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ROCKETDYNE

A DIVISION OF NORTH AMERICAN AVIATION, INC.

CANOGA PARK, CALIFORNIA

R-5316

16

FINAL REPORT, DEVELOPMENT OF DOWNRATED ATLAS YLR101-NA-15 VERNIER ENGINE

ROCKETDYNE

A DIVISION OF NORTH AMERICAN AVIATION, INC.

6633 CANOGA AVENUE

CANOGA PARK, CALIFORNIA

Contract AF04(695)-306

Part I, Item 2b as
Amended by Request
For Service Order
SSD-63-03

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NO. OF PAGES 147 &

DATE 8 Nov 1963

REVISIONS

DATE	REV. BY	PAGES AFFECTED	REMARKS

FORM R 18-G-1 (PLATE)

FOREWORD

This report was prepared under G.O. 8468 in compliance with Contract AF04(695)-306, Part I, Item 2b, as amended by Request For Service Order SSD-63-03.

ABSTRACT

Presented is a summary of test results from a program to develop the YLR101-NA-15 vernier engine. The program was completed in three phases: (1) Downrating the tank-fed thrust of the YLR101-NA-13 vernier from 830 pounds to 525 pounds, (2) modifying and repackaging the 525-pound-thrust vernier into the YLR101-NA-15 configuration, and (3) developing a modified vernier injector to minimize a thrust chamber erosion problem which occurred at the 525-pound-thrust level.

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INTRODUCTION AND SUMMARY

The concept of vernier engine usage on the Atlas missile was changed during the development of Atlas standard space launch vehicle SLV-3. Specifically, it was found that the thrust level of the existing MA-5 vernier engine (1000 pounds of pump-fed thrust and 830 pounds of tank-fed thrust) was considerably higher than was necessary to accomplish adequate roll and attitude control of the SLV-3 Atlas for its proposed applications. Because the axial specific impulse of the vernier engine at altitude is lower than that of the sustainer engine, a net gain in specific impulse of the sustainer vernier system can be achieved by reducing the vernier engine propellant flowrates (and thrust) thereby providing an additional quantity of propellants to be used at the higher level of sustainer specific impulse. Calculations indicate that a reduction in tank-fed vernier thrust from 830 pounds to 500 pounds produces an increase of 2.1 seconds in the altitude axial specific impulse of the sustainer/vernier system.

Prior to 1961, several vernier engine and thrust chamber component tests were conducted at approximately the 500-pound thrust level. During August 1961, Rocketdyne proposed a test program to further investigate vernier engine operation at low thrust levels of from 400 to 700 pounds. The proposal was accepted by the Air Force Space Systems Division and was funded under Request For Service Order (RFSO) 135-62-6 in October 1962 This RFSO specified two major items in the program to develop the downrated vernier engine. The first (Phase I) included modifying and testing the MA-5 vernier engine to operate at a sea-level thrust level of 500 pounds. The second item (Phase II) included modifying and testing the 500-pound-thrust vernier to provide a revised interface between the engine and missile as required for the Atlas SLV-3.

Vernier engine tests under Phase I began in November 1962 and were completed in December 1962. These tests successfully established vernier engine performance characteristics at the downrated thrust level and verified compatibility of the downrated vernier engine with the sustainer engine system, but revealed difficulties with engine starting transients, vibration, and thrust chamber erosion. The vibration was experienced at thrust levels between 400 and 450 pounds, and was eliminated when customer requirements dictated a nominal tank-fed operating thrust level of 525 ±25 pounds. The undesirable engine starting transients were eliminated by decreasing the diameter of propellant transfer tubes within the engine package. No obvious solution existed for the thrust chamber erosion problem, but data analysis indicated that the probable cause of the erosion was operation of the vernier injector at a performance level significantly below the original design point.

A program to design, fabricate, and test alternate injector configurations to minimize thrust chamber metal erosion at low thrust levels was initiated under RFSO SSD-63-03 in March 1963. This injector development program was not scheduled for completion in time to accomplish initial production deliveries of the new repackaged YLR101-NA-15 vernier engine with the modified injector, so a decision was made to increase the tank-fed thrust level of the first 10 production YLR101-NA-15 engines to 777 pounds, thereby avoiding the thrust chamber erosion problem at the 525-pound thrust level. This "uprated" vernier engine was given the model designation YLR101-NA-15 MD 1.

Vernier engine tests under Phase II of RFSO 135-62-6 were conducted during May 1963. The YLR101-NA-15 MD 1 configuration was used, and the tests were completely satisfactory in (1) verifying the integrity of the repackaged configuration, (2) determining engine gain factors (required for acceptance test), and (3) demonstrating conformance to all model specification requirements of the YLR101-NA-15 MD 1 vernier engine.

The development of a modified injector for the YLR101-NA-15 vernier engine began in March 1963 with the selection of four modified flat-face injector designs for fabrication and testing. A prototype splash-plate injector also was selected for testing on the basis of previous successful R&D tests at low thrust levels.

Each modified injector and a standard injector were photographed during cold-flow tests using colored water. The photographs were used to predict injector hot-fire success by comparing propellant distribution of each modified injector flow test series to the standard injector series.

The modified flat-face injectors and prototype splash-plate injector were then subjected to hot-fire tests on a thrust chamber/injector test stand. Technical requirements for successful operation were 3000 seconds of hot fire with no erosion, high performance, and satisfactory operating characteristics. Three of the flat-face injector types produced severe erosion of the inner walls of the thrust chamber at the 500-pound thrust level, but two units of the fourth flat-face design (P/N EO 123829) met all technical requirements, although slight erosion occurred during operation at a mixture ratio well above nominal. No thrust chamber erosion occurred during testing with the prototype splash-plate injector, but this unit was subject to rough cutoffs and to midtest performance shifts.

The thrust chamber/injector component test program revealed that the initial use of the term "erosion" was not very specific when used to describe the condition of a vernier thrust chamber. At the beginning of the test program the term erosion was used to describe any change in the condition of the thrust chamber inner wall. Some of the observed "erosions," however, were actually only streaks or melted spots ("puddles") in the layer of nickel plating which lines the thrust chamber. The only function of the nickel plating is to protect the thrust chamber parent metal (4130 steel) from rusting. The nickel plating melts at a considerably lower temperature than the parent metal, and "streaking" and "puddling" of the plating can occur without any actual erosion of the parent metal. Because the durability of the thrust chamber is not affected by the plating streaking and puddling, the term "erosion" was directed to be used only when a chamber developed damage to the parent metal.

Analysis of the thrust chamber/injector tests resulted in the selection of the P/N EO 123829 flat-plate injector configuration for use in a series of vernier engine system tests. The splash-plate injector was used as a backup. Eighty-seven tests were conducted with nine vernier engine systems at the Rocketdyne Neosho facility. Mixture ratio and thrust were varied over a wide range to determine if the P/N EO 123829 injector would cause erosion of the thrust chamber parent metal. Some erosion did occur with the initial tests of the P/N EO 123829 injector, but not to the extent previously experienced during Phase I testing with the standard P/N 350604 injector. One unit of the backup splash-plate design also was tested, and resulted in an excessive buildup of carbon in the thrust chamber throat. This caused large fluctuations in engine performance and eventual complete burnthough of the chamber throat. Testing of the splash-plate configuration was discontinued.

A review of the operating regimes and damage patterns of the first three engines tested with the P/N EO 123829 injector appeared to indicate that thrust chamber erosion might be eliminated if operation at the 525-pound thrust level was restricted to mixture ratios below approximately 1.9. Four additional P/N EO 123829 units were subjected to testing on the basis of this conclusion All testing was satisfactory with no occurrence of thrust chamber erosion, although puddling and streaking of the thrust chamber nickel plating were observed.

Because of the successful test results with P/N EO 123829 injector, which demonstrated a clear superiority of this design over the standard injector, Rocketdyne recommended incorporation of the P/N EO 123829 injector into the production YLR101-NA-15 vernier engine.

CONCLUSIONS

PHASE I TEST PROGRAM

Analysis of the Phase I tests resulted in the following conclusions:

1. Thrust chamber erosion will be experienced when the YLR101-NA-15 vernier engine is operated at the 525-pound thrust level with the standard injector.
2. The thrust chamber erosion experienced during Phase I testing was severe, and resulted in thrust chamber leakage.
3. The thrust chamber erosion experienced during Phase I testing had no noticeable effect on engine performance.
4. The condition of the Phase I engines following testing was such that they would have performed satisfactorily during flight use.
5. Vernier operation at the 525-pound thrust level does not adversely affect sustainer engine operation.

PHASE II TEST PROGRAM

The Phase II test program demonstrated that the repackaged YLR101-NA-15 MD 1 vernier engine met all model specification requirements.

MODIFIED INJECTOR PROGRAM

Analysis of results of modified injector tests resulted in the following conclusions:

1. Vernier thrust chamber operation at the 525-pound thrust level offers no heat transfer problems other than those encountered at the 830-pound thrust level
2. Injector cold-flow tests using water with color additives to simulate propellants were unsuccessful in allowing prediction of injector hot-fire success.
3. Vernier thrust chamber erosion experienced at the 525-pound thrust level during Phase I testing was caused by poor propellant distribution in the combustion zone. This resulted from operating the standard injector configuration at a performance level significantly lower than the original design point.
4. The P/N EO 123829 injector was the only modified configuration tested which demonstrated a superiority over the standard injector in eliminating thrust chamber erosion at the 525-pound thrust level.
5. Thrust chamber erosion at the 525-pound thrust level can be further minimized with the P/N EO 123829 injector by lowering the nominal tank-fed mixture ratio from 1.80 to 1.65.
6. The P/N EO 123829 injector has a higher rated tank-fed specific impulse than the standard P/N 350604 injector. Start and cut-off transients and steady-state operation of the two injector types are similar.

RECOMMENDATIONS

Based on analysis of the results of the Phase I, Phase II, and modified injector testing, Rocketdyne recommends the following action to be taken:

1. Accept the P/N EO 123829 injector configuration for incorporation in the YLR101-NA-15 vernier engine. This would require no change in present acceptance testing or inspection procedures, would provide an increased tank-fed specific impulse, and would significantly reduce the incidence of thrust chamber erosion at the 525-pound thrust level.
2. Further develop the use of color additives in water-flow testing to establish criteria for an accurate production of the behavior of an injector under hot-fire conditions.
3. Retain the snubbers in the pitch gimbal actuators used with the YLR101-NA-15 vernier engine. This will prevent the possibility of breaking teeth on the pitch sector gear, which might otherwise occur under certain extreme gimbaling conditions with the snubbers removed.

PHASE I TEST PROGRAM

OBJECTIVES

The prime objective of Phase I of the MA-5 vernier engine downrating program was to design and test the necessary modifications to the existing YLR101-NA-13 vernier engine to accomplish operation at a tank-fed sea-level thrust level of 525 ±25 pounds. Testing during Phase I was accomplished with production-equivalent MA-5 vernier engines supplied from Rocketdyne engineering R&D stock. Specific test objectives of the program were to:

1. Determine start and cutoff transient characteristics of the vernier engine at the downrated performance level
2. Determine values of specific impulse, thrust, mixture ratio, and cutoff impulse
3. Evaluate hardware integrity and over-all integration with the sustainer engine

TEST SUMMARY

Fifty-two tests were conducted at the Rocketdyne Neosho test facility, and 10 tests were conducted at the Rocketdyne Propulsion Field Laboratory (PFL) to accomplish the Phase I test objectives. The vernier engine operating levels during these tests were obtained by varying the engine inlet pressures. At the Neosho facility, this was accomplished by changing the facility tank pressures; at PFL, this was accomplished by placing orifices in the sustainer supply lines to the verniers.

Three vernier engines were used for the 52 Phase I Neosho tests. Table 1 shows the modifications made to the engines during the tests. The changes in engine orifice location and improvements in the orifice configuration were incorporated to obtain better control of engine operation. The changes to engine LOX and fuel line sizes were made to improve engine ignition characteristics. A summary of the Phase I Neosho testing is presented in Table 2.

Two standard YLR101-NA-13 vernier engines (Configuration 1, Table 1) were used for the 10 Phase I tests on the Alfa-1 test stand at PFL. These tests were conducted in conjunction with sustainer engine operation to determine the compatibility of performance of the sustainer with downrated verniers. A summary of the Phase I PFL testing is presented in Table 3.

TABLE 1

PHASE I ENGINE CONFIGURATIONS

Configuration	Basic Engine	Modifications
1	Standard MA-5 (YLR101-NA-13)	None
2	Standard MA-5	5/8-inch LOX line (propellant valve to pitch body) 5/8-inch LOX transfer line
3	Standard MA-5	5/8-inch LOX line (propellant valve to pitch body) 5/8-inch LOX transfer line Fuel orifice at hypergol inlet LOX orifice in line between propellant valve and pitch body
4	Standard MA-5	1/2-inch LOX line (propellant valve to pitch body) 1/2-inch LOX transfer line
5	Standard MA-5	All LOX lines 1/2-inch diameter
6	Standard MA-5	All LOX lines 1/2-inch diameter Fuel orifice at hypergol inlet LOX orifice in line between propellant valve and pitch body
7	Standard MA-5	Same as Configuration 6 plus 1/2-inch fuel line (propellant valve to pitch body)

1

TABLE 2

SUMMARY OF PHASE I TESTIN(

Engine Serial No.	Configuration	Test No.	Duration, seconds	Cumulative Duration, seconds	
0002-6	1	8842	78.5	78.5	
		43	73.1	151.6	
		44	78.8	230.4	
		45	329.0	559.4	
		46	325.8	885.2	
		47	325.5	1210.7	
		48	325.4	1536.1	
		49	325.5	1861.6	Eroded in th
		50	324.3	2185.9	
		51	80.1	2266.0	
		52	325.4	2591.4	
		53	325.4	2916.8	Erosion at 6:
		54	327.2	3244.0	Erosion at 6:
		55	325.4	3569.4	
	2	56	80.3	80.3	
		57	80.3	160.6	
		58	10.9	171.5	
		59	81.0	252.5	
0003-4	2	8860	80.3	80.3	
		61	89.8	170.1	
	3	62	80.0	80.0	
		63	80.2	160.2	
		64	80.1	240.3	
		65	80.0	320.3	
		66	325.0	645.3	
		67	325.1	970.4	Eroded in th:
		68	325.2	1295.6	Additional e
		69	325.3	1620.9	Additional e:
		70	325.5	1946.4	All erosions
		71	325.0	2271.4	All erosions
0002-6	4	8872	40.3	40.3	
		73	40.0	80.3	
	5	74	80.6	80.6	
		75	80.0	160.6	

2

TABLE 2

SUMMARY OF PHASE I TESTING AT NEOSHO

ion, nds	Cumulative Duration, seconds	Comments
.5	78.5	
.1	151.6	
.8	230.4	
.0	559.4	
.8	885.2	
.5	1210.7	
.4	1536.1	
.5	1861.6	Eroded in thrust chamber throat at 5:30 and 6:30 o'clock positions
.3	2185.9	
.1	2266.0	
.4	2591.4	
.4	2916.8	Erosion at 6:30 o'clock position is wider
.2	3244.0	Erosion at 6:30 o'clock position is wider
.4	3569.4	
.3	80.3	
.3	160.6	
.9	171.5	
.0	252.5	
.3	80.3	
.8	170.1	
.0	80.0	
.2	160.2	
.1	240.3	
.0	320.3	
.0	645.3	
.1	970.4	Eroded in thrust chamber throat at 5:00, 7:00, and 9:00 o'clock positions
.2	1295.6	Additional erosion in throat at 3:00, 5:00, 7:00, and 11:00 o'clock positions
.3	1620.9	Additional erosion in throat at 9:00 o'clock position
.5	1946.4	All erosions enlarged
.0	2271.4	All erosions enlarged
.3	40.3	
.0	80.3	
.6	80.6	
.0	160.6	

TABLE 2

PHASE I TESTING AT NEOSHO

3

	Comments
	Eroded in thrust chamber throat at 5:30 and 6:30 o'clock positions
	Erosion at 6:30 o'clock position is wider
	Erosion at 6:30 o'clock position is wider
	Eroded in thrust chamber throat at 5:00, 7:00, and 9:00 o'clock positions
	Additional erosion in throat at 3:00, 5:00, 7:00, and 11:00 o'clock positions
	Additional erosion in throat at 9:00 o'clock position
	All erosions enlarged
	All erosions enlarged

TABLE 2

(Continued

Engine Serial No.	Configuration	Test No.	Duration, seconds	Cumulative Duration, seconds	
0003-5	6	8876	80.2	80.2	
		77	80.2	160.4	
		78	80.4	240.8	
		79	170.0	410.8	
		80	325.1	735.9	Erosion in th
		81	325.0	1060.9	Injector clea
		82	325.3	1386.2	
		83	325.1	1711.3	Injector clea
		84	325.9	2037.2	Additional er
		85	324.9	2362.1	Injector clea
		86	324.9	2687.0	
		87	324.9	3011.9	Injector clea
		88	324.9	3336.8	
	7	89	325.0	325.0	Injector clea
		90	325.0	650.0	
		91	323.8	973.8	Injector clea
		92	325.6	1299.4	
		93	324.9	1624.3	

1

TABLE 2

(Continued)

re 1, ;	Comments
	Erosion in thrust chamber throat at 2:00 and 9:00 o'clock positions
	Injector cleaned prior to test
	Injector cleaned prior to test
	Additional erosion at 1:00 and 1:30 o'clock positions
	Injector cleaned prior to test
	Injector cleaned prior to test (additional erosion at 4:00 o'clock position)
	Injector cleaned prior to test
	Injector cleaned prior to test

2

TABLE 3

SUMMARY OF PHASE I TESTING AT
PROPULSION FIELD LABORATORY

Engine Serial No.	Test No.	Duration, seconds	Cumulative Duration, seconds
0024-1 and 0026-1	128	10	10
	129	290	300
	130	35	335
	131	290	625
	132	125	750
	133	290	1040
	134	290	1330
	135	290	1620
	136	290	1910
	137	20	1930

NOTE: Standard YLR-101-NA-13 vernier engines were used during sustainer and vernier tests at Propulsion Field Laboratory

TRANSIENT PERFORMANCE

Start transients of the downrated Configuration 1 vernier engine (shown in Table 1) were unsatisfactory. The initial thrust buildup rate was approximately 3.02 lb/ms as compared to approximately 8.50 lb/ms experienced with production YLR101-NA-13 vernier engines. Photographic data indicated that the quality of oxidizer reaching the chamber at start was too poor to provide satisfactory combustion at the transition from hypergolic igniter to RP-1 fuel combustion.

The lower flowrate caused the velocity of the oxidizer in the uncooled propellant lines between the propellant valve and the chamber to drop from 16.4 ft/sec to 11.4 ft/sec. The heat transfer to a given mass of LOX was increased, resulting in a lower-density, warmer oxidizer reaching the chamber at start. Decreasing the diameter of the LOX system line from 3/4 inch to 1/2 inch increased the velocity of oxidizer in those lines to 30.0 ft/sec and provided an initial thrust buildup rate of 6.94 lb/ms (Fig. 1).

To determine the required setting of the fuel injection pressure switch, actual values of the fuel injection pressure at ignition were used. An optimum setting of 90 ±15 psig was determined by considering run-to-run variations in pressure and by computing the minimum setting required to ensure continuation of combustion after switch pickup.

