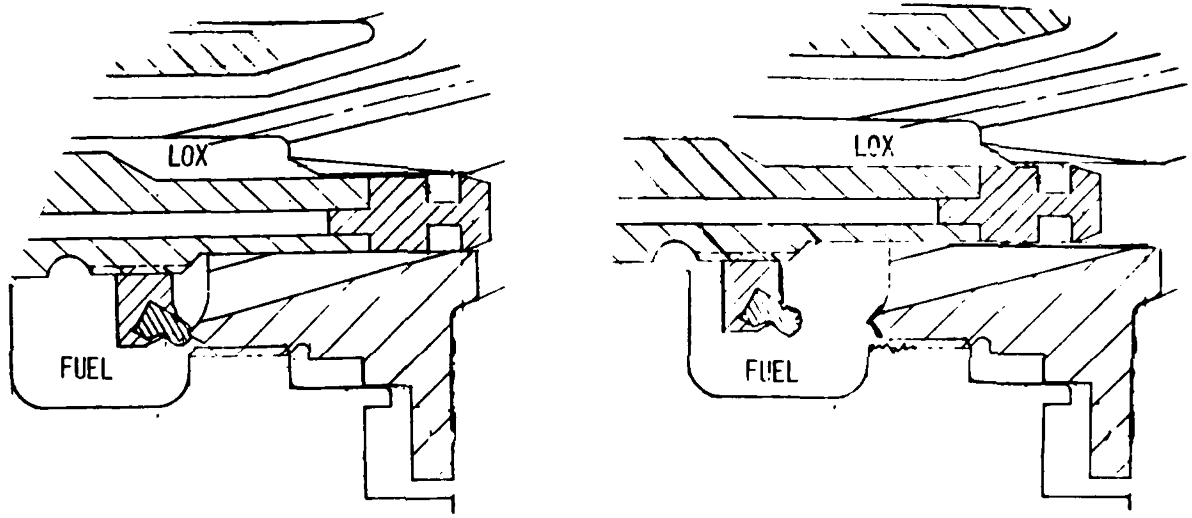


Figure 13. Hot Gas Nozzle

FIGURE 14

THROTTLING AREA VERSUS PINTLE STROKE



PINTLE CLOSED

PINTLE OPEN

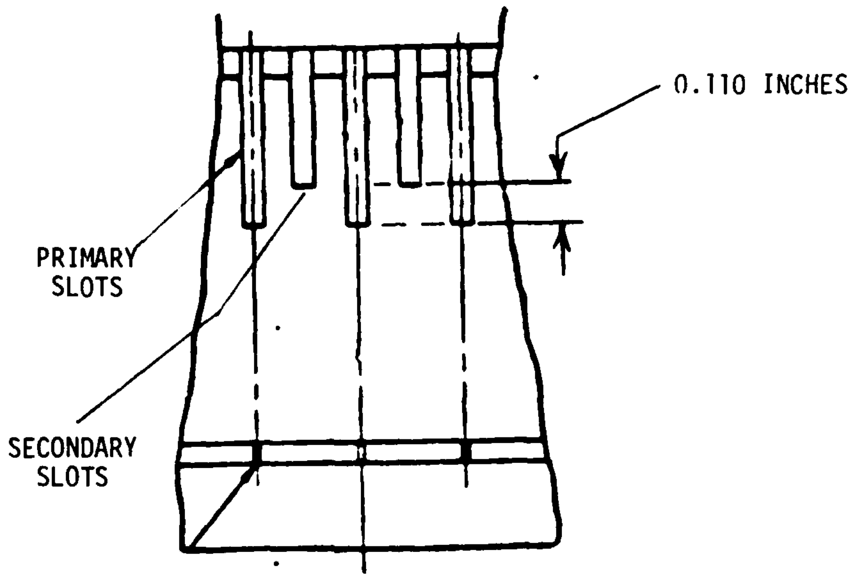


FIGURE 15. PLAN VIEW OF INJECTION SLOTS

chamber pressure, the injector differential pressure increases.

INJECTOR INTERPROPELLANT COMMUNICATION

Due to the moving pintle within the injector, precautions were taken to assure that the possibility of interpropellant communication was eliminated. Figure 16 shows the injector with all internal seals and seal cavity vents.

PINTLE SERVO CONTROL

Modulation of the pintle is controlled by a Moog 35 series hydraulic servo valve capable of a response time of 0.017 seconds. The operating media is the JP-4 fuel. The servo loop was closed through a Lance Sustainer pintle position transducer. Pintle position control was achieved, provided by a six-channel control center servo programmer.

A math model was developed to analyze the opening and closing response of the pintle. The objective was to verify that the capacity of the selected servo valve was adequate to meet the pintle opening time of .050 seconds.

Curves of control system flowrate, differential pressure, and stroke versus time are shown in Figures 17 through 19. Three curves for each parameter are shown, representing three different piston areas: 6.64, 6.14, and 7.14 square inches. The curves in Figure 17 indicate that a decrease in piston area slightly increases the pintle velocity, thus reducing the opening and closing times. This, however, is accompanied by an increase in required ΔP across the actuator piston, as shown in Figure 18. The design was finalized using a 6.640 square inch piston area, and it is concluded that this is satisfactory from the standpoint of opening and closing force margins and will open within .050 seconds (opening travel time = .030 seconds). The closing response will be less than .065 seconds (travel time = .044 seconds).

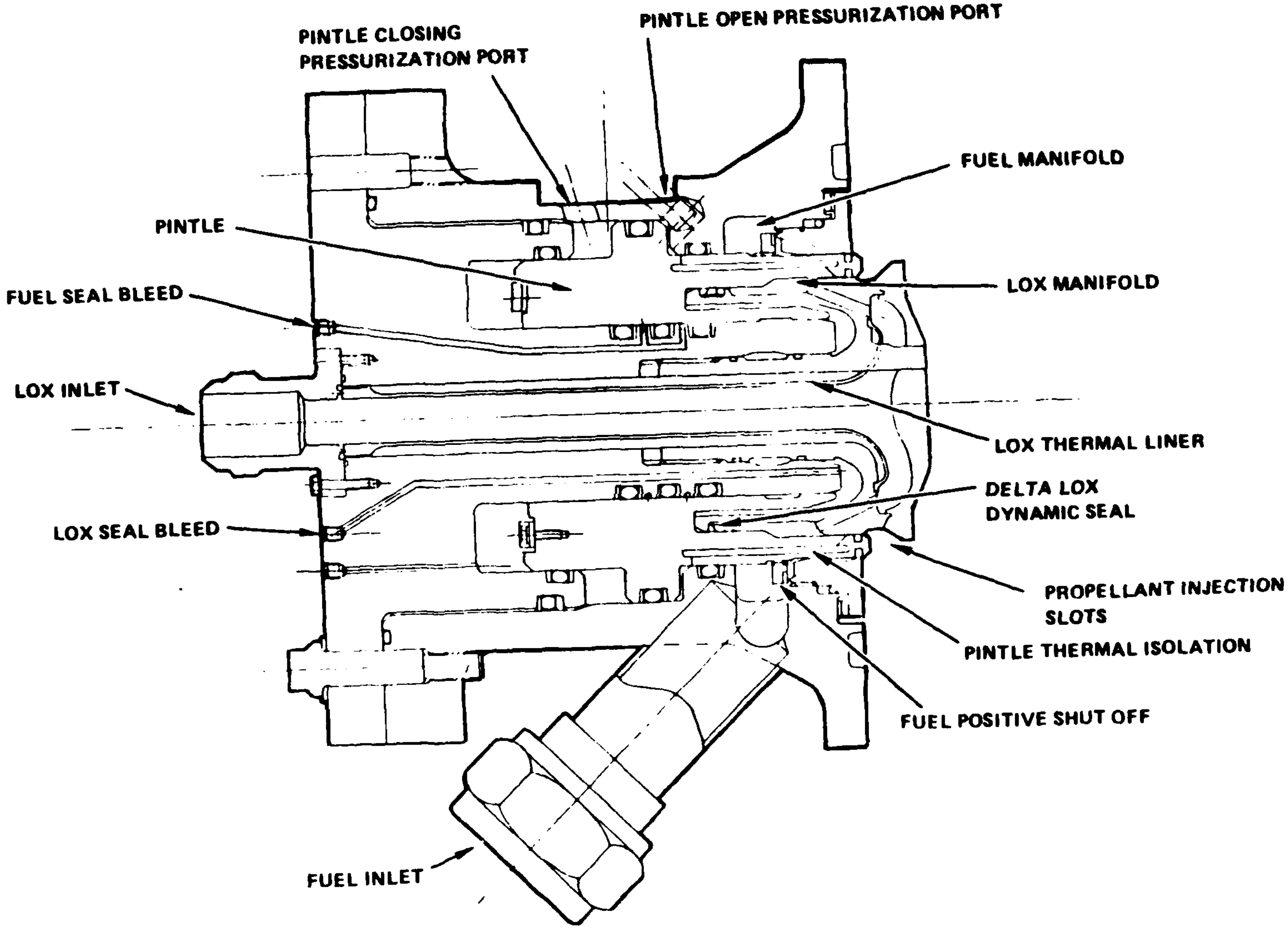


Figure 16. Internal Seal Configuration

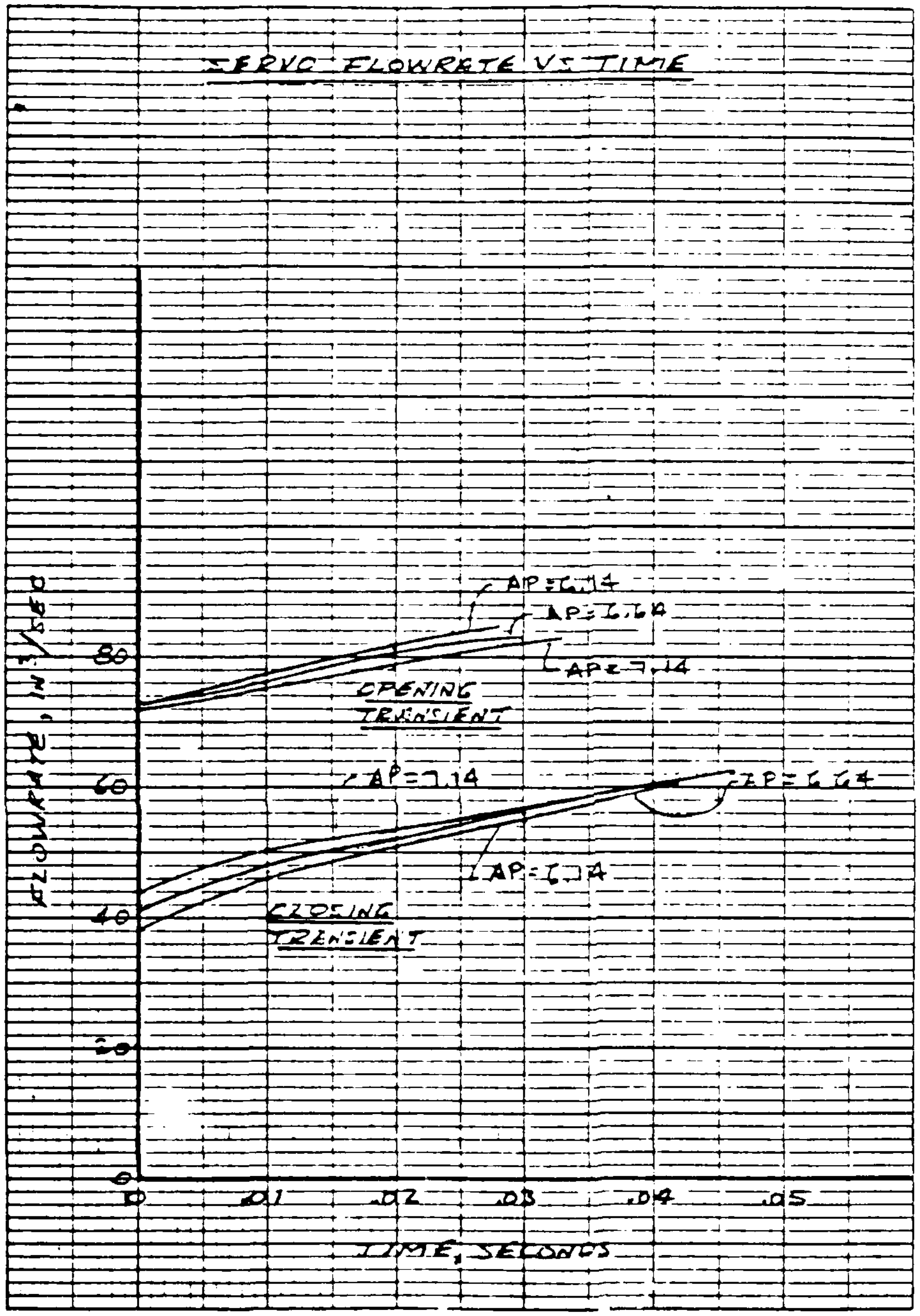


FIGURE 17. CONTROL SYSTEM FLOWRATE vs. TIME

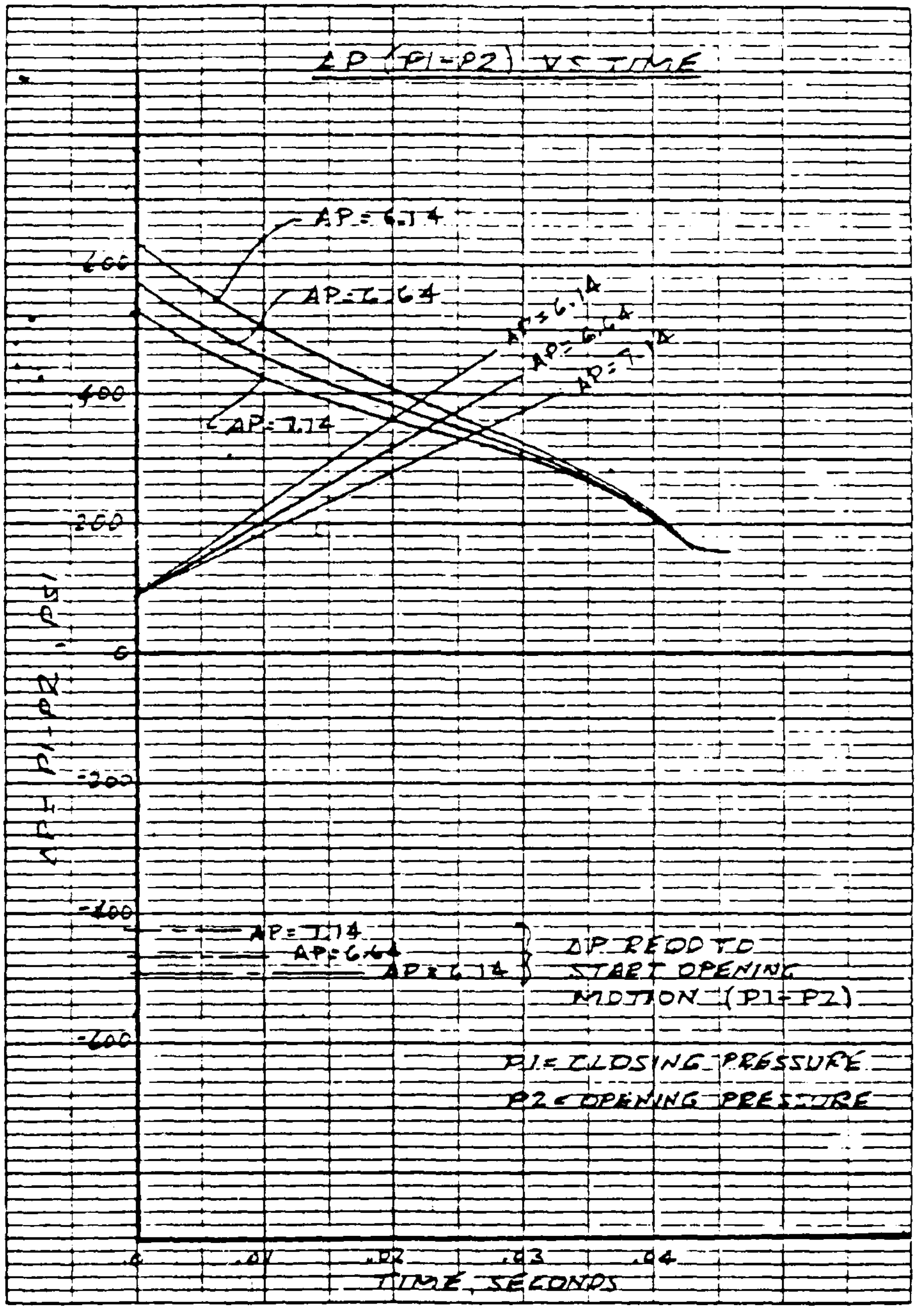


FIGURE 18. CONTROL SYSTEM ΔP vs. TIME

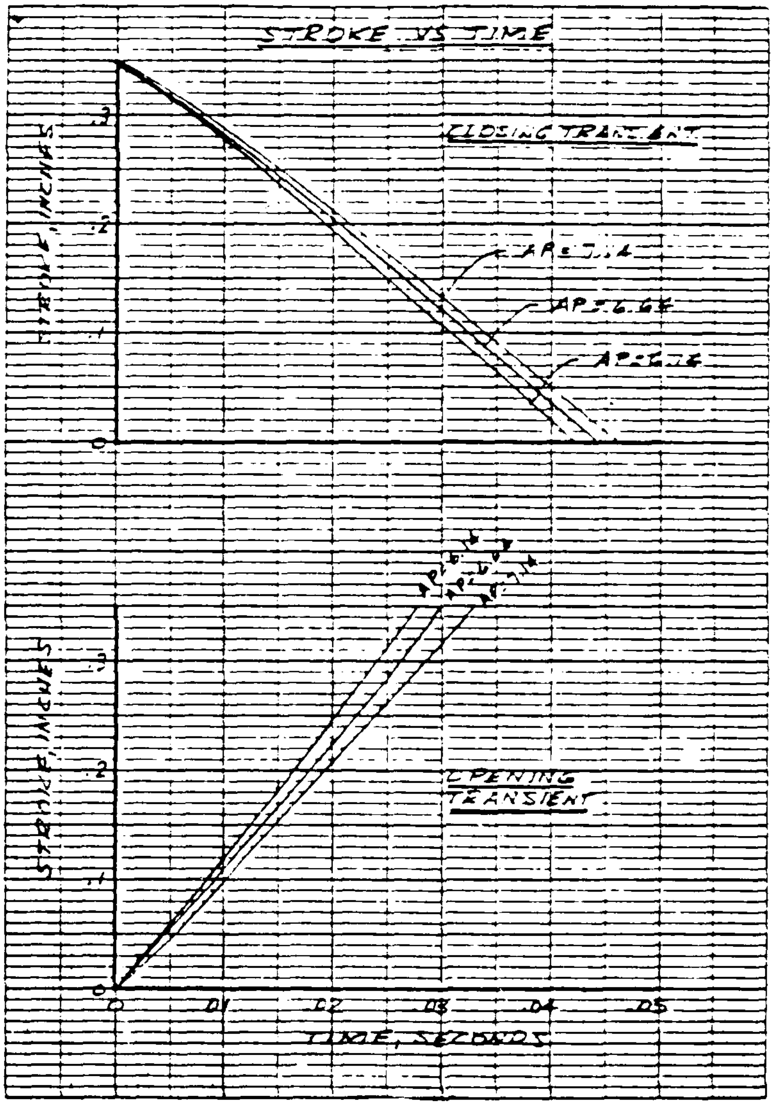


FIGURE 19. PINTLE STROKE vs. TIME

During all hot fire tests, the performance of the servo system was well within the target design limits. Problems were encountered during the initial throttling tests; however, these problems were associated with leakage of the core LOX dynamic seal, which produced a pressure imbalance in the pintle. This is discussed in the hot fire section of this report.

COOLANT AND PROPELLANT THERMAL MANAGEMENT

Injector operation with a cryogenic oxidizer and relatively low freezing point JP-4 fuel was of concern for long duration operation. To minimize cooling of the fuel, the injector was equipped with thermal isolation.

As shown in Figure 20, the section of the pintle separating the fuel from the LOX was fabricated with a hollow center section. The thermal analysis performed in this configuration indicated excellent thermal isolation at both the maximum and minimum power levels.

Thermal isolation was also provided to minimize childown of the injector from the axial LOX inlet passage.

The injector LOX inlet was equipped with a thermal liner. Two configurations were tested: a teflon tube and a 347 Cres liner, providing a dead area space between the LOX flow and the injector housing. The teflon tube failed during hot fire Test No. 3 (see test section), and was replaced with the Cres liner as shown in Figure 21.

The Cres liner provided an air gap of 0.1 inches between the liner flowing liquid oxygen and the interfacing injector housing. During operation, the gap was filled with static LOX or GOX (no flow velocity).

Figure 22 shows a comparison of injector temperature with respect to time within the injector.

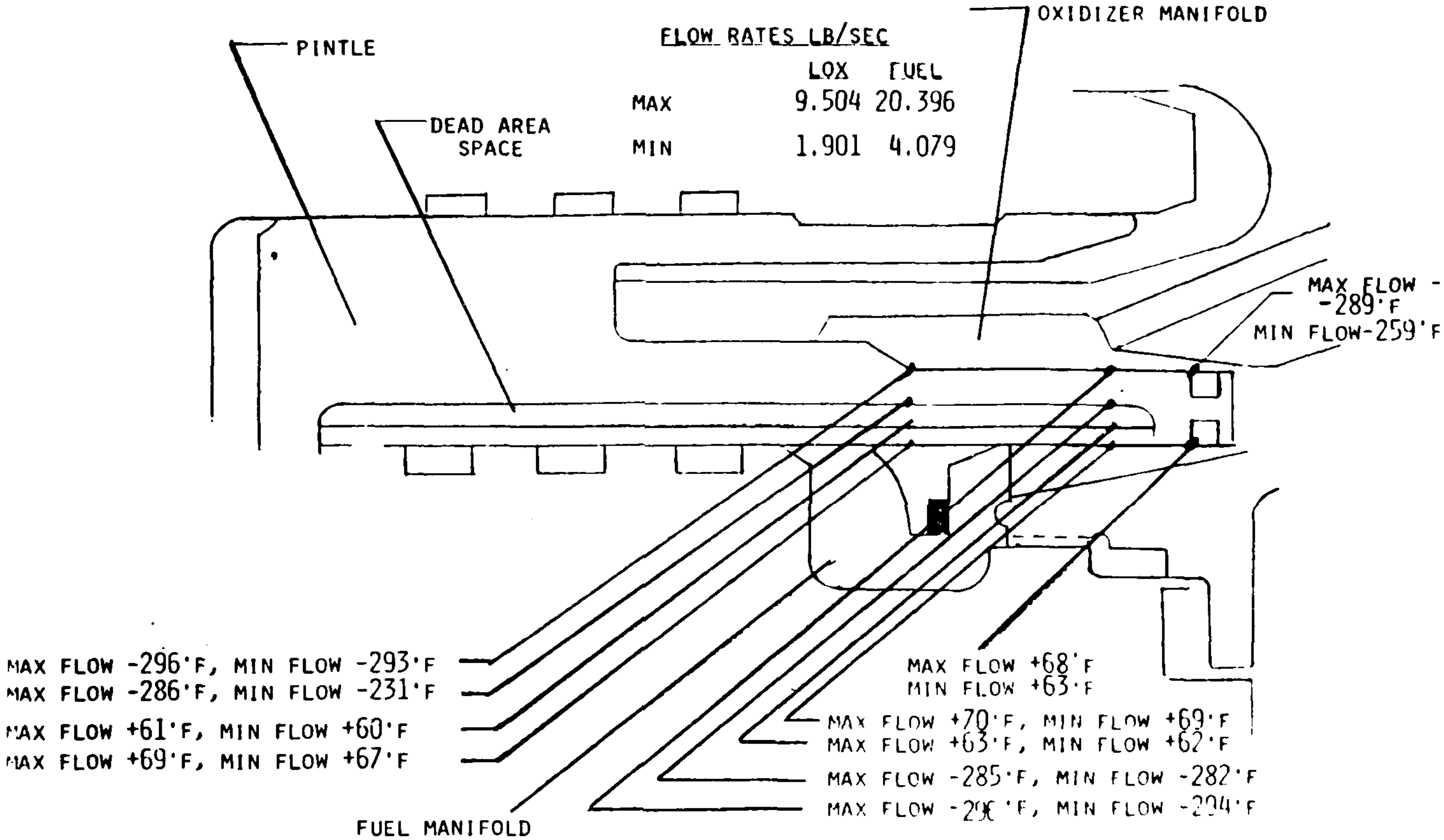


FIGURE 20. PINTLE THERMAL ISOLATION

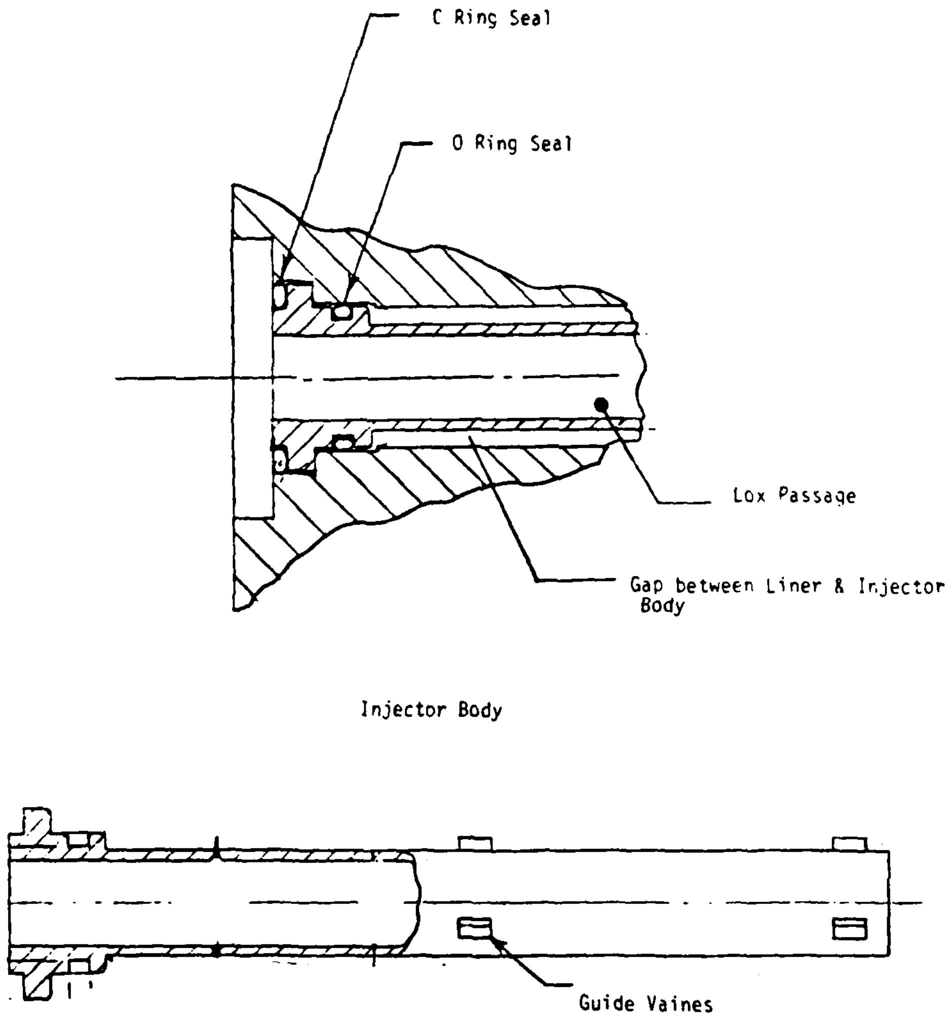


FIGURE 21. CRESS THERMAL LINER

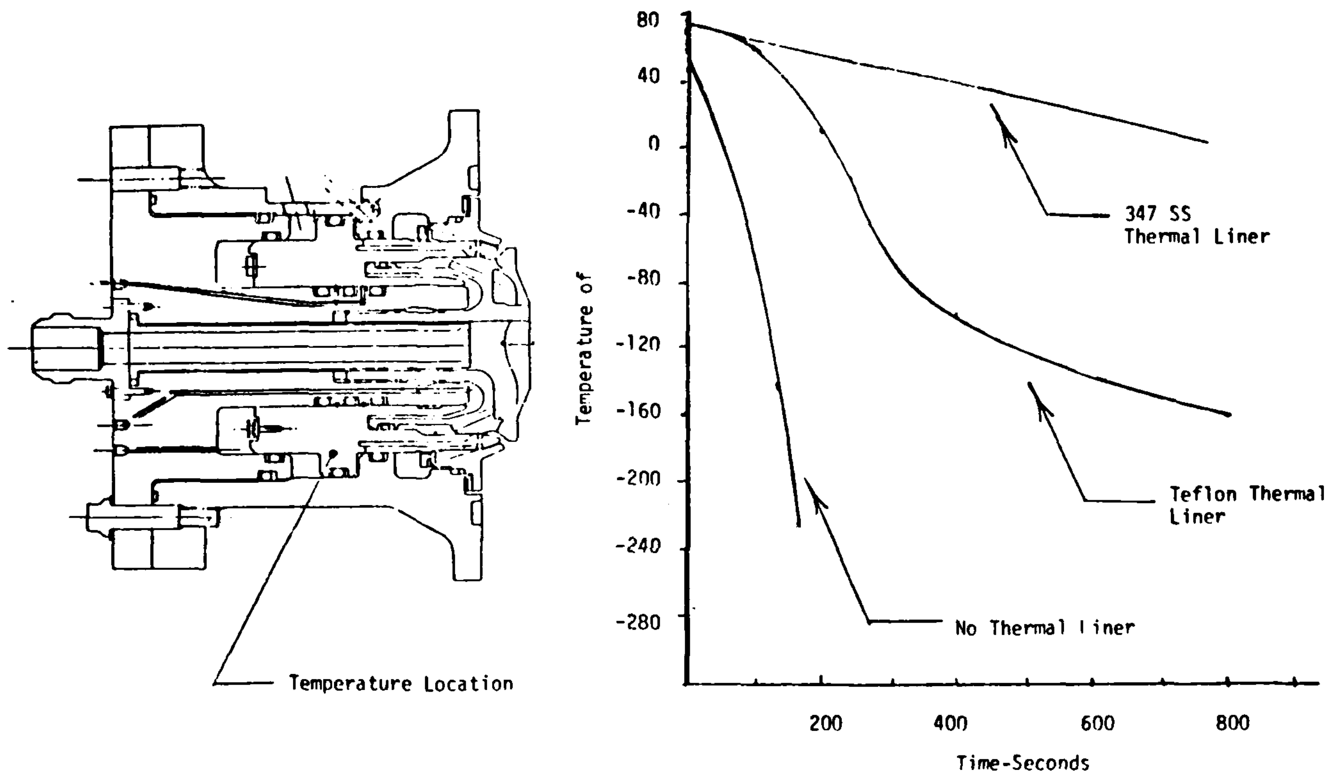


FIGURE 22 INJECTOR TEMPERATURE VS. TIME

The results of this analysis indicate that the 347 Cres liner is superior to the teflon liner from a heat transfer standpoint. The thermal conductivity of the LOX or GOX entrapped in the gap between the liner and the injector is 1.85 X 10^{-6} BTU/sec-in°F, as compared to 3.24 X 10^{-6} BTU/sec-in°F for the teflon.

IGNITION

The fast start and restart capability necessitated the use of a direct spark ignition system. The initial concern was to determine the optimum location for the spark plug and optimum oxidizer lead to assure ignition of the initial injected propellant to preclude the possibility of accumulation of a quantity of unburned propellant which could result in a detonation.

An internal research and development program was performed to optimize these parameters. Optimum placement of the spark plug was determined to be through the injector face as shown in Figure 23. In this location, the LOX lead was directed toward the spark plug tip by the injector splash plate. These tests also indicated that approximately 230 milliseconds LOX lead was adequate to assure repeatable reliable ignition. Figure 24 shows schematically the test configuration, using an external LOX shutoff valve, and the final test start sequence.

The start sequence consists of the following:

1. With the pintle closed and fuel system pressurized, chill the LOX system to achieve quality LOX at the main LOX valve in the closed position by using the LOX bleed.

2. Sequence the LOX bleed closed and the LOX main valve open. The injector manifold is pressurized with oxygen and a small LOX flow into the chamber initiated due to the LOX metering ring leakage.