As expected, the cutoff transient at the 525-pound thrust level (Fig. 2) was similar in configuration to the cutoff transient experienced at the 830-pound thrust level. A summary of the reduced cutoff impulse calculations indicates that the cutoff impulse experienced with the

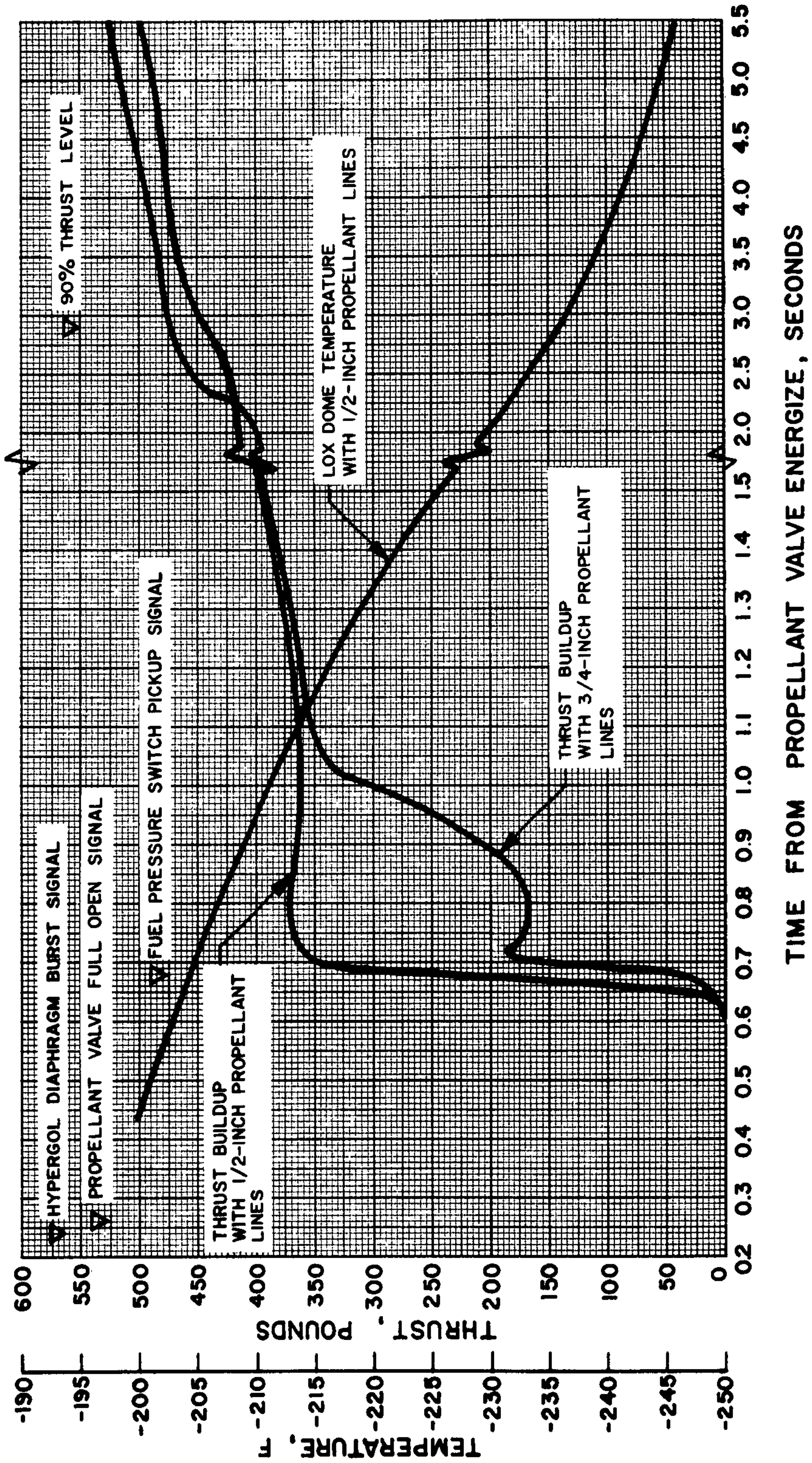


Figure 1. Typical Thrust Buildup After PROPELLANT VALVE ENERGIZE During Phase I Testing

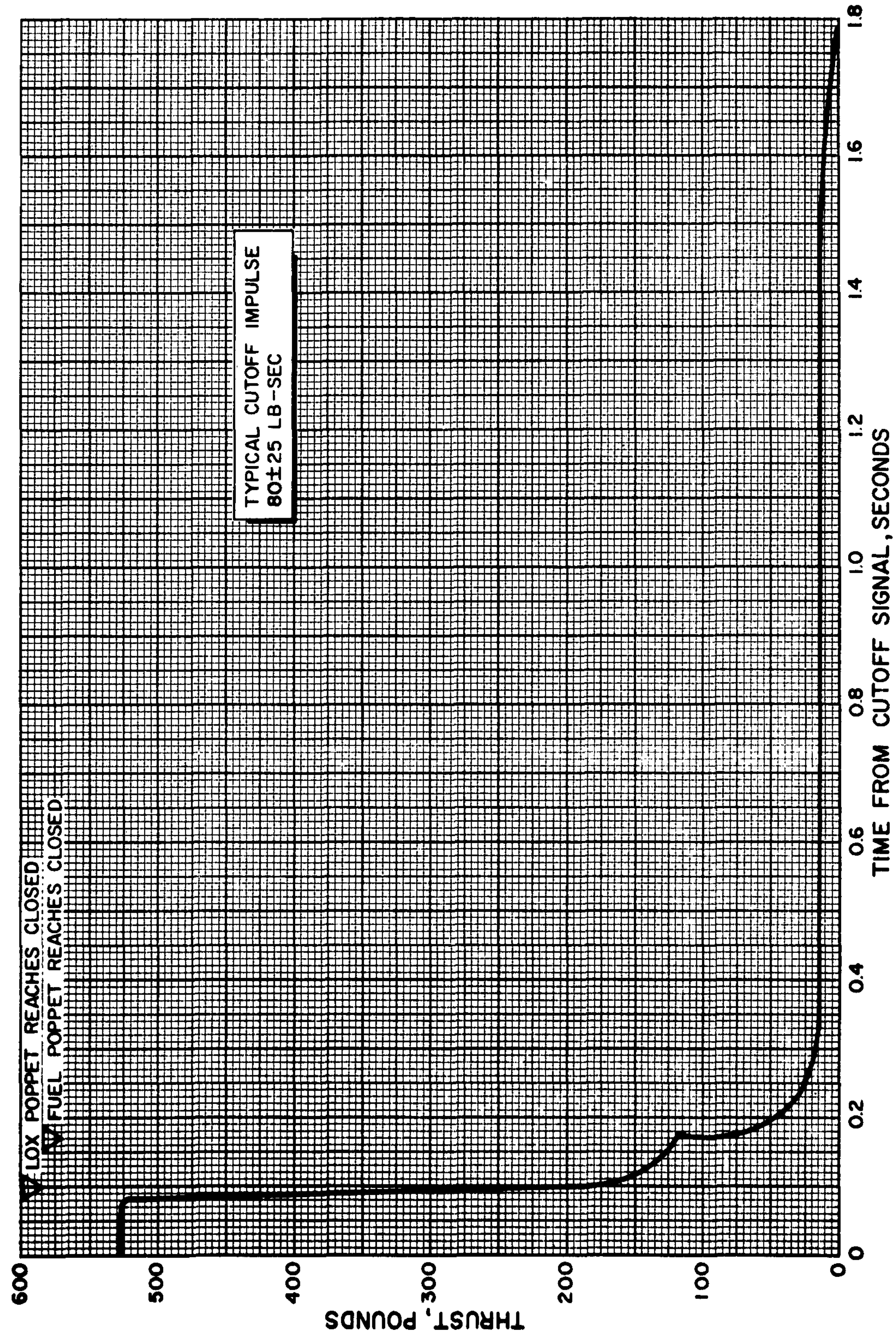
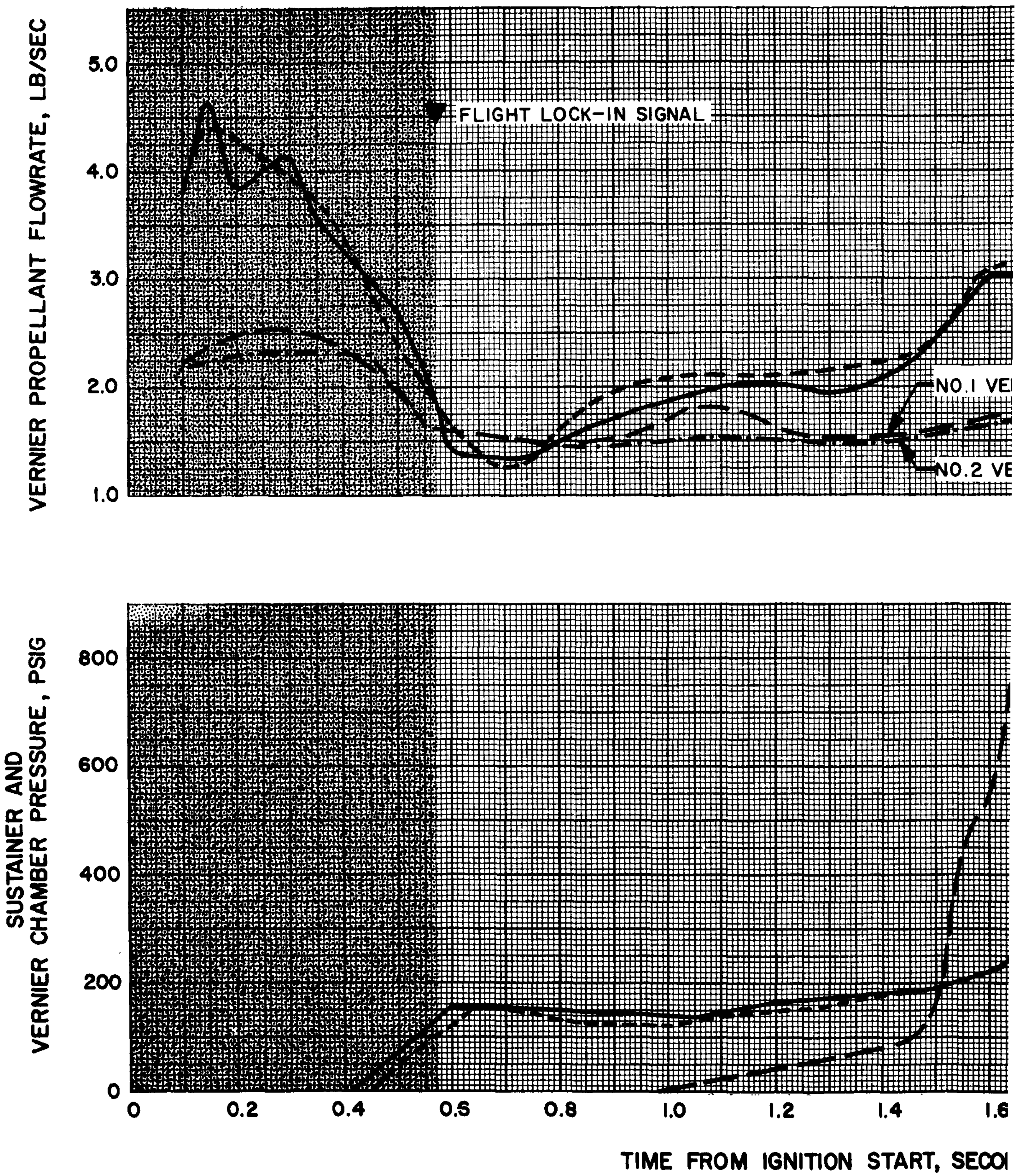


Figure 2. Typical Thrust Decay After Vernier Cutoff During Phase I Testing

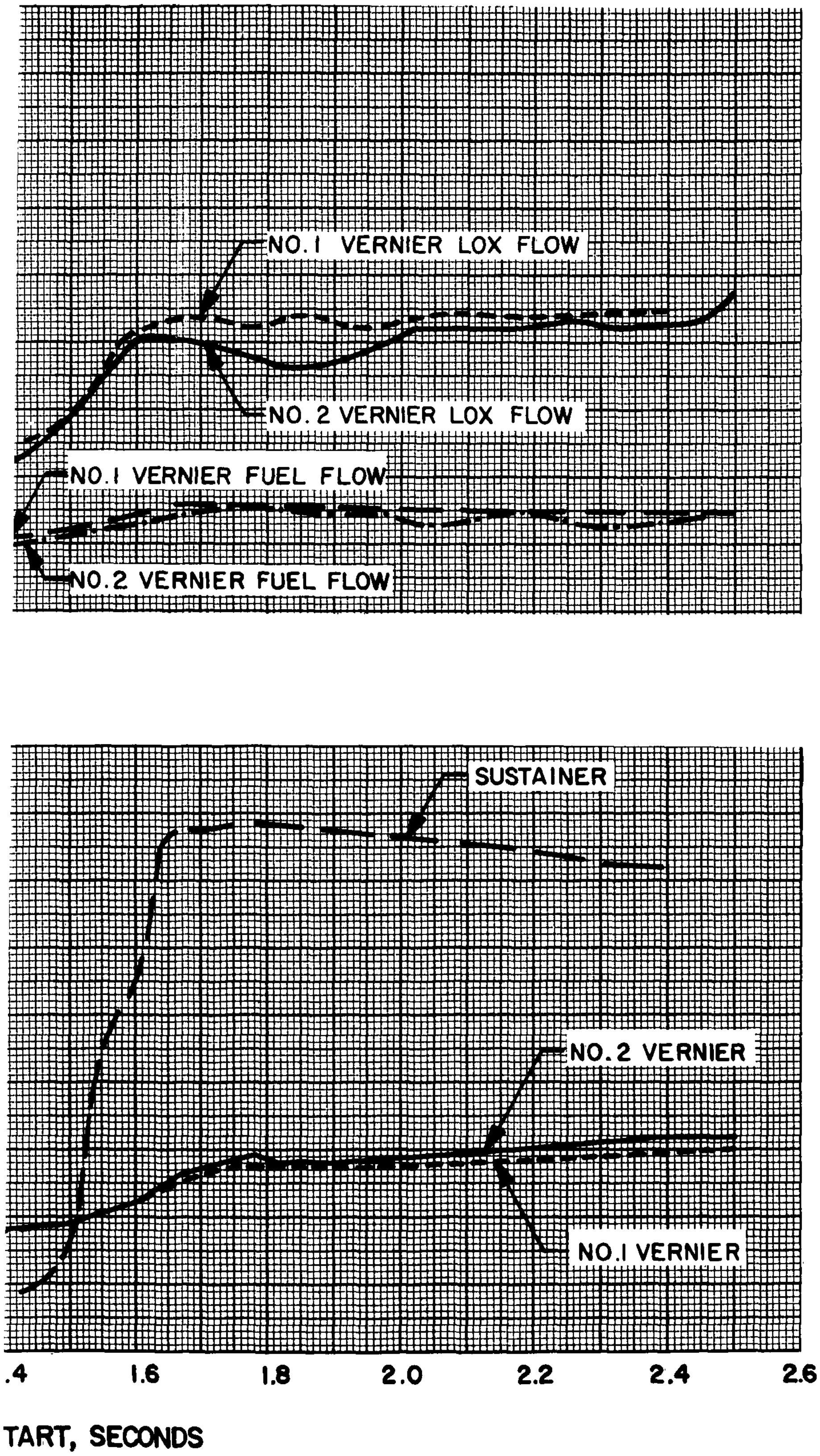
Configuration 7 vernier engine (Table 1) was 80 ±25 lb-sec. The cutoff circuit used during the analyzed tests did not include the delay of 55 ±18 milliseconds imposed by the missile cutoff delay circuit.

Analysis of data from the PFL sustainer/vernier tests confirmed the fact that start transients of the standard YLR101-NA-13 vernier are unsatisfactory when the vernier is downrated to the 525-pound thrust level. Figure 3 is a plot of the sustainer/vernier start transient with the vernier engines orificed for 830 pounds of tank-fed thrust. Figure 4 is a plot of start transients of the same engines several tests later, with the vernier engines orificed to produce 500 pounds of tank-fed thrust. Comparison of Fig. 3 and 4 indicates the slow buildup of vernier chamber pressure when the thrust is downrated by changing the orifices only.

Although the combined sustainer/vernier tests verified the unsuitability of the start transients of the downrated standard vernier, the sustainer engine start transient was not adversely affected by the vernier downrating. A comparison of Fig. 3 and 4 indicates that no significant effect on sustainer thrust chamber pressure buildup occured when the vernier engine orificing was changed. Further verification that the downrated vernier does not interfere with the sustainer engine start transient is provided by Fig. 5 and 6. These figures are plots of the sustainer engine gas generator fuel injection pressure and turbine inlet pressure buildups for the two tests summarized in Fig. 3 and 4, and show that the differences between the two tests are insignificant.

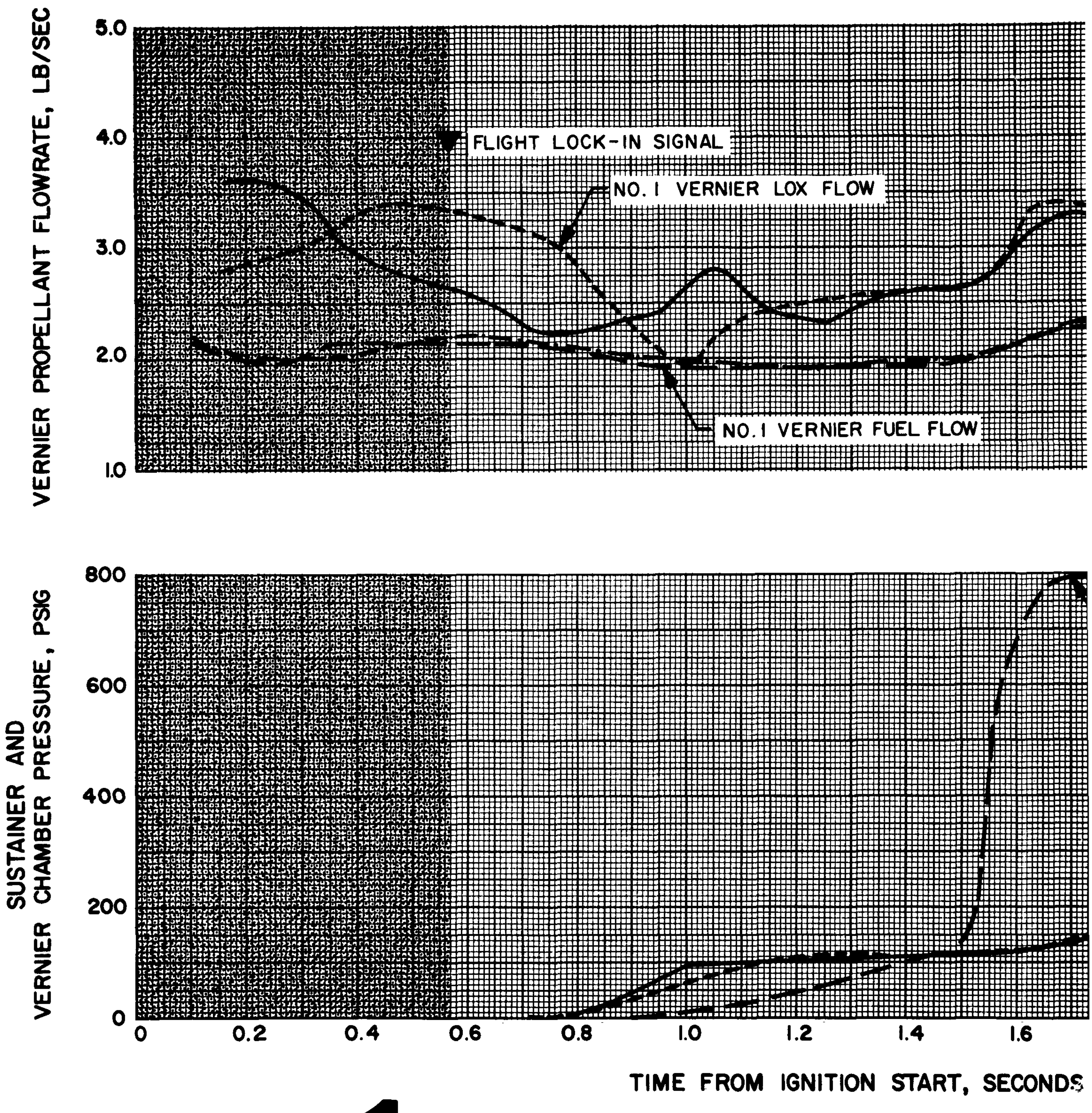

VERNIER PROPELLANT FLOWRATE, LB/SEC
5.0
4.0
3.0
2.0
1.0
FLIGHT LOCK-IN SIGNAL
NO.1 VE
NO.2 VE
SUSTAINER AND
VERNIER CHAMBER PRESSURE, PSIG
800
600
400
200
0
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
TIME FROM IGNITION START, SECO