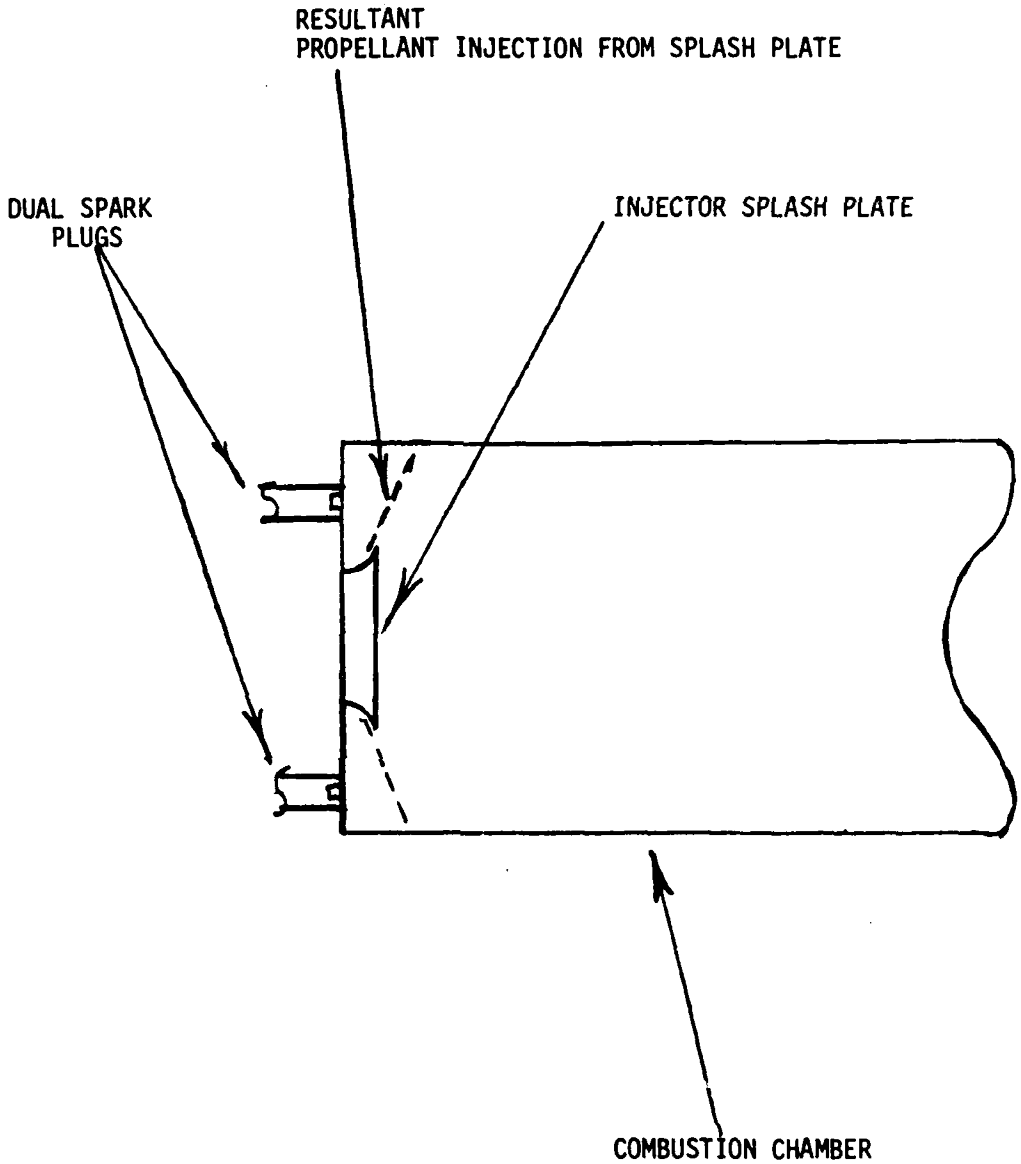


FIGURE 23 SPARK PLUG LOCATION

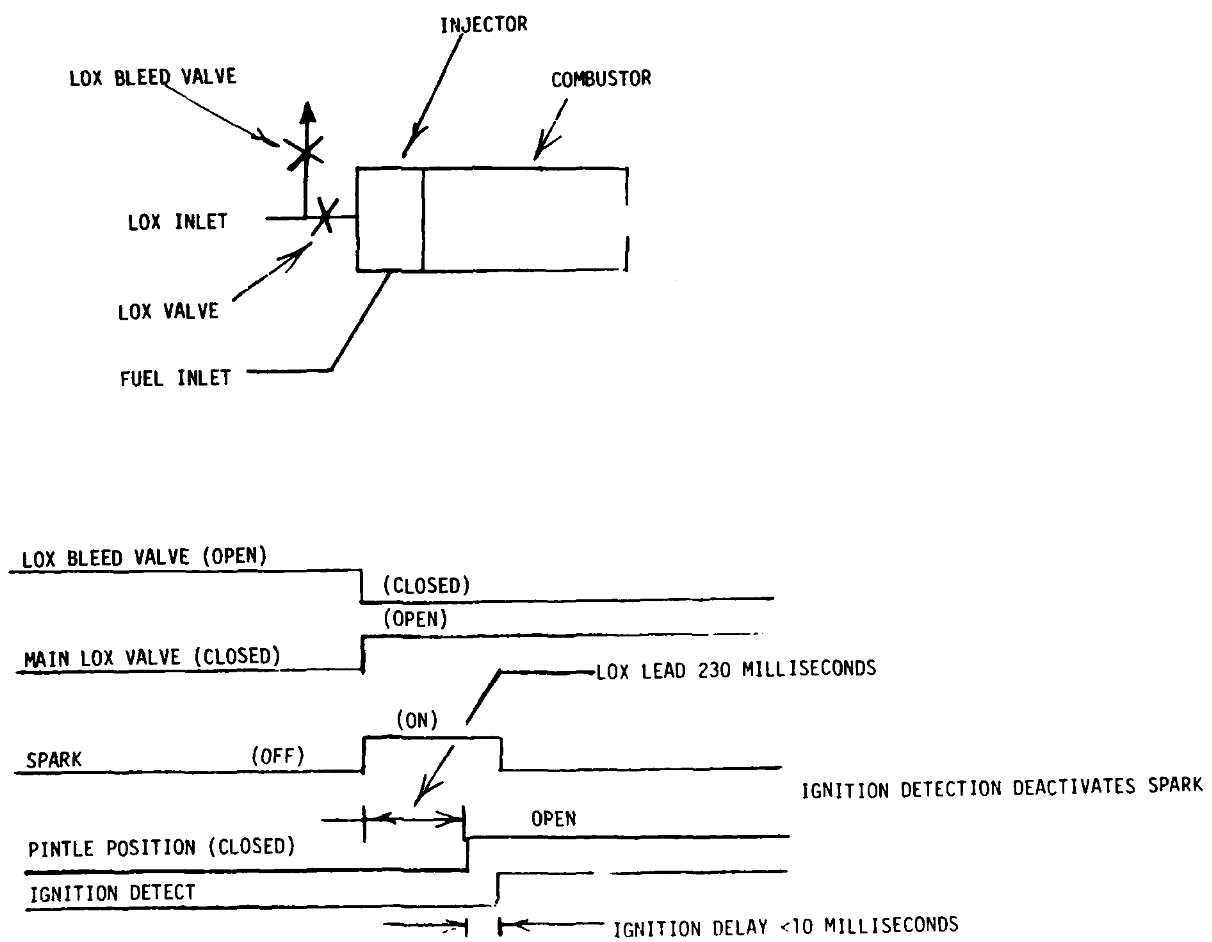


FIGURE 24 IGNITION TEST START SEQUENCE

3. The pintle is commanded open 230 milliseconds after the main LOX valve is opened and the main fuel flow starts.

Approximately ten milliseconds after the initiation of the pintle movement, ignition occurs. This start sequence was used for all tests, with no anomalies noted with respect to ignition or start transient.

To increase ignition reliability, two spark plugs and two spark exciters were used. The spark exciter was a prototype unit which has been used in numerous programs. The unit is capable of delivering .1 joules of energy at the spark plug tip at a spark rate of 200 sparks per second.

The spark plugs used were single electrode axial gap units which had been previously used in the J-2 engine spark ignition system.

HOT GAS TEMPERATURE DISTRIBUTION

The specified pattern factor was expressed as: $\frac{T_{max}}{T_{avg}} - 1 < 0.065$

At a nominal hot gas temperature of 1600°F, the maximum temperature allowable was 1704°F. Due to the highly localized propellant injection provided by the throttling injector, it was realized that secondary hot gas mixing would be required. The initial design consisted of a nickel 200 cone with 260 1/4 inch diameter holes directing the hot gas into the center of the cone. The nose of the cone was fitted with a vane plate designed to produce a vortex within the cone to mix with the hot gas injected through the 1/4 inch diameter holes.

The turbulator is shown in Figure 25. Hot fire tests indicated that the turbulator was not effective in mixing the hot gas at the maximum power level.

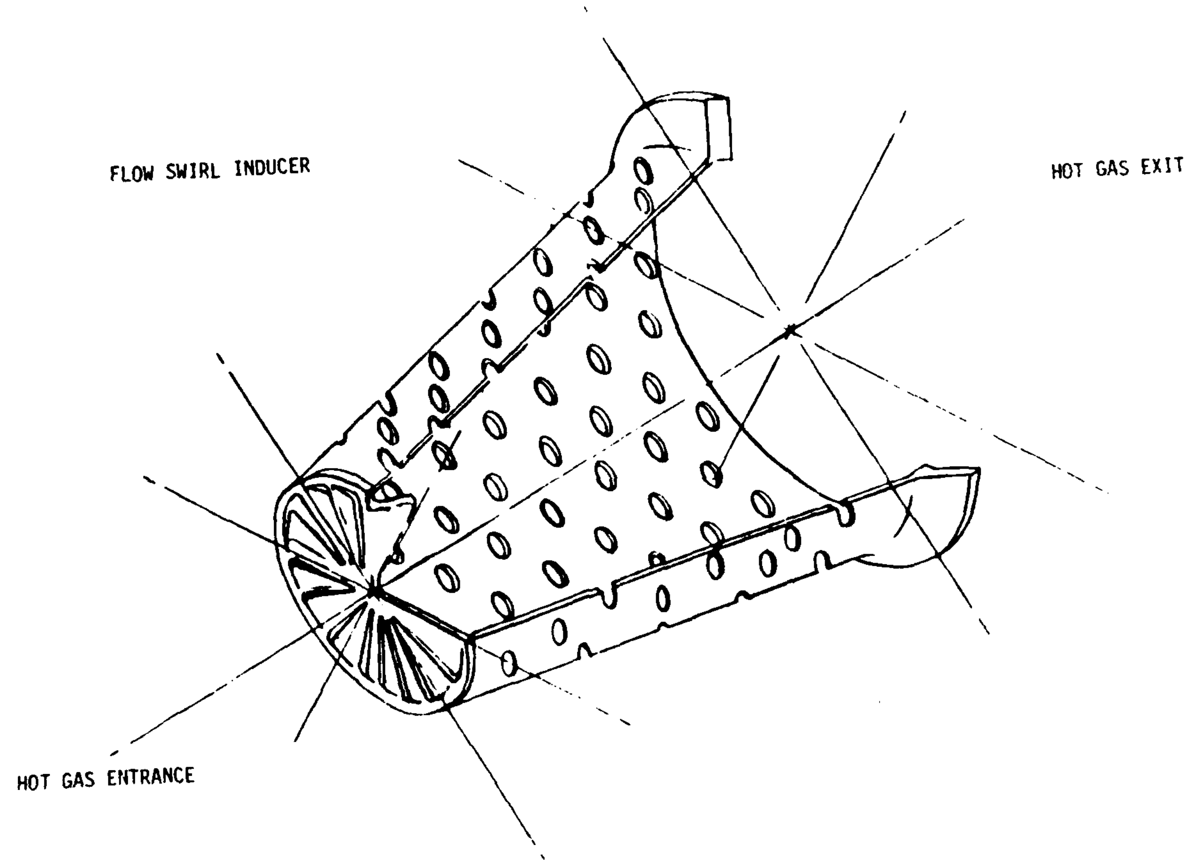


FIGURE 25. ORIGINAL TURBULATOR DESIGN

Also, the vane plate was eroded as a result of the initial full power level test. Replacement of the vane plate with a solid nickel nose section, Figure 26, did not improve the hot gas temperature distribution (Reference Test 9). Due to the hot gas temperature distribution problem, injector cold flow tests and combustion modeling effort was accomplished. The results of this effort are discussed in Appendix A.

To improve combustion chamber head end mixing, a turbulence ring was installed, as shown in Figure 26. Operation at maximum power level with the turbulence ring and the cone turbulator equipped with the nickel 200 nose resulted in excessive nose erosion of the turbulator and no improvement in hot gas temperature distribution (Reference Test 10).

Review of other gas generators exhibiting a hot gas temperature distribution problem indicated that a right angle mitered bend combustion chamber produced a marked improvement. Figures 27 and 28 indicate a cross section view of a high pressure gas generator equipped with smooth well rounded 90 degree bend and the same gas generator with a 90 degree miter bend. The hot gas temperature data produced by both configurations is presented in Figure 29. The well rounded bend produced a 500 degree temperature differential from the chamber wall to the centerline whereas the miter bend produced a 100 degree temperature differential. Based on this data, a miter bend turbulator was designed and fabricated. The final configuration is shown in Figure 30. The significant operating parameters of the LOX/H_2 gas generator configuration and the Restartable Gas Generator are presented in Figure 31a. The key design parameter was the turbulator Mach number. A Mach number of 0.2 is considered near the upper limit for turbine inlet considerations. It is recognized that turbulator gas velocity is a key parameter in mixing; however, matching the turbulator velocity of the LOX/H_2 gas generator would have resulted in a Mach number of 0.31 and considerable increase in differential pressure.

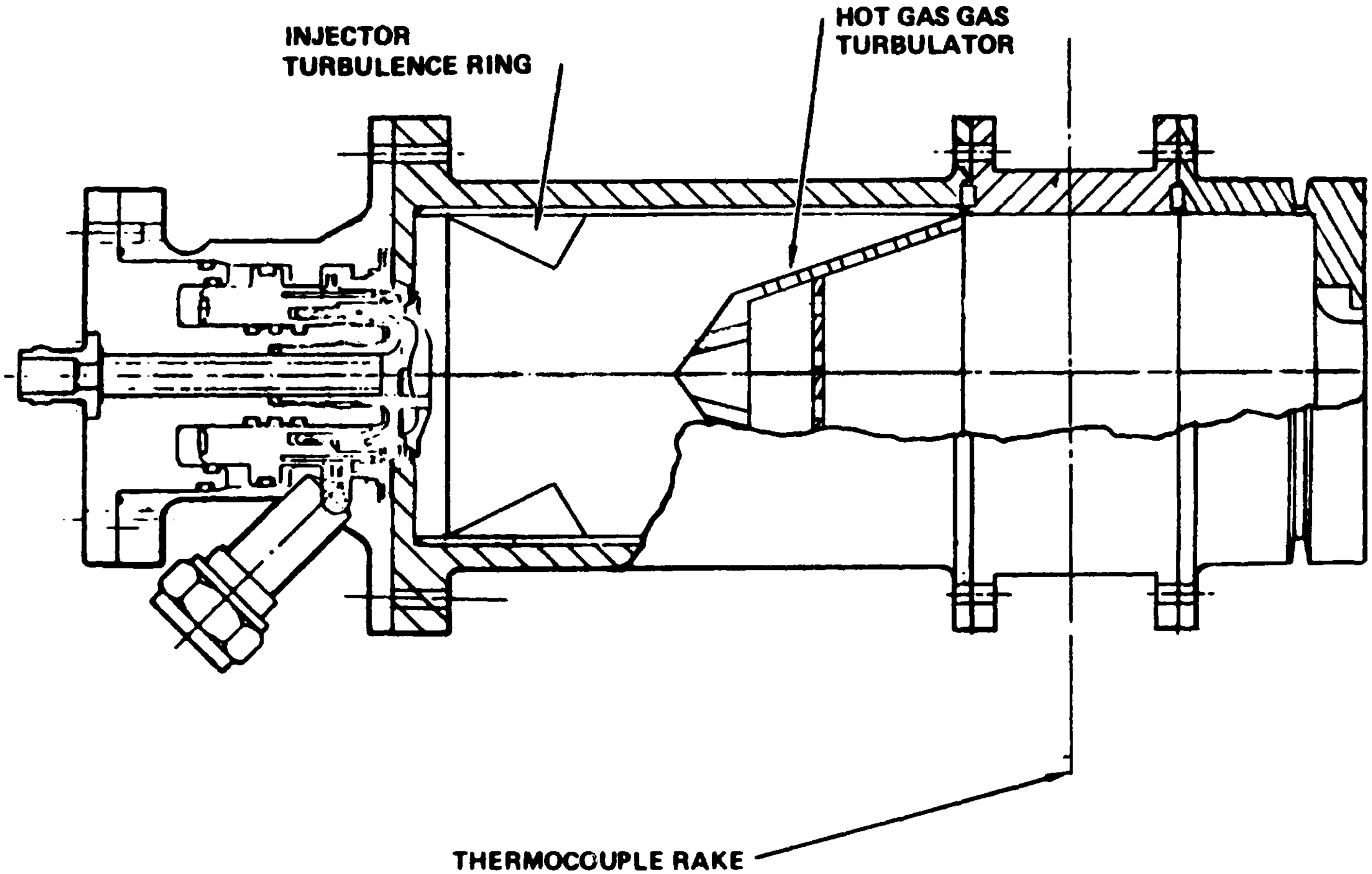


Figure 26. Modified Hot Gas Turbulator With Injector Turbulence Ring

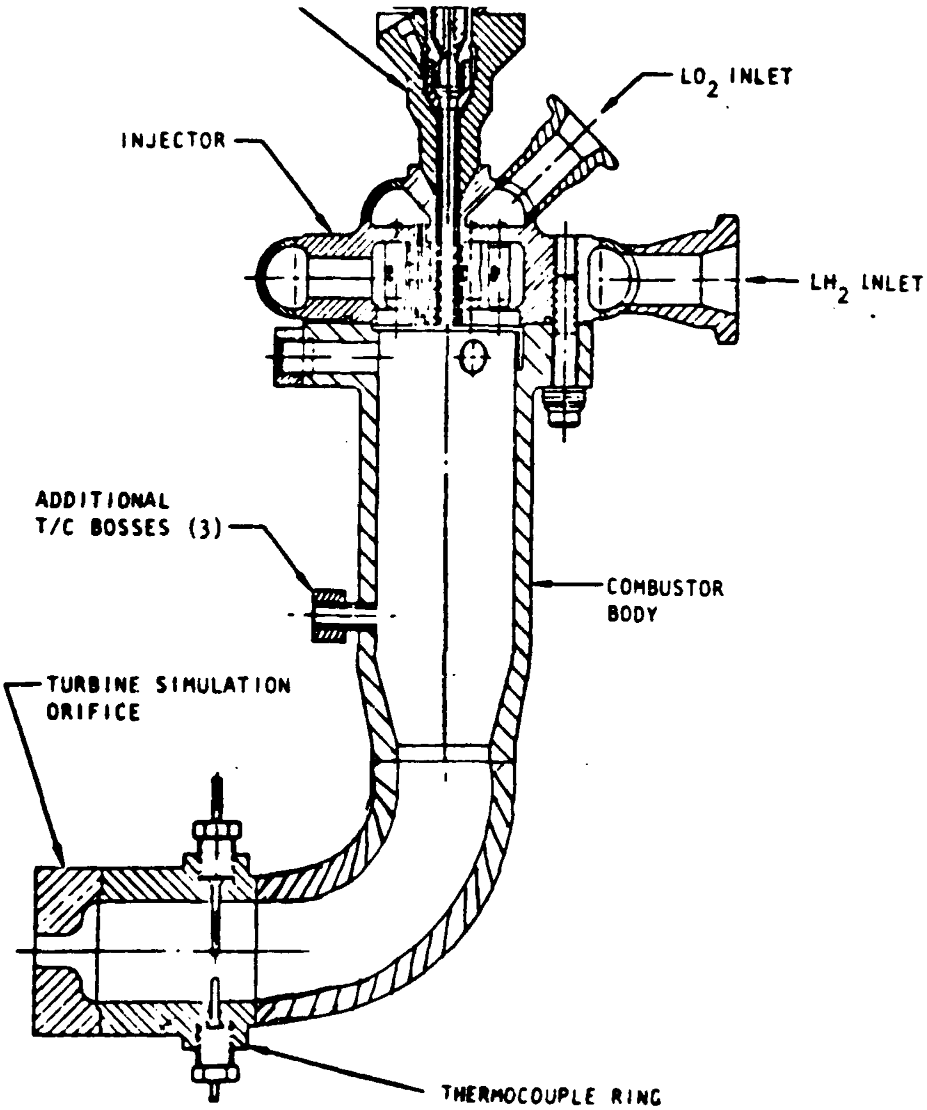


Figure 27 . Small, High-Pressure Gas Generator Combustor with well-rounded 90° bend

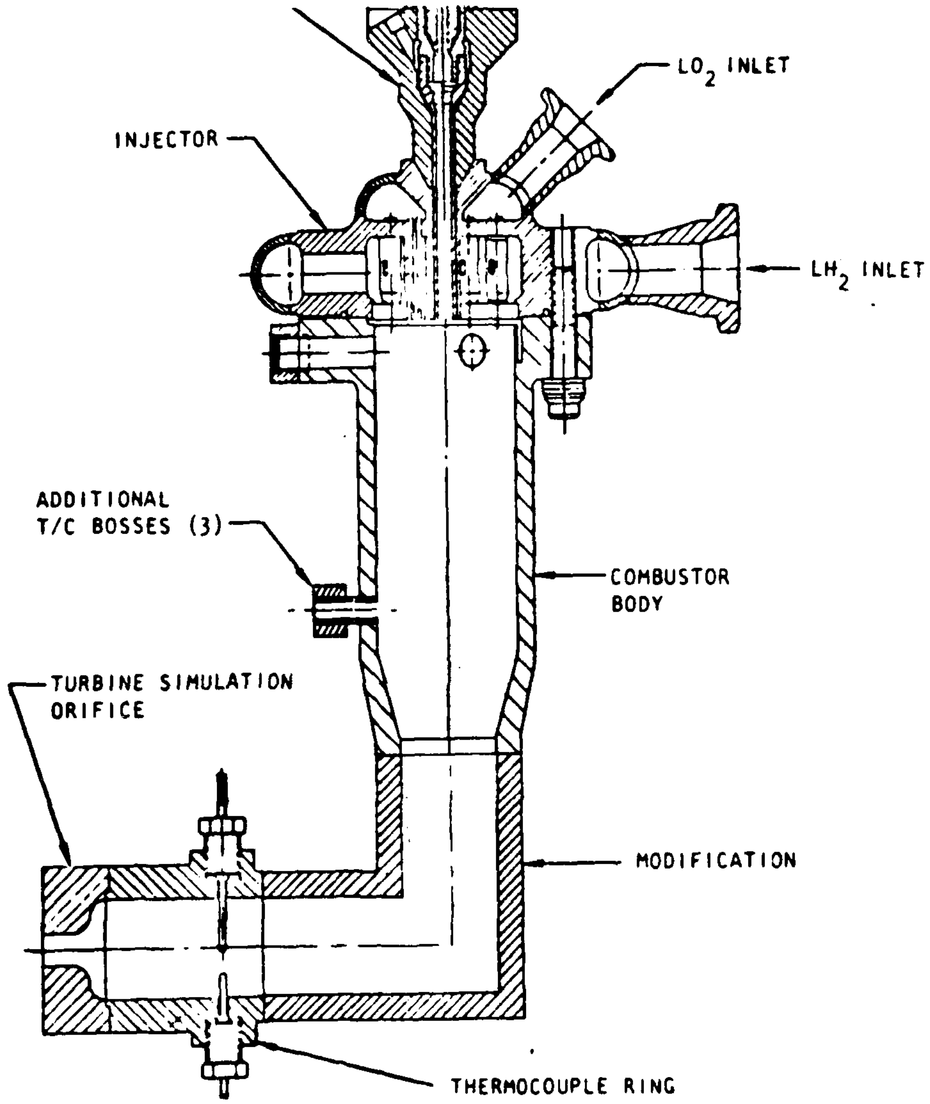


Figure 28. Small, High-Pressure Gas Generator Combustor with 90° Miter Combustion Chamber

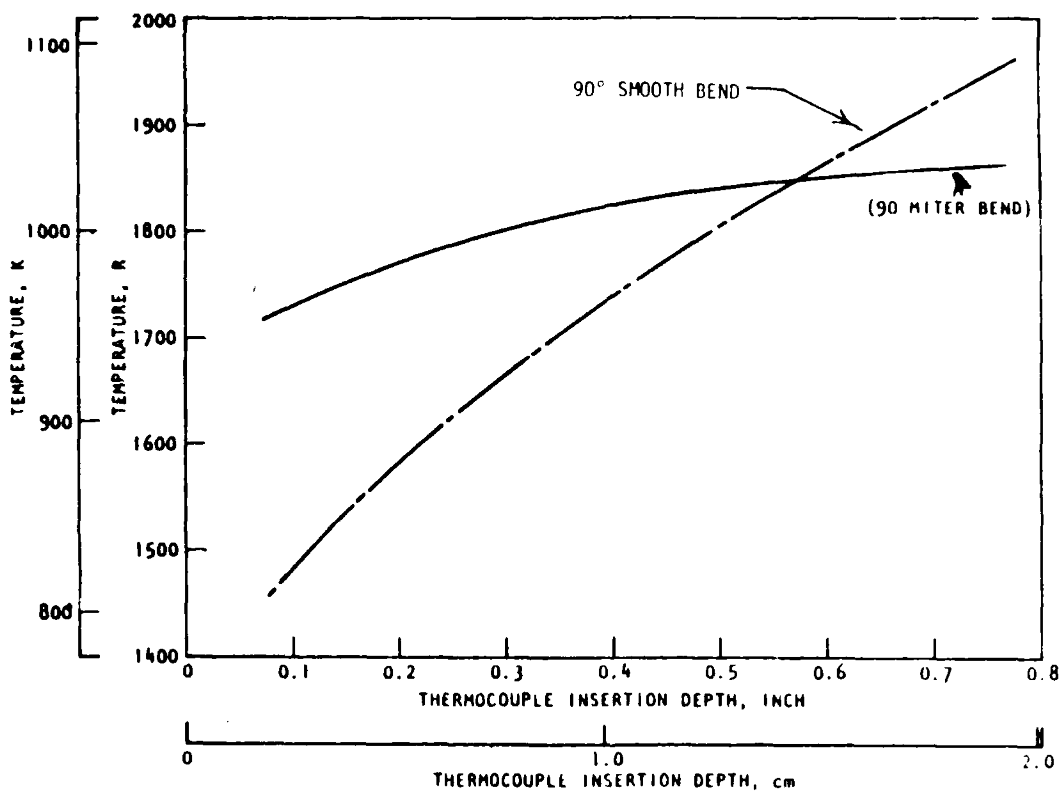
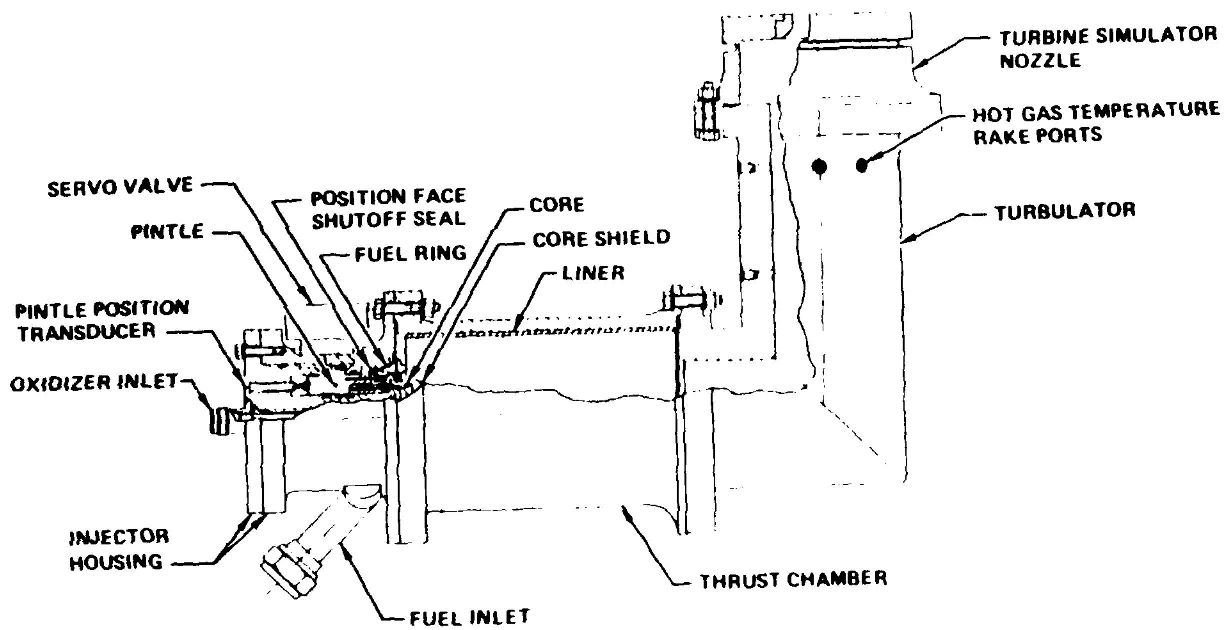


Figure 29. Gas Generator Exit Plane Temperature Profile

FIGURE 30

RIGHT ANGLE TURBULATOR



	LOX/H_2 TURBULATOR	RESTARTABLE GG TURBULATOR
Total Flowrate lbs/sec	6.46	29.9
Chamber Velocity ft/sec	351	128
Chamber Velocity Head psi	8.33	1.38
Turbulator Velocity Head psi	36.8	11.3
Contraction Area Ratio	6.64	2.7
Hot Gas Density lbs/ft^3	0.62	0.7
Chamber Pressure psia	3445	700
Hot Gas Acoustic Velocity ft/sec	5700	2312
Turbulator Velocity ft/sec	737.9	386.7
Turbulator Mach Number	0.129	0.167

FIGURE 31a. COMPARISON OF LOX/H_2 GAS GENERATOR RIGHT ANGLE TURBULATOR AND RESTARTABLE HIGH POWER GAS GENERATOR TURBULATOR

COMBUSTOR DESIGN

The combustor design layout provides a 10:1 contraction ratio to maintain low velocity, 128 ft/sec at the maximum power level. It is considered advantageous to maintain a low chamber velocity to minimize the possibility of a flameout during transition from the relatively high mixture ratio ignition phase to the low mixture ratio mainstage operation. Also, the relatively high contraction ratio will tend to promote turbulence near the injector face which may enhance ignition.

The initial chamber consisted of three sections, with the provisions of a removeable hot gas turbulator. The turbulator could be installed eight inches from the injector face or at the interface between the mid-section and the exit section. Mid-section length can be changed to modulate overall chamber length as may be dictated by the test results.

The forward section of the combustion chamber is equipped with a 0.25 inch thick nickel liner to distribute localized hot streaks.

The aft nozzle section is provided with a frangible ring designed to separate from the chamber at 1700 psig in the event of a chamber detonation, thus minimizing potential hardware damage.

COMBUSTION STABILITY

A combustion stability analysis was made in support of the design effort. This analysis consisted of identifying the principal theoretical modes of instability and making comparisons with other gas generators of similar power levels. The principal modes of instability which may be of concern are the first and second tangential and first longitudinal modes. Analytically these modes were found to be:

First tangential	-	2446 Hz
Second tangential	-	4057 Hz
First longitudinal	-	696 Hz

These frequencies are based on the 7.4 inch diameter and the 22 inch length combustion chamber.

A comparison of these frequencies with other gas generators indicated that the theoretical frequencies were lower. It was realized that lower frequencies tend to couple with the combustion process; however, the low mixture ratio combustion devices tend to be acoustically stable.

During the performance of the hot fire tests, the first tangential frequency was noted; however, the amplitude as measured with high frequency combustion chamber pressure transducers was found to be approximately 20 psi peak-to-peak.

During several tests, self-damping 10 milliseconds, 100-150 psi, 2400 Hz disturbances were noted at the maximum power level. These tests were performed with a 250 psid injector differential pressure at the maximum power level. At lower power levels with higher injector differential pressures, no evidence of instability was noted (see test section, Test No. 9).

The final tests were performed with the injector differential pressure increased to 350 psig at the maximum power level. The higher differential pressure was obtained by reducing the maximum power level pintle stroke from .360 inches to 0.325 inches, and increasing the propellant inlet pressures.

Data analysis indicated the low level 3600 Hz second tangential frequency, but no indications of self-damping disturbances. Increasing the differential pressure apparently decoupled a tendency for the propellant feed system to couple with the combustion process.

Throughout the hot fire test program, no evidence of combustion instability was noted except during the last two tests, 13 and 14. The instability noted is not characteristic of this design in that it was triggered by another unrelated anomaly. This is discussed fully in the test section.

STRUCTURAL ANLAYSIS

The injector and combustion chamber structural analysis supported the detail design. The stress levels are based on limit loads and include dynamic and thermal effects. The minimum required safety factors are two based on ultimate or yield material properties, whichever is lower.

The injector components are similar to the Lance Sustainer injector. The Lance operating pressures and loads, consequently, are in excess of those for the Restartable High Power Gas Generator. The Lance operating loads were employed for the structural analysis.

The structural loads are as follows:

1. Load occurring at approximately two seconds after engine ignition
   Chamber pressure Pc = 1000 psi
   Oxidizer cavity pressure Po = 1300 psi
   Fuel cavity pressure Pf = 1300 psi

2. Ignition start pressure surge
   Chamber pressure Pc = 1700 psi
   Oxidizer cavity pressure Po = 2600 psi
   Fuel cavity pressure Pf = 4400 psi

3. Dynamic loading at the two joint interface (injector to chamber)
   Moment = 395,400 in-lb (limit)
   Shear = 69,200 lb (limit)

4. The steady-state random vibration environment of $.3g^2/Hz$ from 50-1000 Hz and $1.0g^2/Hz$ from 1000-2000 Hz and handling loads results in the following injector to thrust chamber loads:
Moment = 45,000 in-lb (limit)
Shear = 8,500 lb (limit)
Axial - 17,400 lb (limit)

5. Static loads

Parameter	Start Transient Pressure (psig)	Steady State Pressure (psig)
Fuel manifold	4250	1000
Pintle open	1560	1000
Pintle close	Vented	1000
Fuel inlet	4400	1300
Oxidizer inlet	2600	1300

GAS GENERATOR TEST

This section includes gas generator checkout and leakage test procedure, injector water flow calibration, hot fire test facility, hot fire test procedure, and a detailed description of the hot fire tests performed. Included within the hot fire test discussion is the detail discussion of design changes incorporated as the test program progresses.

INJECTOR CHECKOUT AND LEAKAGE TESTS

Following assembly of the injector, the unit was subjected to a rigorous leak and proof pressure test to assure the integrity of the unit prior to hot fire. All tests were accomplished with clean dry Mil spec gaseous nitrogen to assure maintenance of LOX clean conditions. A section view of the injector showing the internal seal leak check ports and the general test setup are shown in Figure 31 b.

Internal O-Ring Leak Check

Pintle Open System. The pintle open cavity was pressurized to 1100 psig and isolated from the pressurization source for a period of five minutes. No loss in pressure was allowed.

Pintle Closed System. The same procedure was used for the pintle closed system.

Positive Face Shutoff Seal

The pintle was pressurized at 1100 psig. The fuel inlet was pressurized to 1100 psig and isolated from the pressurization for a period of five minutes. A maximum of five psig pressure decrease in five minutes was allowed.

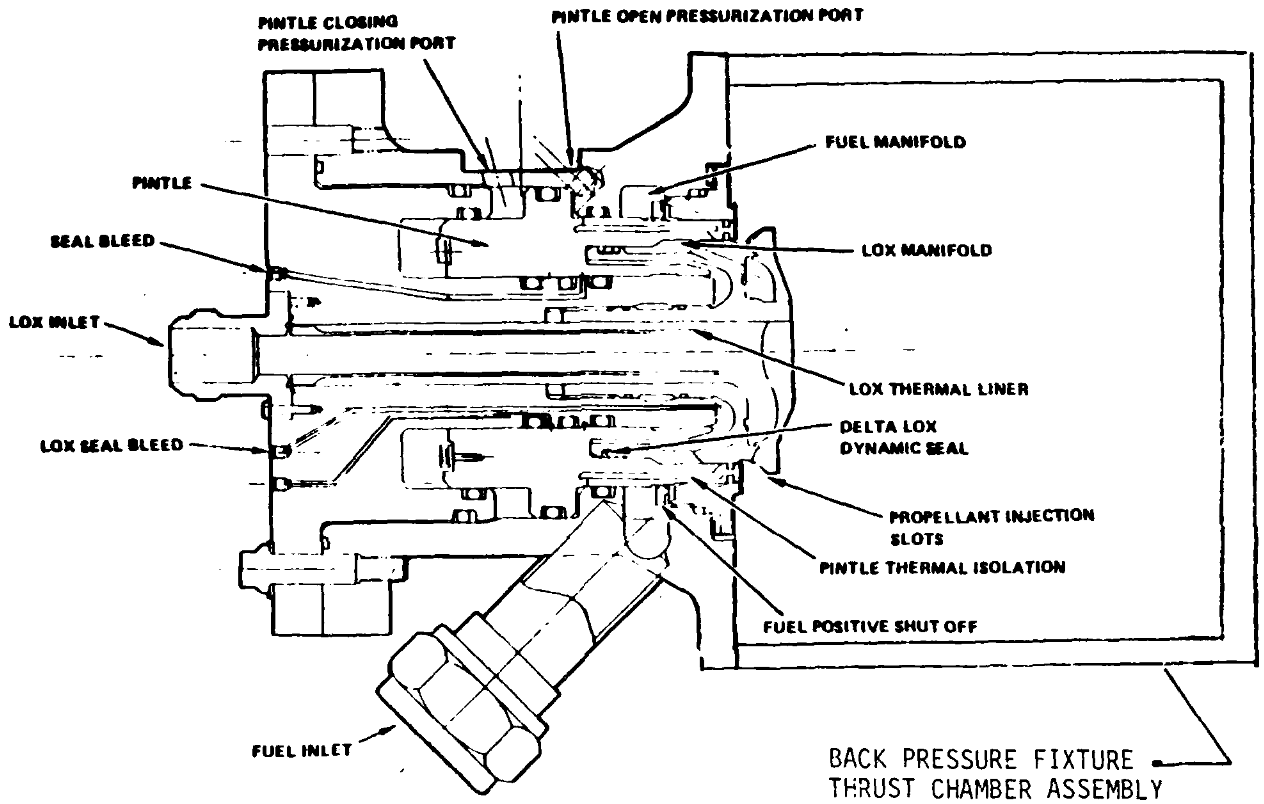


Figure 31 b . Ignition Leak Check Setup

Dynamic Delta Seal Leak Test

The combustion chamber was pressurized to 700 psig with the pintle in the open position. A gaseous nitrogen flowmeter was used to measure the leakage from the Delta seal port. Maximum allowable leakage was 50 standard in^3/min.

The pintle O-ring vent ports were leak-checked at the same time. No leakage was allowed.

Structural Proof Pressure

Prior to the initial hot fire test, the injector and combustion chamber was subjected to a structural proof pressure test to verify the integrity of all welds in the injector and combustion chamber.

With the combustion chamber installed, the entire unit was subjected to a five cycle proof pressure at 1200 psig (1.7 x nominal chamber pressure of 700 psi). Following completion of the proof pressure test, the complete injector leak test was repeated.

WATER FLOW CALIBRATION

Following each injector buildup, the unit was water flow calibrated to determine the LOX and fuel resistance over the complete 5 to 1 throttling range. Based on the resistance data, the axial position of the fuel injection ring was adjusted to yield a constant mixture ratio over the throttling range.

The injector was installed in the water flow calibration facility as shown in Figure 32.

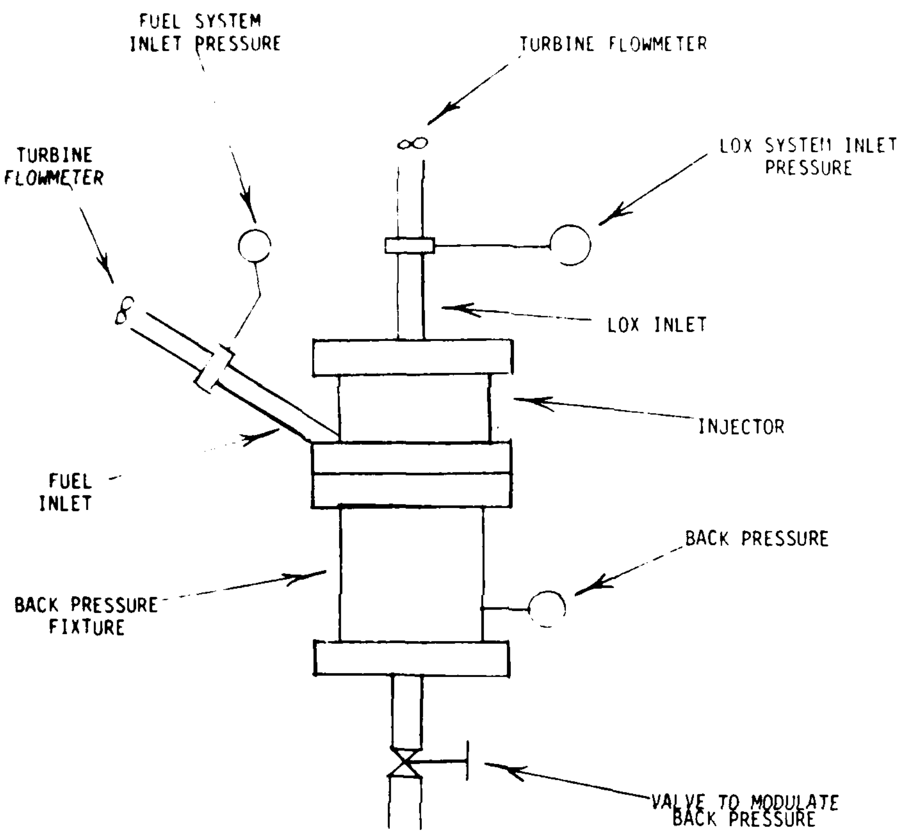


FIGURE 32 WATER FLOW CALIBRATION TEST SETUP

The injector was equipped with a back pressure fixture to provide sufficient chamber pressure to prevent cavitation and thus preclude erroneous results. Figure 32 also indicates the location of the instrumentation for water flow calibration.

Figure 33 presents a sample of the injector water flow resistance data as a function of pintle position. The injector resistance data and the test facility propellant system data were used to determine the required hot fire test facility tank pressures.

A computer program based on the injector and facility resistance data and theoretical c* was used to determine gas generator operation over the throttling range. A sample computer printout is shown in Table III.

TEST FACILITY

The hot fire test program was conducted on the Bravo-2B Test Stand at the Santa Susana Field Laboratory. The propellant tanks are existing installations. The portions of the systems downstream of the tank shutoff valves were fabricated and installed. The existing thrust mount was used as an attachment point for the gas generator.

Installation of the original gas generator design in the test facility is shown in Figure 34.

The oxidizer system used a 1200-gallon, 2000 psig rated supply tank. A stainless steel tubing system was used between the tank and the main oxidizer valve. The main oxidizer valve body was chilled with an orificed bleed system which permits LOX flow through the main valve upstream of the valve seal to complete temperature stabilization. The valve was located as close to the gas generator as possible to minimize downstream fill volumes.

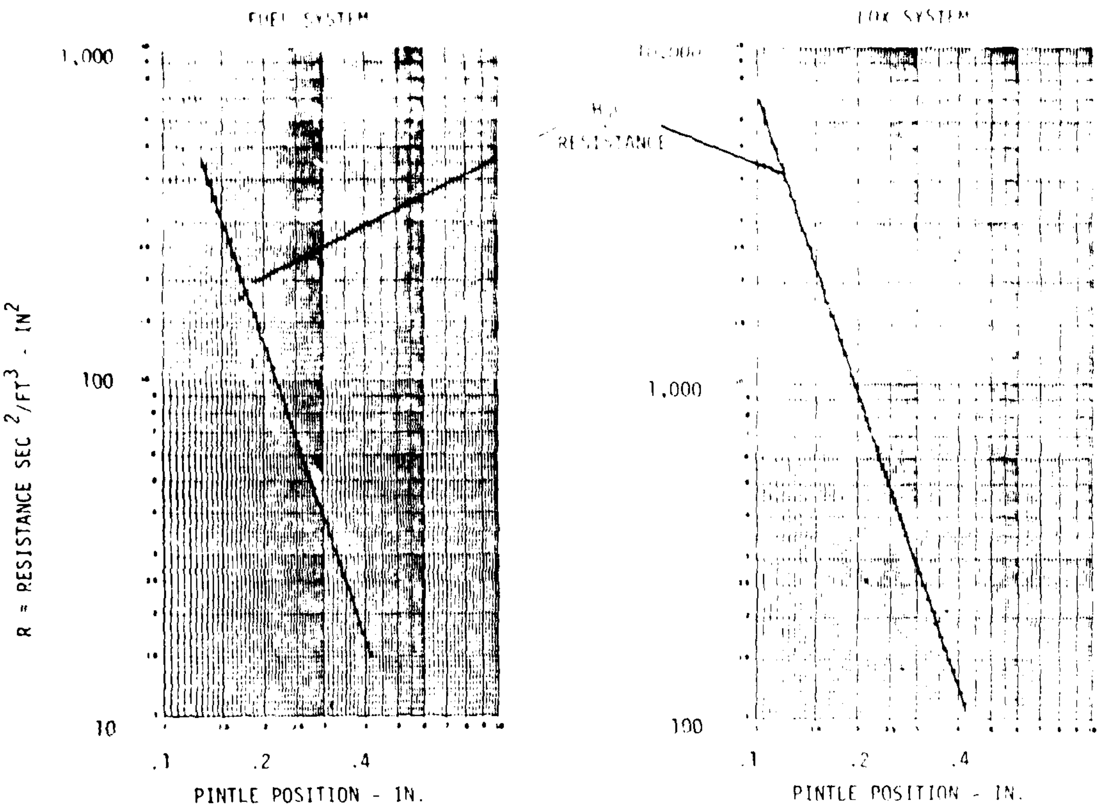


FIGURE 33. INJECTOR RESISTANCE VERSUS PINTLE POSITION

INPUT OXID AND FUEL TANK PRESS (PSIA)...
>1046.,1005.

OXID TANK PRESS (PSIA)= 1046.00

FUEL TANK PRESS (PSIA)= 1005.00

STROKE	MR	OX WDOT	FU WDOT	WDOT TOT	PC
.3600	.4601	9.4482	20.5334	29.9816	742.1
.3400	.4612	9.1831	19.9130	29.0961	721.5
.3200	.4622	8.8831	19.2192	28.1023	698.3
.3000	.4632	8.5454	18.4471	26.9926	672.0
.2800	.4643	8.1663	17.5890	25.7553	642.5
.2600	.4653	7.7427	16.6390	24.3816	609.4
.2400	.4664	7.2721	15.5924	22.8646	572.6
.2200	.4675	6.7534	14.4472	21.2006	532.0
.2000	.4685	6.1867	13.2041	19.3909	487.6
.1800	.4697	5.5743	11.8683	17.4426	439.5
.1600	.4709	4.9206	10.4498	15.3704	388.1
.1400	.4722	4.2331	8.9648	13.1980	334.1
.1200	.4737	3.5225	7.4363	10.9589	278.2
.1000	.4755	2.8030	5.8951	8.6981	221.5
.0800	.4777	2.0928	4.3808	6.4735	165.6

TABLE III . HOT FIRE RUN CONDITIONS AS A FUNCTION OF PINTLE POSITION

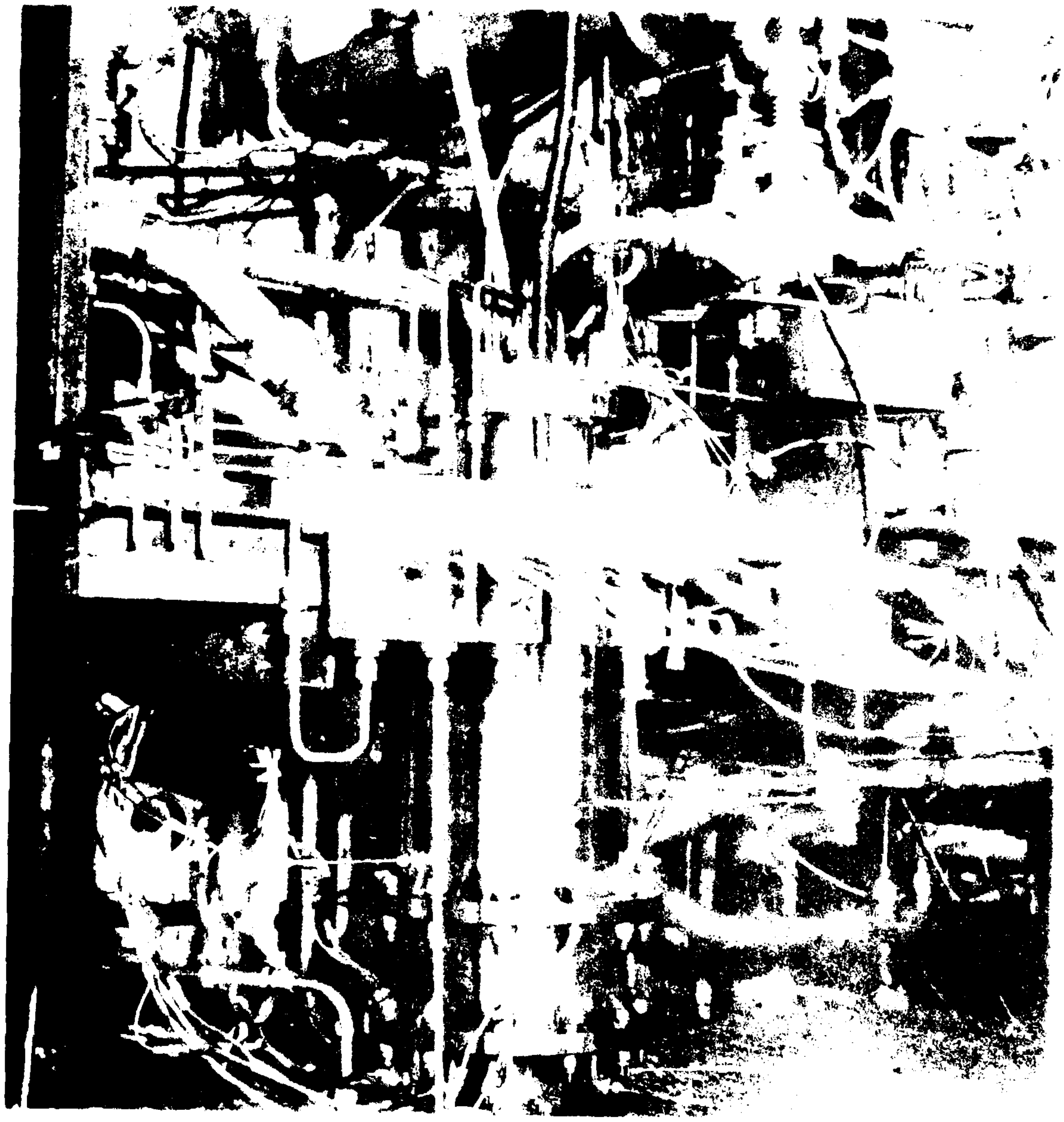


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Figure 34. Gas Generator Installation in Test Facility

The main oxidizer valve was an Annin valve equipped with a high-pressure pneumatic operating cylinder. A 3000-psig actuation pressure was used, and valve actuation times on the order of 20 milliseconds.

A purge system was provided to secure the test stand at the completion of firing activities. The propellant system purges were not used during hot fire testing.

The fuel supply system used a 2500-gallon, 3000-psig rated supply tank for the JP-4. A stainless-steel tubing system was installed, with an Annin valve to serve as the test stand main valve. This valve was not required to actuate rapidly, since the fuel valve was opened well before the firing sequence was initiated. The gas generator pintle valve employed a tight shutoff feature, and since fuel was used as the pintle actuating fluid, it was necessary to supply fuel pressure to the pintle prior to initiation of hot firing.

A fuel purge system was provided to accommodate normal test stand practices. However, as previously cited for the oxidizer purge system, this purge was not used during hot firing.

The gas generator instrumentation is listed in Table IV. Tabor, straingage type pressure transducers were used for all low-response (steady-state) pressure measurements. Two photocon pressure transducers were used to provide high-response chamber pressure data. These transducers allowed accurate characterization of the chamber pressure buildup time, and permitted display of any chamber pressure oscillations. The propellant flowrates were measured with turbine-type flowmeters.

The gas generator body wall temperatures were monitored at various selected locations by means of chromel/alumel thermocouples spot-welded to the wall. Propellant temperatures were measured with immersed iron/constantan thermocouples installed immediately downstream of the propellant flowmeters.

TABLE IV INSTRUMENTATION LISTING

PARAMETER	TRANSDUCER	RANGE	RECORDING METHOD				
			TAPE	OSCILLOGRAPH	BRUSH	DYNALOG	DIGITAL
Chamber Pressure, $P_c^{(2)}$	Photocon	0 to 1000 psia	X	X	--	--	--
Chamber Pressure, $P_c^{(4)}$	Tabor	0 to 1000 psia	--	X	X	--	X
Oxidizer Tank Pressure, P_{to}	Tabor	0 to 2000 psia	--	--	--	X	X
Fuel Tank Pressure, P_{tf}	Tabor	0 to 2000 psia	--	--	--	X	X
Oxidizer Injection Pressure, P_{Io}	Tabor	0 to 1500 psia	--	X	X	--	X
Fuel Injection Pressure, P_{If}	Tabor	0 to 1500 psia		X	X	--	X
Oxidizer Purge Pressure, P_{po}	Tabor	0 to 1500 psia		--	--	X	--
Fuel Purge Pressure, P_{pf}	Tabor	0 to 1500 psia	--	--	--	X	--
GG Wall Temperature, Tw (8)	Cr/Al	0 to 2000 F	--	--	X	--	--
GG Gas Temperature, Tg (8)	Cr/Al	0 to 2000 F	--	X	X	--	X
Fuel Temperature, T_{If}	I/C	0 to 200 F	--	--	--	X	X
Oxidizer Temperature, T_{Io}	I/C	-300 to + 100 F	--	--	--	X	X
Fuel Flowrate, w_f	Turbine	0 to 25 lb/sec	--	X	--	--	X
Oxidizer Flowrate, w_o	Turbine	0 to 12 lb/sec	--	X	--	--	X
Pintle Position, P_p	--	0 to 100%		X	--	--	X
MFV Power	--	--		X	--	--	--
MFV Travel	--	--	--	X	--	--	--
MOV Power	--	--		X	--	--	--
MOV Travel	--	--	--	X	--	--	--
Accelerometers 3	Tri Axis		X	--	--	--	--
Spark Monitor 2 a	Accels.	0-200 Hz	X	X	--		
Fuel Flowmeter Temperature	I/C	0-200 F	--	--	--	X	X
LOX Flowmeter Temperature	I/C	-300 to + 100 F	--	--	--	X	X
Fuel Flowmeter Press	Tabor	0 to 1500 psig	--	--	--	X	X
LOX Flowmeter Press	Tabor	0 to 1500 psig	--	--	--	X	X

The combustor gas flowfield temperature was characterized by means of a grid of eight thermocouples. These thermocouples were total temperature probes employing exposed junction chromel/alumel wire.

The pintle position was monitored by means of a linear travel transducer. This monitored transducer also was used as one of the elements of the pintle position control system.

All hot firings were controlled by means of a programmer. The run sequence was present and was automatic.

The automatic timer was overridden by cut signals, either instituted by observers or by comparator circuits. The comparator checks of system operations and other safety monitors included:

1. LOX main valve interlock - the LOX valve reached its full-open position before the pintle valve movement was initiated.

2. Chamber pressure level - a comparator circuit was used to ascertain that a minimum acceptable chamber pressure level was reached by a pre-determined time after initiation of the firing signal. Failure to reach or exceed this value, then, or subsequently during the run, would have caused an automatic cut to be instituted.

3. Selected combustor hot gas rake temperatures were monitored with provision for automatic test cut in the event of an over temperature condition.

4. A vibration safety cut-off system was provided to protect the hardware.

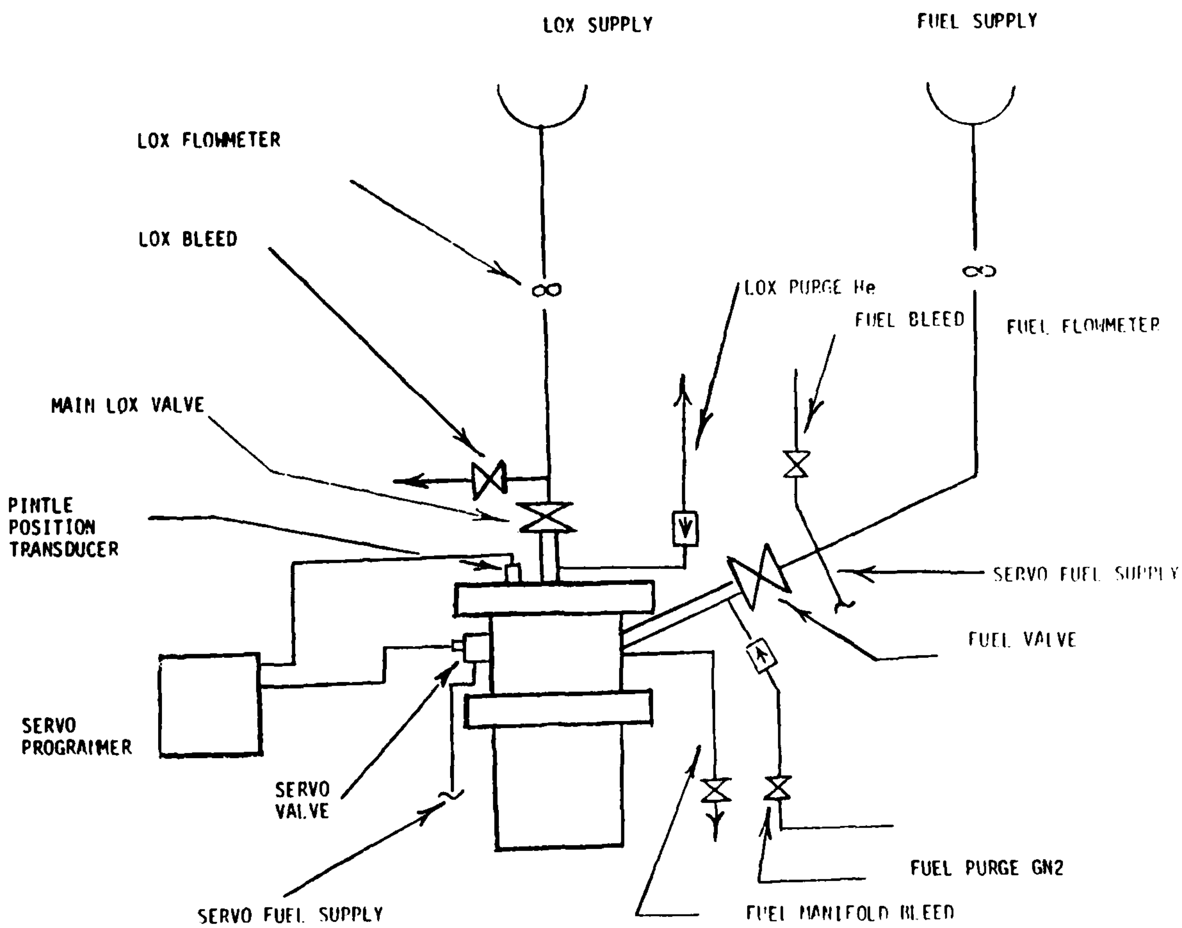


Figure 35. Restartable High Power Gas Generator Test Setup

Gas Generator To Test Facility Installation

The gas generator was mounted in the facility in the vertical position. Propellant and electrical systems were installed as shown in Figure 35 . The main LOX and main fuel valves were close-coupled to the hardware. The LOX system included a bleed valve upstream of the main oxidizer valve to be used to obtain LOX quality pretest.

The servo valve fuel supply was obtained upstream of the main fuel valve. This line was fitted with a 10 micron hydraulic filter located within one foot of the servo valve inlet to protect the servo valve from contamination.

To achieve relatively constant fuel and oxidizer inlet pressure over the entire throttling range, the propellant line and valve hydraulic resistances were held to a minimum and were balanced to operate with near tank pressures.

Test Sequences

Test start and cutoff sequence consisted of the following:

Prior to test start, the following test stand conditions were established:

1. Pressurize oxidizer and fuel tanks to specified levels.

2. Open main fuel valve and bleed air from fuel manifold.

3. Open LOX bleed valve and establish LOX temperature at the main LOX valve of -280°F or less.

Start Sequence (Reference Figure 36)

1. Start signal starts the main stage timer and signals the LOX bleed valve closed.

2. The bleed valve closed signal initiates opening of the main LOX valve.

3. Full open position of the main LOX valve arms the LOX lead timer.

4. At the expiration of the LOX lead timer, the pintle is commanded to the initial position and the ignition detect timer is armed.

5. Obtaining ignition detection prior to expiration of the ignition delay timer allows the test to continue.

6. Failure to achieve the ignition detection signal prior to expiration of the delay timer will initiate test cutoff.

7. Achieving ignition detection terminates operation of the spark igniters.

8. For those tests requiring a single power level, the initial power level timer shall be set for the total main stage duration.

9. Those tests requiring more than one power level will be sequenced by the subsequent timers up to a maximum of 5 power levels.

10. Test termination will be initiated by the expiration of the main-stage timer.

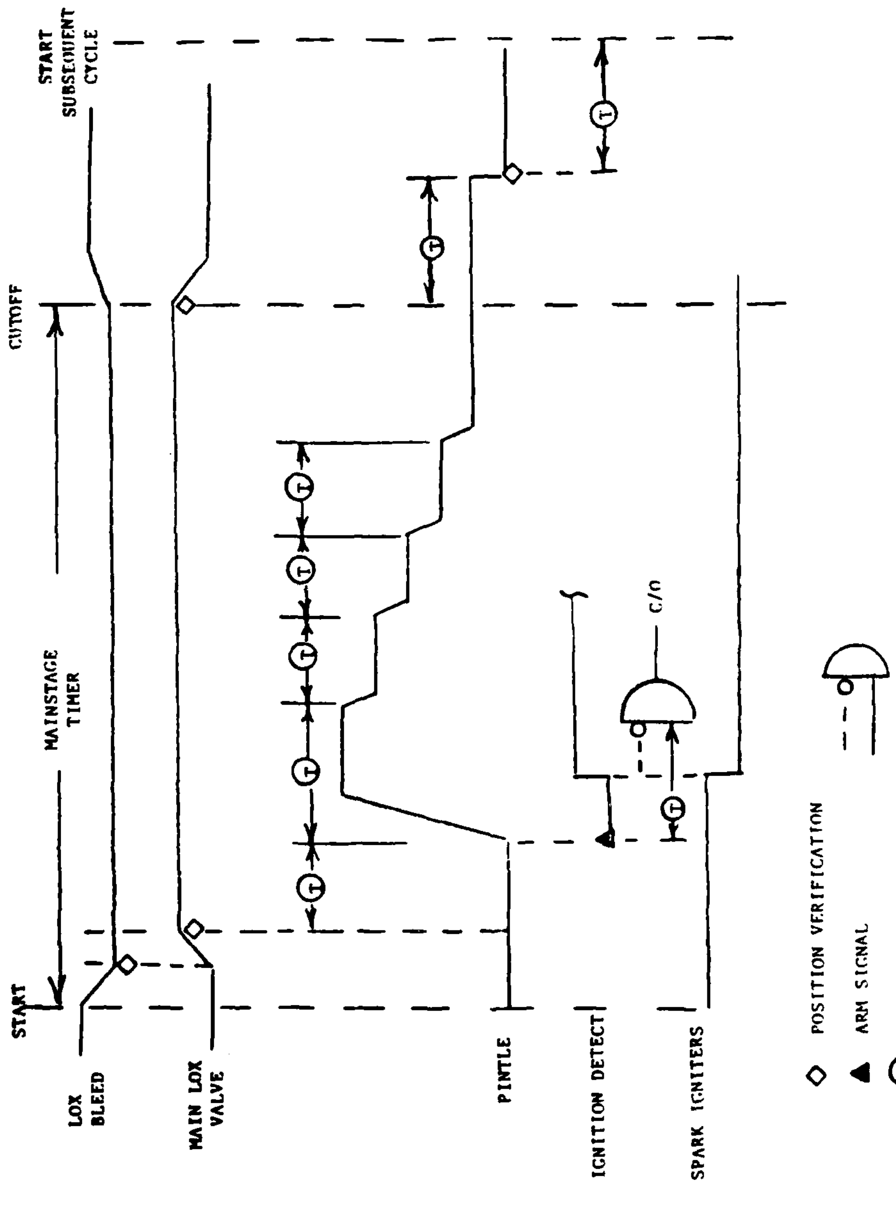


FIGURE 36. START AND CUTOFF SEQUENCE

Test Termination

1. Test cutoff initiated by the mainstage timer or failure to detect ignition shall close the main oxidizer valve, open the LOX bleed valve and start the pintle open override timer.

2. At the expiration of the pintle override timer, the pintle is commanded closed and starts the timer delay prior to the start of the next mainstage test.

As a result of test termination and hot gas temperature spikes noted during the early hot fire tests, the test termination phase was modified. The sequence was modified to include a low flow fuel bypass and opening the pintle to the 100% position immediately after closing the LOX shutoff valve. This allowed expulsion of the residual oxidizer in the injector concurrent with a low fuel flowrate to react with the residual at a relatively low mixture ratio. The revised sequence is shown in Figure 37.

HOT FIRE TEST RESULTS

A total of fourteen (14) hot fire tests were performed. The following section discusses the test objectives, hardware configuration and results for each test.

Test No. 001

Facility Test No. 634-001 — 14 April, 1980

Hardware Configuration. Baseline design with turbulator (vortex).

Test Objectives. Initial one second ignition test with pintle open to 55% position.

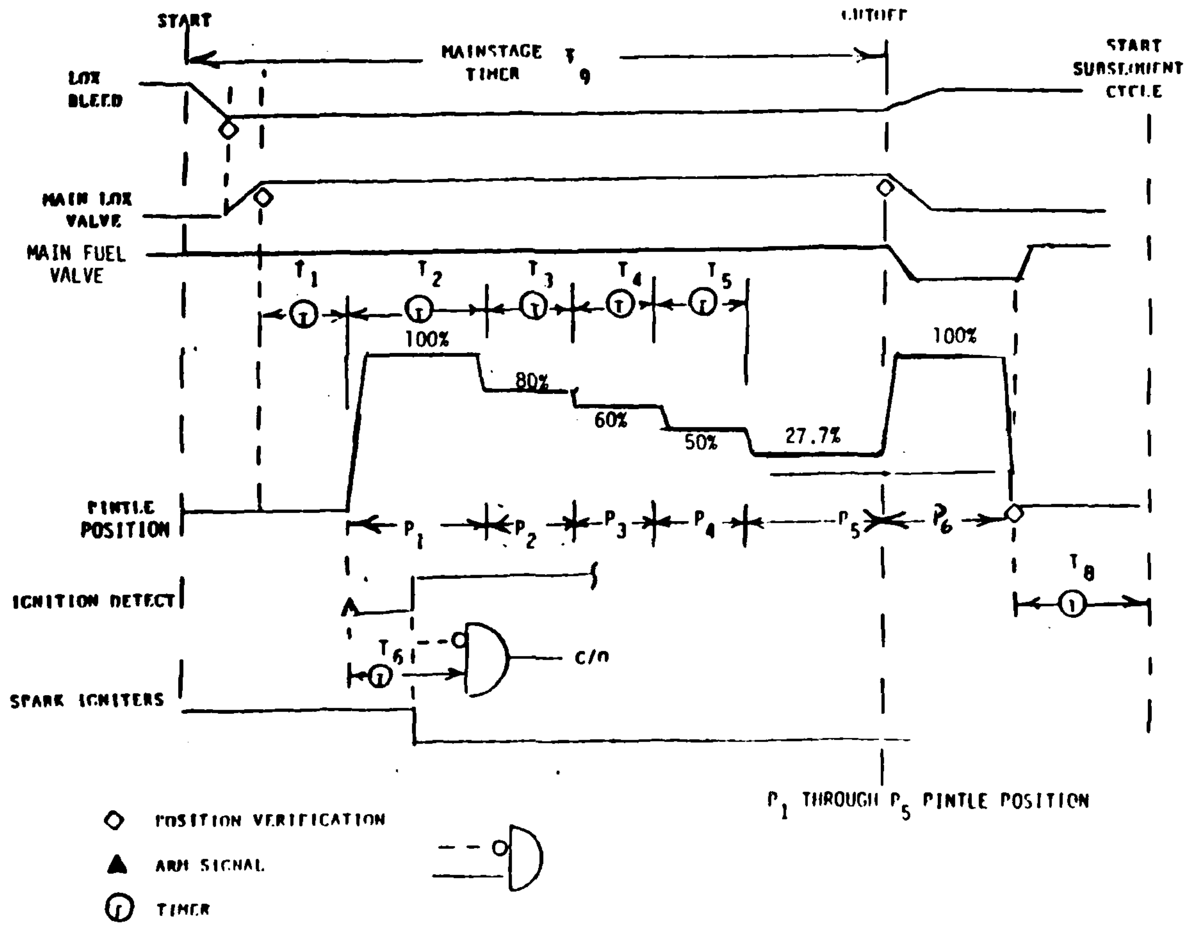


Figure 37. Revised Test Sequence

Test Results. Test prematurely terminated due to failure to detect ignition. Ignition occurred 20 milliseconds after ignition detection timer expired.

Hardware Condition. No hardware anomalies.

Test No. 002 16 April 1980

Hardware Configuration. Same as Test 001.

Test Objectives. Evaluate ignition and operation at 77% pintle position.

Test Results. Test performed the programmed one second duration. Mixture ratio was 0.33 (target 0.466). Hot gas temperature pattern factor was excellent: 0.0588 target, and 0.065 maximum.

Hardware Condition. All hardware in excellent condition.

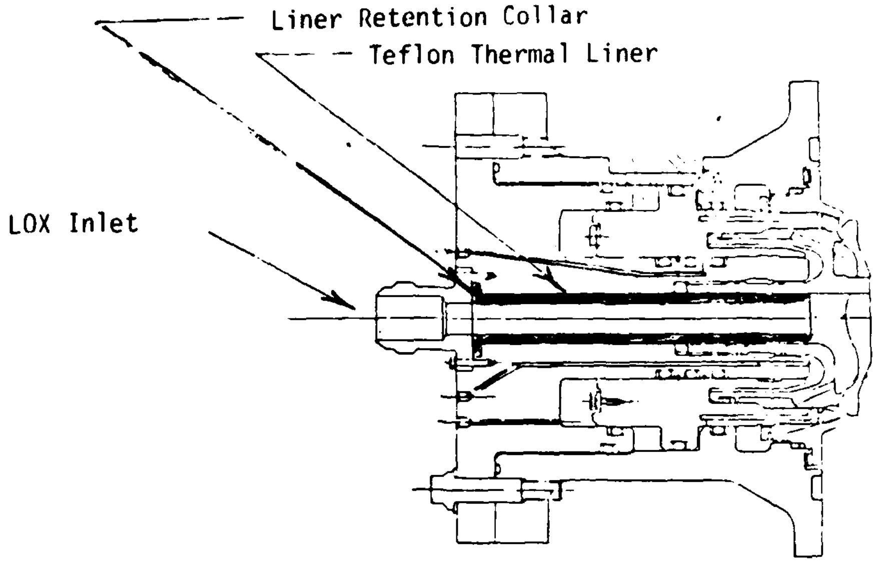
Test No. 003

Facility Test No. 634-003 18 April 1980

Hardware Configuration. Same as test 001 and 002.

Test Objectives. Initial five second test at maximum power level.

Test Results. The liquid oxygen thermal liner retainer sheared off at test start, resulting in the liner being driven aft into the core, producing a restriction in LOX flow, as shown in Figure 38 . The resulting increased LOX injector differential pressure decreased the LOX flow, resulting in a mixture ratio of 0.326; target was 0.466. The measured hot gas temperature pattern was excellent, even though the LOX manifold was partially restricted by the failed thermal liner.



TEFLON THERMAL LINER INSTALLATION

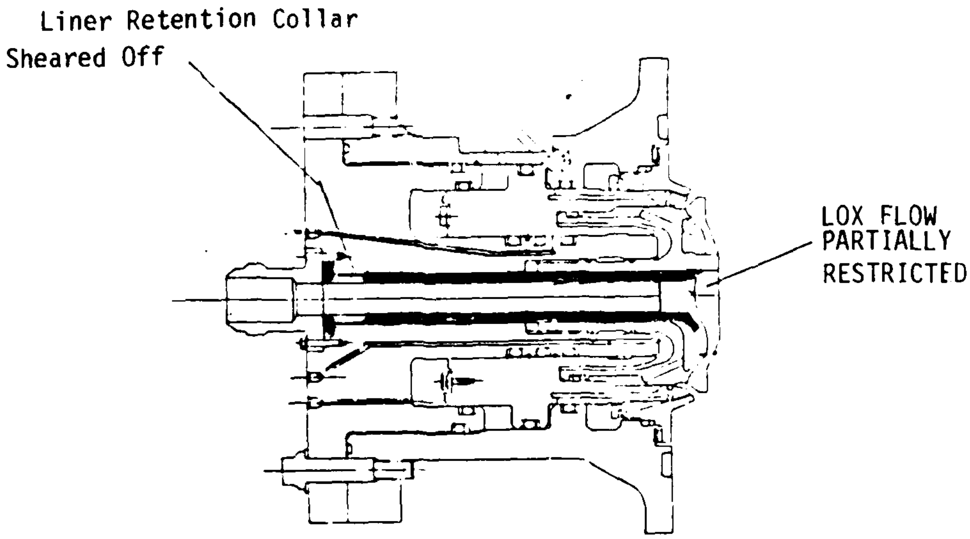


FIGURE 38. TEFLON THERMAL LINER FOLLOWING TEST 003

Hardware Condition. The injector face and fuel injection ring were severely eroded as a result of the restricted injector LOX flow. A photograph of the injector damage is shown in Figure 39 .