[redacted]



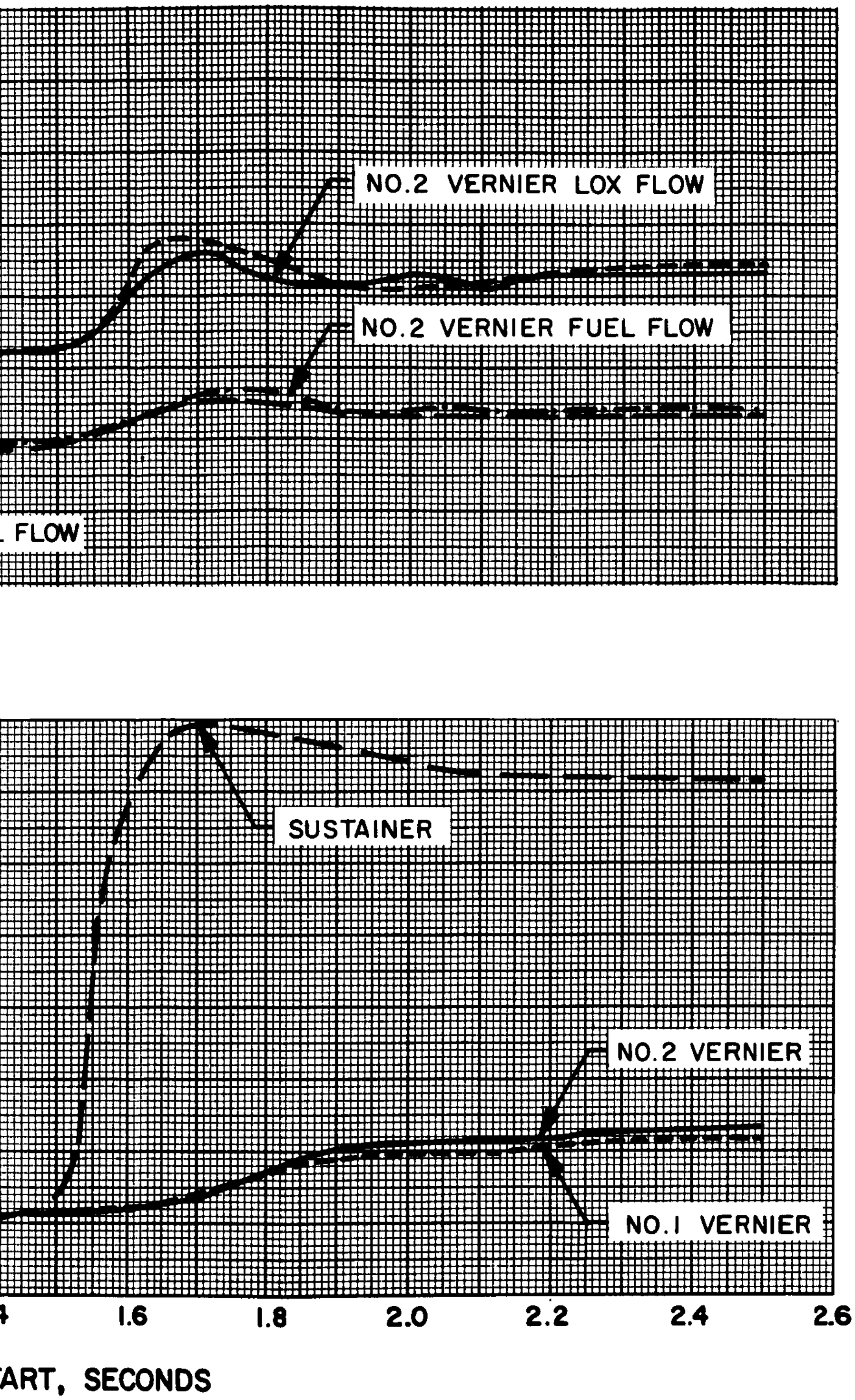
2

Figure 3. Chamber Pressure and Flowrates Using Standard Vernier Engines During Test No. 512-127



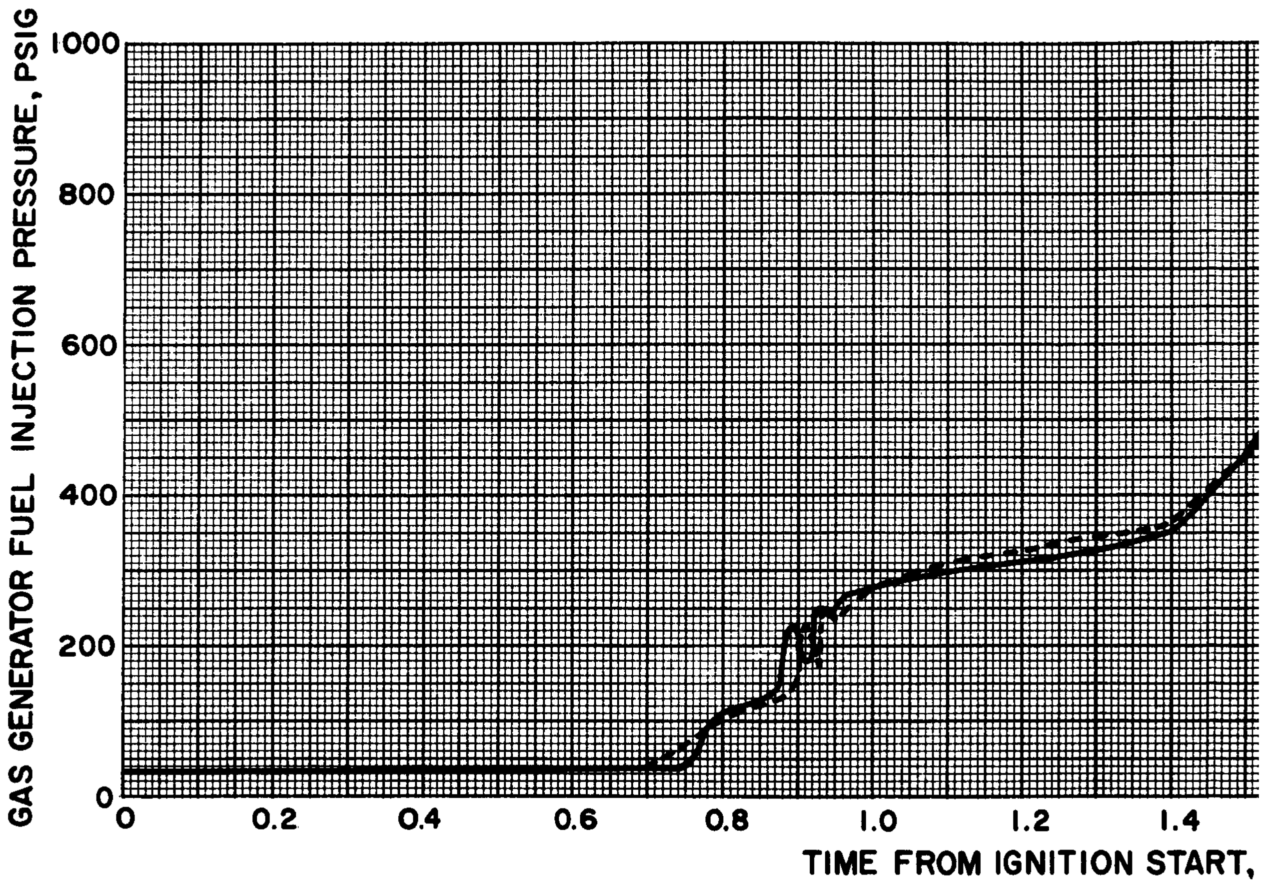
VERNIER PROPELLANT FLOWRATE, LB/SEC
5.0
4.0
3.0
2.0
1.0
FLIGHT LOCK-IN SIGNAL
NO. 1 VERNIER LOX FLOW
NO. 1 VERNIER FUEL FLOW
SUSTAINER AND
VERNIER CHAMBER PRESSURE, PSIG
800
600
400
200
0
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
TIME FROM IGNITION START, SECONDS

1

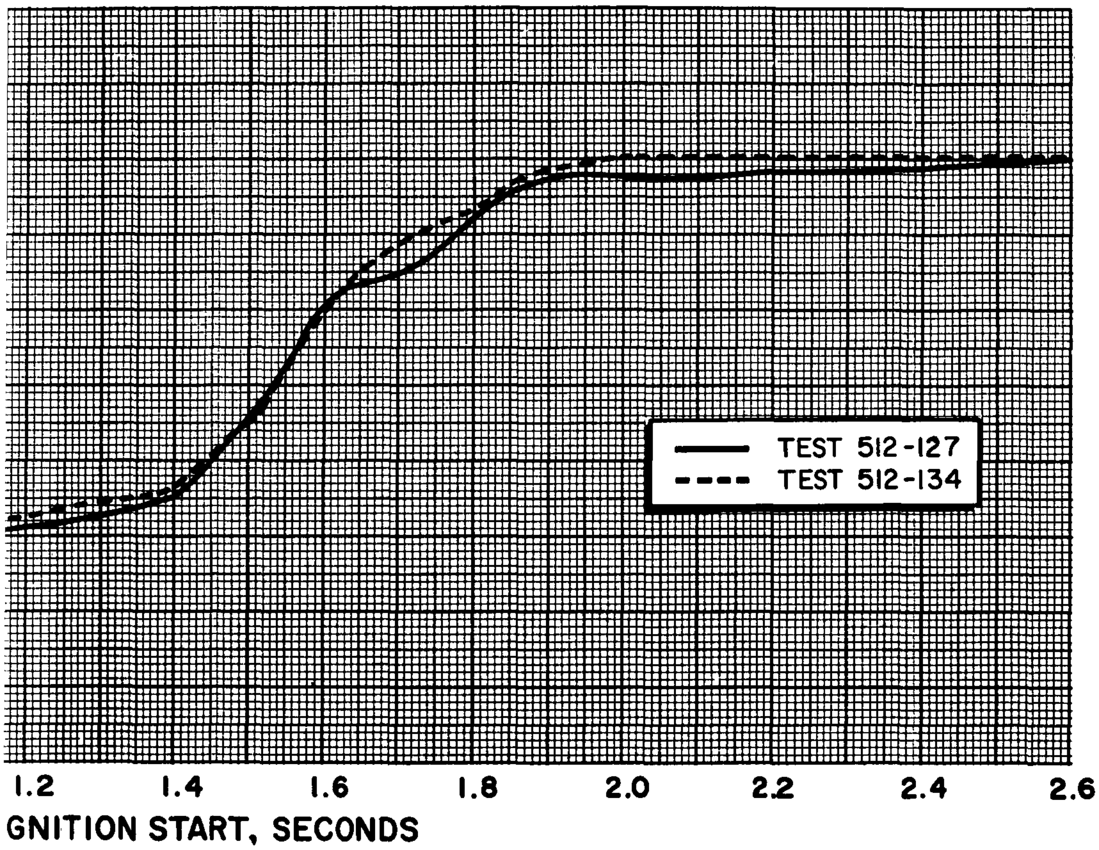


2

Figure 4. Chamber Pressure and Flowrates Using Downrated Vernier Engines During Test No. 512-134

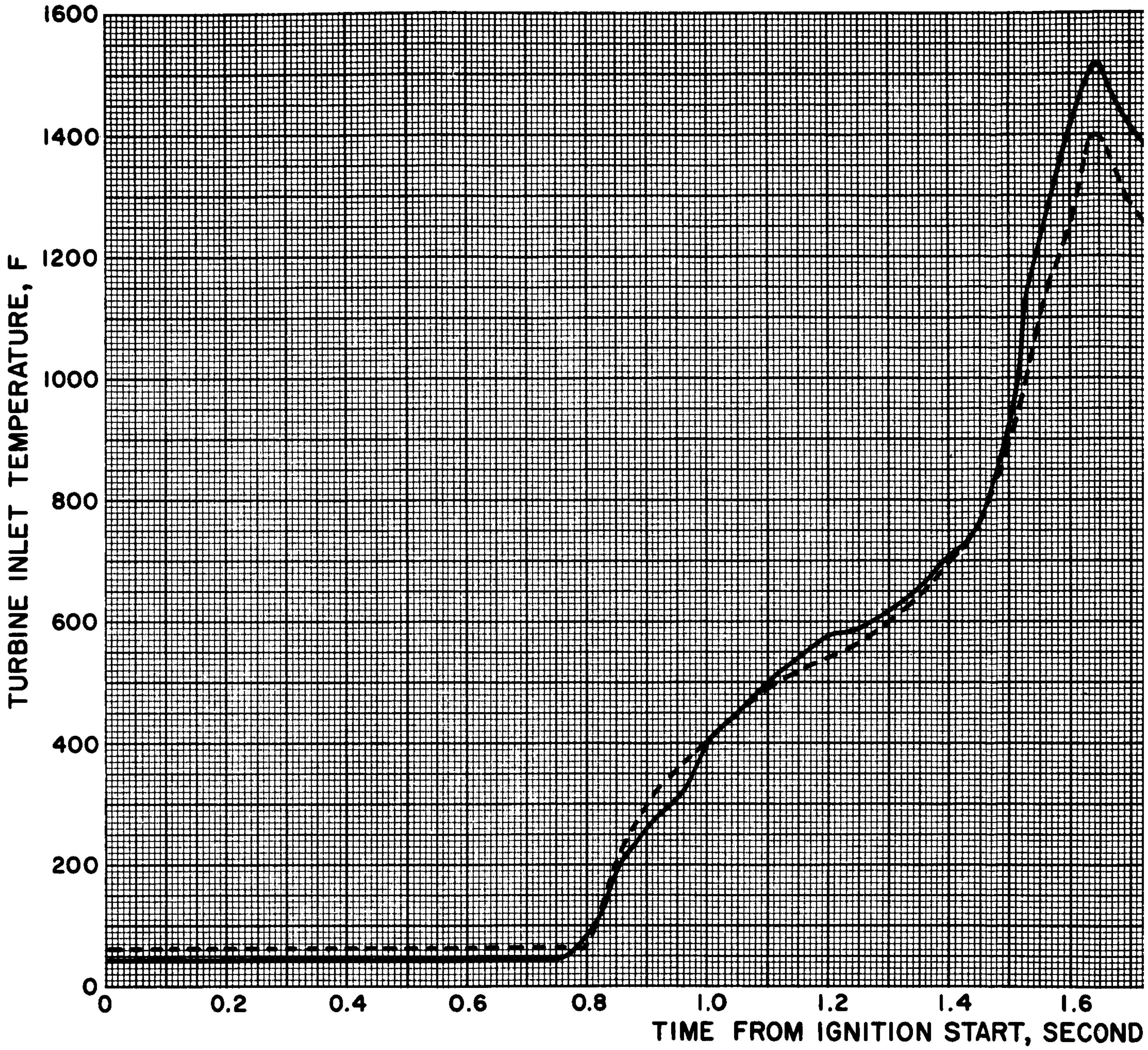

GAS GENERATOR FUEL INJECTION PRESSURE, PSIG
1000
800
600
400
200
0
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
TIME FROM IGNITION START,

1



2

Figure 5. Gas Generator Fuel Injection Pressure Profile After Ignition Start



1600
1400
1200
1000
800
600
400
200
0
TURBINE INLET TEMPERATURE, F
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
TIME FROM IGNITION START, SECOND

1

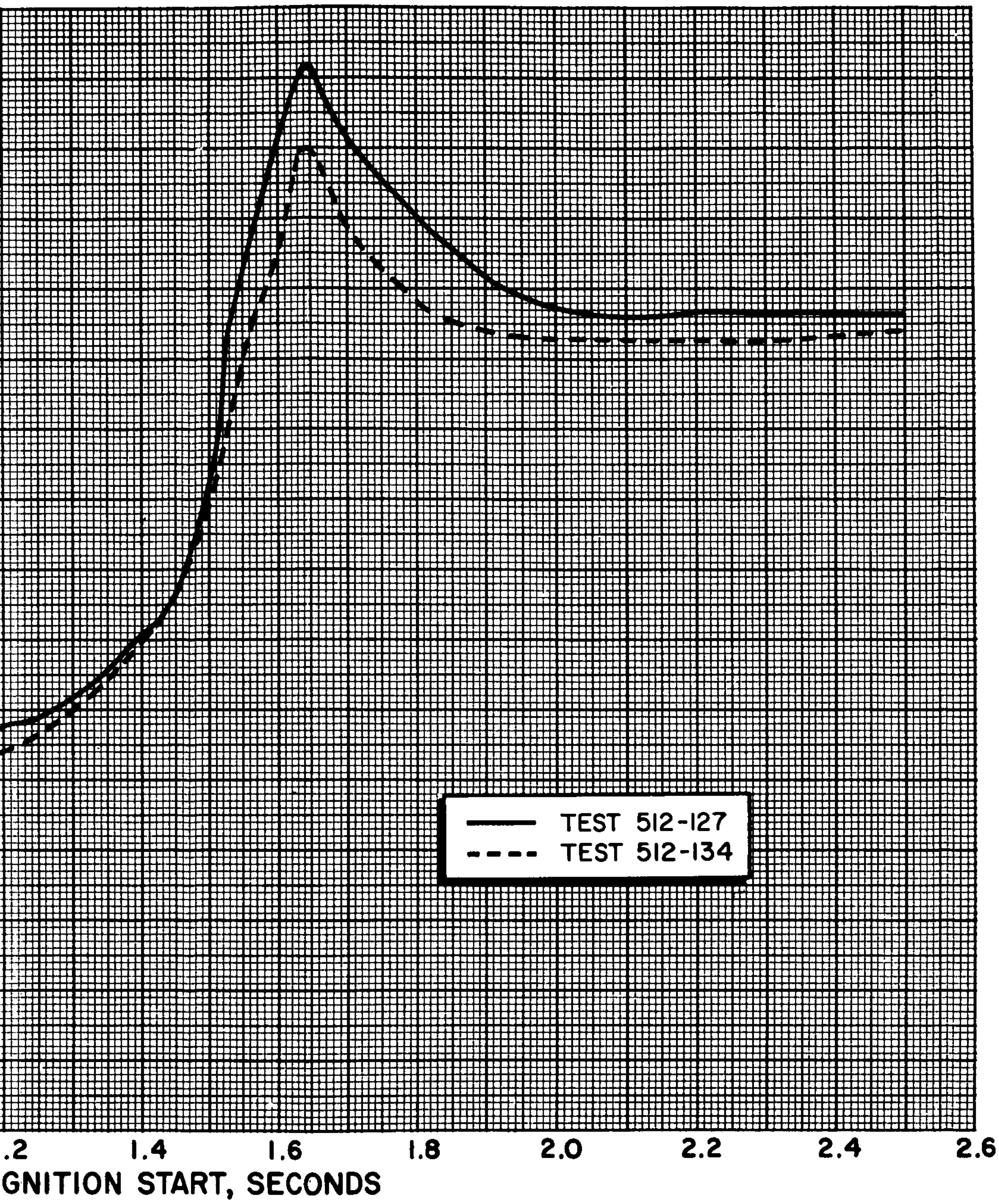


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Figure 6. Turbine Inlet Temperature Profile After Ignition Start

STEADY-STATE PERFORMANCE

Rated and predicted performance obtained from the Phase I testing are presented in Table 4. The tank-fed data presented in this table were tabulated from 49 of the Neosho tests after being reduced to rated tank-fed values of 525 pounds thrust and a mixture ratio of 1.8. Pump-fed performance was predicted from a mathematical balance for this engine system based upon missile orificing for tank-fed performance. Although average performance values obtained from the PFL tests agreed with the data observed during the Neosho testing, a comparison of data slices taken at various times during the testing revealed that the steady-state vernier engine performance shifted during the Neosho and the PFL tests. These shifts were in the form of gradual increases in engine performance and took place in two stages.