Test No. 004

Facility Test No. 634-004 14 July 1980

Hardware Configuration. The injector was rebuilt, incorporating a new fuel injector ring and forward section of the injector housing. Both were severely eroded as a result of Test 003. The injector teflon LOX thermal liner was replaced with a Cres tube (Figure 40), concentric with the LOX inlet passage. The design provided a gap between the liner flowing LOX and the injector housing. During operation the gap was filled with static LOX or GOX (no flow velocity).

The thermal conductivity of the GOX is 1.85×10^{-6} BTU/sec-in°F as compared to 3.24×10^{-6} BTU/sec-in°F for the teflon. The new liner, therefore, provided an improvement in thermal isolation in addition to eliminating the teflon liner failure mode.

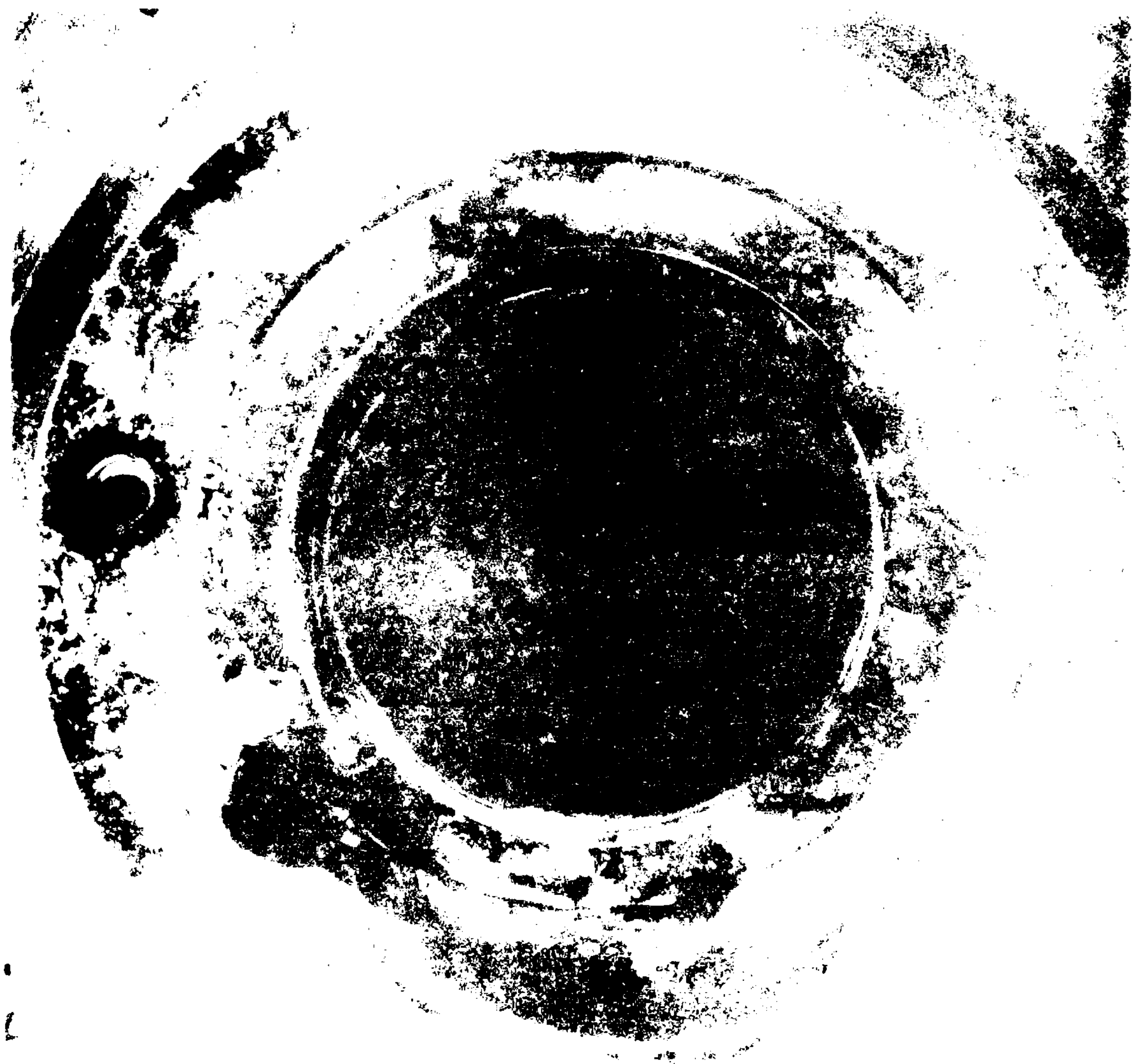
Test Objectives. Operation at maximum power level for five seconds.

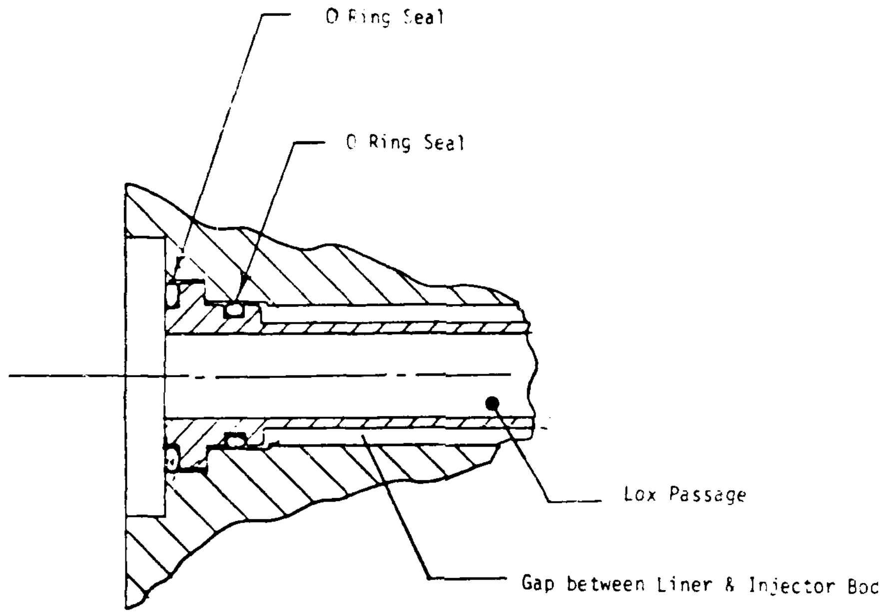
Test Results. Premature test termination due to an error in setting ignition detect chamber pressure level. The ignition detect was erroneously set at 800 psig rather than the specified 100 psig.

Hardware Condition. No hardware anomalies.

Test No. 005

Facility Test No. 634-005 14 July 1980





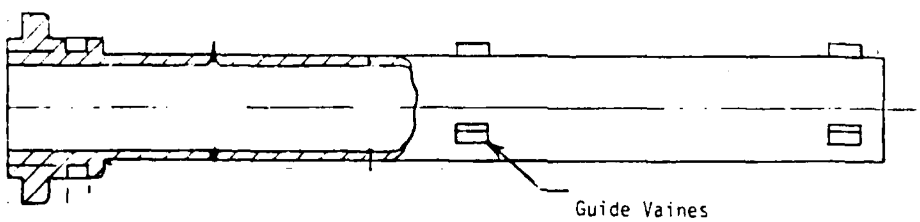


FIGURE 40. CRES THERMAL LINER

Hardware Configuration. Same as Test 004.

Test Objectives. Same as Test 004.

Test Results. Programmed duration five second test. Mixture ratio was 0.435, hot gas temperature 1454°F, (target was 0.465, hot gas temperature 1608°F, and hot gas temperature pattern factor 0.068).

Hardware Condition. No hardware anomalies

Test No. 006

Facility Test No. 634-006 16 July 1980

Hardware Configuration. Same as Test 004 and 005

Test Objectives. Initial ten second throttling test of two seconds duration at 100, 83, 61, 44, and 33.3 percent power levels.

Test Results. Programmed duration at 100 percent power level, the pintle failed to respond to commands to lower power levels. There was hot gas temperature variation, 300°F, and temperature spike during cutoff in excess of 2000°F.

Hardware Condition. The center section of the hot gas turbulator eroded through the vortex generation portion, as shown in Figure 41.

The nose of the pintle was slightly eroded, and the surface of the fuel ring was eroded (Reference Figure 42). The fuel ring erosion may have been caused by hot gas recirculation in the gap between the injector face and the head end of the combustion chamber, Reference Figure 43. The blisters in the ablative core shield were caused by minor outgassing of the ablative and do not represent a problem.

Figure 31. Hot Gas Turbulator Post Test 006

Figure 42. Minor Pintle and Fuel Injection Ring Erosion

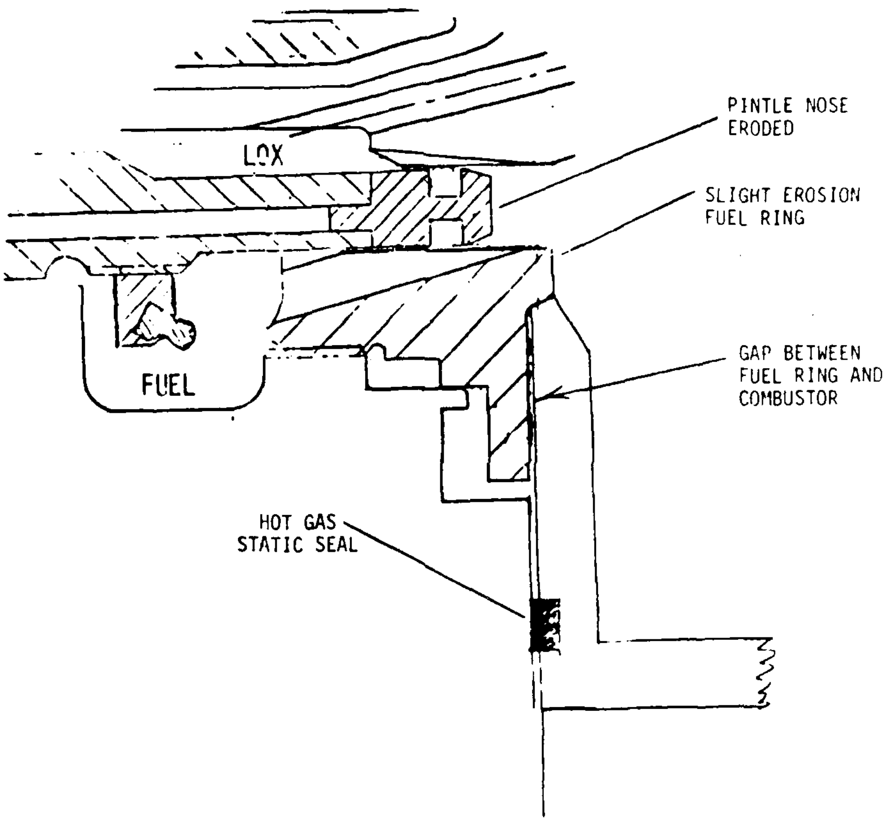


FIGURE 43 GAP BETWEEN INJECTOR AND COMBUSTOR HEAD END

Test No. 007

Facility Test No. 734-007 24 July 1980

Hardware Configuration. The gap between the fuel ring and the head end of the thrust chamber was sealed with silicone graphite high temperature sealant.

Test Objectives. Ten second throttling test. The initial pintle position was programmed for 55% followed by two seconds each at 82.5, 100, 55, and 27.5 percent. The previous attempt to throttle (Test 006) was programmed for the initial pintle position at 100 percent followed by successive steps down to 33.3 percent. The servo system failed to control to the lower throttle position. The complete test was run at 100 percent power level. Programming this test to start at 55 percent and move up in power level was an attempt to duplicate Tests 002 and 003 which successfully controlled the pintle at 55 and 77 percent. The test was also programmed for three 10 second throttling tests performed back-to-back with three seconds off between tests.

Test Results. The test was terminated at 0.9 seconds by the hot gas temperature redline set at 1800°F. Mixture ratio was 0.49, targeted 0.466. The servo system did not control to the initial set point of 55 percent.

The hot gas temperature ranged from 1828°F to 2117°F during the test termination phase.

Performing servo system checkouts with ambient chamber pressure and ambient LOX manifold pressure indicated that the servo valve and programmer were operating properly.

Servo system tests were performed simulating chamber pressure with gaseous nitrogen. These tests indicated that the servo system was capable of throttling at chamber pressures up to 560 psig. Above this pressure, the system would not operate. The gaseous nitrogen tests also indicated considerable leakage from the pintle LOX dynamic delta seal.

The hardware was disassembled and the delta seal was found to be damaged, resulting in massive leakage. The overboard seal drain, Figure 44 , was sized to 0.060 inch diameter to vent minor leakage, which may occur during operation of the delta seal. Gross leakage past the seal resulted in a pressure increase in the cavity downstream of the seal producing a load imbalance on the pintle.

The pressure increase was caused by the inability of the 0.060 inch diameter seal drain to vent copious leakage. Figure 45 indicates the pintle areas exposed to control pressure, LOX manifold pressure, and chamber pressure. From this Figure, it can be seen that if the Delta seal leaks, the area exposed to LOX manifold pressure increases from 1.21 in^2 to 5.11 in^2. This dramatic increase in area results in a force imbalance in the pintle of sufficient magnitude that the pintle will not move closed during hot fire.

The delta seal was replaced with a dynamic O-ring to verify this hypothesis. Copious leakage was again observed from the seal. Critical dimensional inspection of the interfacing core and pintle indicated that the clearance between the mating parts was 0.007 in. as compared to the drawing requirements of 0.003 in.

The excessive clearance caused the damage to the delta seal and prevented sealing of a dynamic O-ring. The out of specification dimensions were associated with the core assembly. This area of the core was nickel-plated and re-machined to the specified dimensions.

Hardware Condition. All hardware was found to be in good condition except a slight increase in the minor pintle tip erosion noted as a result of Test 006.

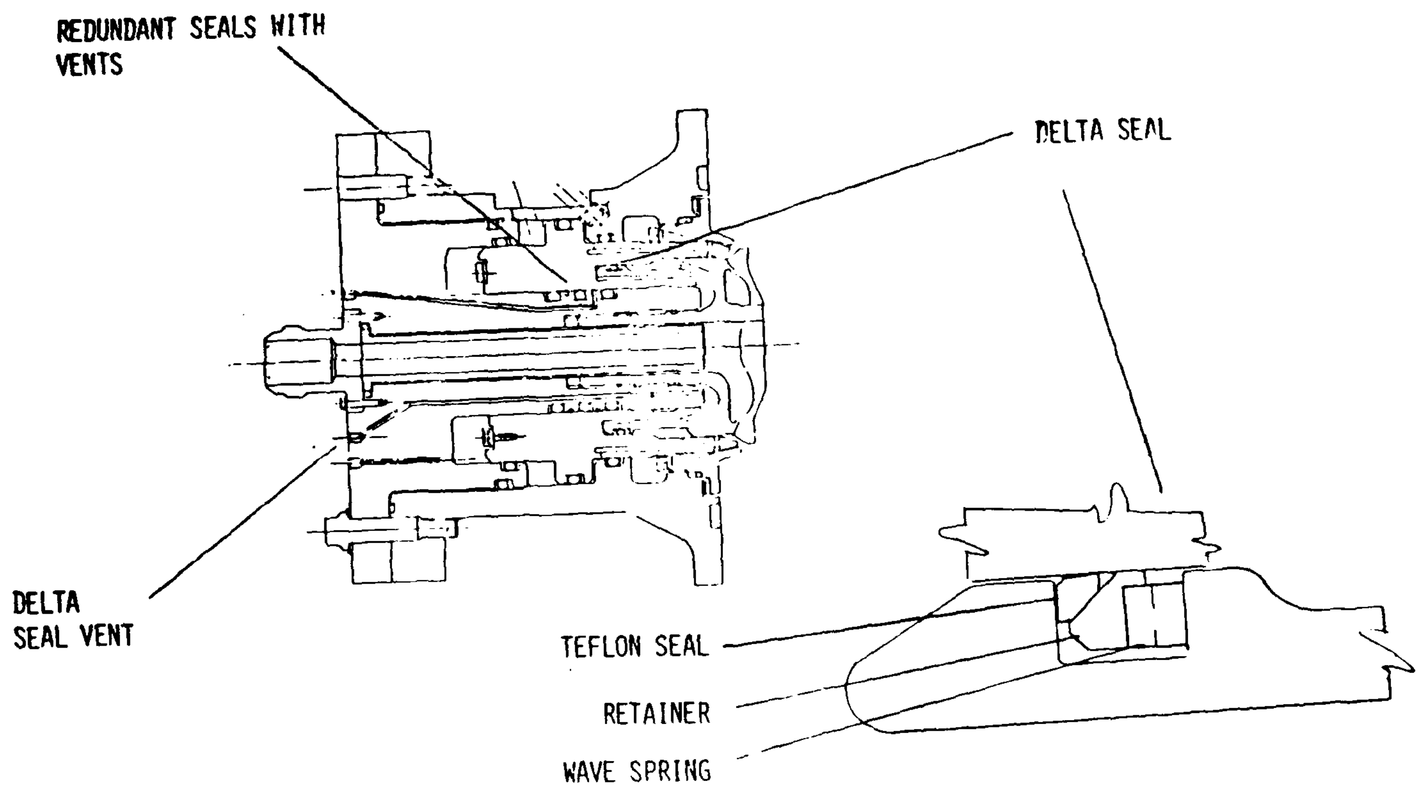


Figure 44 LOX Dynamic Delta Seal Vent

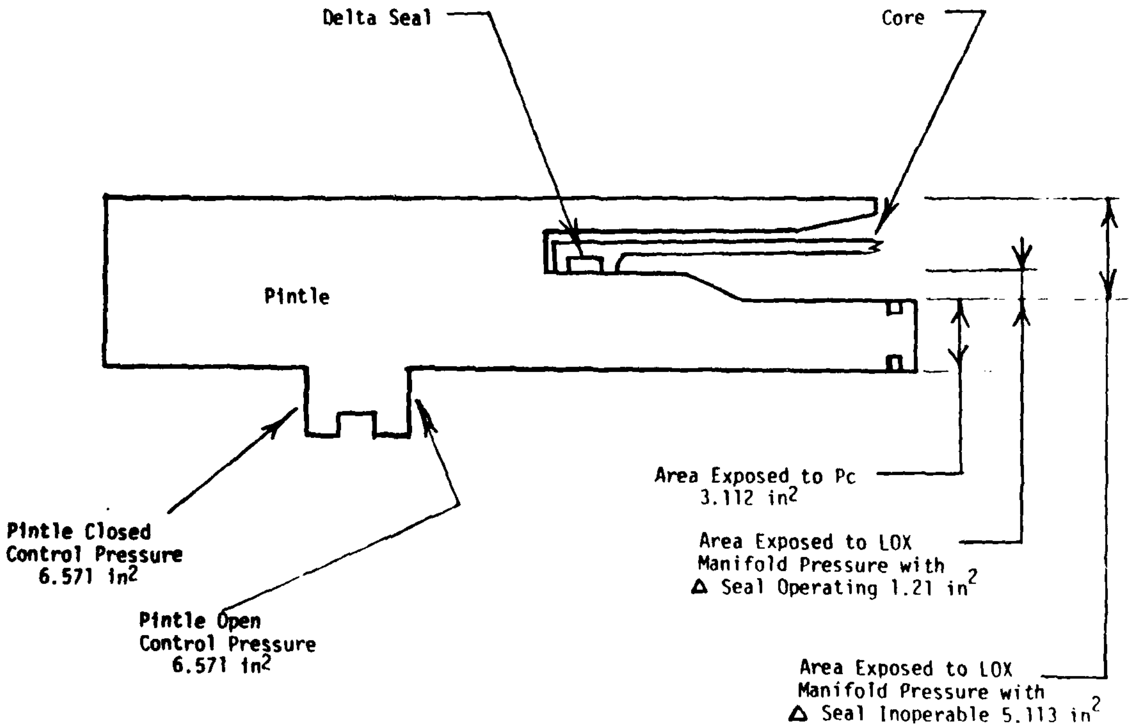


Figure 45 Pintle Area Balance

Test No. 008

Facility Test No. 634-008 20 November 1980

Hardware Configuration. The LOX system dynamic delta seal was replaced. The seal groove on the core was nickel-plated and re-machined to correct a discrepant dimension, resulting in an excessive gap between the core and the interfacing pintle. This excessive gap allowed the teflon delta seal to extrude into the gap and thus be vulnerable to excessive wear and ultimate leakage.

The nose of the fuel ring was nickel-plated to increase the erosion resistance.

Test Objectives. Ten second throttling test from 100 percent power level to 35 percent power level. With the hot gas turbulator removed to determine the hot gas temperature distribution without the secondary hot gas mixing device, the fuel override was extended from 150 milliseconds to 300 milliseconds in an effort to minimize the hot gas temperature spike during test termination.

Test Results. The test was terminated at 1.315 seconds by the hot gas temperature redline cutoff device, with hot gas temperature in excess of 2000°F.

The high hot gas temperature was caused by 0.546 mixture ratio, resulting from pieces of the positive face shutoff seal restricting the fuel injection slots.

Post-Test Hardware Condition. All hardware except the positive face shutoff seal were in excellent condition.

Test No. 009

Facility Test No. 634-002 6 March 1981

Hardware Configuration. Design changes were incorporated to compensate for the deficiencies noted in testing to date: positive face seal O-ring cracking, turbulator erosion, pintle tip erosion, and fuel injection ring erosion.

Laboratory tests were performed on several positive face shutoff configurations in an effort to optimize the seal. The final configuration consisted of using a Viton O-ring in place of the nitride O-ring used for the previous tests. The amount of compression of the seal ring edges into the rubber was optimized to preclude cutting of the O-ring.

The flow swirl inducer section of the hot gas turbulator eroded through due to lack of heat transfer from the thin swirler vains to the main body of the turbulator (Reference Figure 41). The swirler was replaced with a heavy nickle cap equipped with flow passages directing hot gases such that they impinge with the gas directed through the side of the turbulator. Between the third and fourth row of holes, a plate was installed, equipped with holes which are misaligned with the holes in the cap. Gases flowing through the cap are forced to turn prior to exiting through the holes in the plate, thus promoting hot gas mixing.

Heat transfer analysis and gas flow path analysis indicates that this configuration should provide excellent hot gas mixing and durability. The configuration is shown in Figure 46

The pintle tip was copper-plated to distribute the heat load. Previous tests had indicated minor surface erosion adjacent to the LOX metering rings. No evidence of overheating had been noted on the fuel side of the pintle tip. Copper plating has been found to be effective in eliminating localized erosion by distribution of the heat load on similar combustion devices. Figure 47 indicates the copper-plated pintle tip configuration.

Minor erosion on the fuel ring was noted. The fuel ring had been nickel-plated in an effort to provide increased heat transfer. The nickel-plated

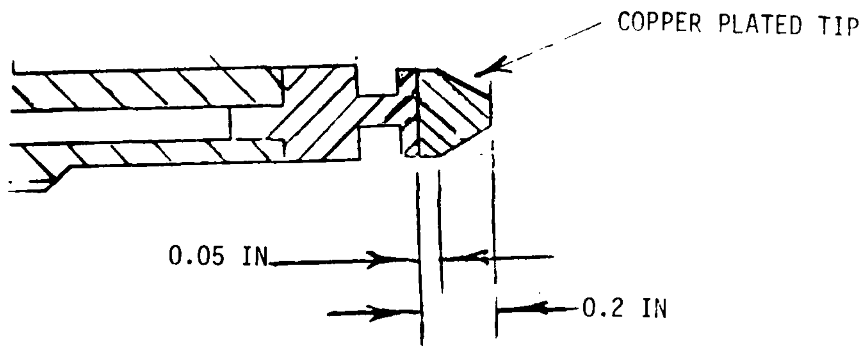


FIGURE 47. COPPER PINTLE TIP

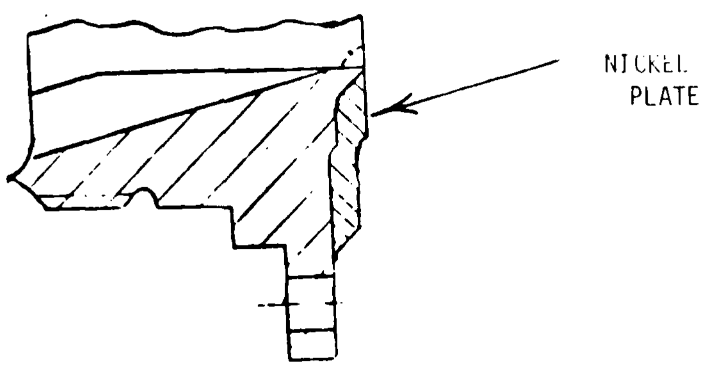


FIGURE 48. NICKEL PLATED FUEL RING

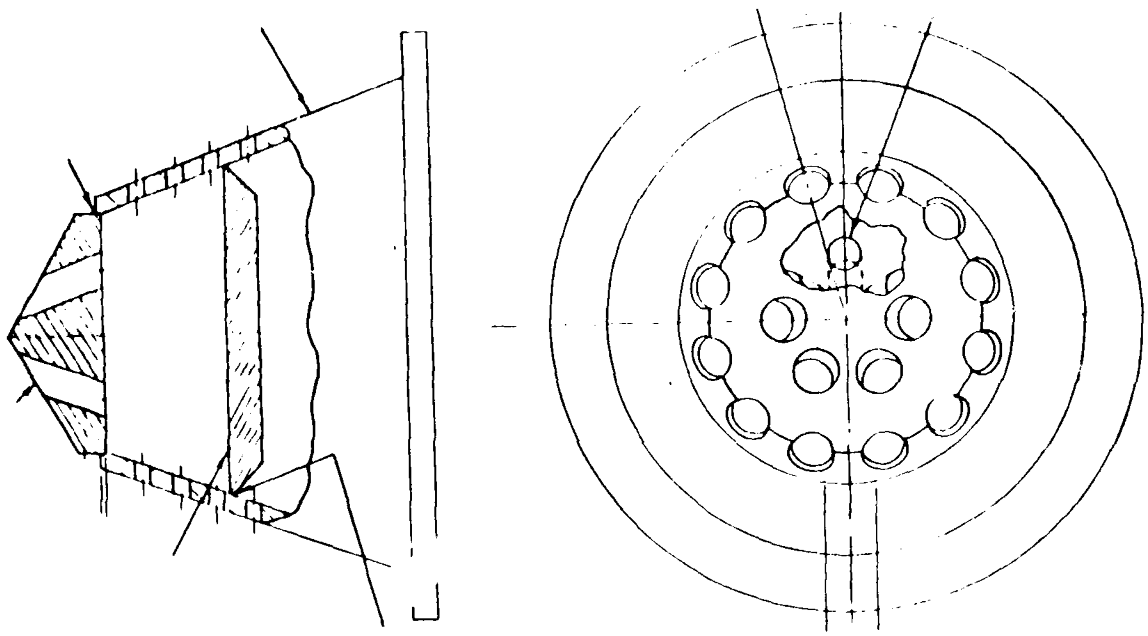


Figure 46. Redesigned Turbulator

fuel ring is shown in Figure 48 .

Test objectives. Ten second throttling test from 100 percent to 27.7 percent power level. The test termination phase was modified in an effort to reduce the test termination temperature spikes. The revised sequence consisted of ramping the pintle to the 100 percent position coincident with closing the oxidizer shutoff valve. The pintle was programmed to remain open for 0.3 seconds with a small 3.5 lb/sec fuel bypass flow to burn the remaining LOX expelled from the injector at a low mixture ratio and, consequently, lower the hot gas temperature during test termination. The fuel bypass system is shown in Figure 49.

Test Results. The test was performed as programmed except due to a test console operator error, restart occurred two seconds following test termination, and a second 10 second test was performed. The data from the two tests were very repeatable. The chamber pressure traces from both tests are shown in Figure 50. The propellant flowrate data for the second cycle of the two cycle test is presented in Table V .

Table V indicates a reasonable agreement in measured LOX flow as compared to targeted flow based on water flow calibration. The fuel flowrate falls below the targeted values as the power level is decreased. Figure 51 shows the injector resistance as a function of pintle position for the hot fire test as compared to the water flow calibration data. The decrease in resistance on

AD-A127 291 RESTARTABLE HIGH POWER GAS GENERATOR(U) ROCKWELL INTERNATIONAL CANOGA PARK CA ROCKETDYNE DIV M G GANTS DEC 82 RI/RD82-224 AFWAL-TR-82-2119 F33615-79-C-2004

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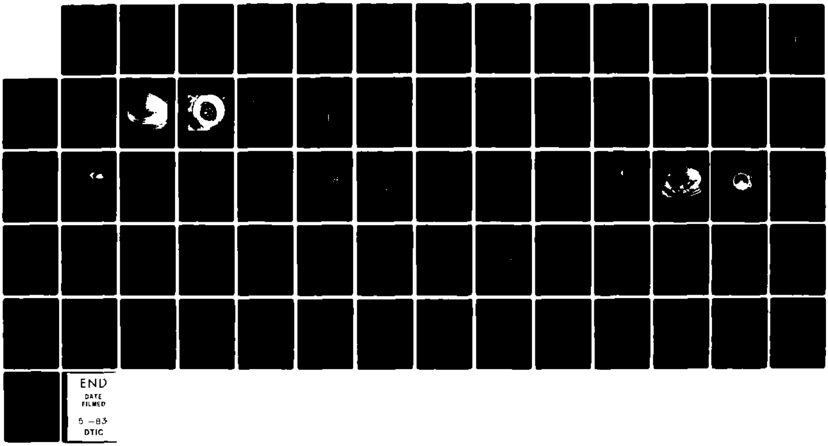
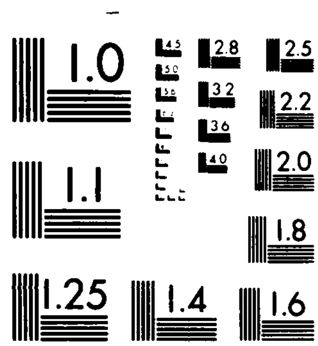




MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

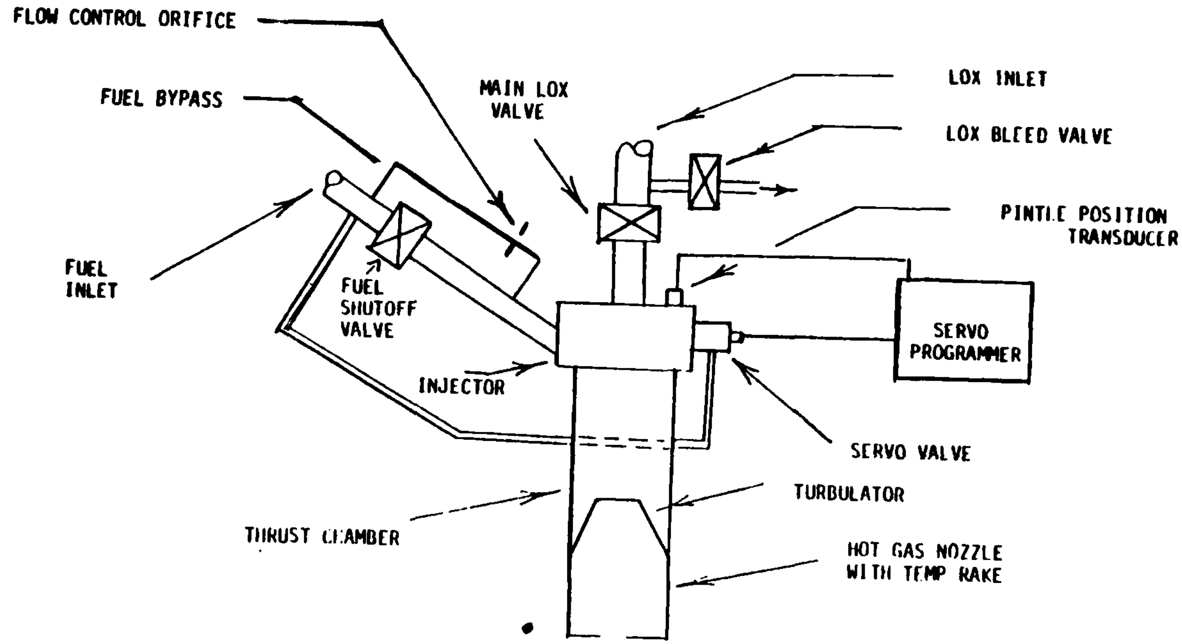
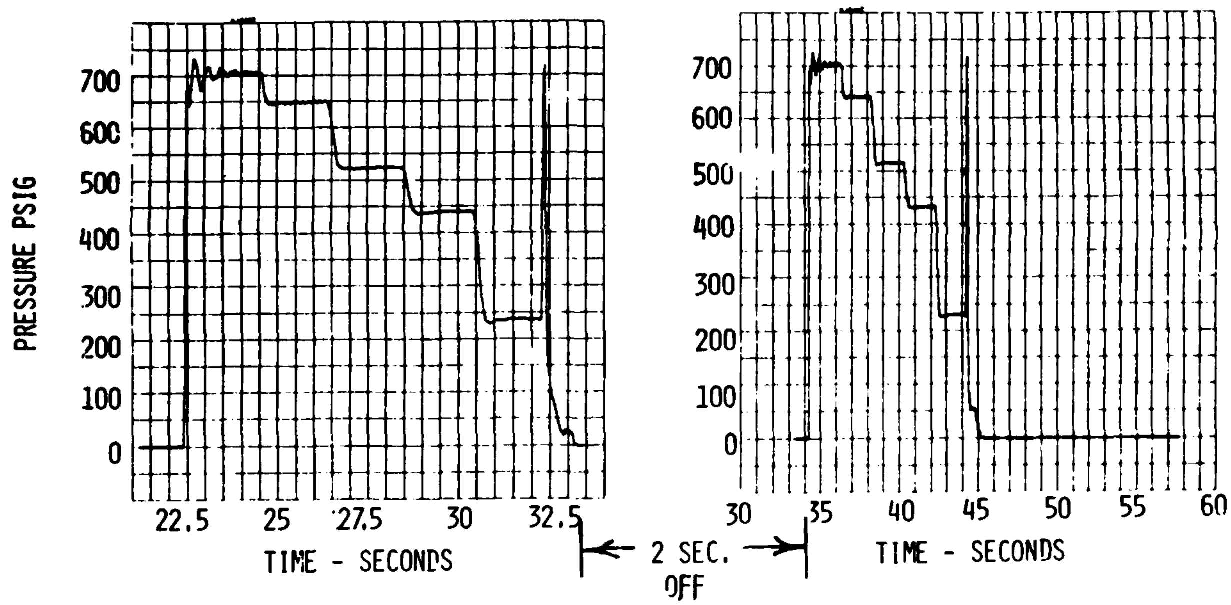


Figure 49. Test Termination Fuel Bypass System

FIGURE 50
COMBUSTION CHAMBER PRESSURE



CYCLE NO. 1

CYCLE NO. 2

TABLE V TEST 009 - SECOND CYCLE

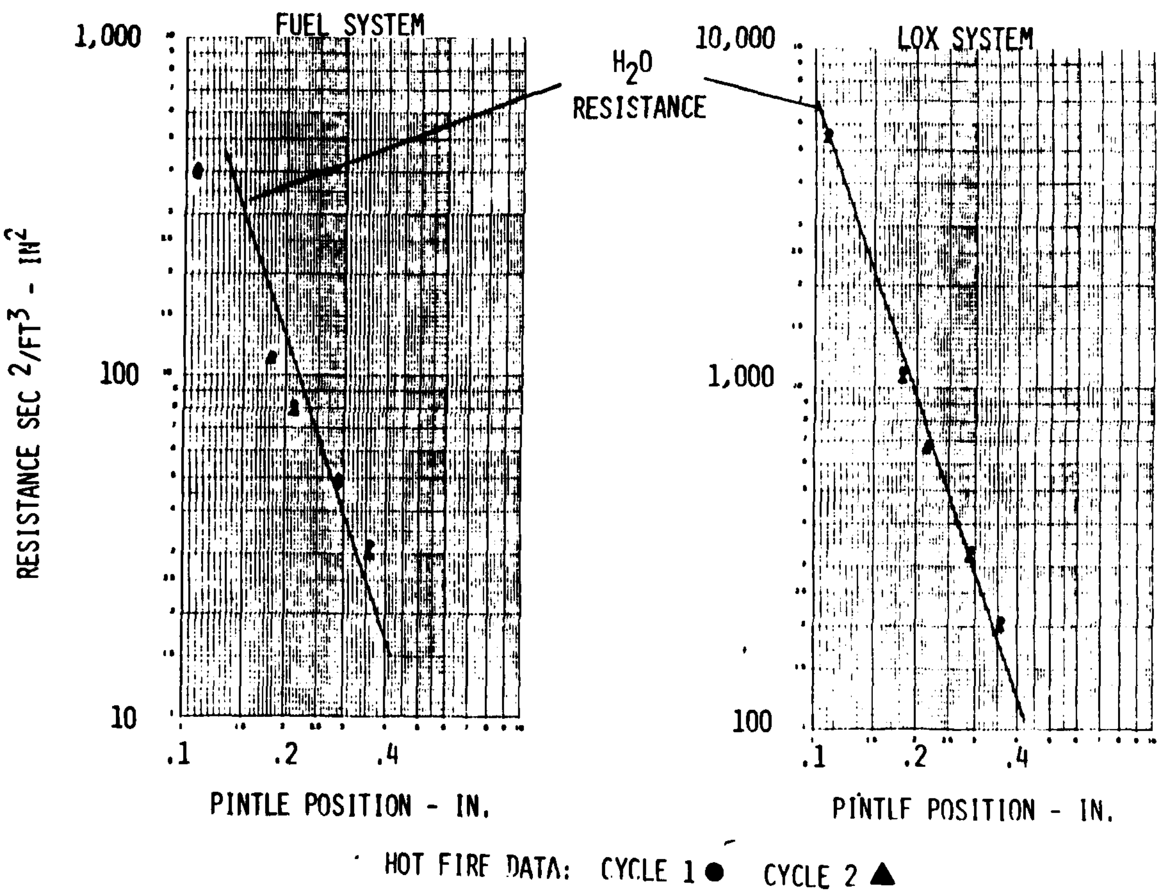
PROPELLANT FLOWRATE

O/O	PINTLE POSITION IN	$\dot{W}_o$ LBS/SEC	TARGET $\dot{W}_o$ LBS/SEC	$\dot{W}_f$ LBS/SEC	TARGET $\dot{W}_f$ LBS/SEC	M.R. TARGET	M.R. ACTUAL
100.6	0.360	9.2469	9.394	19.099	20.319	.462	0.484
80.28	0.288	8.393	8.350	17.897	17.95	.460	0.468
59.359	0.214	6.992	7.08	16.147	15.134	.468	0.433
49.89	0.1796	5.938	5.55	14.799	11.79	0.47	0.401
30.098	0.108	3.160	2.79	9.355	5.86	0.476	0.337*

*HP LEVEL 2.7K HP

FIGURE 51

INJECTOR RESISTANCE VERSUS PINTLE POSITION



fuel side of the injector may have been related to the thermal distortion of the fuel injection ring. Figure 52 presents the fuel ring dimensions pre-test. The slot land where the metering ring rides was of a uniform diameter. Following the test, the tip of the fuel ring diameter was 0.010 less than pre-test. In addition to the noted physical distortion, evidence of hot gas flow into the gap between the fuel ring and the thrust chamber was noted by evidence of the discoloration of the ring. It is hypothesized that heat input to the tip of the fuel ring caused the ring diameter to increase as shown in Figure 52 during the run, causing an increased fuel flow area and, therefore, giving the lower than targeted resistance. Following the test, the ring cooled and local yielding or thermal ratcheting occurred, resulting in the final measured smaller diameter.

The hot gas temperature data at each power level for both cycles of the test is presented in Table VI, and Table VII, and Figures 53 and 54. These data indicate that at the maximum power level, the temperature profile is outside of specified limits at power levels less than 80 percent. The temperature profile is within specified limits with the exception of the 30 percent power level. The thermal distortion of the fuel ring may have had an impact in the temperature profile at this power level. The hot gas turbulator is clearly ineffective at the higher power levels.

Review of the high frequency chamber pressure (photocon) and accelerometer data indicates one self-damping combustion disturbance during the first cycle at 100 percent power level and thirteen 5 to 10 millisecond combustion disturbances during operation at 100 percent power level during the second cycle. No combustion disturbances were noted during operation at lower power levels (Figure 55). Figure 56 presents an expanded trace of a typical combustion disturbance.

Review of the post-test hot gas temperature spikes, Figure 57, indicates a substantial improvement as a result of the revised test termination procedure.

FIGURE 52

FUEL INJECTION RING DEFORMATION

TEST 009

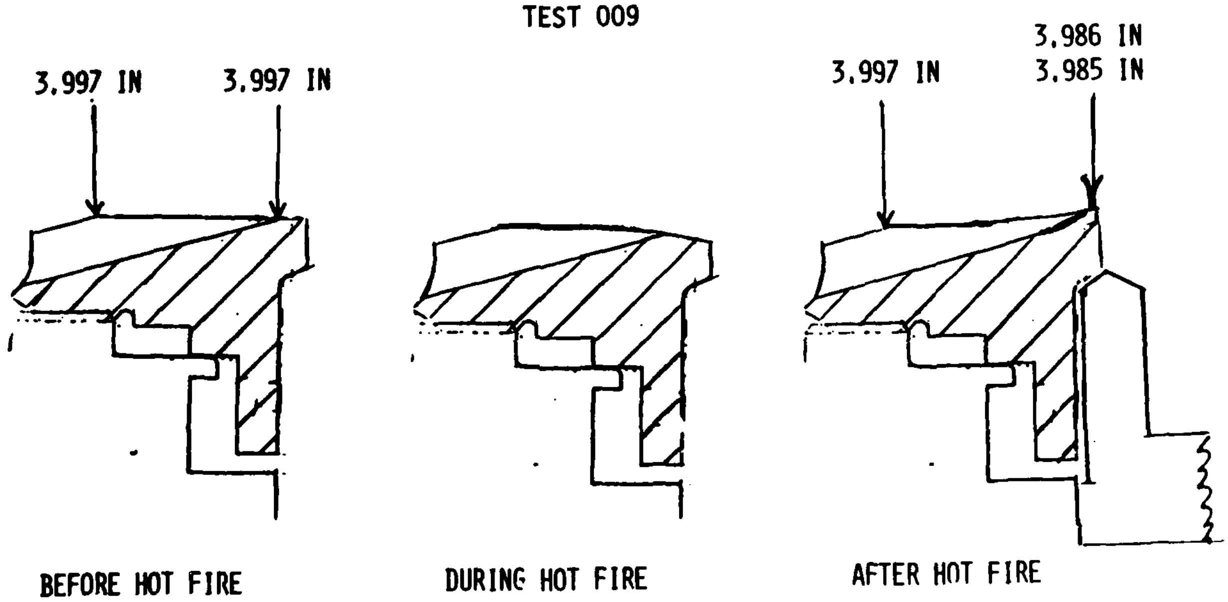


TABLE VI

TEST 009

HOT GAS TEMPERATURE SUMMARY

	PINTLE POSITION	THEORETICAL HOT GAS TEMP °F	AVERAGE TEMP °F	MAX. TEMP °F	PATTERN FACTOR
RUN 1	100	1750	1648	2101 (7)	0.2748
	80.74	1625	1646	1846 (4)	0.1215
	59.53	1440	1466	1521 (4)	0.0375
	50.07	1370	1363	1416 (4)	0.0388
	30.3	1000	1163	1407 (3)	0.209
RUN 2	100.6	1725	1612	2047 (7)	0.269
	80.28	1600	1579	1761 (7)	0.115
	59.35	1400	1451	1478 (3)	0.0186
	49.89	1300	1355	1413 (4)	0.042
	30.09	1050	1151	1285 (7)	0.116

○ THERMOCOUPLE NO.

PATTERN FACTOR = $\frac{T_{MAX}}{T_{AVE}} - 1$ MAX. GOAL 0.065.

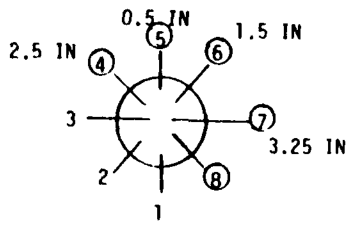


TABLE VII

TEST 009

HOT GAS TEMPERATURE

PINTLE POSITION PERCENT	P_{C_3} PSIG	M.R.	THEO. HOT GAS TEMP.	RAKE TEMPERATURE NO. 1	2	3	4	5	6	7	8	AVERAGE
100	670	0.49	1750	1401	1373	2016	1769	1441	1378	2101	1712	1648
80.74	617	0.471	1625	1590	1529	1777	1846	1645	1458	1659	1665	1646
59.53	499	0.436	1440	1434	1467	1482	1521	1427	1443	1468	1487	1466
50.07	418	0.396	1370	1329	1361	1377	1416	1339	1338	1368	1377	1363
30.306	223	0.331	1000	1039	1055	1407	1173	1056	1116	1360	1104	1163
100.6	669	0.484	1725	1399	1329	1944	1596	1383	1343	2047	1862	1612
80.28	607	0.468	1600	1523	1394	1721	1596	1451	1460	1761	1726	1579
59.359	490	0.433	1400	1422	1457	1478	1467	1422	1456	1457	1451	1451
49.89	411	0.401	1300	1326	1349	1364	1413	1340	1351	1355	1348	1355
30.098	216	0.337	1050	1003	999	1318	1227	1137	1107	1285	1139	1151

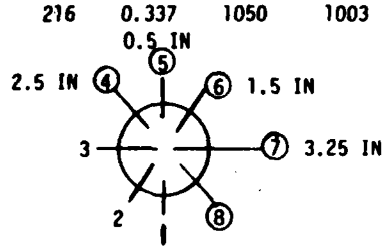
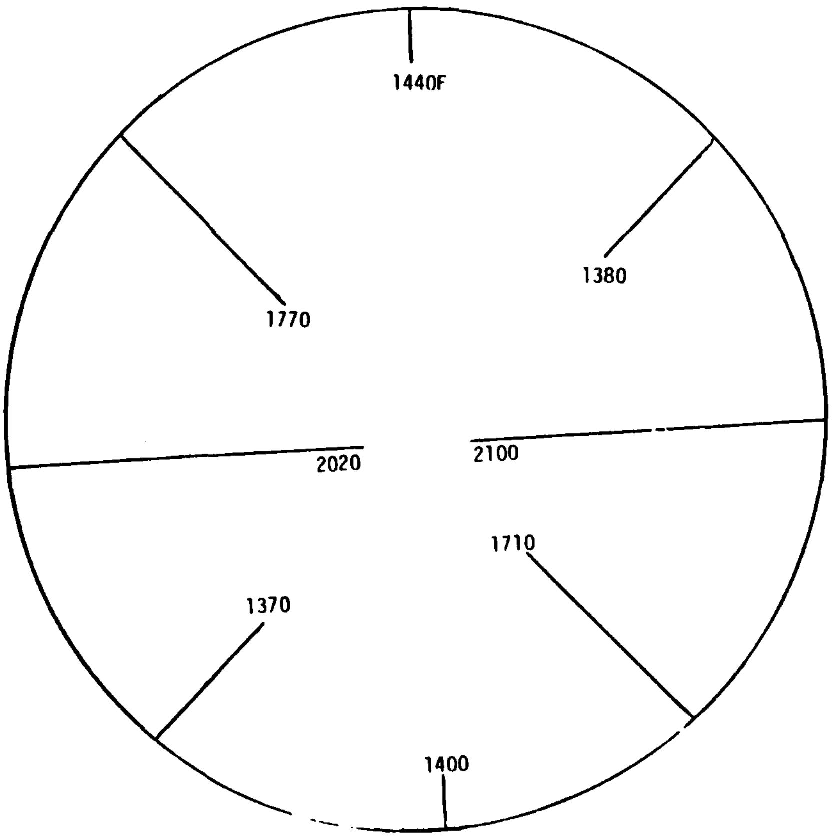


FIGURE 53

TEST 009 RUN 1

COMBUSTION CHAMBER TEMPERATURE MEASUREMENT

FULL OPEN PINTLE

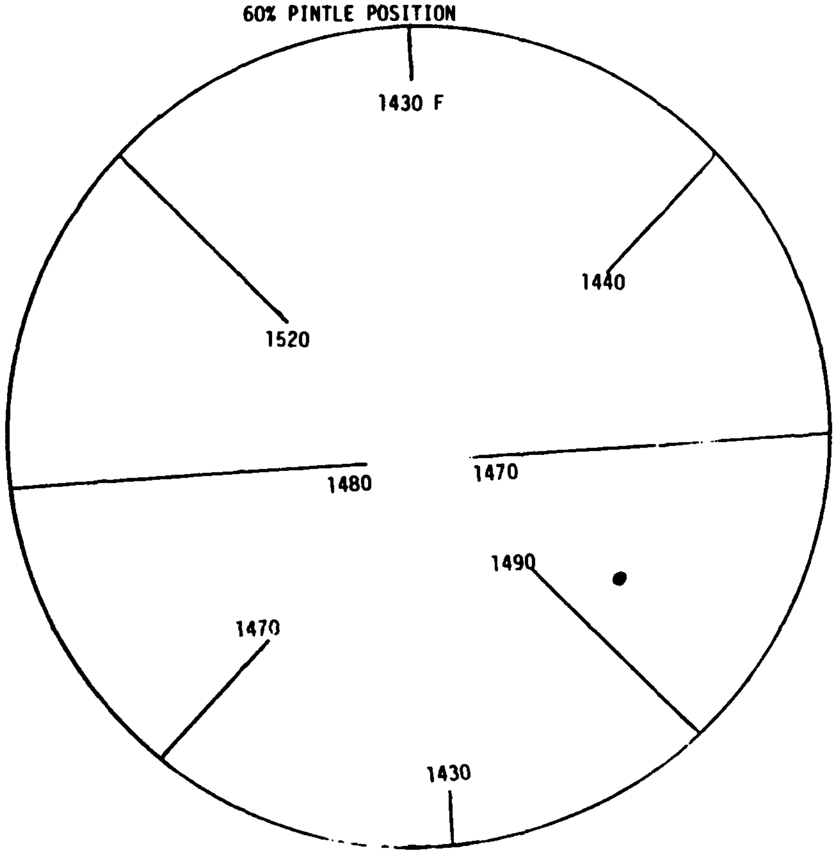


AVERAGE TEMP = $1648^{o}F$

THEORETICAL TEMP = $1750^{o}F$

FIGURE 54
TEST 009 RUN 2

COMBUSTION CHAMBER TEMPERATURE MEASUREMENT
60% PINTLE POSITION



AVERAGE TEMP = 1466°F

THEORETICAL TEMP = 1440°F

FIGURE 55
HIGH FREQUENCY CHAMBER PRESSURE DATA

TEST 009

SECOND CYCLE

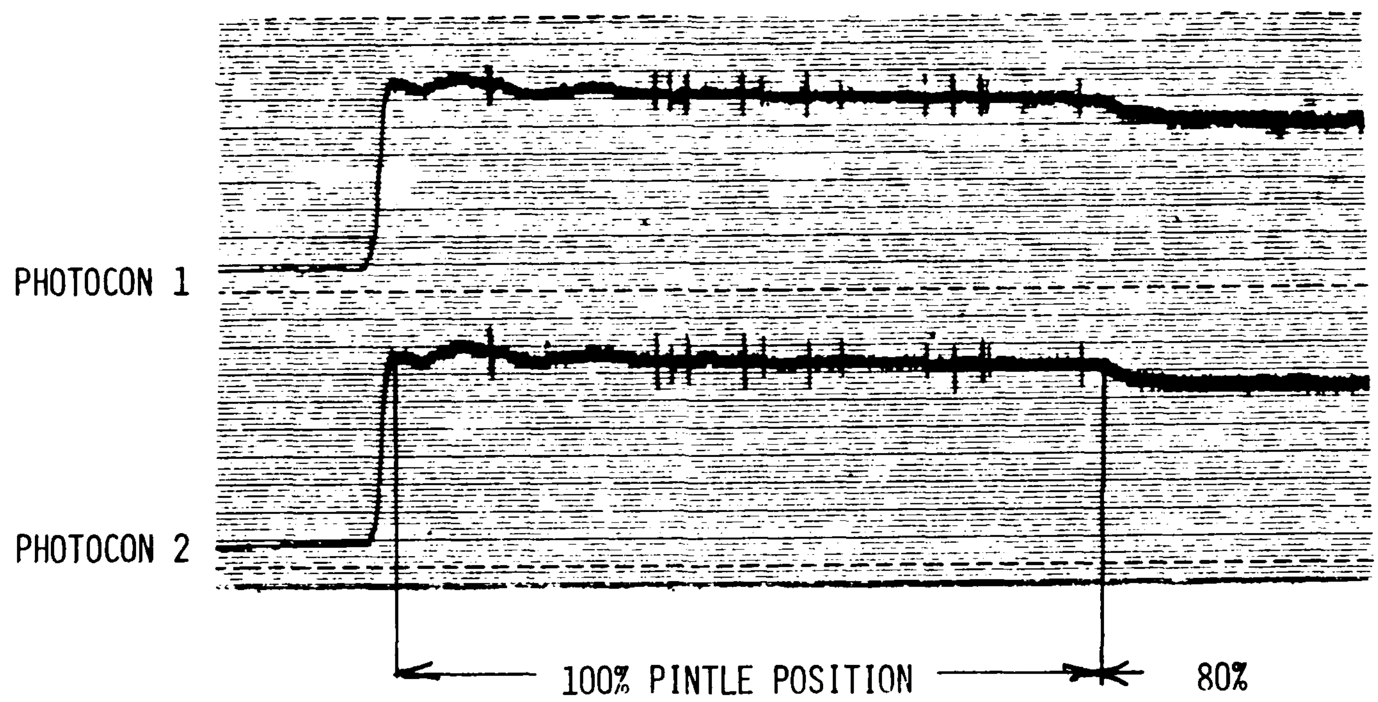


FIGURE 56
CHAMBER PRESSURE DISTURBANCE AMPLITUDE AND DURATION

TEST 10

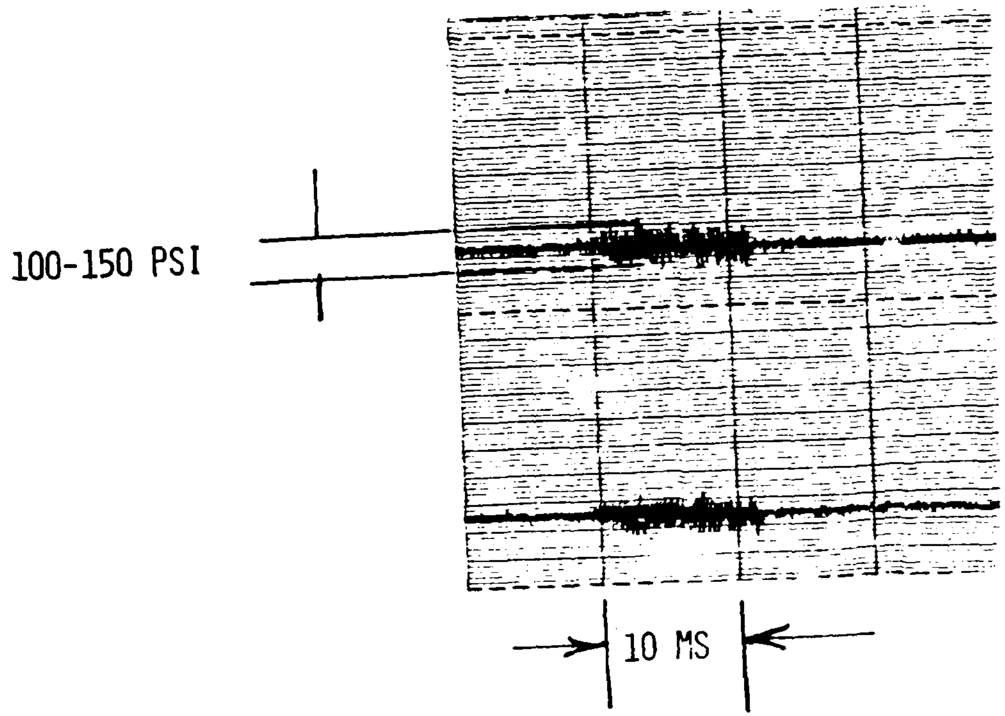
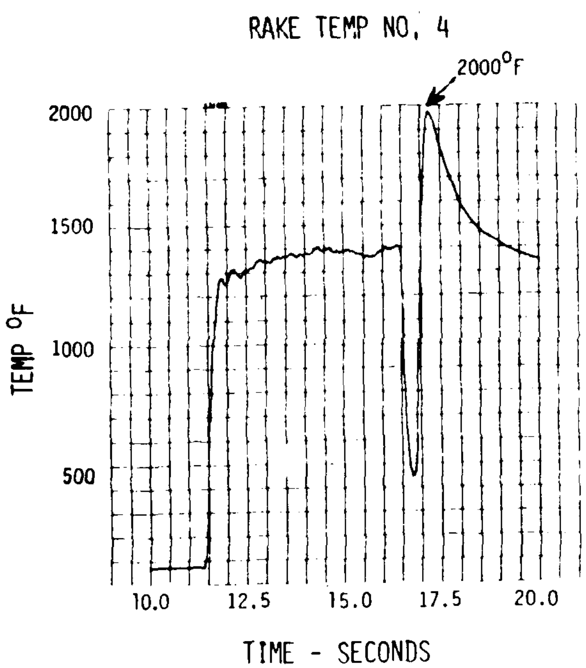


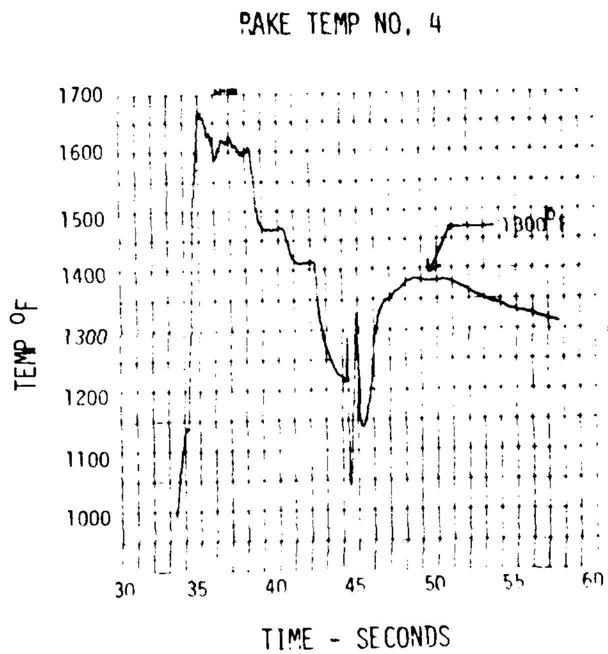
FIGURE 57

POST TEST HOT GAS TEMPERATURE SPIKES



TEST 5

.150 SEC. FUEL OVERRIDE



TEST 10

.8 SEC. FUEL OVERRIDE

Post-Test Hardware Condition. The copper pintle nose was in excellent condition, (Figure 58). The fuel ring was found to be distorted with slight surface erosion of the nickel exposed to the hot gas. The nose of the turbulator was found to be slightly eroded, Figure 59, indicative of a hot core injector.

Test No. 010

Facility Test No. 634-006 13 November 1981

Hardware Configuration. The head end of the thrust chamber was equipped with a turbulence ring, Figure 60, in an effort to improve hot gas mixing. Refer to the Design and Analysis Section discussion concerning hot gas mixing.

The fuel injection ring was installed with a nickel insert providing thermal protection in an effort to minimize the thermal distortion problem noted during Test No. 9. Figure 61 indicates the fuel ring installation.

Test Objectives. Evaluate the effectiveness of the turbulence ring and the fuel injection ring modifications at the maximum power level.

Test Results. Test No. 010 was a programmed ten second full power test. The turbulence ring was not effective in eliminating the hot core injector effects. A hole approximately two inches in diameter was eroded through the forward section of the Nickel 200 hot gas turbulator. Hot gas rake temperature measurements indicated 1500°F near the chamber wall and 2000°F in the centerline of the chamber.

Accelerometer and photocon data indicated a total of 24 self-damping chamber pressure disturbances, ranging in duration from 10 to 1200 milliseconds. The magnitude of the disturbances ranged from 100-350 psi peak-to-peak at a frequency of 3600 Hz. Incorporation of the turbulence ring clearly decreased the combustion stability characteristics.

1XZ35-3/6/81 - SIB

Figure [illegible]. Copper Plated Pintle Tip Post Test 009

1XZ35-3/16/81 - 81D

Figure 59. Turbulator Condition Post Test 009

SECONDARY HOT GAS MIXING

TEST 10

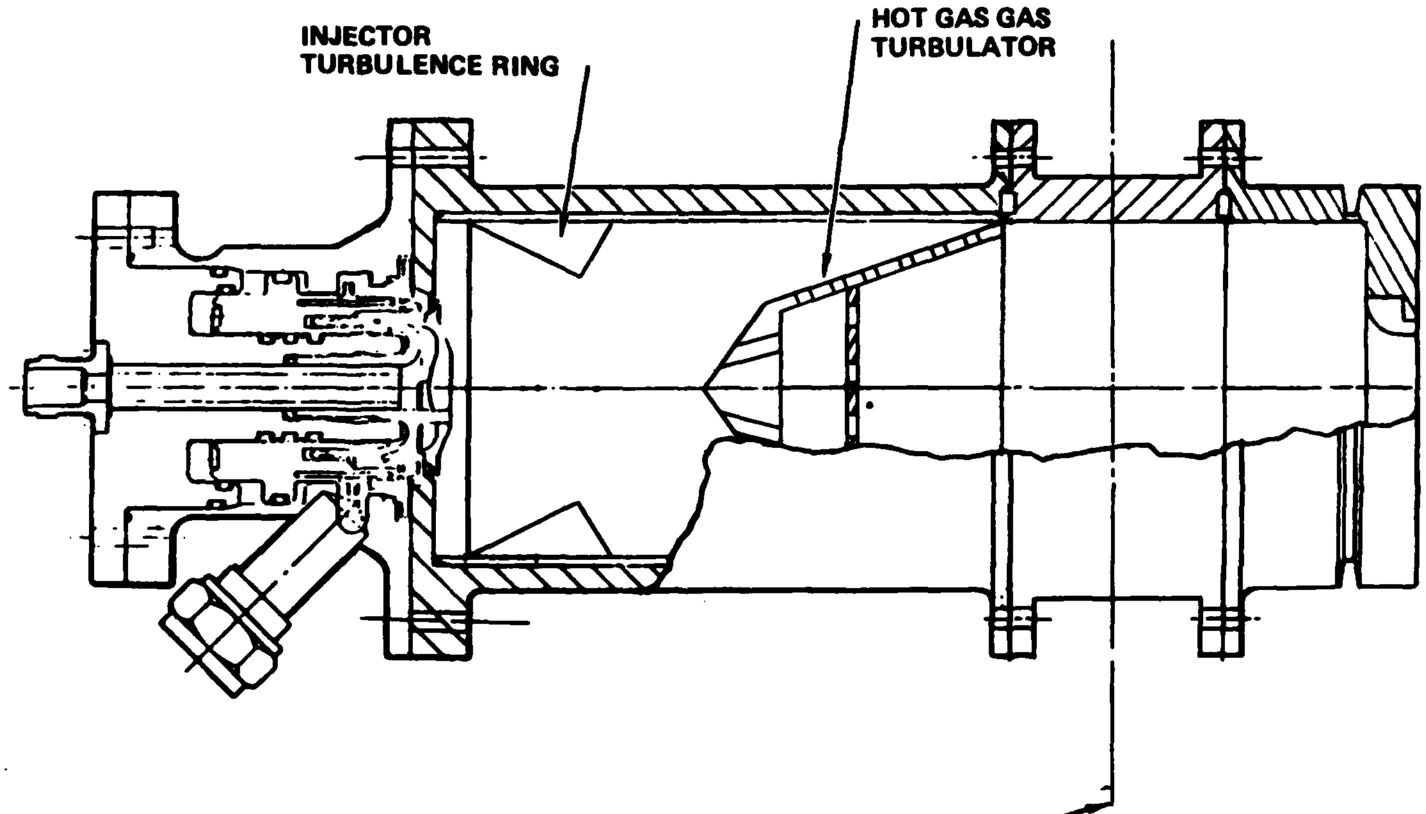
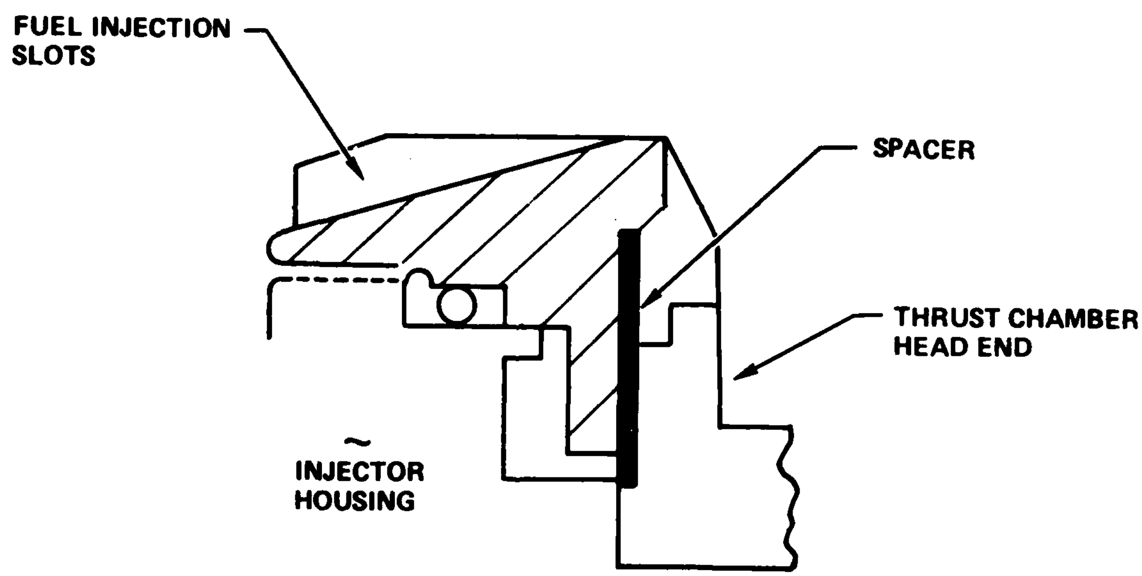


FIGURE 60

FIGURE 61

FUEL INJECTION RING THERMAL SHIELDING

TEST 011



Hardware Condition. No anomalies were noted with respect to the fuel ring. The thermal shielding was effective in eliminating the problem.

Test No. 011

Facility Test No. 634-007. 09 December 1981

Hardware Configuration.
As shown in Figure 61 , a nickel insert was installed between the fuel ring and the thrust chamber head end. The remaining gap between the injector and thrust chamber was sealed with silicone graphite. Both the hot gas turbulator and turbulence ring were removed.

Test Objectives. Evaluate temperature distribution and stability at increased injector differential pressure. The data from Test No. 9 indicated that the hot gas temperature distribution and the combustion stability was substantially improved at reduced pintle positions, and higher injector differential pressure, reference Table VIII. The objective of this test was to evaluate stability and temperature distribution at maximum power level flowrates with the pintle position at 90 percent.

The reduced pintle position results in an increase of injector differential pressure from 250 psid to 350 psid.

Test Results. The test was performed for programmed duration. Data analysis indicated no evidence of combustion chamber pressure disturbances. The hot gas temperature distribution was substantially improved. Previous test data indicated a 500°F hot gas temperature difference from the chamber wall to the centerline. This test indicated a 200°F difference (reference Figure 62).

Hardware Condition. The hardware was found to be in excellent condition post-test. The revised installation of the fuel ring eliminated the erosion and thermal distortion problem.

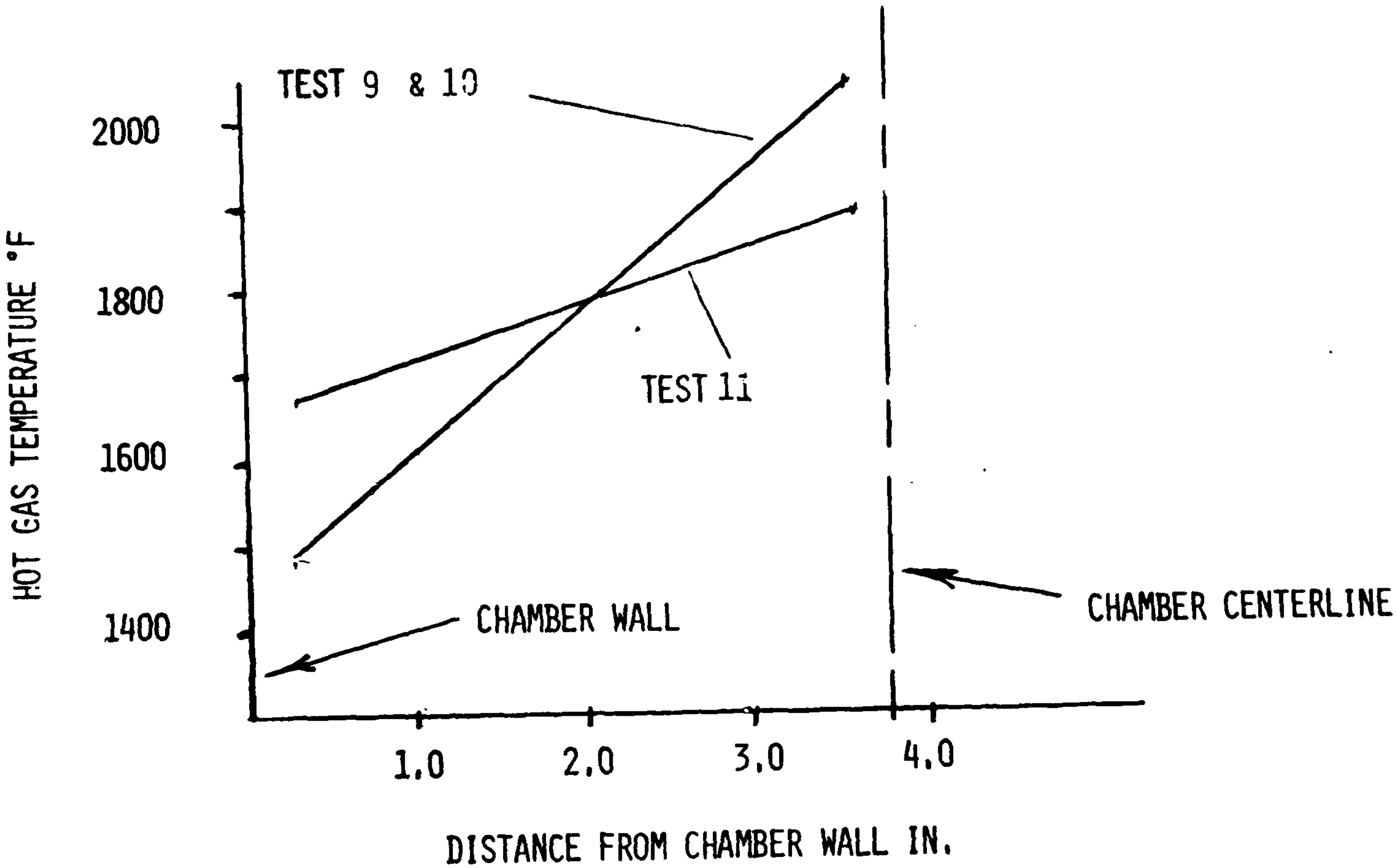
TABLE VIII

TEMPERATURE DISTRIBUTION AND STABILITY SUMMARY

TESTS 9 AND 10

TEST	HARDWARE CONFIGURATION		PINTLE POSITION	INJECTOR ΔP		HOT GAS TEMP DISTRIBUTION	CHAMBER PRESSURE DISTURBANCES
	TURBULATOR	TURBULENCE RING		LOX	FUEL		
009	YES	NO	100	248	245	600	YES
			80	317	302	200	NO
			60	462	429	100	NO
			50	562	518	50	NO
			30	804	740	300	NO
010	YES	YES	100	257	250	500	YES

FIGURE 62
TEMPERATURE DISTRIBUTION SUMMARY



Test No. 012

Test Facility No. 634-008 09 December 1981

Hardware Configuration. Same as Test No. 011.