Considering pump-fed operation the most significant performance changes took place during the first stage of the shift (from start to approximately 125 seconds of operation). The performance shift continued at a slower rate during the remainder of pump-fed operation (125 to 300 seconds). Typical shifts of performance parameters during pump-fed operation are shown in Fig. 7; numerical values of the shifts are as follows:

Differential Chamber Pressure, psi		Differential Thrust, pounds		Differential Specific Impulse, seconds		Differential Characteristic Velocity, ft/sec		Differential Thrust Coefficient	
Stage 1	Stage 2	Stage 1	Stage 2	Stage 1	Stage 2	Stage 1	Stage 2	Stage 1	Stage 2
+4.5	+1.3	+5.8	+2.0	+3	+1.5	+115	+40	-0.006	-0.002

The exact cause of the performance shift is not known, although the factors listed below could have contributed to the shift experienced.

1. Stabilized LOX temperature in the thrust chamber dome was obtained approximately 100 seconds after ignition. The dome temperature, which affects LOX density and the momentum of LOX entering the chamber, varied with flowrate and probably was a major contributory factor to the shift observed during Stage 1. The time required for this temperature stabilization reflects the time required for chilling down the vernier hardware downstream of the propellant valve after engine start. Hardware upstream of the propellant valve was chilled to -250 F or colder prior to the start of each test.

2. Posttest inspections revealed a thick layer of soft wet carbon on the walls of the thrust chamber combustion zone. In addition, pieces of hard carbon were found on the ground at the test area. These carbon pieces had holes in them and appeared to have formed on the face of the injector and then been blown off during engine operation. Test data revealed that the differential pressure on the fuel side of the injector had decreased from a nominal value of 55 psi at the 1000-pound thrust level to approximately 18 psi at the 525-pound thrust level. It is possible, therefore, that:

    a. Carbon buildup on the face of the injector could affect the injector differential pressure with a resultant effect upon injector efficiency.

TABLE 4

RATED AND PREDICTED PHASE I STEADY-STATE

Performance Level	Inlet Pressure, psia		Thrust, pounds	Mixture Ratio	Specific Impulse, seconds	Characteris Velocity ft/sec
	Oxidizer	Fuel				
Tank Fed (Rated)	350	350	525	1.8	180.1	4919
Pump Fed (Predicted)	438	454	669	1.72	196.4	5038

1

TABLE 4

PREDICTED PHASE I STEADY-STATE PERFORMANCE

Specific Impulse, seconds	Injector End			Propellant Weight Flowrate, lb/sec	
	Characteristic Velocity, ft/sec	Thrust Coefficient	Chamber Pressure, psia	Oxidizer	Fuel
180.1	4919	1.178	212.2	1.87	1.04
196.4	5038	1.255	254.9	2.151	1.254

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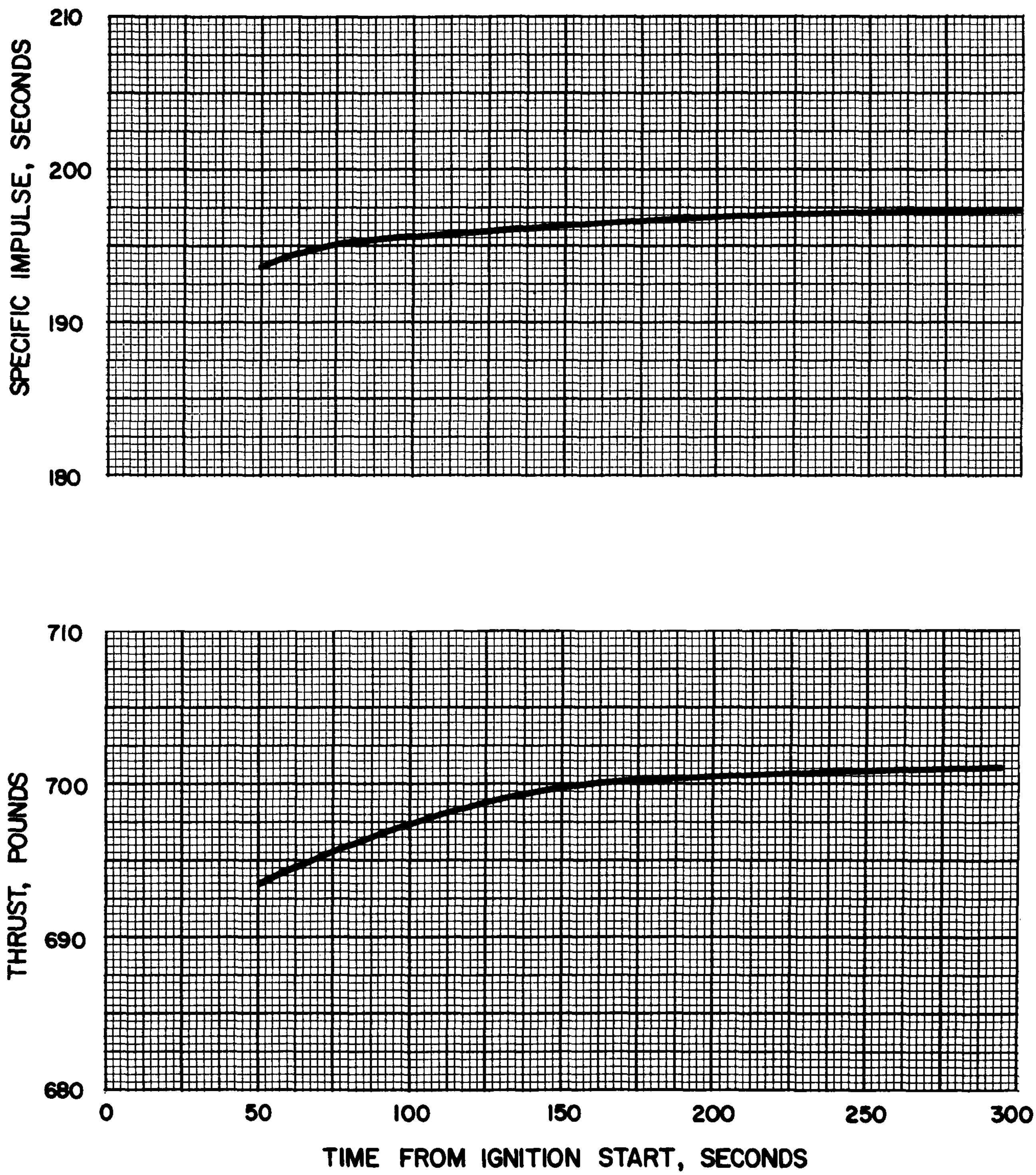

Figure 7. Thrust and Specific Impulse Profiles After Ignition Start

b. Carbon buildup on the walls of the thrust chamber (caused by low-velocity fuel from the showerhead coolant holes) could deflect the low-velocity fuel from the coolant film into the main zone of combustion, affecting combustion efficiency.

The above hypotheses present the possible mechanisms, based on the test observations, by which the performance shift could occur during operation at the downrated thrust level. These shifts were not encountered at the original design points of 1000 and 830 pounds of thrust with a mixture ratio of 1.8.

Combustion instability in the form of a 500-cps "buzz" appeared when the engine was operated at a 450-pound or lower thrust level. The buzz became more pronounced as the thrust level was lowered. At 400 pounds of thrust, the buzz reached 4 g along the axis through the thrust chamber shaft. The normal operation level along this axis is 1.5 g. The buzz was not as pronounced along the other two axes, and reached only 1.5 to 2.0 g (the normal level is approximately 1.0 g).

HARDWARE DAMAGE

Severe thrust chamber throat erosion occurred during the Phase I test program, and Table 2 lists the chamber damage incurred by each of the three thrust chambers used during the Neosho tests. The initial erosion in each thrust chamber occurred at a different duration varying from 736 seconds to 1859 seconds. Although the first erosion on engines S/N 0002-6 and 0003-4 occurred after tests with low mixture ratio and thrust or excessively high mixture ratio, the first erosion on engine S/N 0003-5 was obtained after 736 seconds of nominal performance operation. The thrust chamber from engine S/N 0003-5 was sliced in half and the inner wall (Fig. 8) was removed for examination. Several erosions had progressed to the point where pinholes appeared through the inner chamber wall.

Engine S/N 0026-1, tested on the Alfa-1 test stand at PFL, experienced several throat erosions similar to those encountered during the Neosho testing. Because of the carbon accumulation in the chamber and the lack of accessibility to inspect the chamber on the test stand, the erosions were not observed during the test series but were found during engine checkout after the test program was completed. Therefore, no history can be compiled as to time of damage or engine operation at the time of damage. The majority of the engine operation was at nominal thrust and 1.9 mixture ratio except for one test which, because of faulty orificing, was conducted at a mixture ratio of approximately 1.5.

The occurrence of erosion during Phase I testing is shown in Fig. 9 through 13. These figures indicate the operating regime to which each engine was exposed until the first reported instance of erosion.

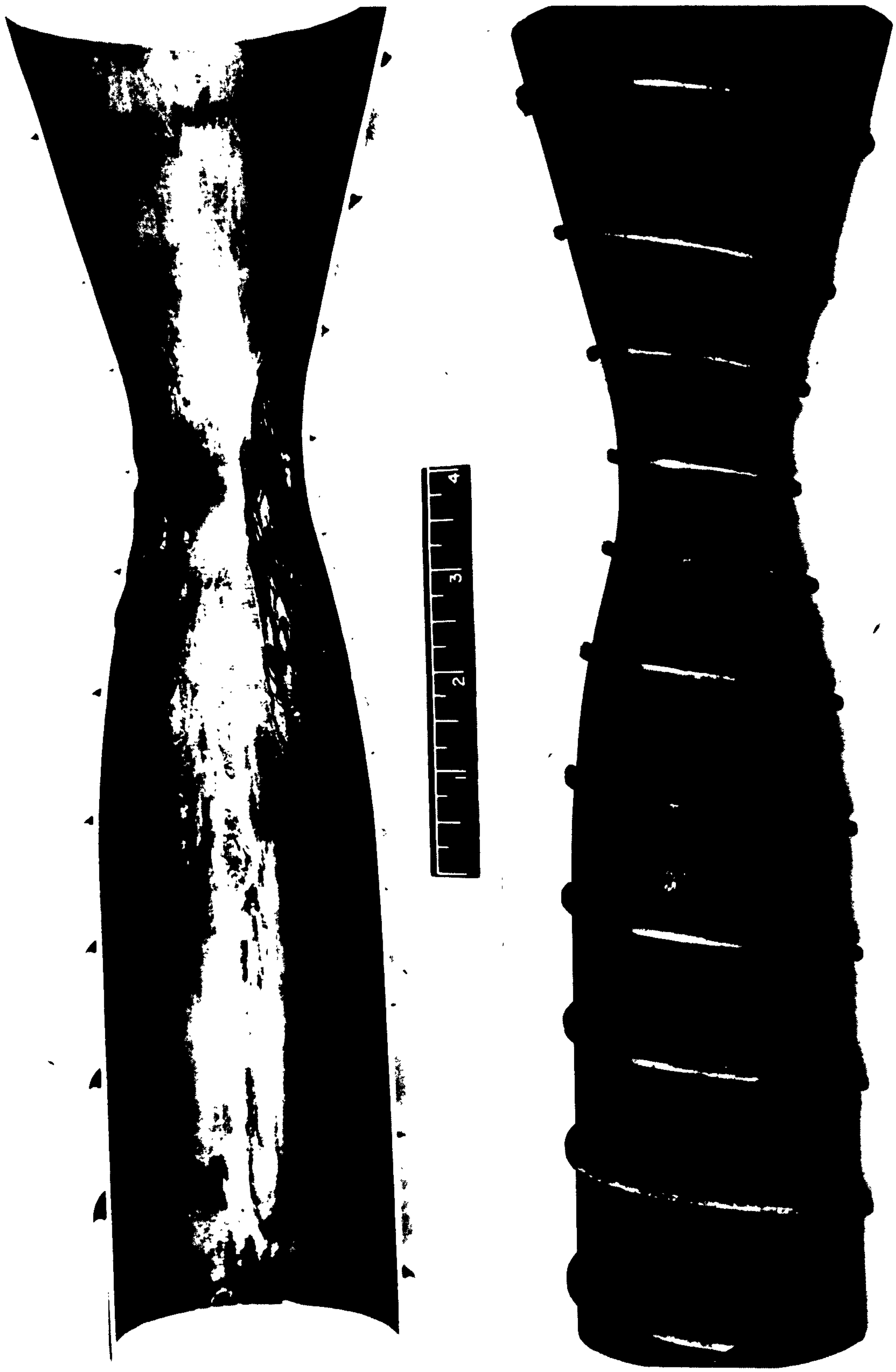

Figure 8. Thrust Chamber From Engine S/N 0003-5

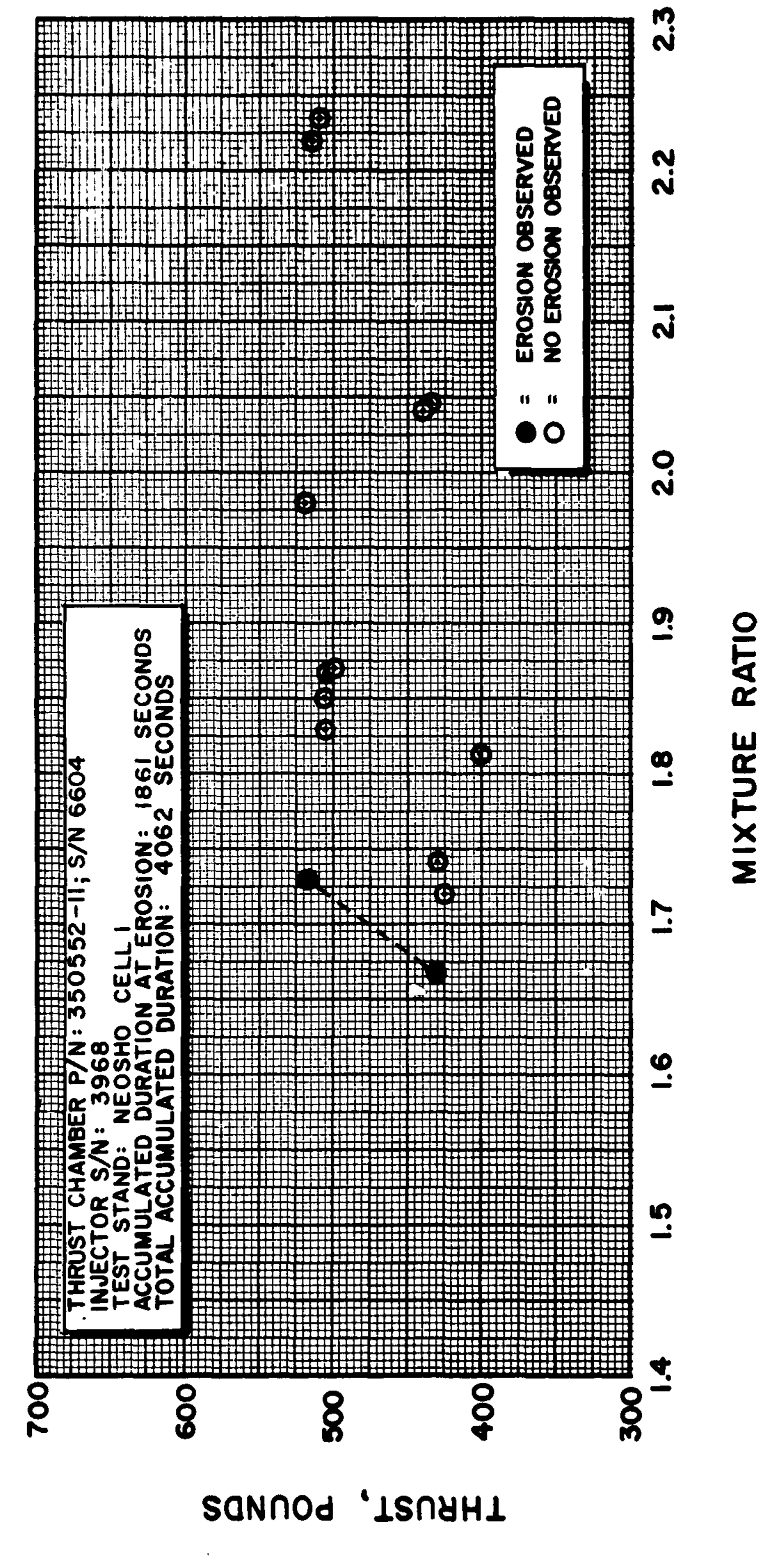

Figure 9. Operating Regime of Injector P/N 350604 Tested With Engine S/N 0002-6

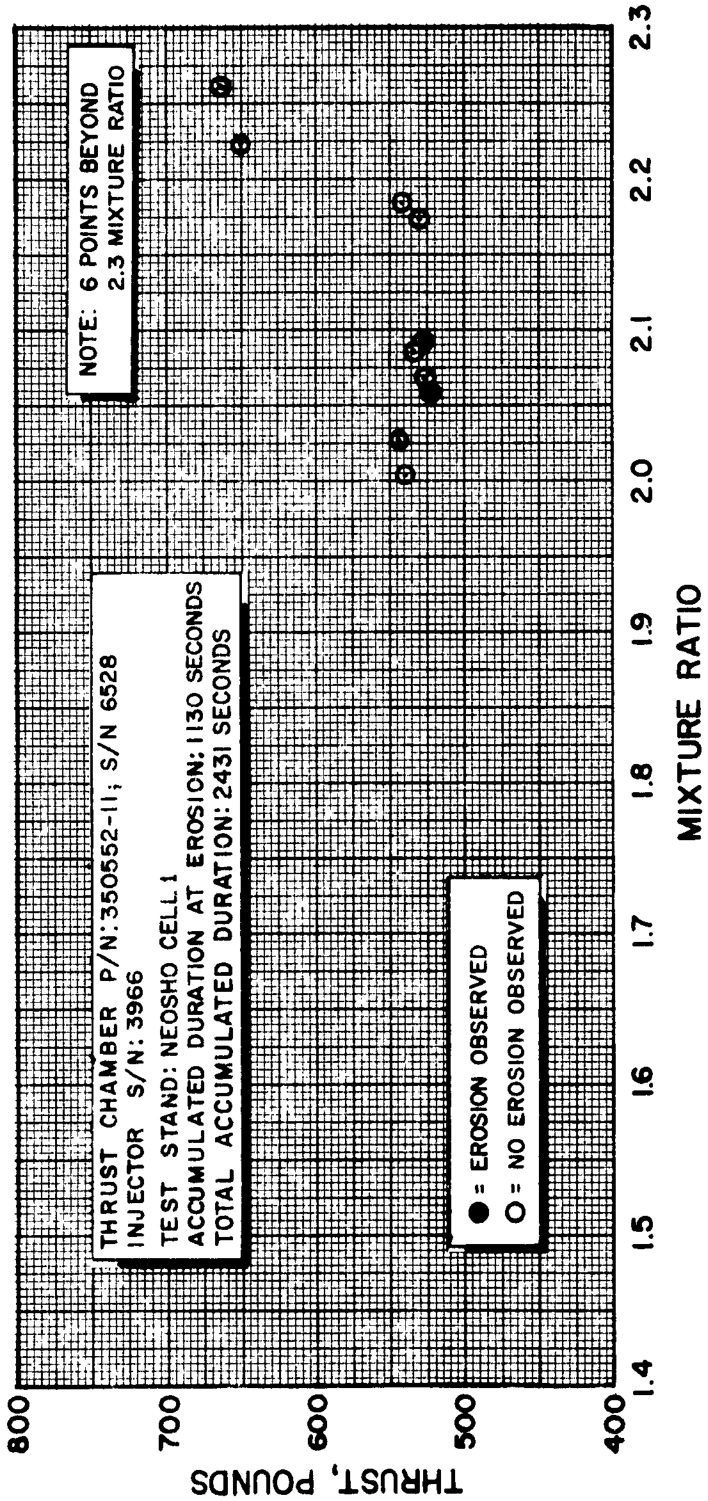

Figure 10. Operating Regime of Standard Injector P/N 350604
Tested With Engine S/N 0003-4