Test Objectives. Evaluate full power level operation at 80 percent pintle position; injector differential pressure 450 psid.

Test Results. The test was performed for the programmed duration of ten seconds. One second after test start, the pintle suddenly opened from the programmed 80 percent position to 100 percent.

Figures 63 and 64 indicate the sudden shift in the pintle position. The loss of control of the pintle was caused by a pressure imbalance on the pintle due to excessive Delta dynamic seal leakage. Figure 65 indicates a sudden decrease in temperature of the Delta seal drain line, indicative of massive seal leakage.

During operation at the 80 percent pintle position, no evidence of combustion instability disturbances were noted. Following ramping to the 100 percent pintle position, a total of 13 self-damping disturbances were noted.

Hardware Condition. The fuel injection ring was found to be in excellent condition; no erosion or thermal distortion.

The dynamic LOX Delta seal was found to be damaged, indicating excessive wear.

Test No. 013

Test Facility No. 634-001 25 February 1982

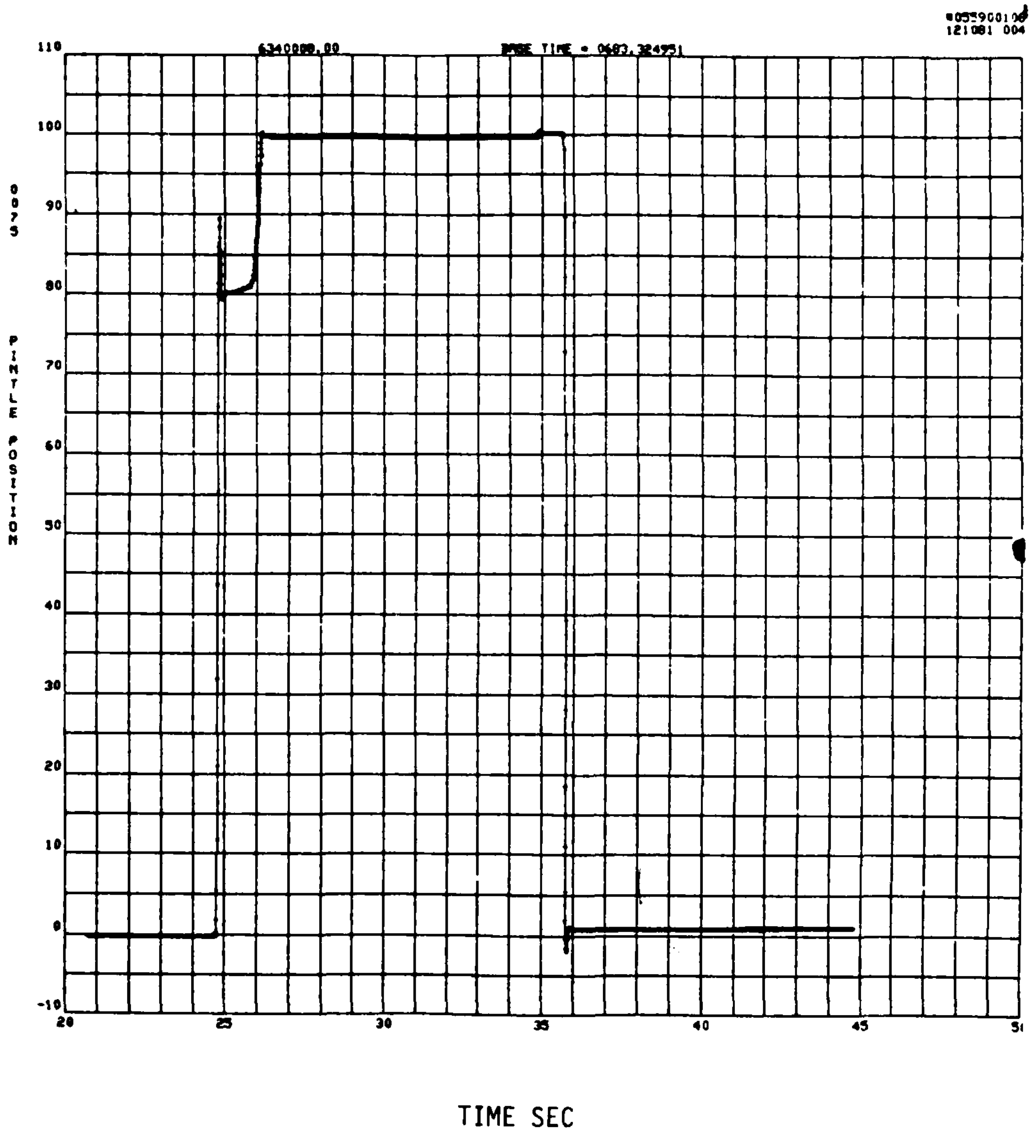
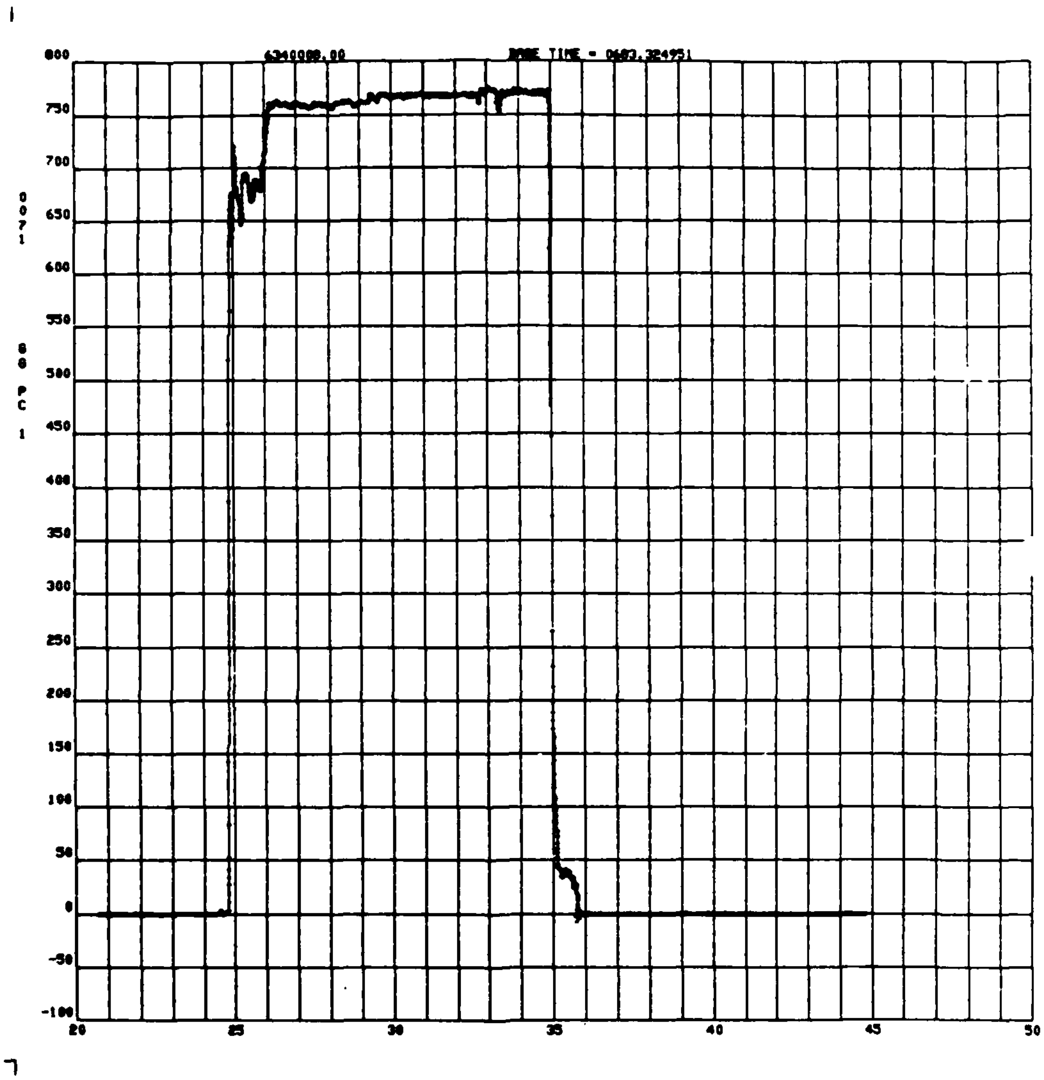


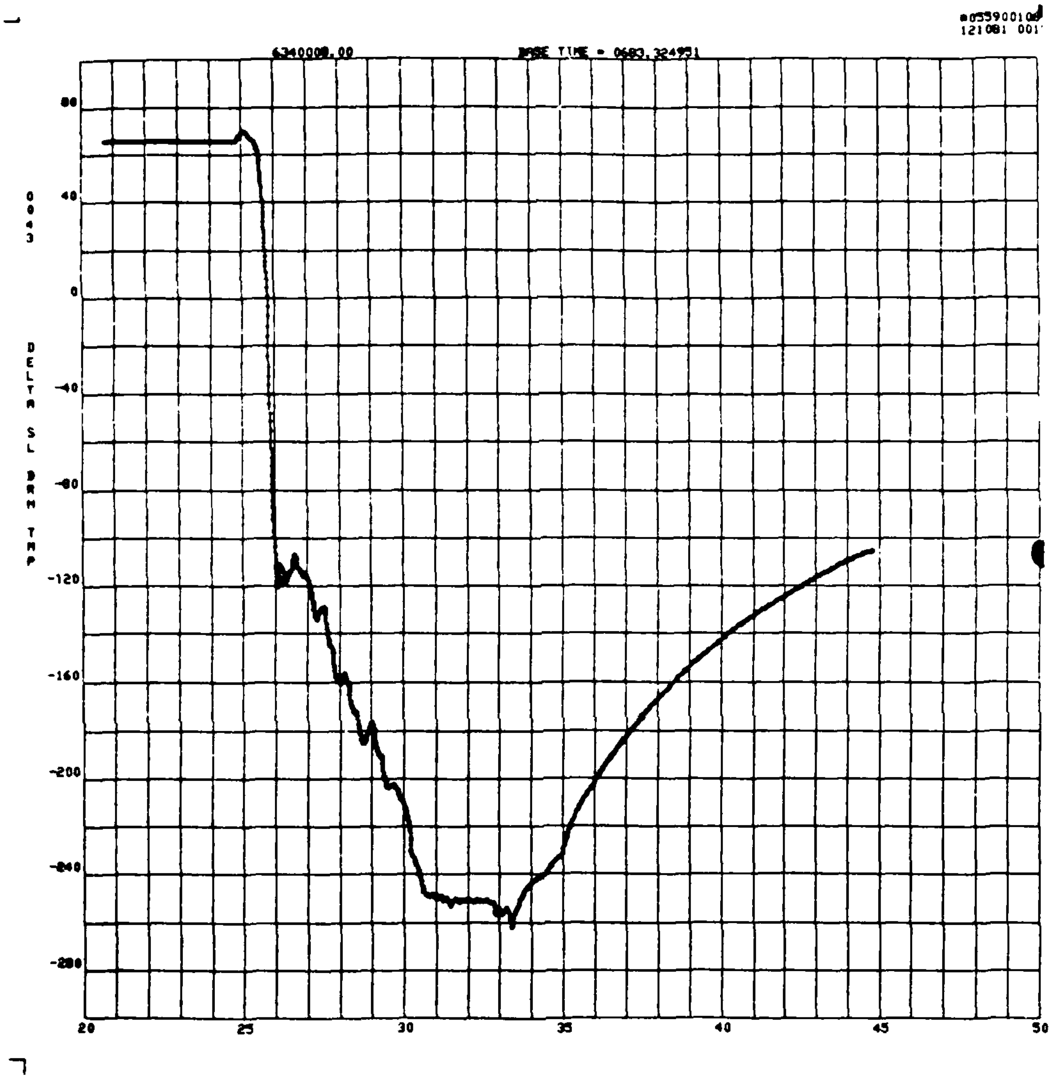
FIGURE 63. Pintle Position vs. Time
Test 012



TIME SEC

Figure 64. Combustion Chamber Pressure vs. Time

TEST 012



TIME SEC

FIGURE 65. Delta Seal Drain Temp

TEST 012

Hardware Configuration. Same as Tests 11 and 12 except a new solid nickel fuel injection ring was incorporated for improved thermal conductivity in an effort to enhance durability. The dynamic LOX Delta seal was replaced.

Test Objectives. Perform three 10 second tests back-to-back at the 90 percent pintle position.

Test Results and Hardware Condition. The test was terminated at 8.33 seconds of the first 10 second cycle by the hot gas temperature cutoff device (hot gas temperature greater than 2000°F). Post-test hardware inspection indicated a hole burned through the side of the core assembly, resulting in a sudden increase in oxidizer flowrate. Data analysis indicated that the burn through occurred at seven seconds when a rapid increase in chamber pressure (Figure 66) and oxidizer flowrate (Figure 67) was noted.

In addition to the core erosion, the fuel ring was eroded approximately 70° from the core burn through. Figure 68 indicates the location of the erosions. Figure 69 indicates the orientation of the eroded areas relative to the combustion chamber hot gas temperatures. A small amount of erosion of the thrust chamber and one spark plug tip was eroded (Figure 69).

Temperature data indicated an abnormally high localized hot gas temperature at test start on the thermocouple in alignment with the burn through. This abnormally high temperature was indicative of a localized high mixture ratio condition existing at test start.

A small combustion chamber "pop" was noted during the 230 millisecond LOX lead as shown in Figure 70 . At the same time the chamber pressure disturbance was noted, a rise in combustion temperature occurred. This condition was noted during all tests which have incorporated the fuel ring to thrust interfacing nickel ring (reference Figure 61). This ring was designed to provide additional thermal shielding to minimize thermal distortion of the fuel injection ring. Review of all test data indicated that prior to incorporation

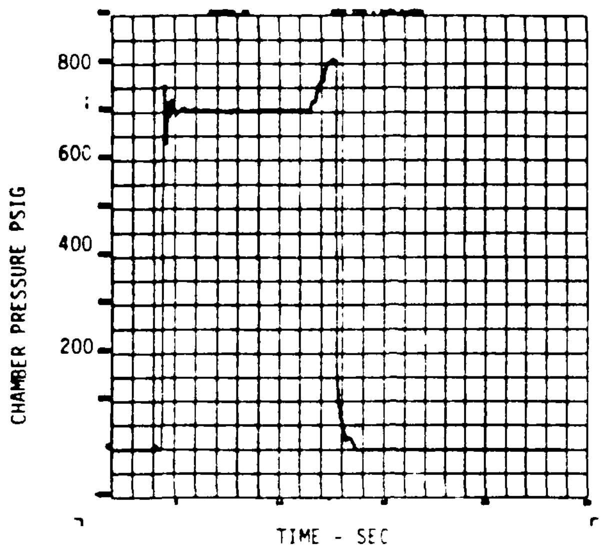


FIGURE 66. Combustion Chamber Pressure
Test 013

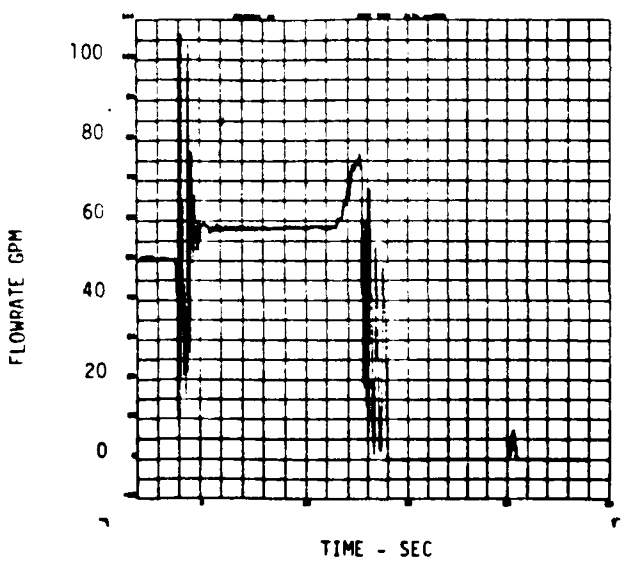
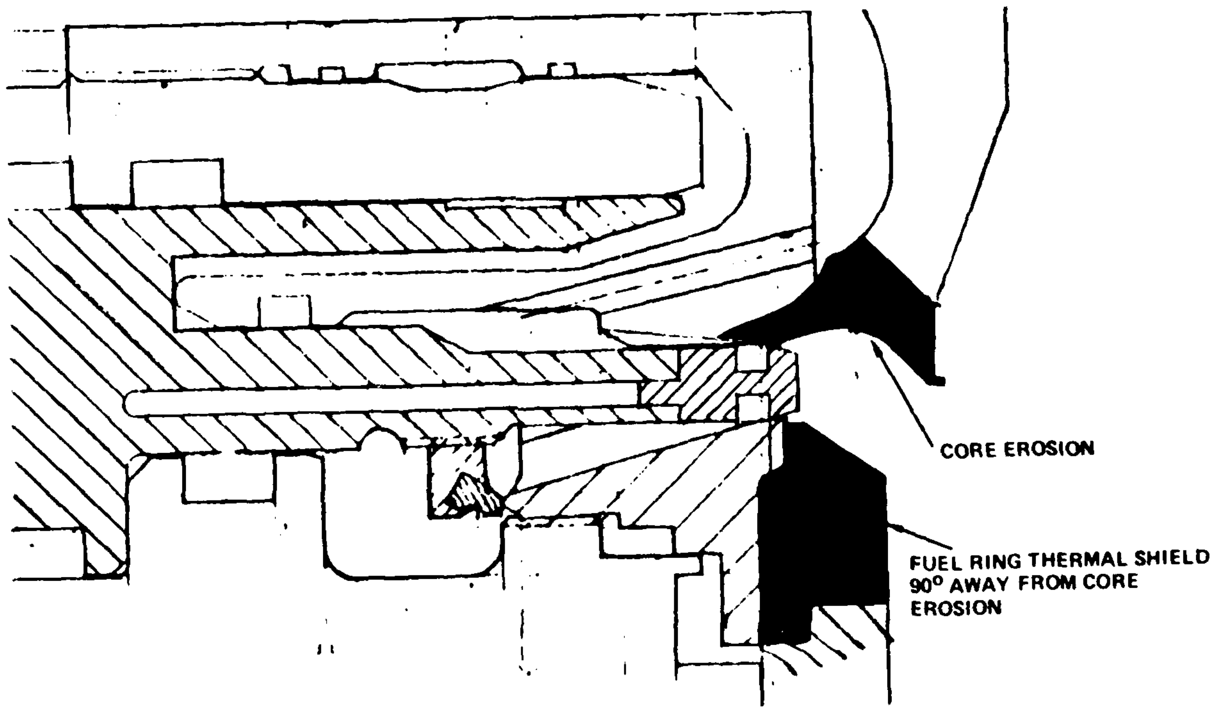


FIGURE 67. LOX Flowrate
Test 013

FIGURE 68

TEST 13 - CORE AND FUEL RING EROSION



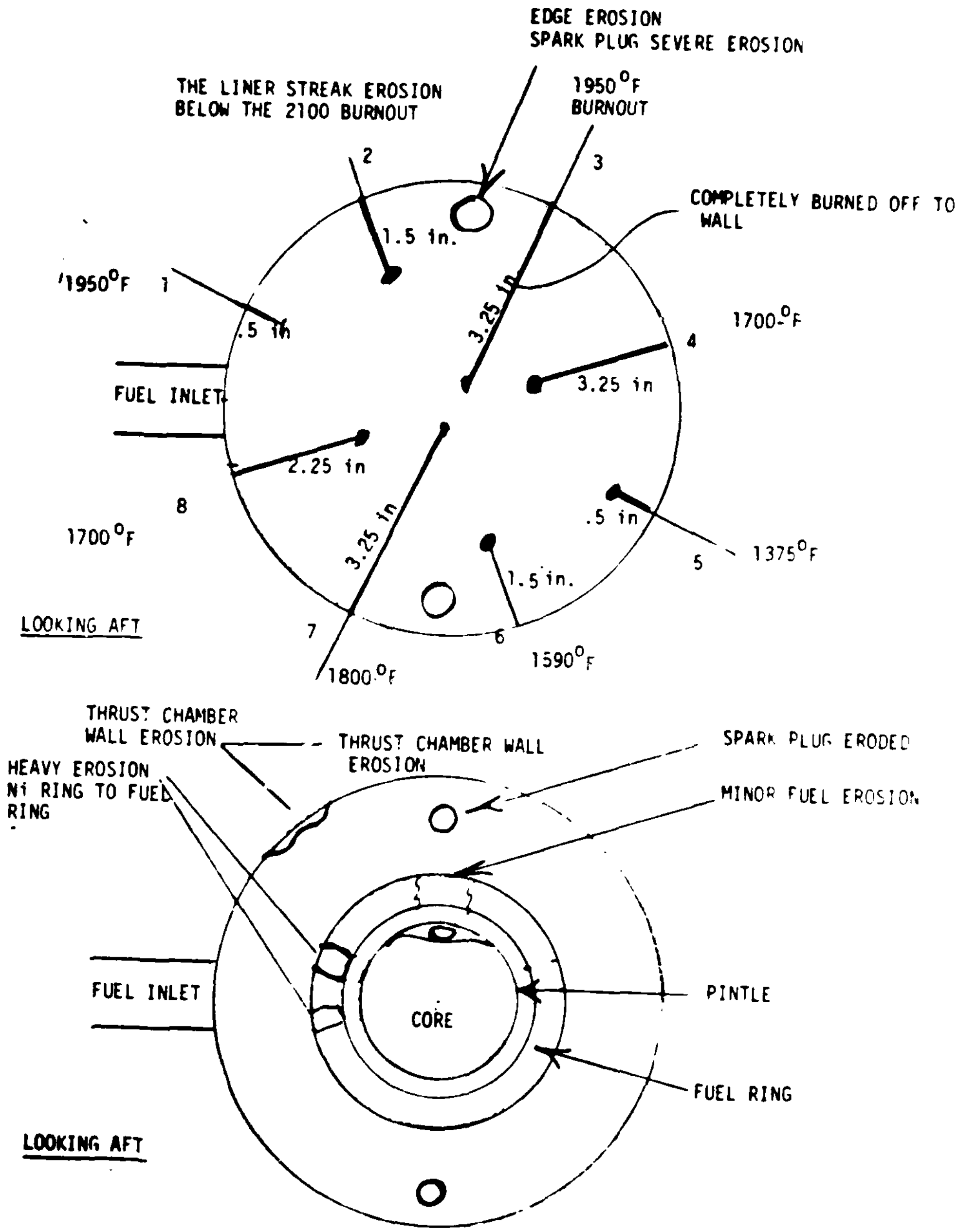
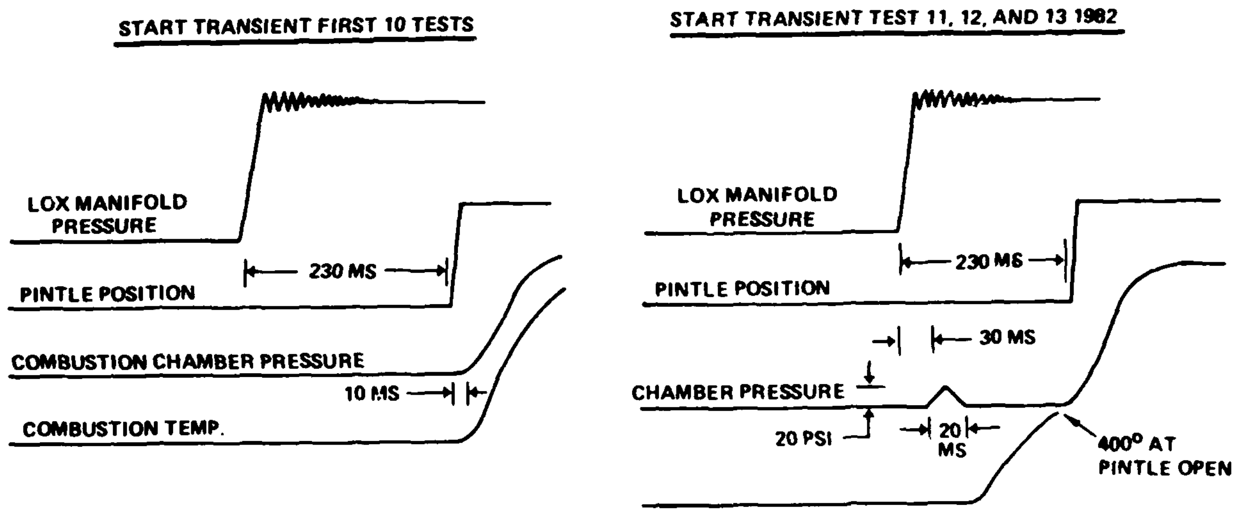


FIGURE 69. Hot Gas Temperature Measurement Locations Relative to Injector Damage

Test 013

FIGURE 70

START TRANSIENT COMPARISONS



of this change, no combustion "pops" or indication of combustion prior to opening the pintle during LOX lead occurred.

The injector to thrust chamber interface is shown in Figure 71 . The nickel thrust chamber insert is machined to close tolerances such that a tight line-to-line fit exists between the insert and the tip of the fuel ring (Surface "A', Figure 71). The resulting gap "B" is sealed with Dow Corning silicon graphite sealant to prevent hot gas recirculation into the gap. The sealant is applied in this area before the injector is mated to the thrust chamber.

Post-test hardware disassembly indicated two anomalies: (1) the fuel ring O-ring seal was cut and voids were found in the silicone graphite sealant; (2) a minor amount of the sealing compound was found on surface A. A small amount of the non-LOX compatible sealant may have been extruded into the combustion area during assembly. It is highly unlikely that a sufficient quantity was present to produce the temperature increase noted during the LOX lead. The most probable cause was a minor fuel leak past the O-ring seal into the combustion area. As shown in Figure 71 , the leak is being driven by the 1100 psig fuel manifold pressure prior to opening the pintle.

A small fuel leak at surface A is directly in alignment with the eroded area. The smaller the leak, the higher the localized mixture ratio and temperature. This localized high temperature then eroded the core locally, probably producing a small LOX leak at test start. The rake thermocouple in alignment with the eroded area burned out at one second. The erosion continued throughout the run until massive burn through occurred at 9.2 seconds.

The injector to thrust chamber interface employed prior to Test 10 is shown in Figure 72. If a small fuel leak existed, the leak would have been directed away from the core.

As previously stated, the small indications of combustion during the LOX lead have been noted only since incorporation of the new interface design. Since no

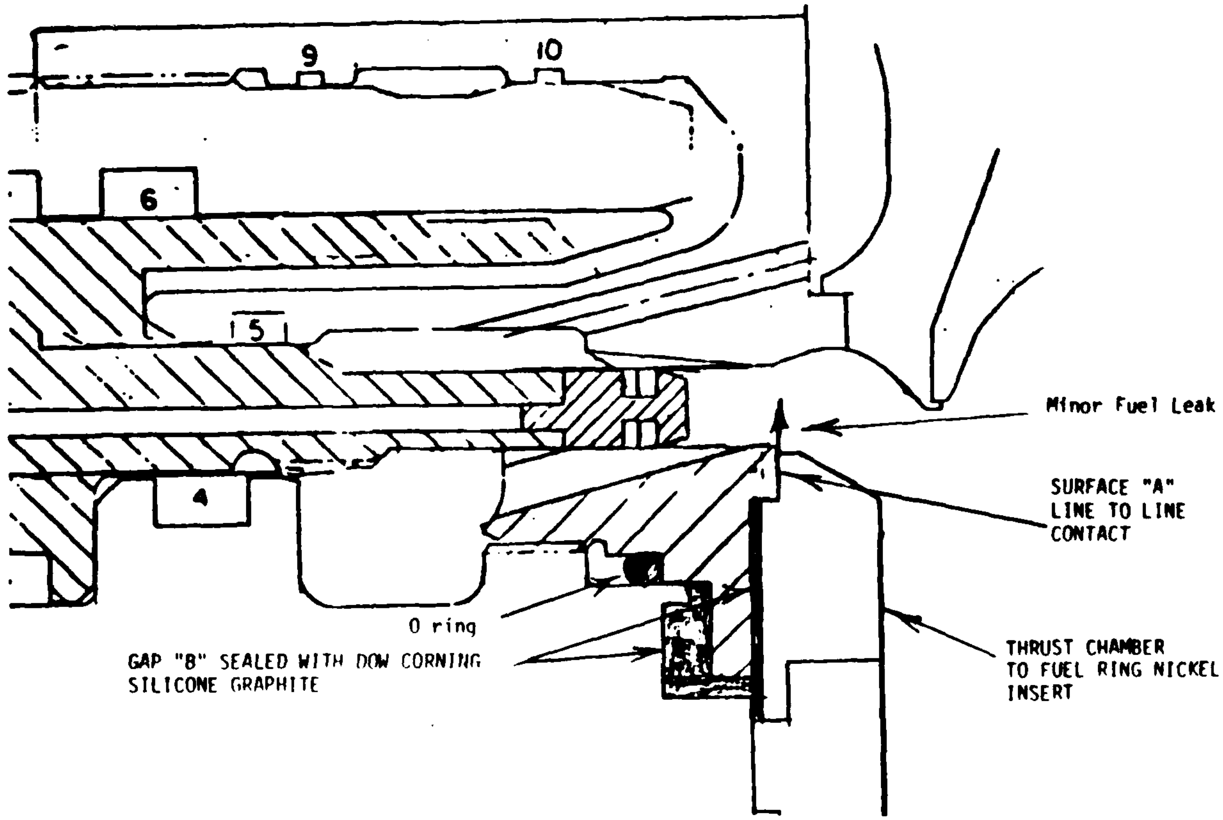


Figure 71. Injector to Combustor Interface

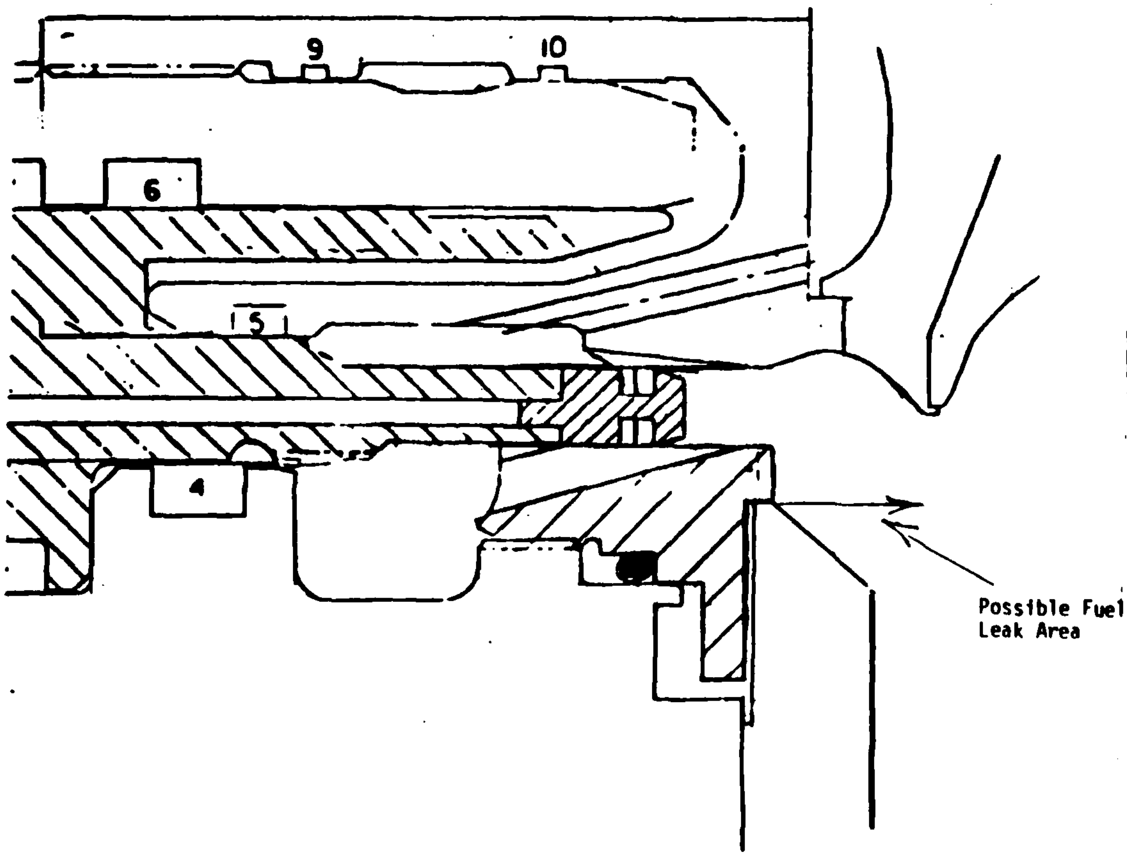


FIGURE 72. Original Injector to Thrust Chamber Interface

indications of core erosion had been noted during the performance of 13 tests accumulating 76 seconds of operation, it is felt that the core erosion is not a basic design concept problem, but a minor hardware assembly and pre-test checkout problem.

Additional analysis of the data and hardware indicated no evidence of: (1) combustion instability, (2) structural inadequacy, (3) test sequence, (4) test performance, or (5) injector contamination anomalies.

The erosion in the fuel ring to thrust chamber is not in alignment with the core erosion, however, the same type fuel leak may have also caused localized overheating in this area. Also, the minor surface erosion of the nickel ring in alignment with the core burn through may have produced sufficient thermal distortion to produce a gap between the nickel ring and the fuel ring to allow hot gas recirculation. The nickel interface ring was found to be distorted post-test.

Test No. 014

Test Facility No. 634-007 5 May 1982

Hardware Configuration. The injector assembly was completely rebuilt. In light of the core erosion noted as a result of test No. 13, extreme care was exercised to assure that no possibility of minor fuel leakage past the positive face shut off seal existed. Following completion of assembly the injector was leak checked by pressurizing the fuel manifold to 1100 psig with the pintle closed. No evidence of pressure decay in the isolated locked up system was noted. The injector was mated with the thrust chamber and the nickel thermal shield was custom machined such that line contact was made between the thermal shield and the fuel ring tip as shown in Figure 61. This effort was accomplished to verify that a gap did not exist which could cause hot gas pumping producing erosion. Following installation of the gas generator in the test facility, with the mounting bolts torqued, the 1100 psig pressure lock up leak check was repeated to assure that a minor leak did not exist as a result of structural loading produced by test stand installation.

The gas generator was fitted with the right angle hot gas turbulator as shown in Figure 30, page 46.

Test Objectives. The objective of this test was to verify the hypothesis that the core erosion was caused by the minor fuel leak and that the mitered hot gas turbulator (discussed in the design section of this report) was capable of producing the desired hot gas temperature pattern factor.

Results. The test was a programmed 30 second duration restart test, three 10 second full power level tests performed back to back with 3 seconds off between cycles. The hot gas temperature pattern factor was measured to be 0.033 as compared to less than target valve of 0.065. Figure 73 indicated the temperature measurements from the chamber wall to the centerline as compared to the values obtained prior to installation of the right angle turburlator. The right angle turbulator was in excellent condition.

The core was eroded similar to test 13 except the erosion did not extend into the LOX manifold. The thermal isolation ring and fuel ring were eroded through into the fuel manifold. The location of the erosion is indicated in Figure 74 and a photograph of the eroded areas is presented in Figures 75.& 76. All other injector and combustion chamber components were in excellent condition.

Data analysis indicated no fuel leaks into the hardware prior to start of cycle No. 1 of the test. As evidence by no indication of combustion chamber temperature or pressure prior to start of the cycle, both cycle No. 2 and 3 indicated a temperature and pressure increase when the main LOX valve opened prior to opening the pintle, reference Figure 77. Evaluation of the fuel flowmeter data (Figure 78) indicated no fuel flow prior to the start of cycle

FIGURE 73

TEMPERATURE DISTRIBUTION SUMMARY

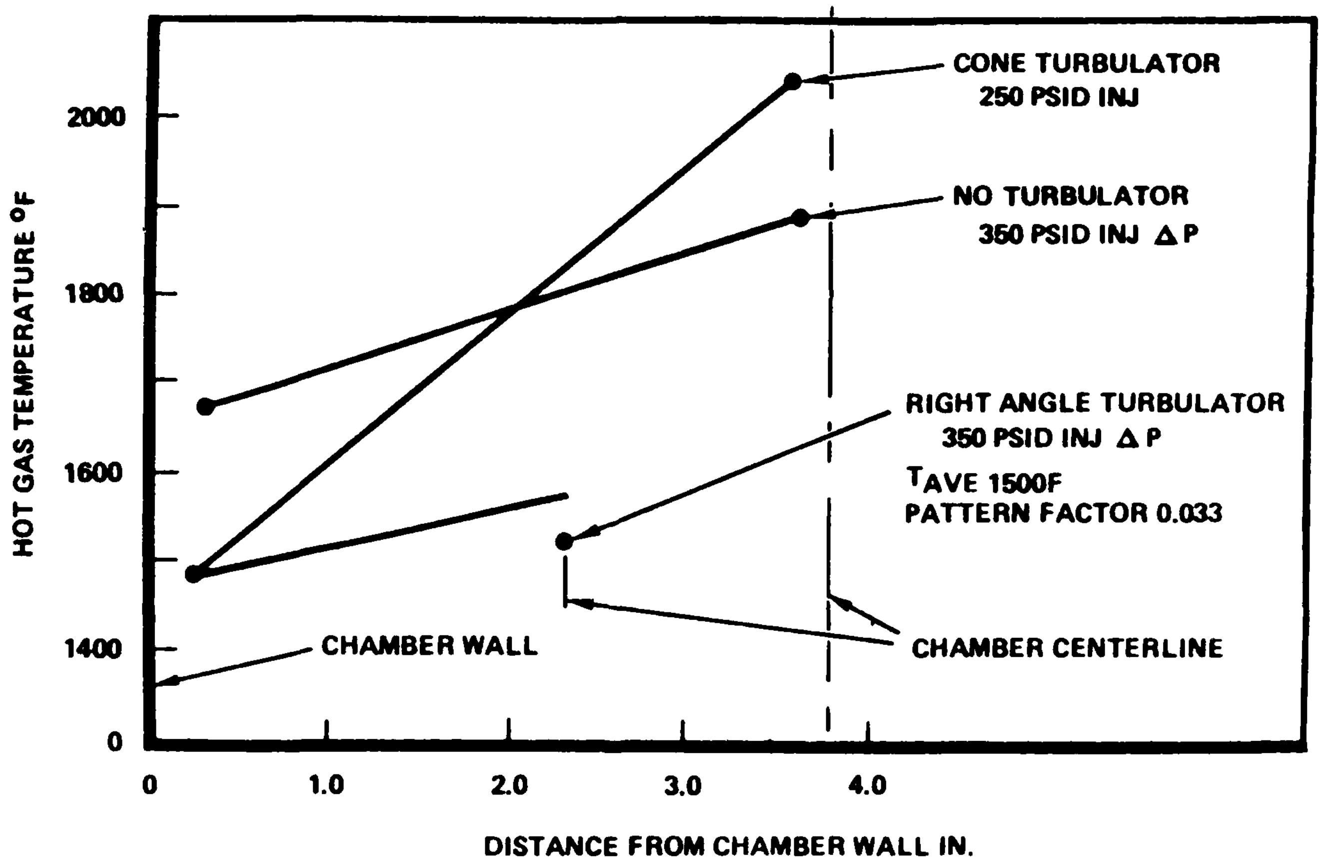
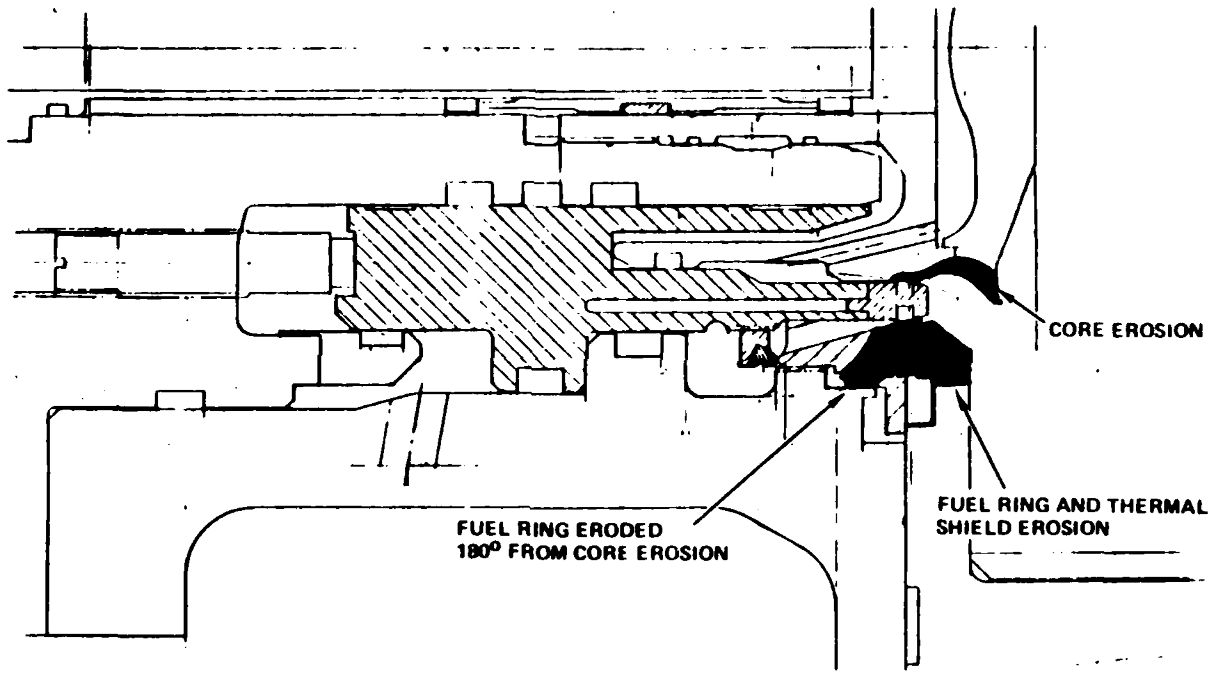


FIGURE 74

TEST 14 INJECTOR EROSION



[illegible] - SIF

[illegible] Core and Fuel Ring Erosion

Test 014

FIGURE 77

START TRANSIENT TEST 14

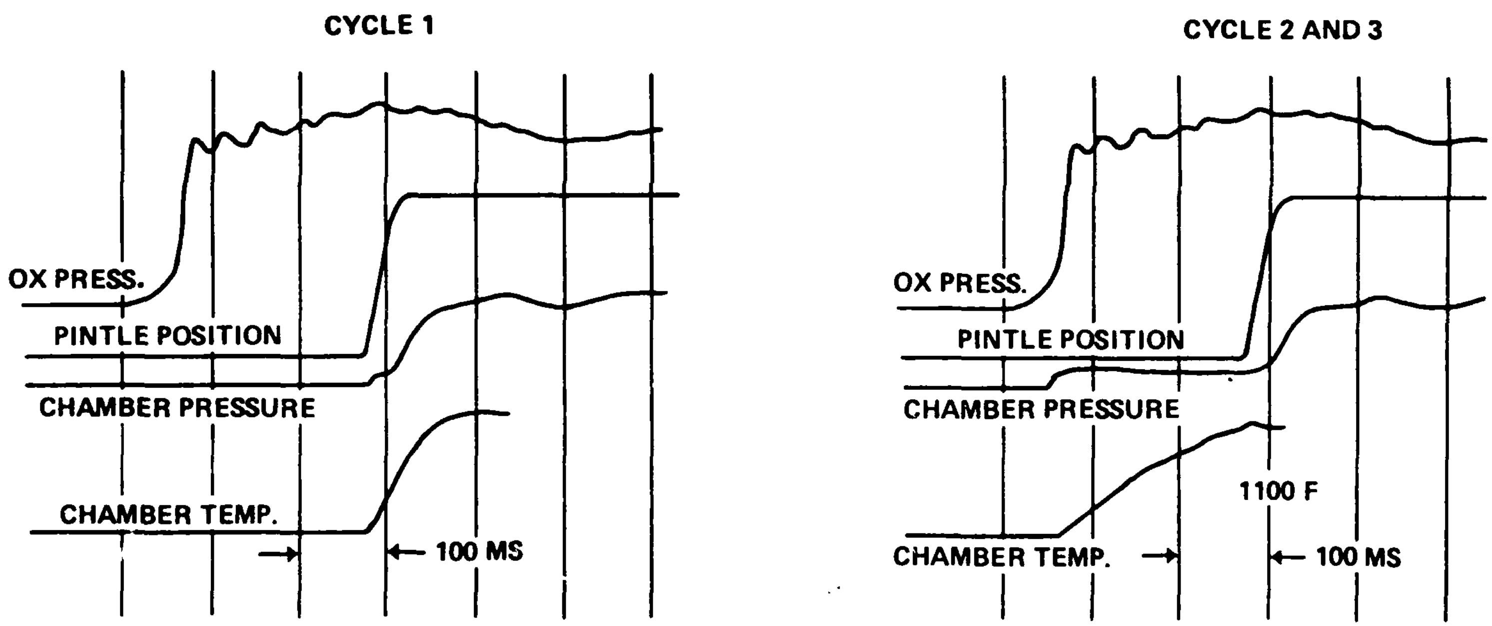
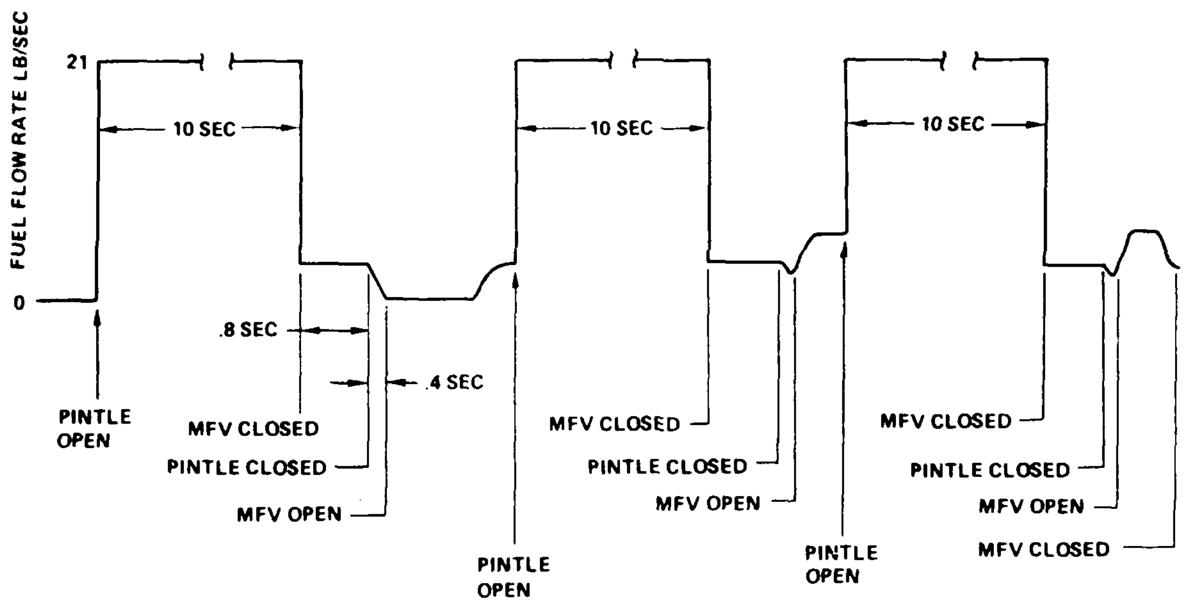


FIGURE 78

FUEL FLOW TEST 14



No. 1. Following the 0.8 second fuel override at the termination of cycle No. 1, the fuel flow decreased to zero. Approximately 0.5 seconds prior to the start of cycle No. 2 the fuel flowrate began to increase indicative of a fuel leak. After the termination of cycle 2 the fuel flow does not decrease to zero after the pintle closes. Based on this data, it appears that the fuel ring eroded into the fuel manifold sometime during or following the first cycle.

Since no fuel leakage was noted prior to the start of cycle No. 1, it appears that the original hypothesis that a minor fuel leak into the system caused the core and fuel ring erosion was in error. As a result, an investigation was initiated concerning the differences between previous successful tests and test 13 and 14 displaying core and fuel ring erosion.

The results of this investigation conducted for all tests performed during the entire gas generator hot fire test program is presented in Table IX . The conclusions from this investigation were that two significant differences were observed relative to test 13 and 14 as compared to all other tests: 1) the core ablative shield installation was different for test 13 and 14, and 2) significant differences in the vibration data was observed.

The core erosion at the interface between the bonded on ablative core shield and INCO 718 core was very similar in appearance for both tests 13 and 14. The core shield was installed with Dow Corning 93104 adhesive for both test 13 and 14. The bonding material used for all previous tests was phenolic resin. The Dow Corning adhesive is known to be less compatible with liquid oxygen than the phenolic resin. In addition the core shield surface for the first 12 tests was coated with phenolic epoxy (Lance production method). The coating, which is a thin spray, seals the relatively poris ablative surface providing a barrier to prevent impregnation of oxygen during the LOX lead for the initial hot fire test of a new core assembly. As a result of the first hot fire test, the coating is burned off and a surface char is developed which tends to prevent oxygen surface impregnation for subsequent

TABLE IX

RESULTS OF EVALUATION
HARDWARE CONFIGURATION CHANGES AND DIFFERENCES BETWEEN TESTS

ITEM EVALUATED	RESULTS
• FUEL RING INSTALLATION	NO CORRELATION ESTABLISHED
• OPERATING CONDITIONS	NO ANOMALIES
• POST TEST HARDWARE CONDITIONS	NO CORRELATION
• *INJECTOR CONTAMINATION*	*NO CONTAMINATION* FOUND
• TEST FACILITY CHANGES AND OPERATION	NO CORRELATION
• HARDWARE DIMENSIONAL INSPECTION	NO ANOMALIES
• CORE CONFIGURATION CHANGES	• CORE SHIELD INSTALLATION CHANGED FOR TEST 13 AND 14 COMPARED TO ALL PREVIOUS TESTS
• VIBRATION DATA	• ALL ACCELEROMETER OUTPUT LOW LEVEL < 10 GRMS • TEST 13 AND 14 INDICATE SIGNIFICANT DIFFERENCES COMPARED TO SUCCESSFUL TESTS

hot fire tests.

Review of hardware condition indicated no ablative glassing at the bond line between the ablative and the core and the ablative material adjacent to the bond line for the core assembly used for the first 12 tests.

The edges of the ablative were found to be glassed for both tests 13 and 14 indicative of achieving a temperature of at least 2600°F, higher than the melting temperature of the INCO 718 core body.

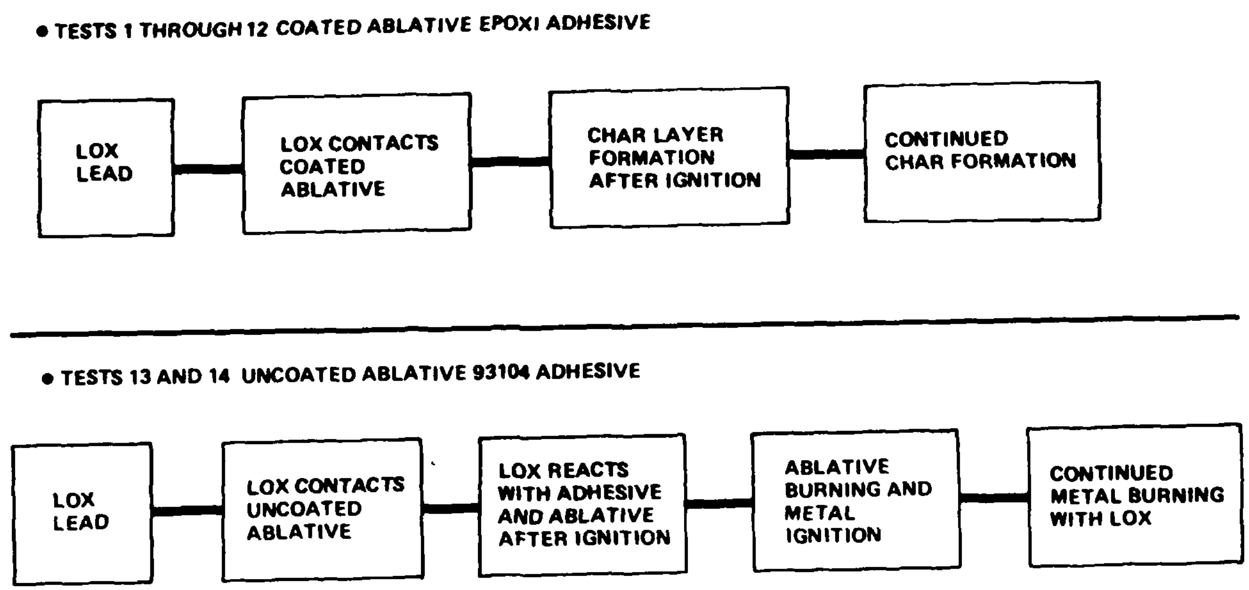
It is theorized that the cause of the core erosion, unique to tests 13 and 14, was associated with the less compatible adhesive used for these tests and the lack of ablative surface coating which prevented ablative oxygen impregnation, during the test start LOX lead. This impregnation could have increased the localized temperature.

Figure 79 presents the core erosion logic. The order of events for the core shield used for the first 12 tests is as follows: 1) during the start transient, the LOX contacts the coated ablative and is prevented from penetrating the surface, 2) after ignition an ablative surface char forms, 3) as the run progresses charing continues. For tests 13 and 14 the flow logic is as follows: 1) during the LOX lead, LOX contacts the uncoated poris ablative, 2) LOX reacts with the adhesive and localized high temperature burning is initiated at the bond line, 3) high temperature burning initiates metal ignition, and 4) metal burning continues throughout the run.

Since the core erosion problem is unique to tests 13 and 14 and the core installation procedure is unique to these two tests, it is felt that the core erosion is not a basic design problem. For future tests the ablative core shield would be replaced with copper for better thermal management similar to the copper plating successfully used on the pintle tip.

FIGURE 79

CORE EROSION LOGIC



The erosion of the fuel ring and thermal shield nad many of the features of damage caused by combustion instability. The initial review of the accelerometer high frequency data from tests 13 and 14 indicated that the amplitudes were very low, less than 10 grms, however, close inspection of the data indicated the following: the classical chamber and injector annulus modes were displayed in the data. Table X indicates the theoretical calculated frequencies. The combustion chamber mode definitions are evident. The injector modes are related to the annulus that is formed when the pintle is open as shown in Figure 80.

Figure 81 indicates the maximum amplitudes of the chamber and annulus frequencies. From this data plot is can be seen that the maximum g level noted was less than 2.8 grms.

A review of the vibration data from all tests was performed. Figure 82 presents a typical accelerometer trace from test 10 which was a successful 10 second duration full power level test. This plot displays discrete slices of relative amplitude data over the complete test duration. It can be seen from this plot the maximum amplitude was associated with the first tangential chamber mode with minor indications of the first annulus, first and second annulus modes. Again all amplitudes were very low. This data plot is typical for all tests except 13 and 14.

A similar data plot is presented for Test 13 (Figure 83) indicating core and fuel ring erosion. For the first 3 seconds of the test, the amplitude of the first annulus mode is extremely low at approximately 2.5 seconds the amplitude begins to develop, and as the run progresses the amplitude of the second annulus mode develops. Similarly the first 10 second cycle of test 14 Figure 84 indicates very low amplitudes of the first annular mode during the first 3 seconds of operation the amplitude of the mode increases after this point in time.

TABLE X

COMBUSTION STABILITY DATA

- ACCELEROMETER DATA INDICATES THE PRESENCE OF THE FOLLOWING COMBUSTION FREQUENCIES

• CHAMBER FIRST TANGENTIAL	2446 HZ
• CHAMBER SECOND TANGENTIAL	4057 HZ
• CHAMBER FIRST LONGITUDINAL	696 HZ
• CHAMBER SECOND LONGITUDINAL	1392 HZ
• INJECTOR ANNULUS FIRST MODE	2961 HZ
• INJECTOR ANNULUS SECOND	5922 HZ

- ALL ACCELEROMETER AMPLITUDES < 10 GRMS

PAST HARDWARE EXPERIENCE INDICATES STABLE COMBUSTION

FIGURE 80

INJECTOR ANNULUS

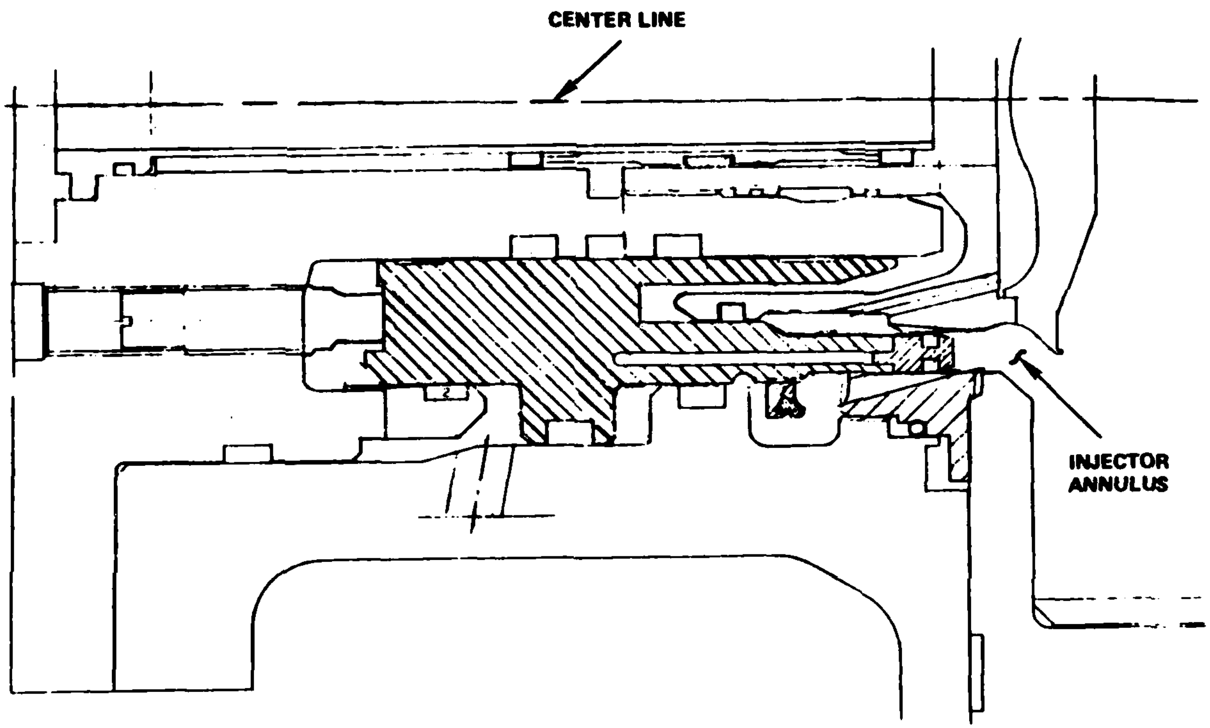


FIGURE 81

ACCELEROMETER AMPLITUDE TEST 14 FIRST CYCLE

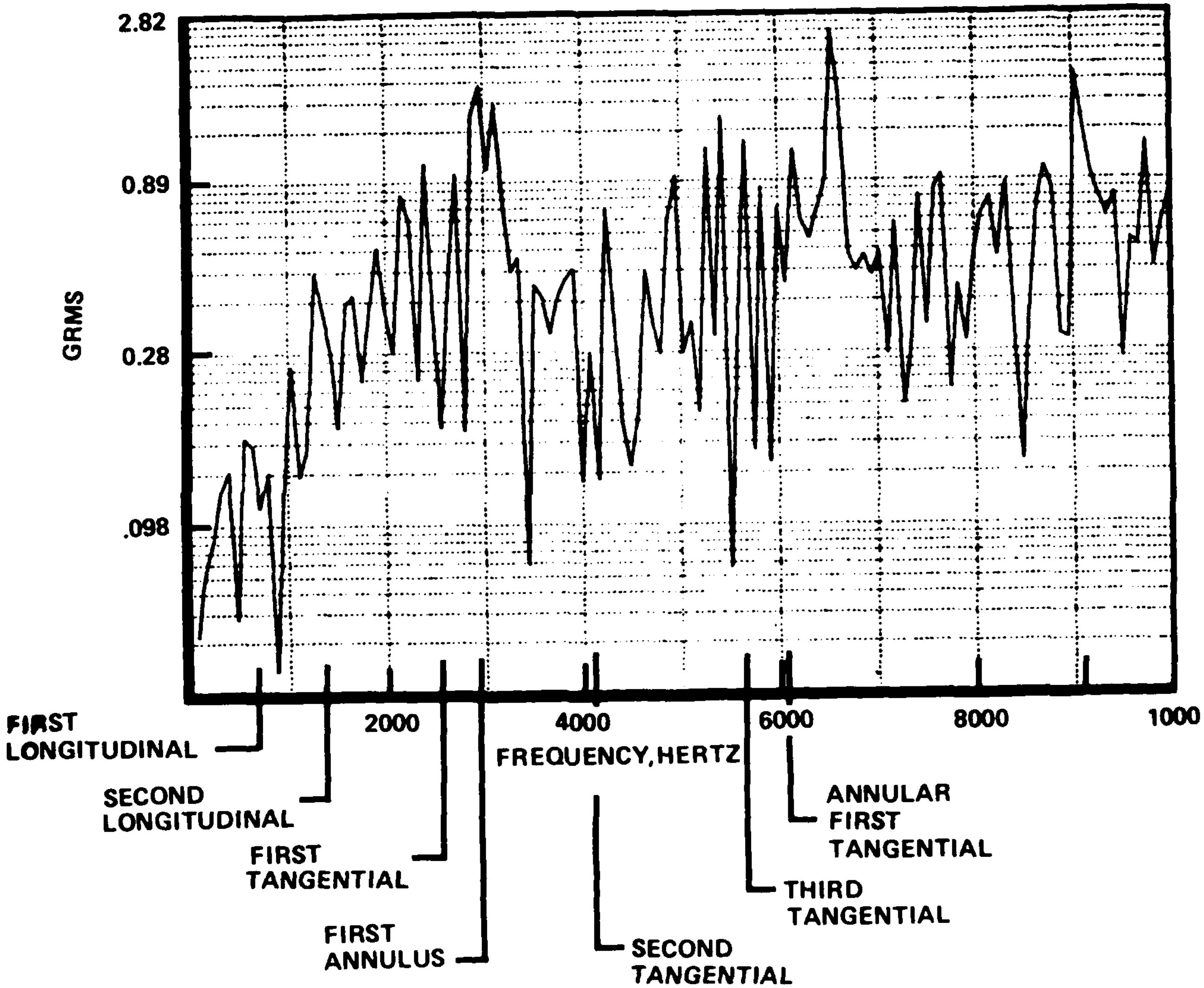


FIGURE 82

ACCELEROMETER DATA TEST 10
NO INJECTOR EROSION

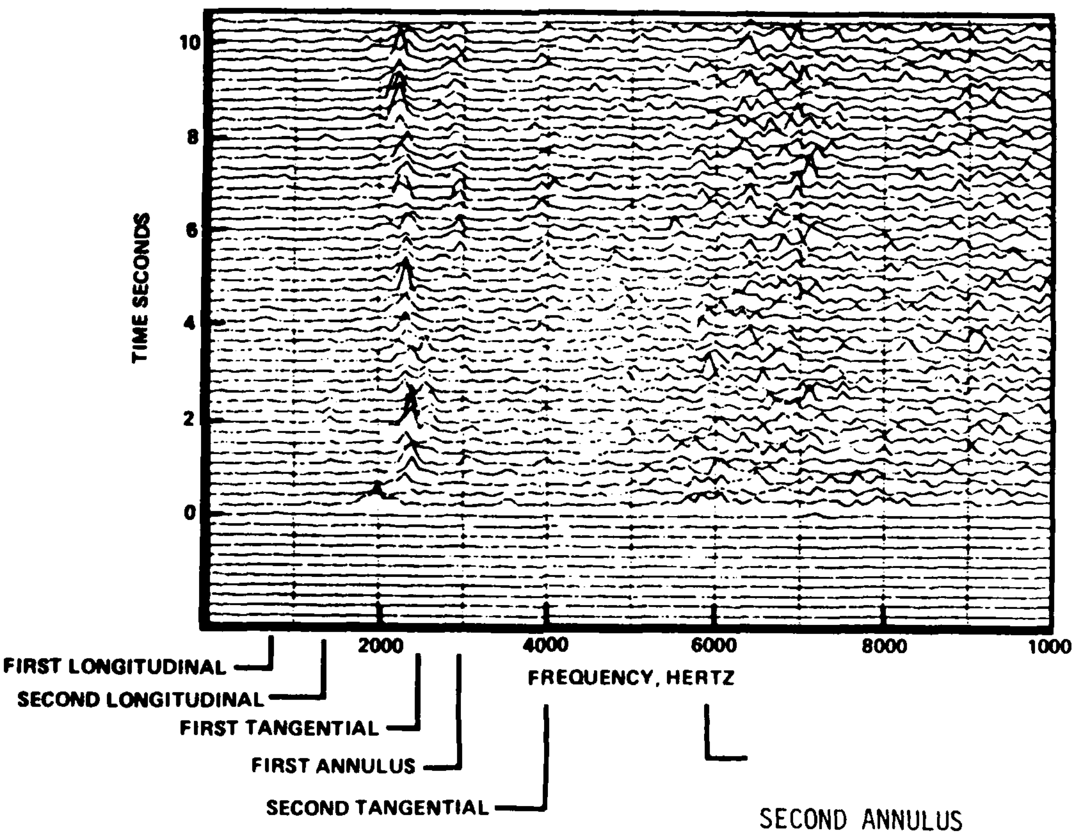


FIGURE 83

ACCELEROMETER DATA TEST 13
CORE AND FUEL RING EROSION

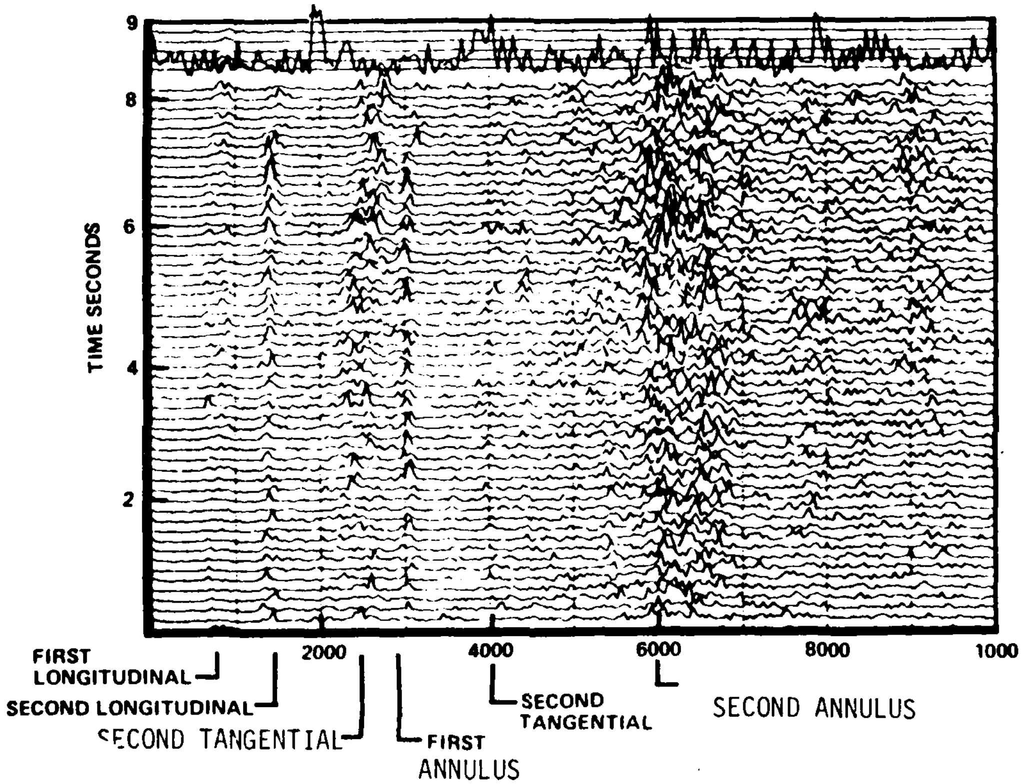
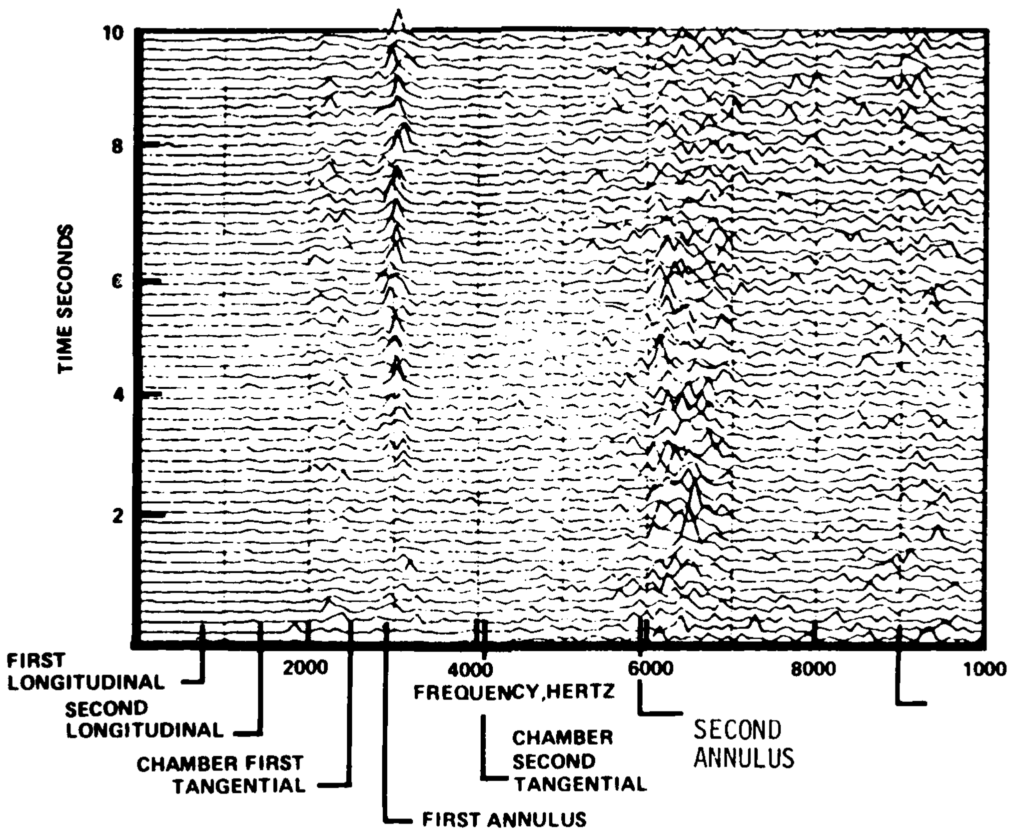


FIGURE 84

ACCELEROMETER DATA-TEST 14
FIRST CYCLE CORE AND FUEL RING EROSION



Continuing on with the data from the second and third cycle (Figures 85 and 86) we see that the first annular mode is always present and the first tangential mode begins to increase and amplitude. Finally the second tangential annular mode develops during the third cycle. It is again emphasized that even though the data appears to indicate high amplitudes at no time during test 14 or 15 does the amplitude exceed 10 grms, which is considered a stable system. The well defined annulus modes and obvious growth in amplitude as the run progresses is unique to test 13 and 14, the only tests resulting in the highly localized massive fuel ring erosion.