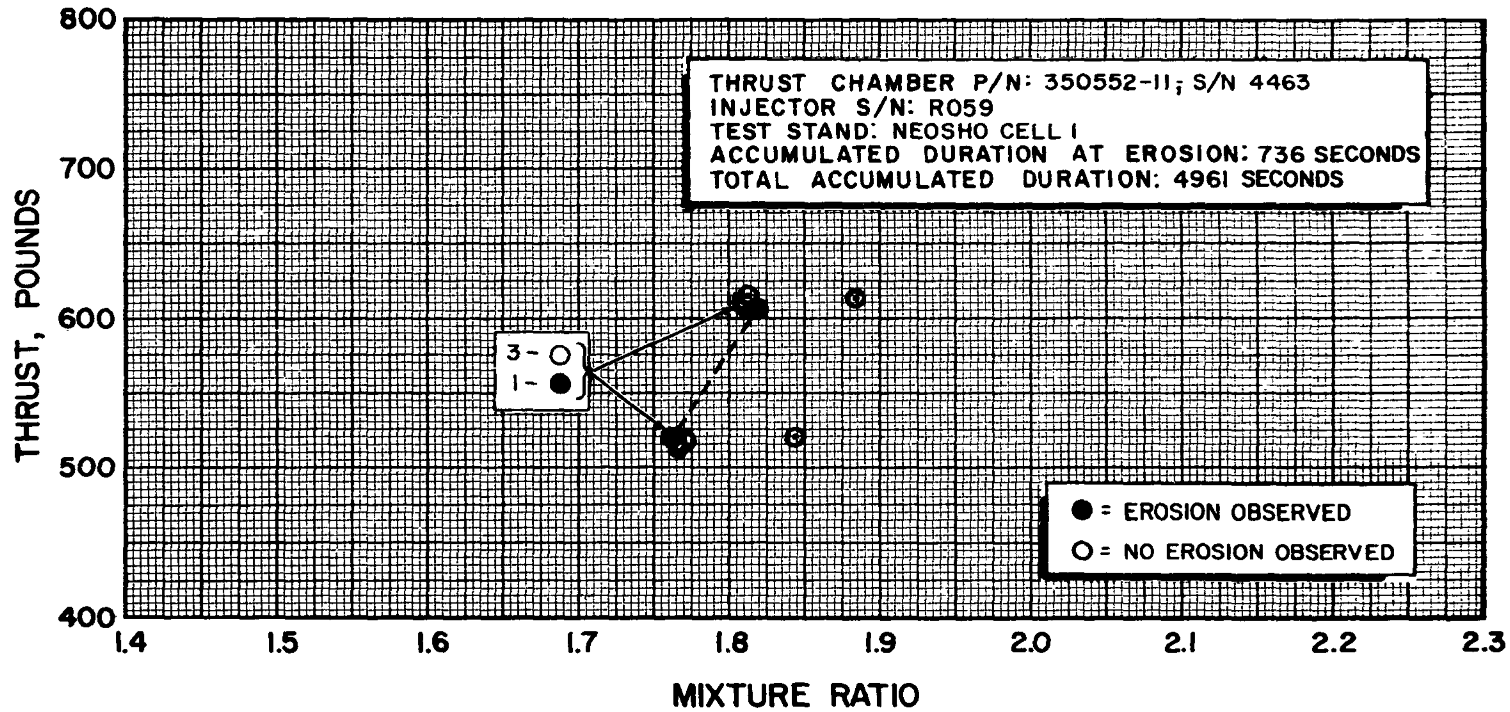

Figure 11. Operating Regime of Standard Injector P/N 350604 Tested With Engine S/N 0003-5

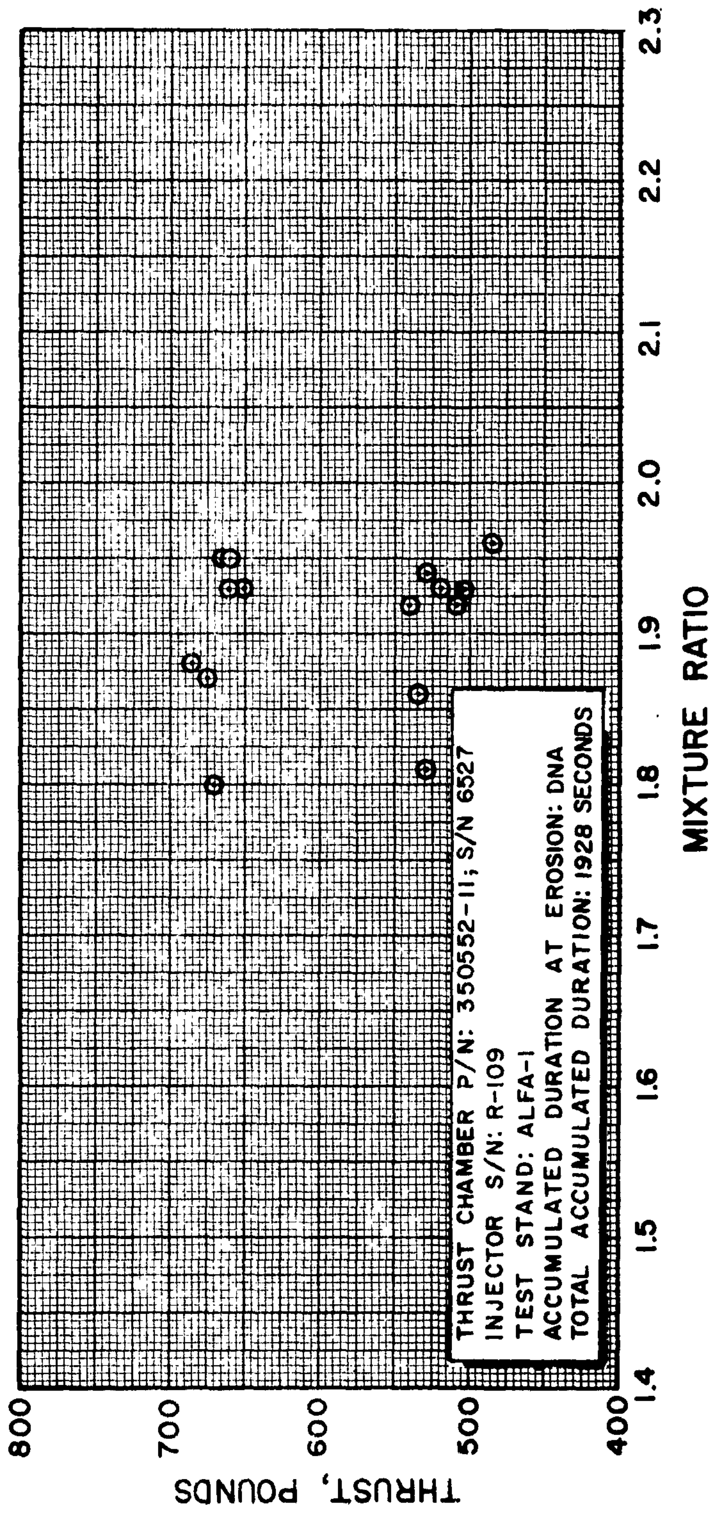

Figure 12. Operating Regime of Standard Injector P/N 350604 Tested With Engine S/N 0024-1

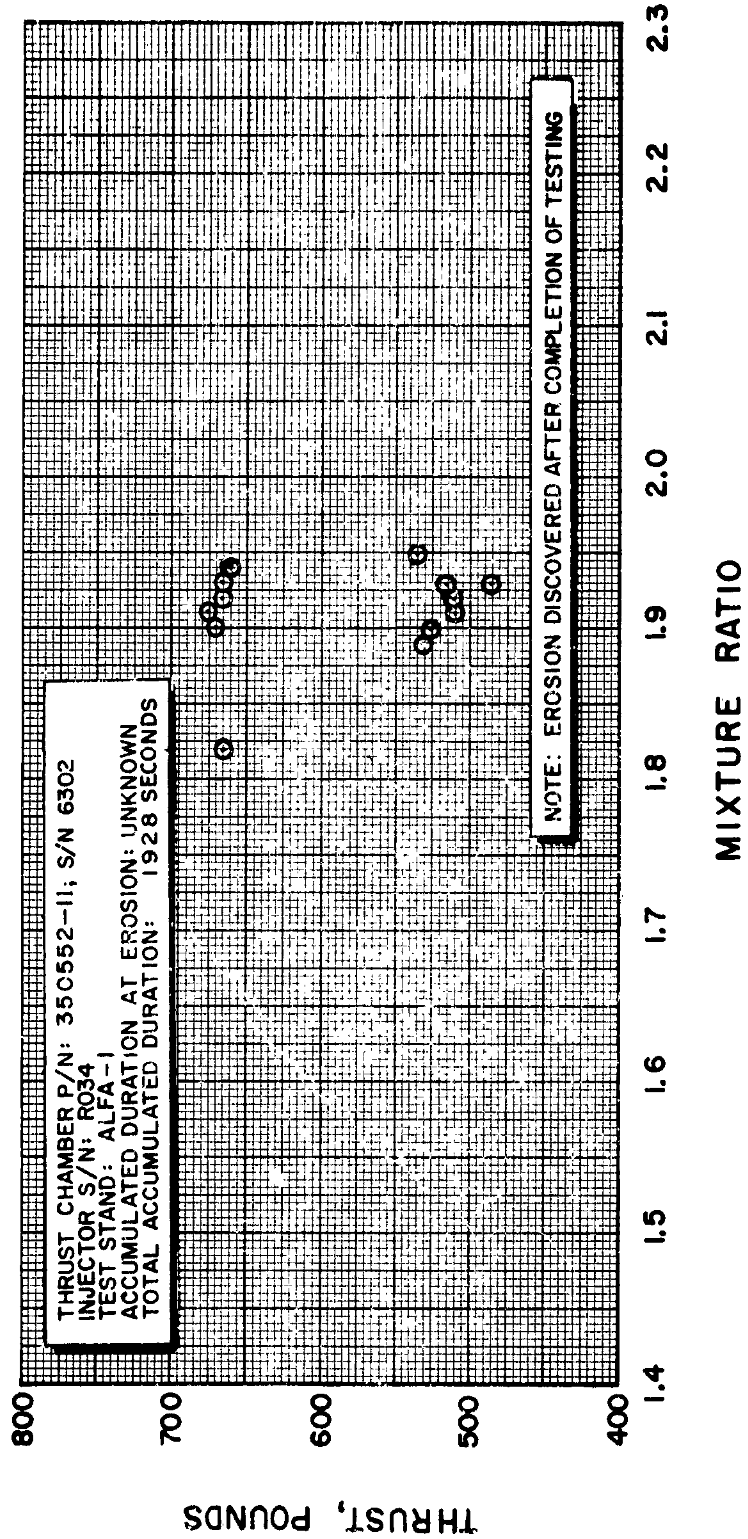

Figure 13. Operating Regime of Standard Injector P/N 350604 Tested With Engine S/N 0026-1

Although the thrust chamber erosions experienced during the Phase I testing were quite severe (Fig. 8), engine transient and steady-state performance were not affected by the damage. Figure 14 is a plot of rated tank-fed specific impulse during testing of engine S/N 0003-5. No significant decrease in specific impulse or operating level occurred as the chamber erosion progressively worsened. The bulk fuel temperature was measured at the fuel injector manifold during the tests on engine S/N 0003-5. During the first 10 to 12 seconds after ignition of each engine, this temperature rose about 120 degrees above the engine fuel inlet temperature. After 60 seconds, the temperature stabilized at 30 to 50 degrees above the fuel inlet temperature. No data are available for comparison, but it is probable that, except for localized hot spots, this stabilized differential temperature was sufficiently low to rule out an excessively high thrust chamber wall temperature.

The erosion spots (Fig. 11) apparently were caused by LOX fans that impinged on the chamber wall. This problem had previously occurred at thrust levels from 830 to 1000 pounds, and was eliminated during development of the P/N 350604 injector by adding 12 fuel showerhead holes around the periphery of the injector. This formed a fuel screen between the LOX fans and the chamber wall. At thrust levels between 525 and 600 pounds, the velocity of the fuel through the injector was reduced by more than half. A subsequent loss in fuel screen momentum also occurred, and apparently allowed the LOX fans to break through to the wall, resulting in hot spots similar to those experienced prior to the last injector modification.

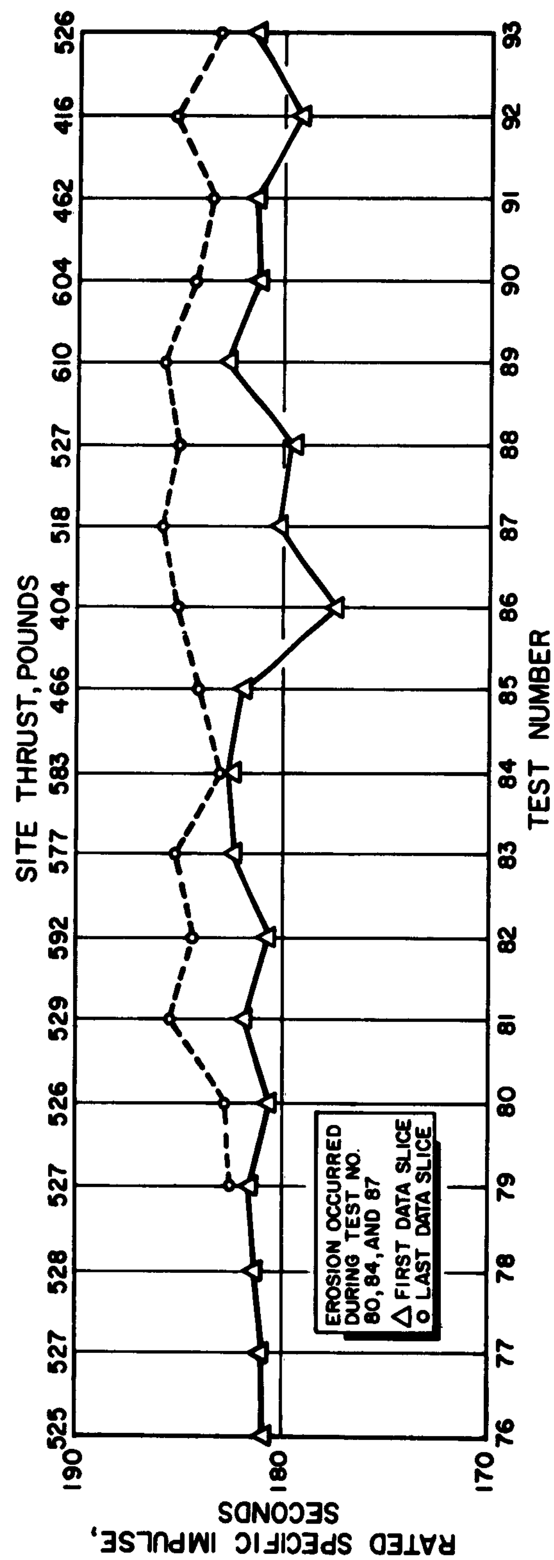

Figure 14. Rated Specific Impulse During Testing With Engine S/N 0003-5

PHASE II TEST PROGRAM

OBJECTIVES

The prime objective of Phase II of the YLR101-NA-15 vernier engine development program originally was to develop and prove the reliability of a 525-pound-thrust vernier engine which had been modified (repackaged) to provide a revised engine-to-missile interface. Specific design changes required for this modification included the following:

1. The line diameters on the oxidizer side were changed from 3/4 inch to 1/2 inch. This change was made to improve the start characteristics of the vernier engine at the lower thrust level of 525 pounds.
2. The LOX and fuel orifices were relocated. The LOX orifice was moved from the inlet to the propellant valve to the middle of the LOX line between the propellant valve and the pitch body. The fuel orifice was moved from the propellant valve inlet to the upstream end of the hypergol container. Both orifices were countersunk on the downstream side to improve repeatability of the pressure loss.
3. The yaw actuator mount pad on the vernier engine T-shaft was moved 1/2 inch outboard to provide additional clearance for the General Dynamics/Astronautics (GD/A) heat shield.
4. The pitch gimbal body was redesigned to provide a suitable mating groove for the GD/A heat shield and to incorporate a special drain fitting for hydraulic fluid.

4. The pitch gimbal body was redesigned to provide a suitable mating groove for the GD/A heat shield and to incorporate a special drain fitting for hydraulic fluid.

5. The vernier engine mount was changed to provide new interface plates.

6. A fuel inlet line was added from the interface plate on the mount to the propellant valve inlet.

7. The thrust chamber shaft was extended because of the yaw actuator being moved outboard. The yaw protractor pointer was added to the thrust chamber body.

8. The fuel injection pressure switch was replaced by a switch with a lower actuation pressure setting.

Because of the thrust chamber erosions which had been experienced at the 525-pound thrust level during Phase I testing, a decision was made to increase the thrust of the first 10 production YLR101-NA-15 vernier engines to a tank-fed thrust level of 777 pounds. This provided time to develop a modified injector which would minimize thrust chamber erosion at the 525-pound thrust level. This "uprated" vernier engine was given the model designation YLR101-NA-15 MD 1. Phase II tests were then conducted on the YLR101-NA-15 MD 1 vernier engine with the following specific objectives:

1. To establish performance values at the revised uprated thrust level

2. To provide confidence in the ability of the engine hardware to operate at the uprated thrust level for a total duration in excess of the required engine life

3. To exceed the required gimbal life of the engine both in total gimbal cycles and gimbal frequency

4. To ensure satisfactory engine start and cutoff transients

5. To obtain orifice size vs differential pressure information during actual engine operation

TEST SUMMARY

Fifty-four tests were conducted at the Neosho facility to accomplish the Phase II program objectives. Two production-quality YLR101-NA-15 engines (S/N 3501 and 3502) were used during the tests.