Pure low amplitude spinning modes are not generally damaging even though they do tend to decrease the heat transfer boundary layer and increase the heat input to the hardware primarily on the external diameter of the annulus. Also, spinning mode hardware damage is not preferential to angular locations the damage noted to the outer diameter was highly preferential as noted in Figure 87 for test 13 and 14.

The presence of a reflection zone in the annulus can force a spinning mode to become a standing mode. The difference in the standing mode as compared to the spinning mode is the existence of pressure and velocity modes at discrete locations. These discrete modes can cause hardware damage in localized areas such as noted as a result of test 14 and 15.

It is suggested that the mechanism which triggered the obvious development of the standing modes noted during test 13 and 14 was the core erosion which produced an axial disruption in the flow field. In other words, produced a dam in the annulus or reflection zone which initiated the destructive standing first and second annular modes.

In summary, it is felt that the fuel ring damage associated with tests 13 and 14 was triggered by the core erosion which was also unique to tests 14 and 15 as previously discussed.

FIGURE 85

TEST 14 CYCLE 2
CORE AND FUEL RING EROSION

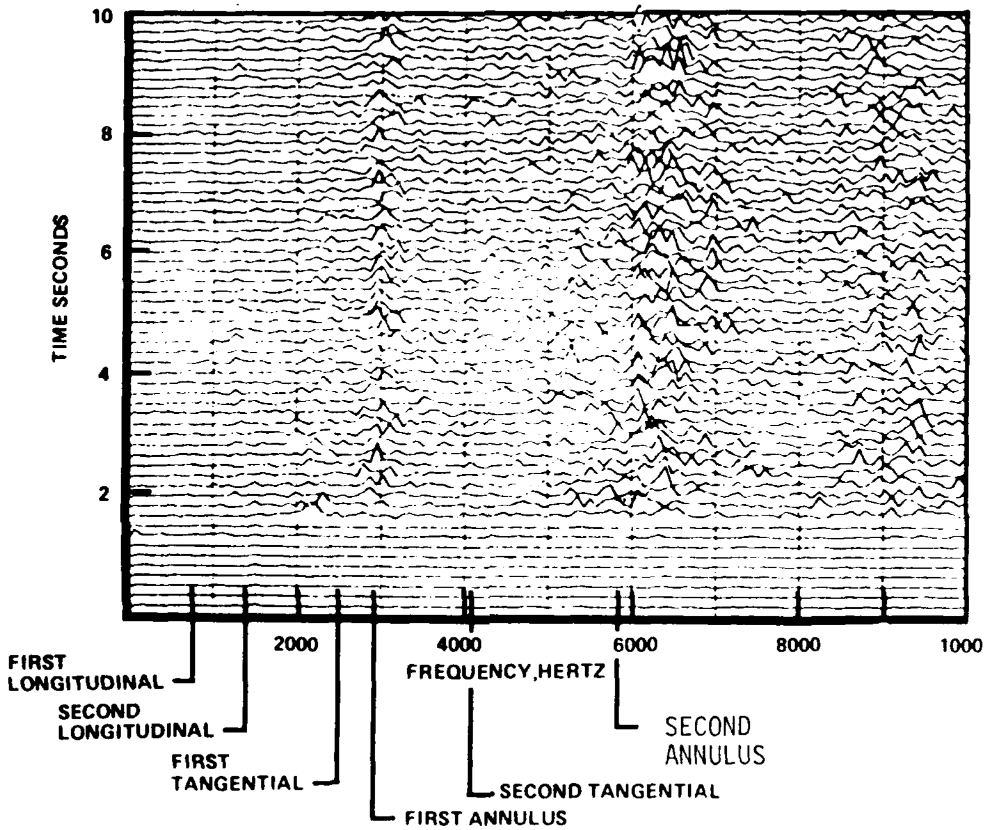


FIGURE 86

TEST 14 CYCLE 3
CORE AND FUEL RING EROSION

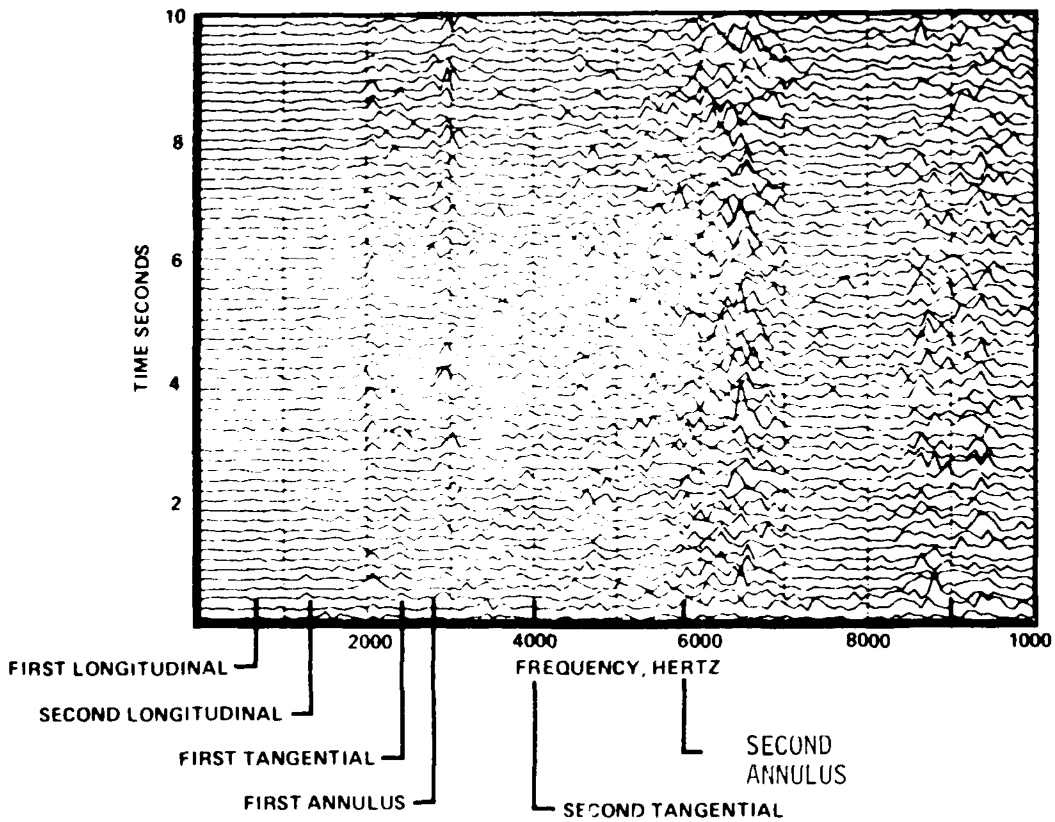
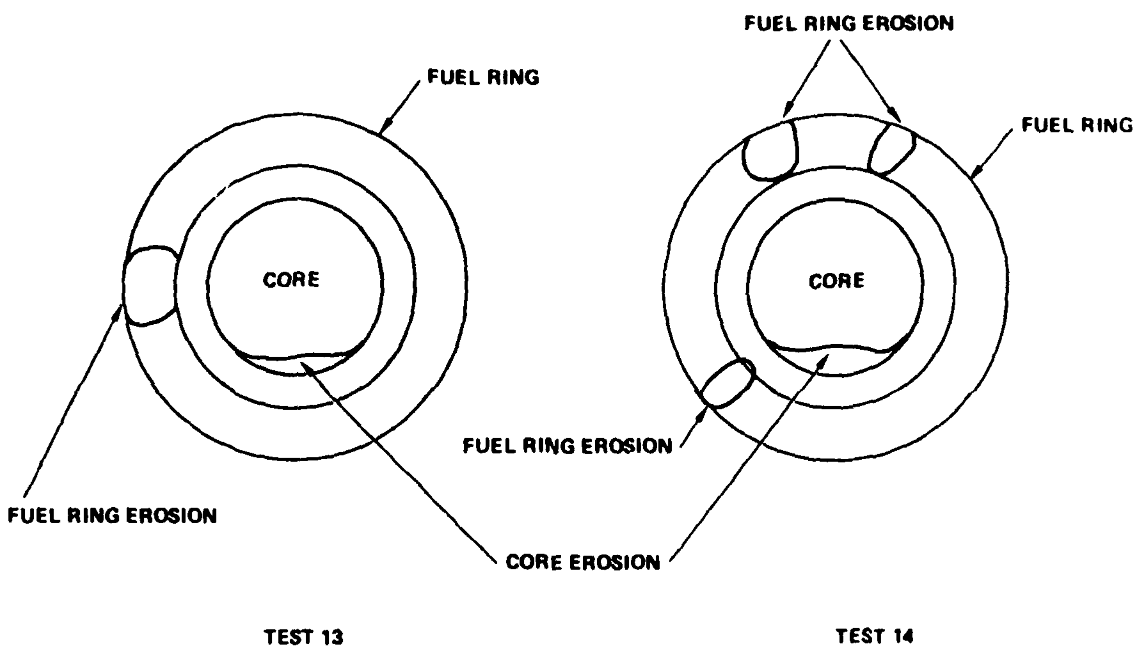


FIGURE 87

LOCATION OF INJECTOR EROSION



The previous tests indicating no core or fuel ring erosion other than to minor random fuel ring edge nibbling which was caused by lack of capability to transfer heat by the relatively low thermal conductivity 347 Cress.

Based on this degree of success and unique changes made in the core ablative shield installation, it is concluded that the core shield installation was the basic cause of the overall erosion problem. It is obvious from the test data that the primary annular modes are always present, however, development into a destructive standing first and second tangential mode requires a triggering mechanism such as the core erosion producing an axial flow disruption or reflection zone.

The core erosion and fuel ring erosions are not considered a basic concept problem but a problem associated with the core shield. Removal of the core shield and incorporation of copper to manage the heat load will probably solve the problem--similar to the success noted with the copper plate pintle tip incorporated to solve an erosion problem.

CONCLUSIONS

It is concluded that the basic objectives of the program were achieved, namely to demonstrate the feasibility of a LOX/JP-4 fast start restartable 15,000 HP gas generator capable of throttling and purgeless operation. The development problems encountered were identified, appropriate hardware changes were incorporated and hot fire test demonstrated the effectiveness of the corrective action. The key gas generator requirements of fast starting, restartability, purgeless operation, throttling and hot gas temperature distribution were demonstrated.

The last two tests did indicate core and fuel ring erosion. The analysis of the data and the uniqueness of these two tests were identified. The overall concept of a restartable high power LOX/JP-4 is sound and worthy of further development.

APPENDIX A

Injector Mixture Ratio Distribution

Previous hot fire testing of the gas generator indicated the presence of a hot core injector. Cold flow tests using immiscible propellant simulants (water and trichloroethane) were performed in an effort to optimize the injector configuration. The configurations tested were:

1) The LOX splash plate configuration used for the hot fire test series (Figure A-1a).

2) The Lance injector configuration with both a fuel and LOX splash plate (Figure A-2a).

3) Both splash plates removed (Figure A-3a).

4) Both splash plates removed with the impinging propellant streams misaligned.

The data from these tests has been analyzed and is shown in Figures A-2 through A-6. The data is presented as propellant mass fraction with respect to the chamber center line and chamber wall. The solid line represents the oxidizer mass fraction and the fuel mass fraction is represented by the dash line. When the solid and dash lines are coincident, the mixture ratio is equal to the injected mixture ratio. The approximate peak mixture ratios are indicated on the data plot. All test configurations indicated a highly localized mass distribution.

The cold flow tests performed on the baseline injector (Figures A2 & A3) LOX splash plate and no fuel splash plate does not indicate a LOX rich core as the hot fire data indicated at the 100 percent power level. The

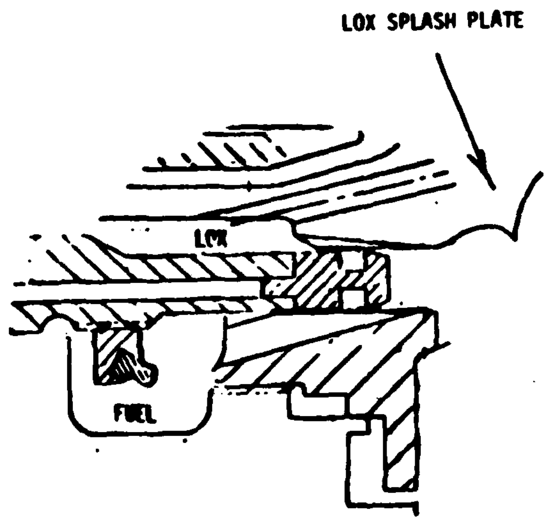


Figure A-1a
LOX Splash Plate

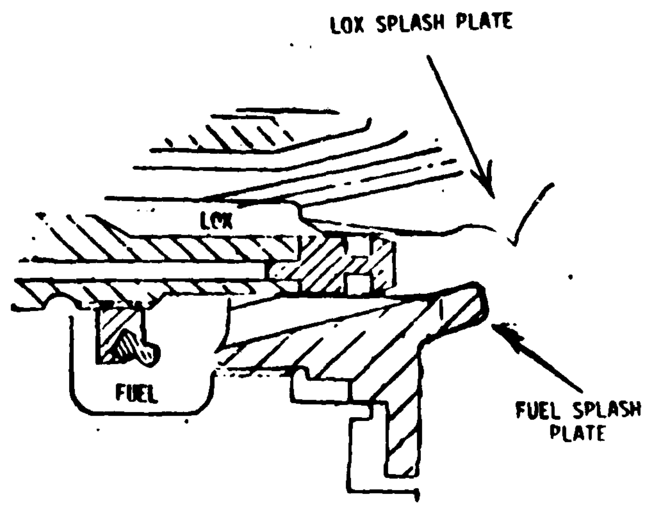


Figure A-1b
LOX and Fuel Splash Plate
(Lance Configuration)

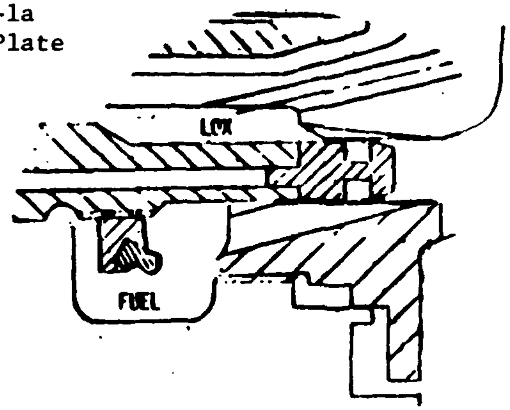


Figure A-1c Splash Plates Removed

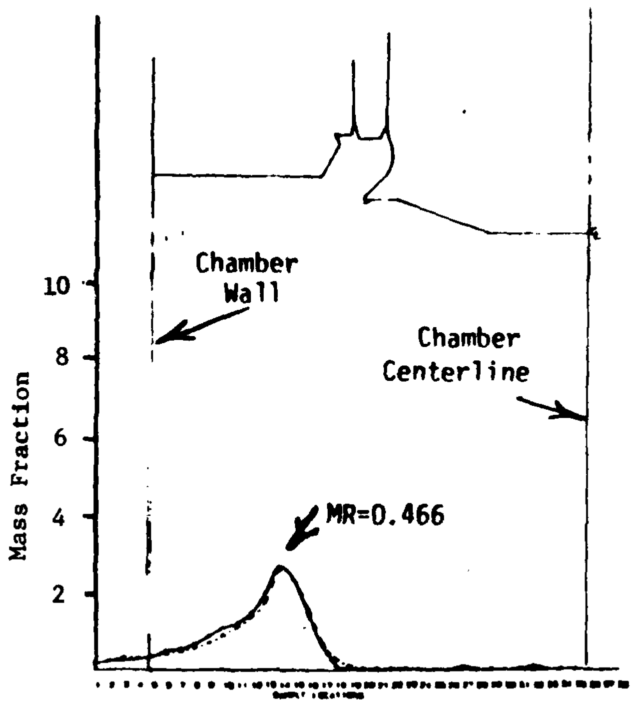


Figure A-2- LOX Splash Plate only
100% Power Level

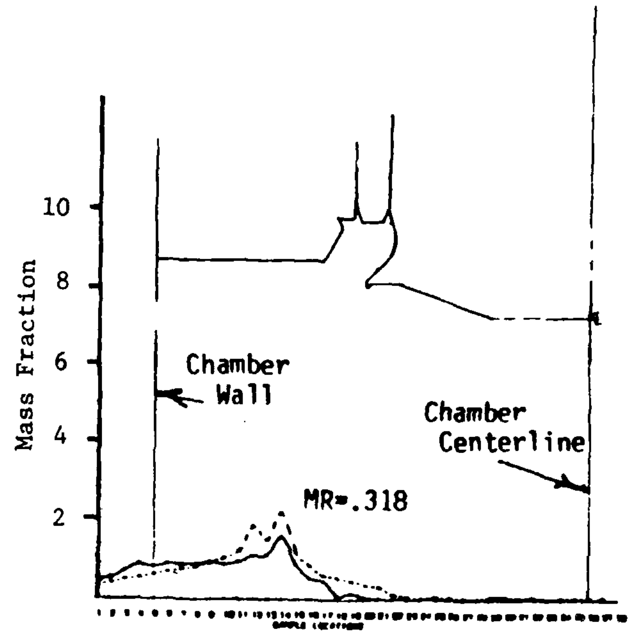


Figure A-3 LOX Splash Plate
50% Power Level

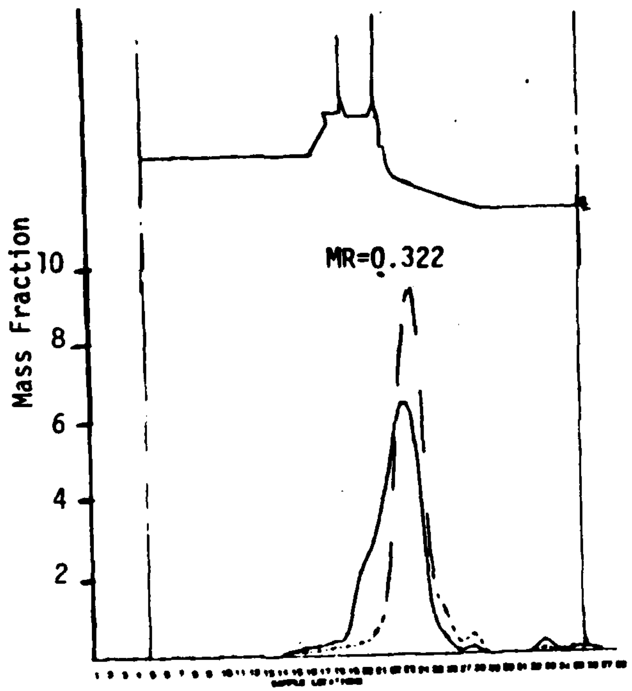


Figure A-4 No Splash Plates

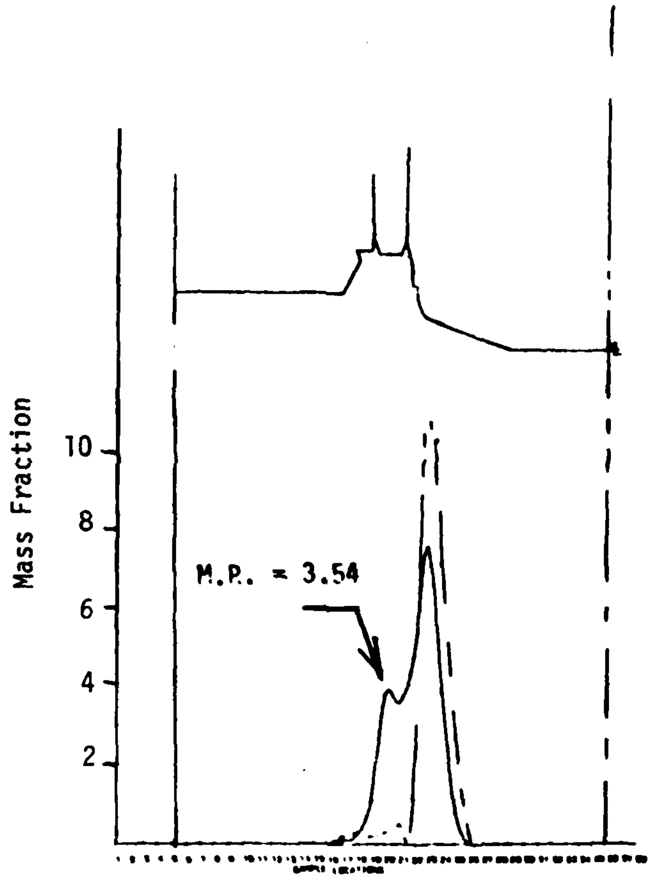
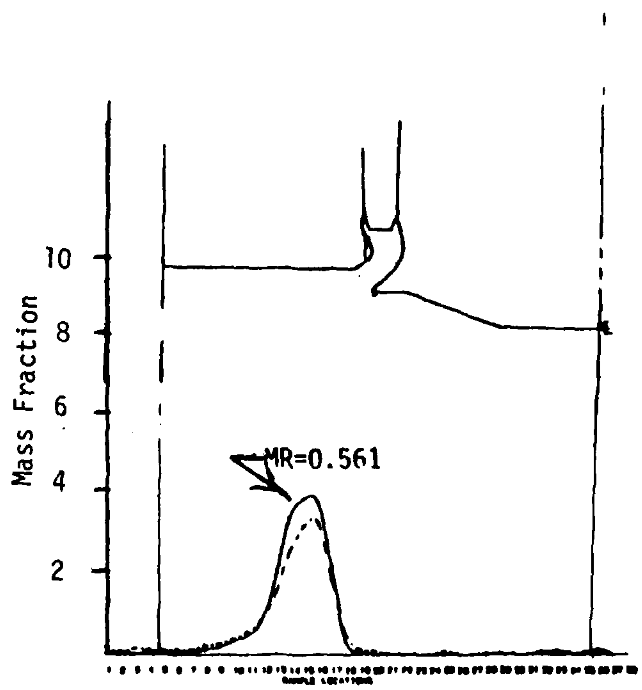


Figure A-5 No Splash Plates
Impingement Misaligned



FigureA-6- LOX and Fuel
Splash Plate

data did indicate massive maldistribution of the mass to the outer chamber wall. This information combined with an analysis using the transient combustion analysis program (Figure A-7) indicates that the central stream of oxidizer rich high temperature gases is the result of "radial winds." Typically, "radial winds" are the result of radial mass distribution faults. Local high mass flux areas generate gases which flow to areas of low mass flux carrying vaporized and reacting propellants to these low mass areas. In a liquid oxygen/liquid hydrocarbon system, the oxidizer is vaporizing much faster than the fuel. These transported gases are significantly higher in oxidizer fraction than the mean mass flow. "Radial winds" have been usually associated with combustor "head end" heat flux and erosion caused by the usual injector mass profiles deficient in the outer zone. In this case, the outer zone is overloaded, the "radial wind" was inward.

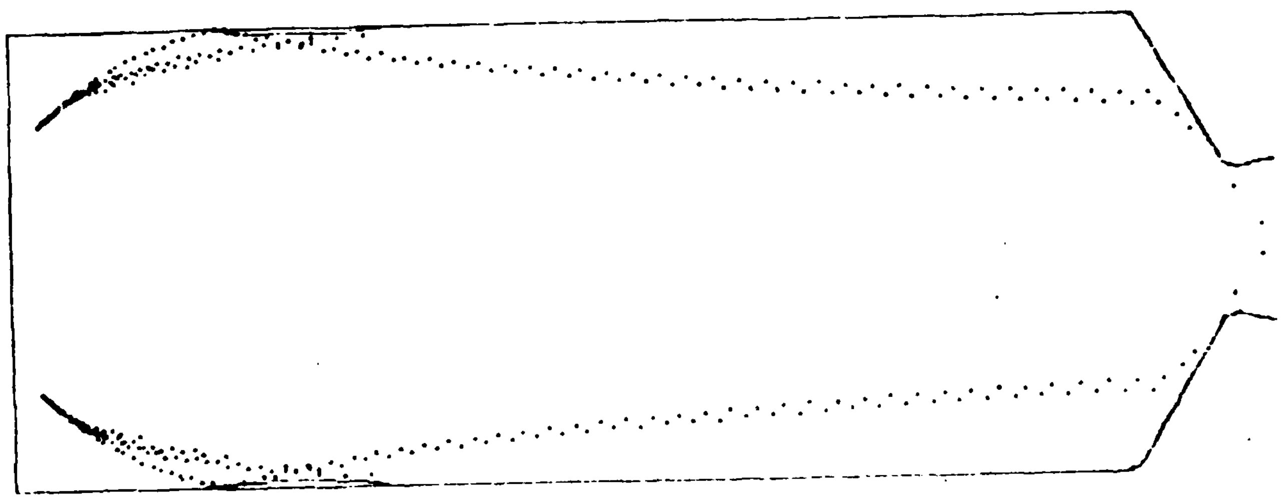
The hot fire data indicated an excellent temperature distribution at the 50 percent power level. The 50 percent power level cold flow data (Figure A-3) indicates a tendency to move the injected propellant mass toward the centerline of the injector. In addition to producing a lower peak mixture ratio, the transient combustion model (Figure A-8) indicates the tendency to move the fuel toward the chamber centerline, thus providing the potential for a more uniform mixture ratio profile. The exact cause for the hot gas uniformity at smaller pintle positions is thought to be associated with increased vaporization of the fuel produced by the smaller fuel drop size at the smaller flow area.

The cold flow study indicated that operation with both splash plates (Figure A-4) removed would improve the "radial wind" problem by concentrating the mass flux near the combustor area centroid. However, the mixing efficiency and atomization of the injector would be measurably worsened and the local mass flux distribution would be even more concentrated. A cold flow experiment was also performed demonstrating mixture ratio control to

FIGURE A-7

FUEL DROP DISTRIBUTION WITH SPLASH PLATE

100 PERCENT PINTLE POSITION

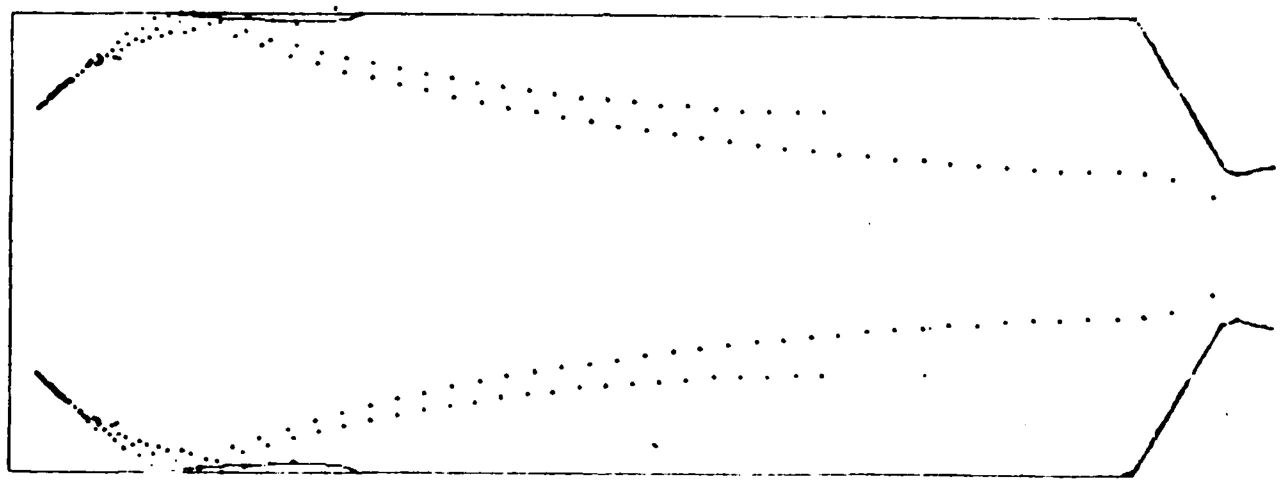


TRANSIENT COMBUSTION PROGRAM (AFRPL)

FIGURE A-8

FUEL DROP DISTRIBUTION WITH SPLASH PLATE

50 PERCENT PINTLE POSITION



TRANSIENT COMBUSTION MODEL (AFRPL)

make the center mass fuel rich and the outer zone oxidizer rich. This was done by deliberate misalignment of the injection slots in an injector assembly without splash plates (Figure A-5). The maldistribution produced by this realignment would result in significant performance loss and may reverse temperature distribution problem to a chamber wall.

Replacing the fuel splash plate (removed in modifying the lance injector for this application)(Figure A-6) would probably improve mixing efficiency slightly, but the mass distribution would still set the stage for the "radial wind" problem that existed during the hot fire testing.

It was concluded from these analyses and test results that the existing injector using a turbulence ring is the most promising configuration.

Injector/combustor turbulence is frequently used to enhance mixing and atomization. Constrictions at the "head end" of the combustion chamber have proven effective in many configurations and under various descriptive names. "Choke rings," "turbulence rings," "performance augmentation rings," and in some cases, so-called injector "splash plates" provide these same functions. The type of devise proposed for the restartable G.G. is intended to be close to the injector, but not so close as to be a true "splash plate." The theory of operation requires that some combustion take place upstream of the constriction, and these gases are accelerated in the converging section. The high velocity gases entrain the unreacted propellants enhancing atomization by shear and improving mixing with turbulence. The sudden expansion and rapid diffusion of the gases exiting the constriction further increase the turbulent mixing and wind shear atomization.

This turbulence ring is based largely on the configuration used in the FLEXEM (Flexible Energy Management) rocket engine which also was a pintle/slot throttling injector configuration. In this program, the PAR (Performanced Augmentation Ring) increased combustion efficiency from the mid-eighty percent level to about 96 percent, reflecting significant mixing improvement.

Other engines and other rocket engine companies have used the turbulence generating constriction to effective advantage. Many of Rocketdyne's earlier gas generators also incorporate configurations that generate turbulence in a similar fashion. These devices are thus frequently used to combat injector deficiencies with effective results.

Two turbulence ring configurations were considered (Figure A-9), one with a 30° ramp angle and a second configuration with a 20° ramp angle. Both configurations employ a 2-to-1 contraction area ratio typical of the FLEXEM configuration. The 30 degree convergence angle and the local reduction to roughly half-chamber area that was typical of the FLEXEM performance augmentation ring (PAR) would undoubtedly improve mixing, but there was some concern about recirculation in the area upstream of the truncated ramp. The rather abrupt angle between the injector spray mass and the converging ramp is also a matter of concern. In the FLEXEM, the ramp angle was also 30 degrees and the spray exit angle was as high as 15 degrees, for a total incidence angle of 45 degrees. This injector has a mass injection spray angle approaching 45 degrees for a resulting incidence angle of 75 degrees.

A more conservative configuration utilizing a 20 degree ramp angle which extends completely to the combustor wall diameter at the upstream end (Figure A-9) eliminates the "pocket" where recirculation was anticipated with the shorter ring and reduces the impingement angle of the injected mass on the ramp to a nominal 65 degrees. The cylindrical length of the reduced flow area section is also lengthened to one inch by this design to improve thermal integrity by increasing the mass of the ring.

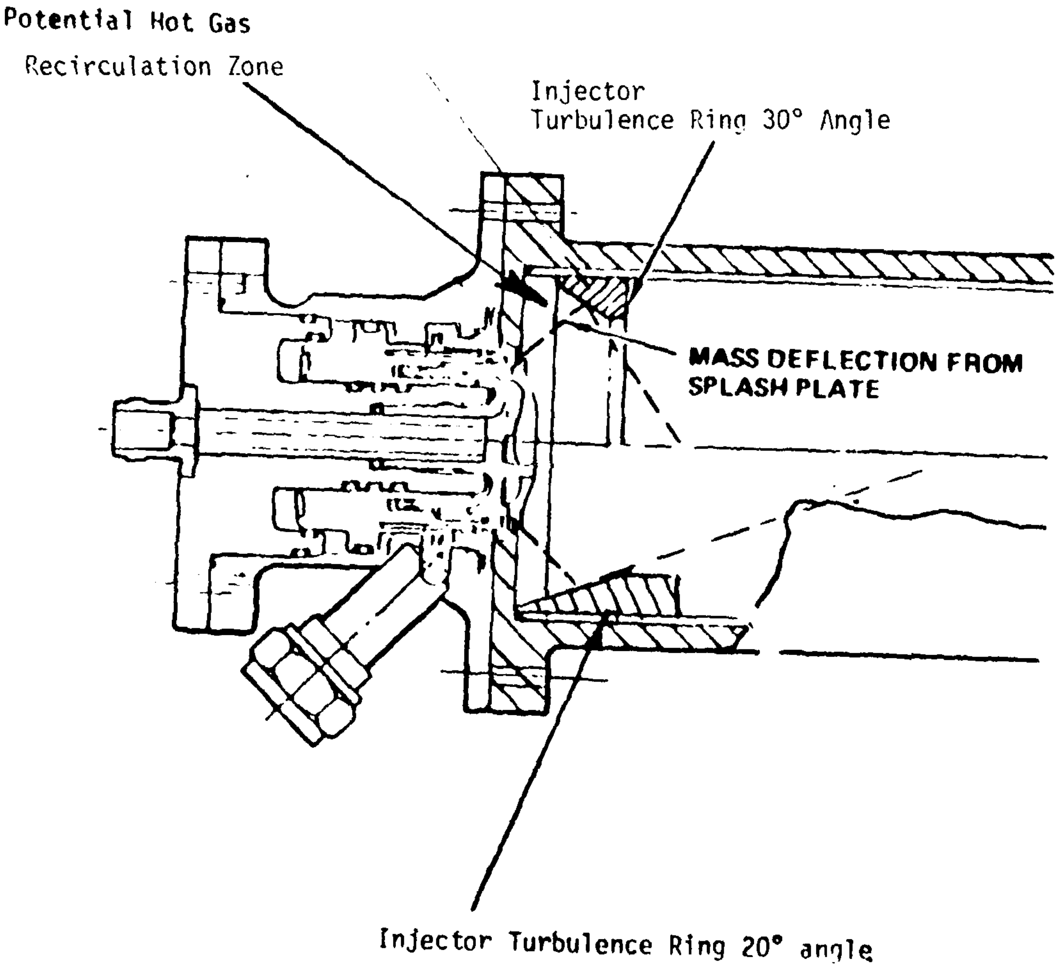


Figure A-9- Turbulence Ring Configurations

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