The Neosho facility bypass system, used to simulate tank- and pump-fed levels, was reorificed to provide the uprated engine inlet conditions shown in Table 5, and various modifications were made to the engine LOX systems (Table 6) to remove excessive pressure losses from the engine LOX system so that the uprated performance could be obtained. The last column of Table 6 shows the amount of pressure loss removed by each modification. The differential pressure values are at the uprated ank-fed LOX flowrate of 2.54 lb/sec. Table 7 presents a summary of test results.

TABLE 5

PHASE II UPRATED ENGINE INLET CONDITIONS

Performance Level	Inlet Pressure, psig		Propellant Flowrate, lb/sec	
	Oxidizer	Fuel	Oxidizer	Fuel
Tank Fed	528	528	2.54	1.41
Pump Fed	645	671	2.85	1.64

TABLE 6

PHASE II ENGINE CONFIGURATION

Configuration	Basic Engine	Modifications	Resulting Decrease in LOX Differential Pressure, psid
1	Standard YLR101-NA-15	None	
2	Standard YLR101-NA-15	Weld dropthrough was cleaned from all lines; 3/4-inch to 1/2-inch reducing fittings countersunk where possible. (Now standard requirement for all YLR101-NA-15 engines)	11.0
		Replaced 1/2-inch dome flex line and yaw elbow with 3/4-inch dome flex line and yaw elbow	27.0
		Replaced 1/2-inch flex line (LOX bleed valve to propellant valve) with 1/2-inch stainless-steel tube	28.3

TABLE 7

SUMMARY OF PHASE II TESTING AT NEOSHO

Engine Serial No.	Test No.	Duration, seconds	Cumulative Duration, seconds	Comments
3501	8894	95.4*	95.4	
3502	95	81.4*	81.4	
	96	98.1*	179.5	
	97	75.1*	254.6	
	98	79.3*	333.9	
3501	99	88.1*	183.5	
	8900	283.5	467.0	
	01	328.3	795.3	
	02	321.4	1116.7	
	03	323.3	1440.0	
	04	325.2	1765.2	
	05	326.5	2091.7	
	06	325.7	2417.4	
	07	326.3	2743.7	Fuel leak from upper and lower ports (
3502	08	325.7	659.6	
	09	326.9	996.5	Slight LOX leak at union in pitch body
	10	326.9	1323.4	Slight LOX leak at union in pitch body
	11	324.9	1648.3	
	12	325.6	1973.9	Small fuel leak from lower port of yaw
	13	326.4	2300.3	
	14	160.1	2460.4	Facility malfunction
	15	255.7	2716.1	Facility malfunction
	16	325.3	3041.4	Injector cleaned prior to test
	17	325.5	3366.9	Small fuel leak from lower port of yaw
	18	330.4	3697.3	
	19	166.4	3863.7	Facility malfunction
	20	350.8	4214.5	
	21	330.7	4545.2	
	22	326.6	4871.8	
	23	328.0	5199.8	Erosion in thrust chamber throat at 3:
	24	326.3	5526.1	
	25	325.3	5851.4	
	26	326.8	6178.2	
	27	329.9	6508.1	
	28	330.2	6838.3	
	29	330.5	7168.8	Small fuel leak from lower port of yaw

TABLE 7

OF PHASE II TESTING AT NEOSHO

2

...ative ...tion, ...onds	Comments
.4	
.4	
.5	
.6	
.9	
.5	
.0	
.3	
.7	
.0	
.2	
.7	
.4	
.7	Fuel leak from upper and lower ports of yaw housing
.6	
.5	Slight LOX leak at union in pitch body
.4	Slight LOX leak at union in pitch body
.3	
.9	Small fuel leak from lower port of yaw housing
.3	
.4	Facility malfunction
.1	Facility malfunction
.4	Injector cleaned prior to test
.9	Small fuel leak from lower port of yaw housing
.3	
.7	Facility malfunction
.5	
.2	
.8	
.8	Erosion in thrust chamber throat at 3:30 o'clock position
.1	
.4	
.2	
.1	
.3	
.8	Small fuel leak from lower port of yaw housing

TABLE

(Contin

Engine Serial No.	Test No.	Duration, seconds	Cumulative Duration, seconds	
	30	330.5	7499.3	
	31	350.4	7849.7	Fuel leak
	32	89.6*	7939.3	
3501	33	324.0	3067.7	
	34	325.0	3392.7	
	35	344.0	3736.7	Small fuel
	36	325.0	4061.7	Erosion i
	37	325.0	4386.7	Erosion e
	38	325.0	4711.7	
	39	326.0	5037.7	
	40	327.0	5364.7	
	41	326.0	5690.7	
	42	326.0	6016.7	
	43	326.0	6342.7	
	44	326.0	6668.7	
	45	327.0	6995.7	Erosion i
	46	327.0	7322.7	
	47	81.0*	7403.7	

NOTE: All tests included gimbal

1

TABLE 7

(Continued)

ve n, s	Comments
	Fuel leak at upper and lower vent ports of yaw housing
	Small fuel leak from lower vent port of yaw housing Erosion in thrust chamber throat at 9:00 o'clock position Erosion enlarging
	Erosion in thrust chamber throat at 6:00 o'clock position
ncluded gimbaling except those denoted by*	

2

TRANSIENT PERFORMANCE

Start transients obtained with the YLR101-NA-15 MD 1 engine (Fig. 15) were identical to those obtained with the 830-pound-thrust YLR101-NA-13 engine. The engine configuration changes did not affect the start transients.

The actuation setting (90 ± 15 psig) of the fuel injection pressure switch originally planned for use on the basic YLR101-NA-15 engine (525 pounds of tank-fed thrust) was too low to be used at the uprated thrust level of 777 pounds. To ensure combustion continuation after switch pickup, the switch was replaced with the original MA-5 fuel injection pressure switch with an actuation setting of 240 ±15 psig.

The cutoff transient at the 777-pound thrust level was similar to the cutoff transient experienced at the 830-pound thrust level. The average cutoff impulse for this series of tests was 150 lb-sec. This value is slightly higher than the 125 lb-sec impulse obtained during production on YLR101-NA-13 vernier tests at the 830-pound thrust level because a missile cutoff delay circuit was used in the test facility during the testing at 777 pounds of thrust. This circuit delays the propellant valve closing signal by 55 ±18 milliseconds. It is estimated that the YLR101-NA-13 vernier (830 pounds of thrust) would give a nominal cutoff impulse of 171 lb-sec if the delay circuit were used.

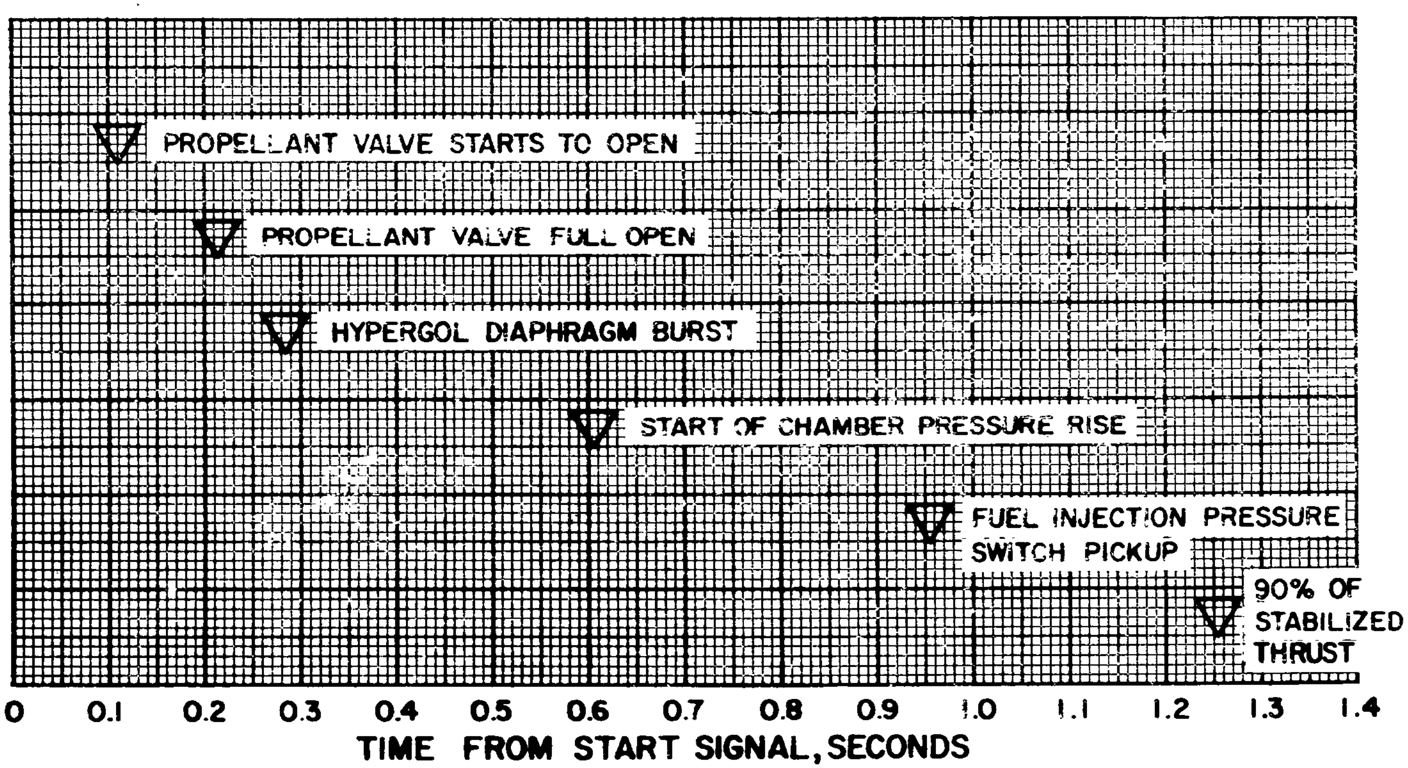

Figure 15. Nominal Start Transients of YLR101-NA-15 Engine Incorporating Modification MD 1

STEADY-STATE PERFORMANCE

Rated Phase II performance at tank and pump levels is presented in Tables 8 and 9. The tank-fed data were tabulated from 46 of the Neosho tests after being reduced to rated tank-fed values of 777 pounds thrust and a mixture ratio of 1.8. Pump-fed data were tabulated from the same 46 Neosho tests after being reduced to rated conditions based on predicted tank-fed orifices. The predicted pump-fed performance values were obtained from a mathematical balance for this engine system based upon missile orificing for tank-fed performance. The actual values compare favorably with the predicted values.

As mentioned previously, performance shifts were observed during Phase I testing at the downrated thrust level. Although no definite conclusions could be formed as to the actual cause of these performance shifts, several possible contributing factors were noted. These factors were:

1. The LOX temperature at the injector did not stabilize until 100 seconds after the start of the test.
2. Carbon buildup on the injector face and thrust chamber walls affected injector and combustion efficiency.

Phase II test observations tend to support the hypothesis that these factors caused the observed Phase I performance shifts. Carbon buildup on the injector face and thrust chamber walls during Phase II testing was very light, the Phase II LOX temperature at the injector stabilized much earlier than the Phase I LOX temperature, and comparison of data slices revealed no performance shifts during the Phase II testing.

In response to a request from GD/A, the last test with each engine was monitored to determine the maximum performance obtainable by installing full-open LOX and fuel orifices. The average sea level data are presented in Table 9.

The engine LOX and fuel orifices were changed periodically throughout the program. The pressure loss across each orifice was measured and corrected to standard densities and nominal flowrates. The LOX flowrate was 1.87 lb/sec, and the fuel flowrate was 1.04 lb/sec. These are nominal flowrates at the 525-pound thrust level. The corrected orifice size and pressure loss data are presented in Fig. 16.

Pressure measurements on the LOX side of the engine system were taken at the inlet to the propellant valve, the inlet to the LOX orifice, and at the LOX injector. Pressure measurements on the fuel side of the engine system were taken at the hypergol inlet and at the fuel injector. The pressure loss through various portions of the system was calculated and corrected to standard densities and nominal flowrates for the 777-pound thrust level. The LOX flowrate was 2.54 lb/sec, and the fuel flowrate was 1.41 lb/sec. These engine pressure loss data are presented in Fig. 17.

TABLE 8

RATED AND PREDICTED PHASE II STEADY

Performance Level	Inlet Pressure, psia		Thrust, pounds	Mixture Ratio	Specific Impulse, seconds	Charac Vel ft
	Oxidizer	Fuel				
Tank Fed	543	543	777	1.80	199.5	50
Pump Fed (Rated)	660	676	921	1.74	206.7	50
Pump Fed (Predicted)			909	1.72	202.0	49

TABLE 9

PHASE II SEA-LEVEL PERFORMANCE WITH FUL

Performance Level	Inlet Pressure, psia		Thrust, pounds	Mixture Ratio	Specific Impulse, seconds	Charac Vel ft,
	Oxidizer	Fuel				
Tank Fed	543	543	842.5	1.65	201.0	49
Pump Fed	660	676	995.7	1.59	206.0	50

TABLE 8

AND PREDICTED PHASE II STEADY-STATE PERFORMANCE

ture tio	Specific Impulse, seconds	Injector End: Characteristic Velocity, ft/sec	Injector End: Thrust Coefficient	Injector End: Chamber Pressure, psia	Propellant Weight Flowrate, lb/sec: Oxidizer	Propellant Weight Flowrate, lb/sec: Fuel
30	199.5	5022	1.278	292.0	2.50	1.39
74	206.7	5065	1.313	337.0	2.83	1.63
72	202.0	4931	1.322	330.4	2.84	1.65

TABLE 9

EA-LEVEL PERFORMANCE WITH FULL-OPEN ORIFICES INSTALLED

ure io	Specific Impulse, seconds	Injector End: Characteristic Velocity, ft/sec	Injector End: Thrust Coefficient	Injector End: Chamber Pressure, psia	Propellant Weight Flowrate, lb/sec: Oxidizer	Propellant Weight Flowrate, lb/sec: Fuel
55	201.0	4986	1.296	312.2	2.61	1.58
59	206.0	5000	1.326	360.8	2.97	1.87

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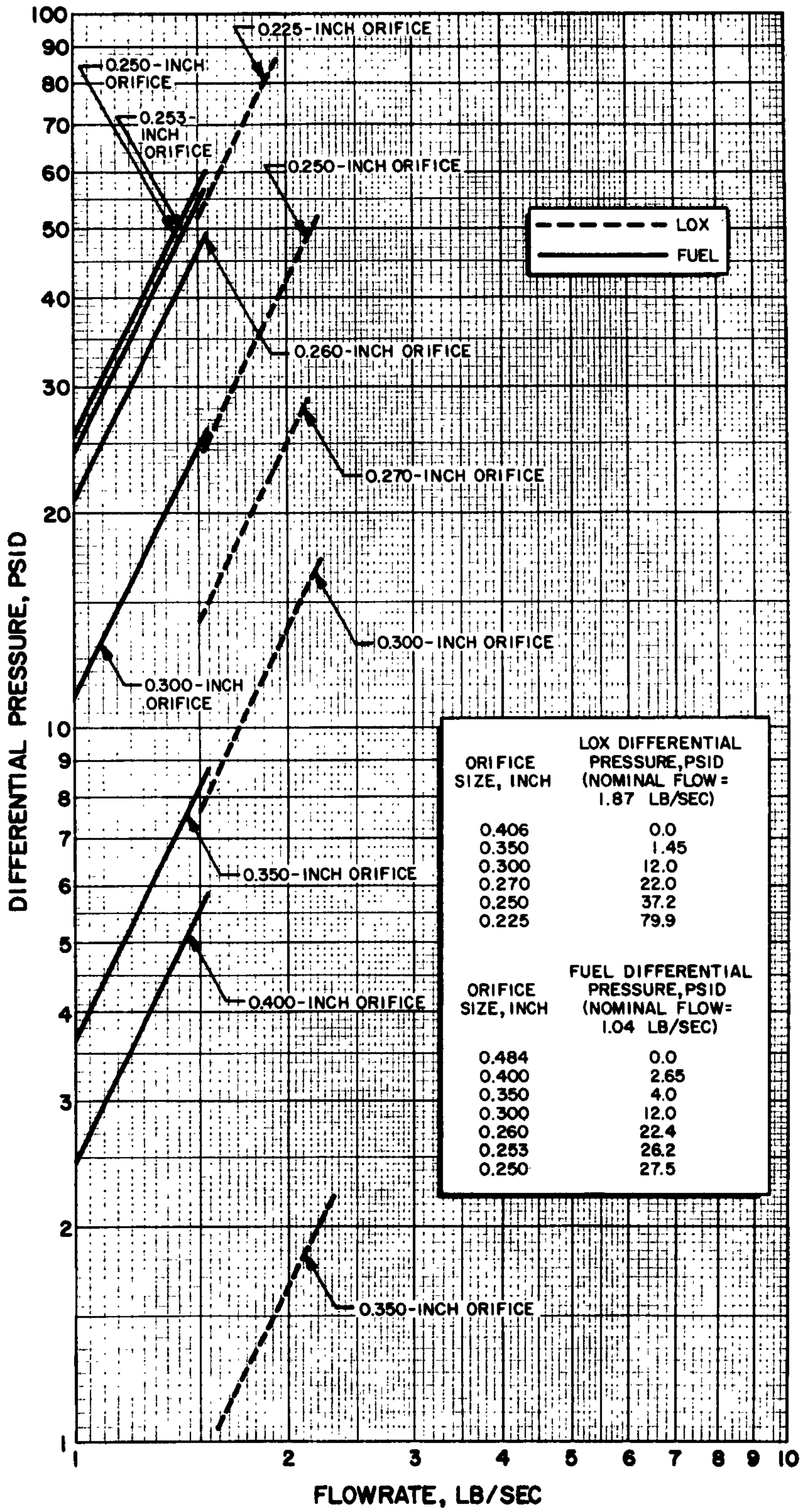

ORIFICE SIZE, INCH	LOX DIFFERENTIAL PRESSURE, PSID (NOMINAL FLOW = 1.87 LB/SEC)
0.406	0.0
0.350	1.45
0.300	12.0
0.270	22.0
0.250	37.2
0.225	79.9

ORIFICE SIZE, INCH	FUEL DIFFERENTIAL PRESSURE, PSID (NOMINAL FLOW= 1.04 LB/SEC)
0.484	0.0
0.400	2.65
0.350	4.0
0.300	12.0
0.260	22.4
0.253	26.2
0.250	27.5

Figure 16. Phase II Orifice Pressure Losses at Various Flowrates

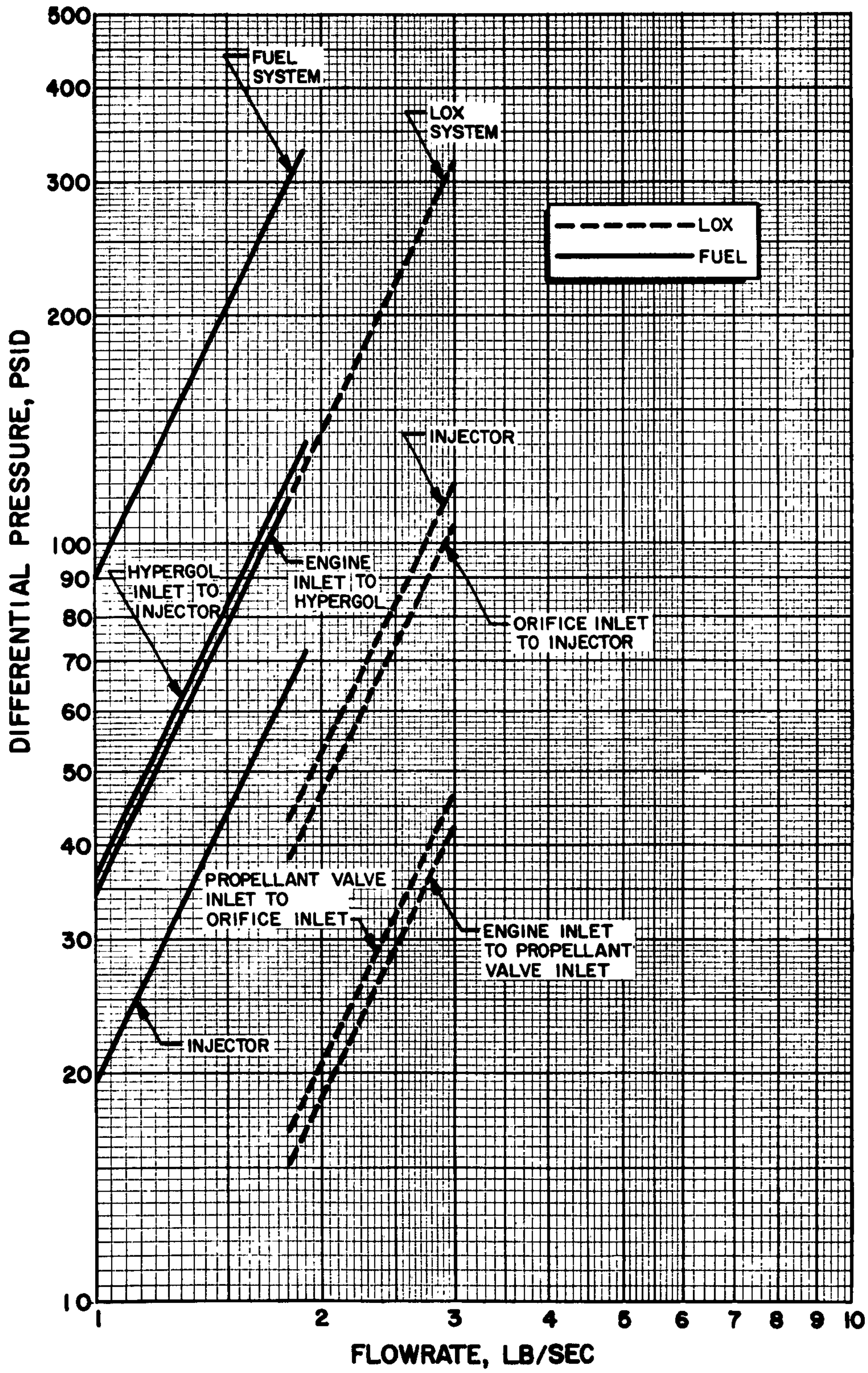

Figure 17. Phase II Propellant System Pressure Losses at Various Flowrates

GIMBAL TESTS

The vernier engines were gimbaled in the pitch and yaw planes for at least 160 seconds during each duration test. A GD/A autopilot and associated equipment was used, and each engine was gimbaled in sine, triangle, and square wave functions at frequencies of 0.5 to 5.0 cycles per second. Engine S/N 3501 accumulated 4330 cycles in pitch and yaw planes; engine S/N 3502 accumulated 4675 cycles in the pitch plane and 4245 cycles in the yaw plane. Although no record was kept, it is estimated that each engine accumulated as many cycles of dry gimbaling between tests as were accumulated during the hot-fire tests.

Prior to the beginning of the Phase II testing, GD/A notified Rocketdyne that the hydraulic snubbers were being deleted from the yaw gimbal actuators of SLV-3 missiles. To simulate the actual gimbal profile that the YLR101-NA-15 engines would experience during flight, the snubbers were removed from the yaw actuators that were used during the Phase II testing. No adverse effects were noted during these tests.

GD/A also suggested removing the pitch gimbal actuator snubbers, but Rocketdyne recommended that this not be done because it would result in excessive loading of the pitch sector gear teeth. Previous vernier gimbal testing with the pitch actuator snubbers removed had caused this overload condition and resulted in failures of the pitch sector gear teeth.

The model specification for the YLR101-NA-15 MD 1 engine states that the gimbal friction, including actuator friction, shall not exceed 75 ft-lb in the pitch plane and 35 ft-lb in the yaw plane. The average friction values obtained during Phase II testing were 34.8 ±30.6 ft-lb (3σ limits) in the pitch plane and 19.5 ±7.5 ft-lb (3σ limits) in the yaw plane.

The model specification thrust alignment requirement is that the thrust vector misalignment shall not exceed 2 degrees angularity and 0.125 inch of lateral displacement at the gimbal point. The average lateral thrust misalignment obtained during Phase II testing was 0.0023 ±0.035 inch (3σ limits). The angular displacement could not be determined because the test stand was not equipped with horizontal load cells.

The model specification moment of inertia requirement is that the thrust chamber shall be accelerated at a minimum of 4000 deg/sec^2 when a force of 1350 pounds is applied on an arm of 1.25 inches. Maximum actuator force used to accelerate the thrust chamber is shown for the pitch and yaw planes in Fig. 18 and 19, respectively. Figures 20 and 21 present the resulting moment of inertia vs acceleration for the pitch and yaw planes, respectively.

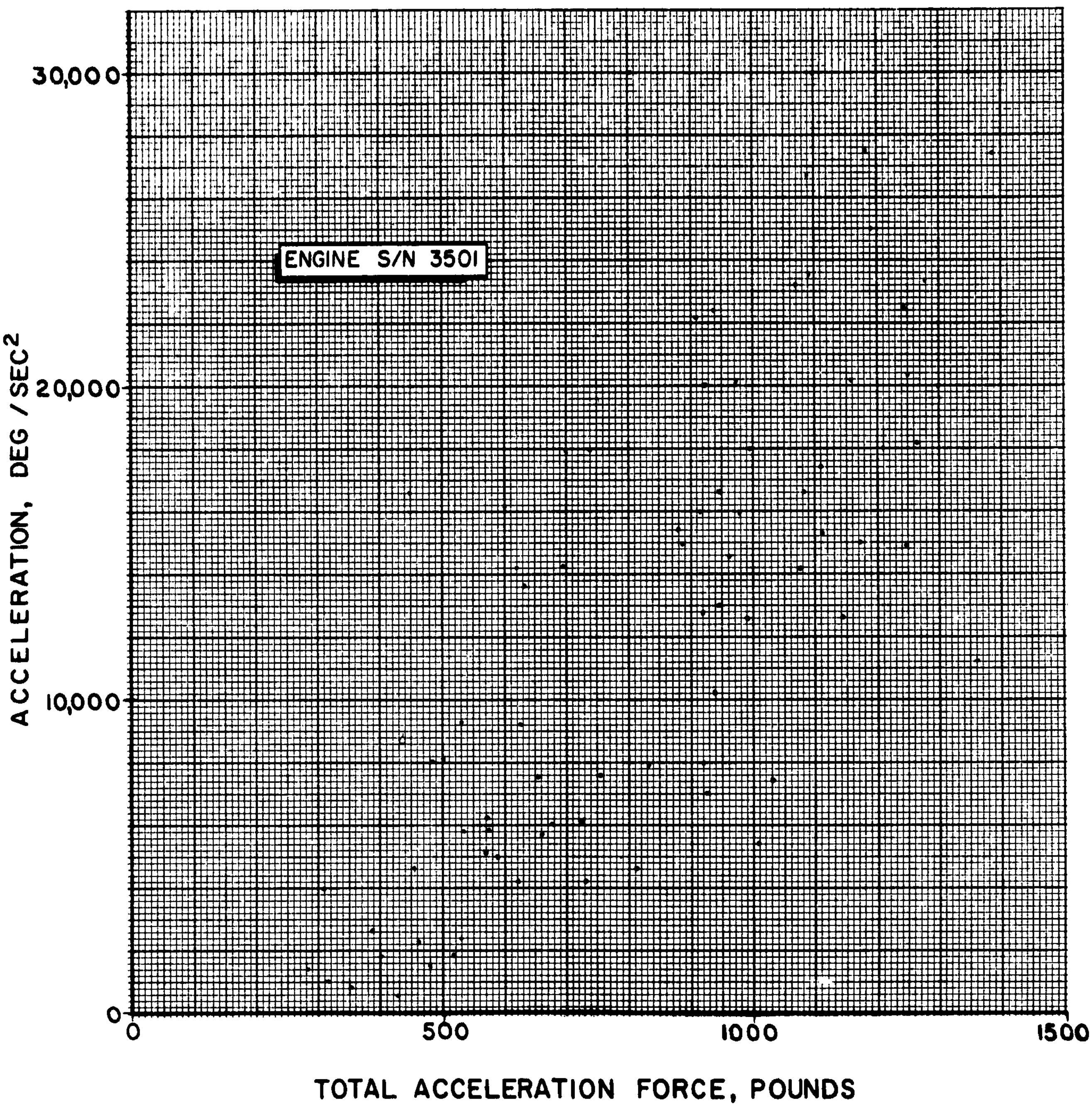

Figure 18. Actuator Force Used to Move Thrust Chamber Within Pitch Plane During Phase II Testing

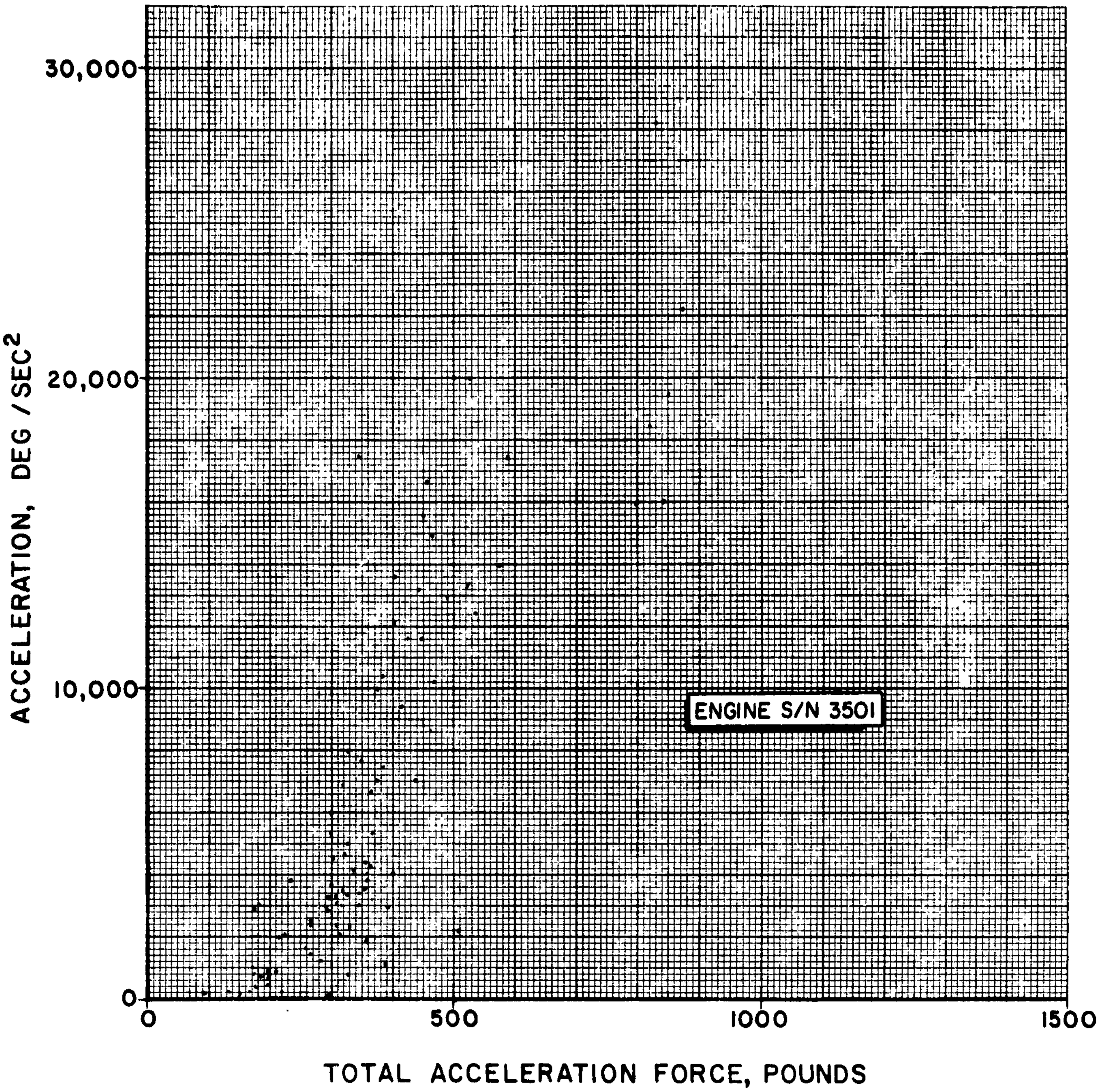

Figure 19. Actuator Force Used to Move Thrust Chamber Within Yaw Plane During Phase II Testing

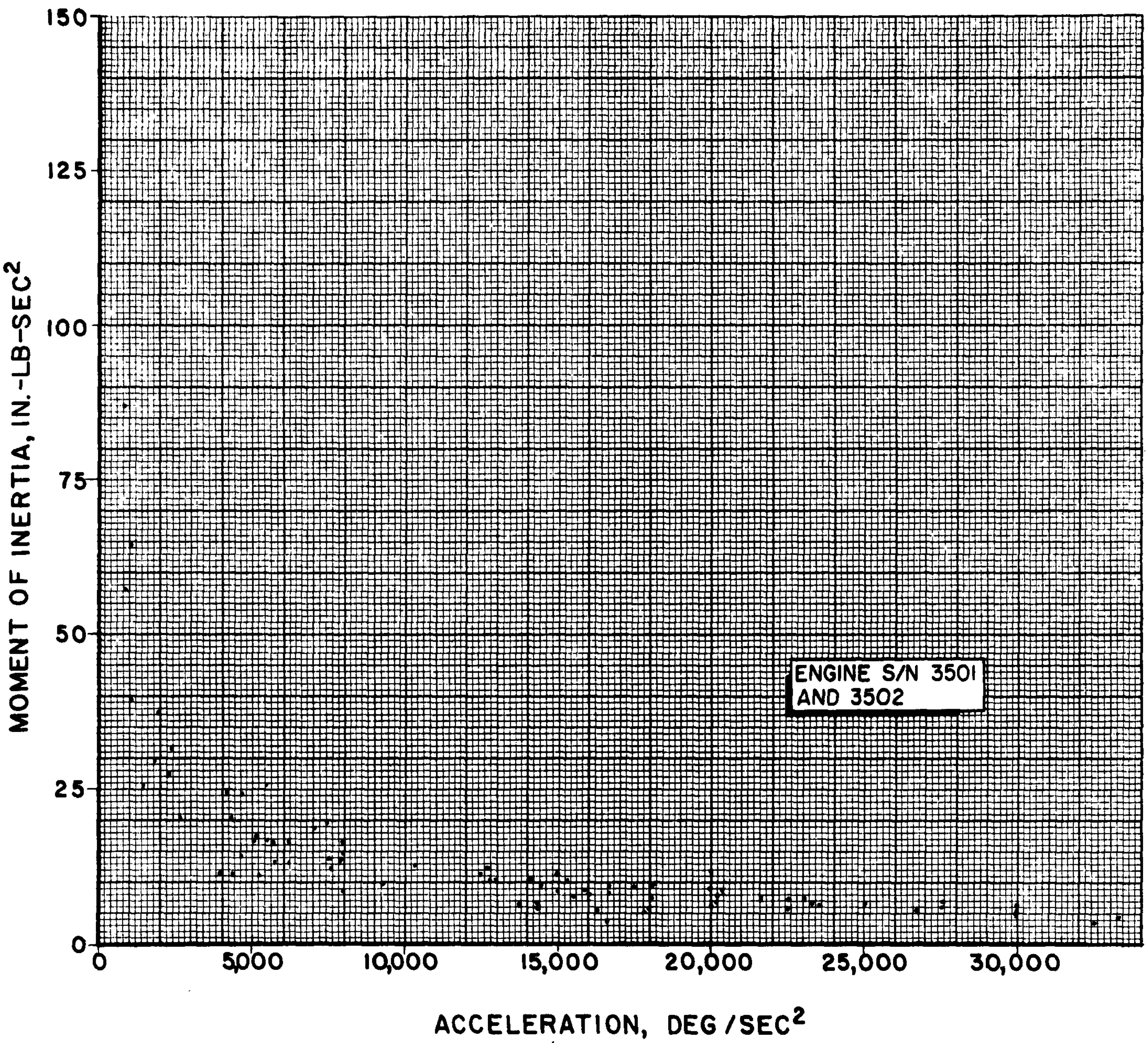

Figure 20. Moment of Inertia Determined From Pitch Plane Acceleration Data

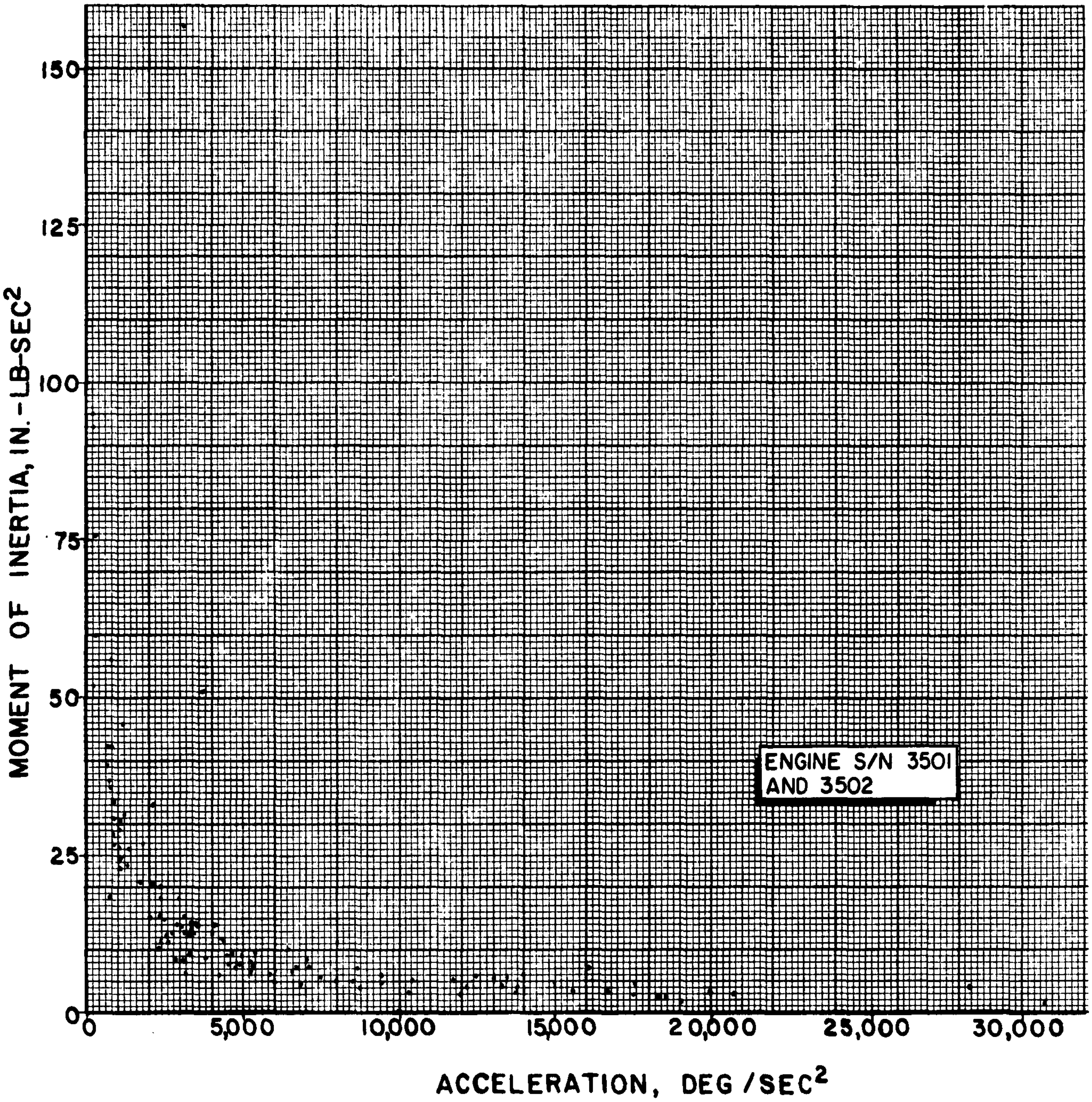

Figure 21. Moment of Inertia Determined From Yaw Plane Acceleration Data

HARDWARE CONDITION

An intermittent fuel leak emanated from the yaw housing vent ports throughout the Phase II test program (Table 7). After the first leak on engine S/N 3501, the thrust chamber and yaw housing were removed and the seals and sealing surfaces were inspected. No cause for the leakage could be found. Testing was continued after the first leak on engine S/N 3502, and the leak did not recur until five tests later. The leakage continued sporadically throughout the remainder of the test series. After completion of testing, both engines were leak and functionally tested, and no leakage was found. A complete disassembly and inspection disclosed no reason for the leak.

Because the leakage involved only a small quantity of fuel, the leaks were probably caused by stretching or bunching of the O-ring at the start of yaw gimbaling. This would allow a spurt of fuel to enter the vent cavity. As the shaft rotated, the O-ring would reseat itself and no further leakage would occur.

A slight LOX leak at the union in the pitch body during two tests was attributed to a worn seal. The wear on the seal was caused by the frequent removal of the LOX line to change the LOX orifice. The seal was replaced and the leak ceased.

The thrust chambers of both engines developed erosion at the throat during the Phase II vernier tests. Engine S/N 3501 experienced the erosion after 14 tests (4061 seconds), and engine S/N 3502 experienced the erosion after 20 tests (5200 seconds). Because both thrust chambers had exceeded their life expectancy of 3900 seconds, these throat erosions were not considered failures.

After the completion of the test program, both engines were disassembled and all parts inspected. Two discrepancies were noted.

1. The T-shaft land used to retain the lower fuel O-ring and backup had scored the front half of the pitch body. This was caused by (a) the shaft bowing slightly during testing, and (b) the engine gimbaling. The scoring did not cause a leak.

2. A granular residue resembling sand was found in the injector manifold of the thrust chamber from engine S/N 3502. A complete chemical analysis revealed that the substance was pure aluminum oxide. Aluminum oxide is a byproduct of triethylaluminum, which is used in the hypergolic igniter of the vernier engine. Although the thrust chamber passages are flushed with fuel during a test and purged with nitrogen after a test, a considerable amount of triethylaluminum usually remains in the thrust chamber passages. Present production procedures require removing and cleaning of the vernier dome and injector and cleaning of the thrust chamber injector manifold prior to engine delivery, so this residue should create no problem during production.

MODIFIED INJECTOR PROGRAM

OBJECTIVES

The over-all objective of the modified injector program was to design, fabricate, and test alternate vernier injector configurations for use with the YLR101-NA-15 vernier engine to minimize thrust chamber erosion at the 525-pound thrust level. To accomplish this objective, a program plan was established to divide the effort into a component development phase and a vernier engine system test phase. Specific objectives of these two program phases are outlined below.

COMPONENT DEVELOPMENT PHASE

The objectives of the component development phase were:

1. To analyze the causes of the thrust chamber erosion experienced during Phase I vernier engine testing
2. To design and fabricate alternate injector types which would minimize thrust chamber erosion
3. To conduct water flow tests of the redesigned injectors to permit selection of a primary and best alternate injector type for hot-fire testing
4. To conduct a series of vernier thrust chamber and injector tests using the modified injectors to evaluate effectiveness in eliminating thrust chamber erosion at the 525-pound thrust level

VERNIER ENGINE TEST PHASE

The objectives of the vernier engine test phase were:

1. To provide engine test verification of the effectiveness of the new injector to eliminate thrust chamber erosion at the 525-pound thrust level
2. To establish performance values of the YLR101-NA-15 vernier engine
3. To ensure satisfactory YLR101-NA-15 engine start and cutoff transients

COMPONENT DEVELOPMENT PHASE

HEAT TRANSFER ANALYSIS

Phase I standard vernier engine testing at downrated conditions at the Neosho facility resulted in severe streak-type erosions in the lower combustion chamber and throat regions. Several erosions had progressed to the point where pinholes had appeared through the chamber inner wall. An analysis of this condition showed it to be the result of:

1. A reduced liquid-side heat transfer coefficient caused by reducing the fuel flowrate. This decreased the ability of the fuel to cool the thrust chamber wall.
2. A reduced fuel velocity and flowrate through the outer fuel orifices. This allowed the oxidizer fan to penetrate to the thrust chamber wall, and occurred at the lower combustion zone and throat region where the film-coolant boundary is minimum.
3. A high local mixture ratio at downrated conditions. This problem does not exist to such an extent at the 830-pound thrust level.

To determine if the existing chamber design might produce unfavorable fuel jacket coolant-flow conditions at the reduced flowrates, the fuel jacket of the present chamber was subjected to heat transfer analysis. The criteria to determine the effect of downrating on heat transfer were to undertake heat transfer analysis at the standard 830-pound-thrust level and modify the results to the downrated conditions. Because heat transfer is most critical at the throat, the downrated calculations were determined at this point.

The results of this study indicated that the existing vernier thrust chamber provides adequate heat transfer for operation at the 500-pound thrust level and recommended that fuel manifold and injector orifice pattern changes be made to eliminate localized thrust chamber burnout.

INJECTOR REDESIGN

The standard injector test data and the heat transfer analysis at downrated conditions revealed that the probable cause of thrust chamber erosion was poor propellant distribution. This resulted from operating the standard injector configuration at a performance level significantly lower than the original design point. A detailed evaluation of the standard injector characteristics was undertaken to determine possible conditions conducive to thrust chamber wall erosion which could result from decreased propellant flow. The possible causes were as follows:

1. Low fuel momentum which allowed high-velocity oxidizer stream penetration and poor film cooling as a result of the shallow fuel-impingement angle
2. Hollow-center fuel spray attributed to the low fuel velocity which allowed the oxidizer stream to break through the fuel spray and impinge against the wall
3. Poor oxidizer stream atomization and inadequate mixing resulting from the high momentum ratio of oxidizer to fuel
4. High local mixture ratio of oxidizer to fuel

The local oxidizer-to-fuel mixture ratio at the outer zone was calculated to be about 1.46 with the standard vernier injector. This was considered acceptable. Because of low fuel momentum and less than adequate mixing at the downrated conditions, significant deviations from the calculated value may occur. The velocity of the oxidizer stream was found to be 10 ft/sec greater than the velocity of the fuel stream, but the momentum of the oxidizer stream was twice the momentum of the fuel stream.

During Phase I testing of the standard injector at downrated conditions, a 500-cps instability "buzz" appeared when the engine was operating at 450 pounds of thrust. This became more pronounced at the 400-pound thrust level where it reached 4 g (rms) along the axis through the thrust chamber shaft. The probable cause was the fuel injection differential pressure decrease from 55 psi at the 1000-pound thrust level to 15 psi at downrated conditions and the fuel velocity decrease from 82.5 ft/sec to 47 ft/sec. The oxidizer system reflected a similar velocity and differential pressure decrease, but was still considered capable of good distribution.

An injector redesign was developed in which the fuel velocity and differential pressure at the 500-pound thrust level were raised approximately to the standard 1000-pound thrust condition. This established good uniformity and momentum, and also prevented any buzzing caused by the fuel system.

The basic injector "fix" required that the 0.032-inch fuel orifice diameter be reduced to 0.026 inch. This raised the injector fuel differential pressure to 42 psi and increased the fuel velocity to 73 ft/sec. Injector pattern changes and β angles (angle between the thrust chamber axis and the resultant momentum vector of a pair of impinging streams) were considered but were not incorporated because of retooling costs, limited time, and the desire to ensure that present combustion characteristics were not drastically altered.

Injector redesign considerations of uniformity and momentum led to four modifications of the standard P/N 350604 vernier injector (Fig. 22) as follows:

1. Injector P/N EO 119924: The fuel orifice diameter was decreased to 0.0260 inch to increase the fuel momentum with the same mass flowrate that was used by the standard injector.
2. Injector P/N EO 123830: The fuel orifice diameter was decreased to 0.0260 inch to increase the fuel momentum. Twelve of the 24 outer oxidizer doublets were relocated closer to the center of the injector to provide better propellant distribution.
3. Injector P/N EO 123864: The fuel orifice diameter was decreased to 0.0260 inch to increase the fuel momentum. Twelve of the outer oxidizer doublets were relocated closer to the center of the injector to decrease the local mixture ratio. The outer fuel triplet showerhead orifice was repositioned between the outer oxidizer doublets, and the outer fuel impingement angle was changed to 30 degrees to allow better propellant distribution of the outer oxidizer doublets.
4. Injector P/N EO 123829: The fuel orifice diameter was decreased to 0.0260 inch except for the showerheads of the outer fuel triplets which remained at 0.0320 inch. This increased the localized fuel mass flowrate and the overall injector fuel velocity.

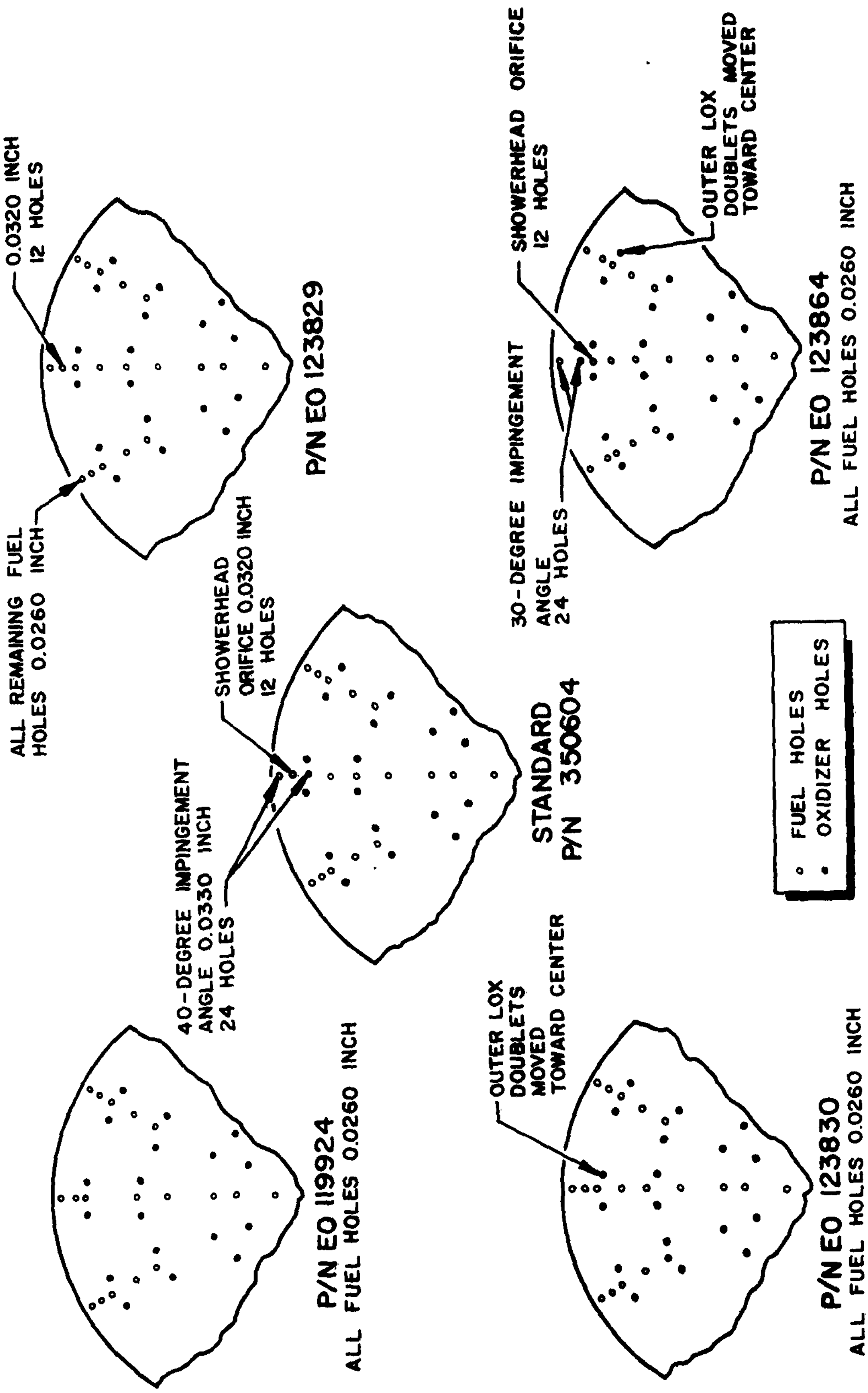

Figure 22. Modifications to YLR101-NA-13 Vernier Injector

Two of each of these injector designs were fabricated at the Neosho facility and cold flowed at the Canoga Park facility.

VERNIER INJECTOR WATER FLOW TESTS

Water flow testing of vernier injectors was conducted to view and photograph spray patterns and mixing characteristics of the oxidizer and fuel streams. The injection of a premixed dye solution into the fuel (blue) and oxidizer (yellow) flow was used as an evaluation aid to determine oxidizer penetration. Ideal mixing of the dye solutions would result in a green solution. Oxidizer-rich areas could be seen as light green and yellow sprays. This method was expected to enable an accurate prediction of the behavior of each injector under hot-fire conditions.

Each injector was mounted in a vertical position on a mounting plate similar to the thrust chamber injector flange. Dye solution was injected into the fuel annulus through ports on each side of the mounting plate and into the inlet line on the oxidizer side. Two individually pressurized 1-gallon dye tanks were used, and each contained a solution of 40 grams of powdered dye. The dye tank flow was controlled by two 1/4-inch electric valves simultaneously actuated at the time of photography. Hand valves controlled the water flow which was measured by Waugh turbine flowmeters and converted to sight readings by a time/function translator.

Each injector was installed to allow photographing of similar orifice sets. An inspection was made for adequate impingement at low flow prior to flowing each injector. Thrust levels of 400, 500, 600, 750 and 900 pounds were simulated. Oxidizer-to-fuel mixture ratios of 1.5, 1.7, 1.9, 2.1, and 2.3 were simulated at each thrust level.

The flow bench limitations prevented a continuous fixed proportion in the dye-to-water flowrates throughout the flow tests, but some control was maintained by pressurizing each dye tank 25 psi higher than the oxidizer and fuel injection pressures. This did not allow photo correlation within a series on an injector, but did allow correlation of one series to another.

Photographic materials consisted of a commercial camera, two flash attachments, and color film. A stroboscopic light was not available, and variation of light intensity, shutter speed (to correlate with water velocity), and color contrasts could not be attained. This necessitated "printing down" the photographs to allow for proper balance of the basic print colors in correct proportions.

PHOTO EVALUATION

The criteria established in rating the colored stills of each injector are listed below:

1. The standard injector was considered to be the "poorest" for comparison with other injectors
2. Each picture of one series at one mixture ratio and thrust was rated to a picture of another series at the same mixture ratio and thrust
3. Only the center orifice set was considered in each picture
4. Good mixing of the orifice set was indicated by green flow
5. Oxidizer penetration was viewed as light green or yellow

6. The area just below the injector face was viewed
7. A well-defined flow pattern indicated poor mixing

A reproduction of the color photographs is included in an envelope attached to the inside of the rear cover of this report. Evaluation of the cold flow photographs by the above criteria indicated the following apparent order of effectiveness in reducing oxidizer spray penetration:

Order of Effectiveness	Injector Part Number
1	EO 119924
2	EO 123830
3	EO 123864
4	EO 123829
5	350604 (standard)
6	350604 (standard with outer fuel triplet showerhead orifices enlarged from 0.032 inch to 0.042 inch)

The above order of effectiveness was not substantiated by subsequent hot-fire tests. The hot-fire test data indicated that the P/N EO 123829 injector was superior to the others. This did not invalidate the basic criteria, but established a further condition not considered. This condition was the evaluation of cold-flow photographs for heavy oxidizer spray and poor mixing in the areas of standard thrust chamber erosion. Because the standard injector had a heavy oxidizer concentration near and several inches away from the injector face, it had been considered sufficient to assume that downstream mixing would be adequate if the oxidizer penetration was not evident near the face. Re-evaluation of cold-flow photographs for poor mixing in the area of erosion indicated that the P/N EO 123829 injector would have been the first choice.

A further conclusion from the photo evaluation was that it would be more effective to use yellow dye for the fuel and blue dye for the oxidizer. The oxidizer stream breakthrough can be more easily seen if blue dye is used, because use of the yellow dye results in a "washed-out" effect when photographed.

Hot-fire performance is the final test of a thrust chamber injector, and other evaluation systems are useful only because they enable prediction of hot-fire performance. It is concluded that although the water flow tests of the five injector modifications permitted observation of differences between the flow characteristics of each type, no firm correlation of these characteristics with hot-fire performance could be made.

SPLASH-PLATE INJECTOR

In addition to the four modified flat-face injectors described previously, a prototype splash-plate injector was selected as a backup configuration for hot-fire test evaluation.

The splash-plate injector (Fig. 23) was designed to force liquid mixing and particle breakup by allowing the streams of oxidizer and fuel to simultaneously impinge at the surface of the splash plate. Advantages of this design were: (1) fabrication simplicity, (2) high performance, and (3) previous history of no thrust chamber erosion.

Previous testing of this injector type was conducted to study the following design variables:

1. Splash-plate body combustion volume upstream of the splash plate

2. Splash-plate opening area compared with the throat area (splash-plate area ratio: $\epsilon_{sp} = A_t/A_{sp}$)
3. Resultant momentum vector impingement angle with respect to the splash-plate surface
4. Splash-plate surface angle with respect to a plane perpendicular to the centerline of the thrust chamber

Major emphasis during the testing was given to performance and stability. Varying the resultant momentum vector impingement angle had a considerable effect on the performance level of operation. The maximum propellant particle breakup occurred when the resultant impingement was normal to the splash-plate surface. Good mixing was augmented by increasing the volume upstream of the splash plate, and a 1:1 area ratio splash plate was found to be near optimum with respect to thrust chamber operating conditions and combustion stability.

The splash-plate injector used for the downrated vernier test program was the latest refinement the injector used during the last previous evaluation program. History of the prototype unit tested indicated previous hot-fire time in excess of 10,000 seconds at thrusts of 100 to 1200 pounds and mixture ratios of 0.9 to 2.4.

THRUST CHAMBER/INJECTOR TEST PROGRAM

Seventy-eight vernier thrust chamber/injector tests were conducted with five injector configurations. Purpose of the testing was to:

1. Determine the effectiveness of injector modifications in reducing thrust chamber erosion

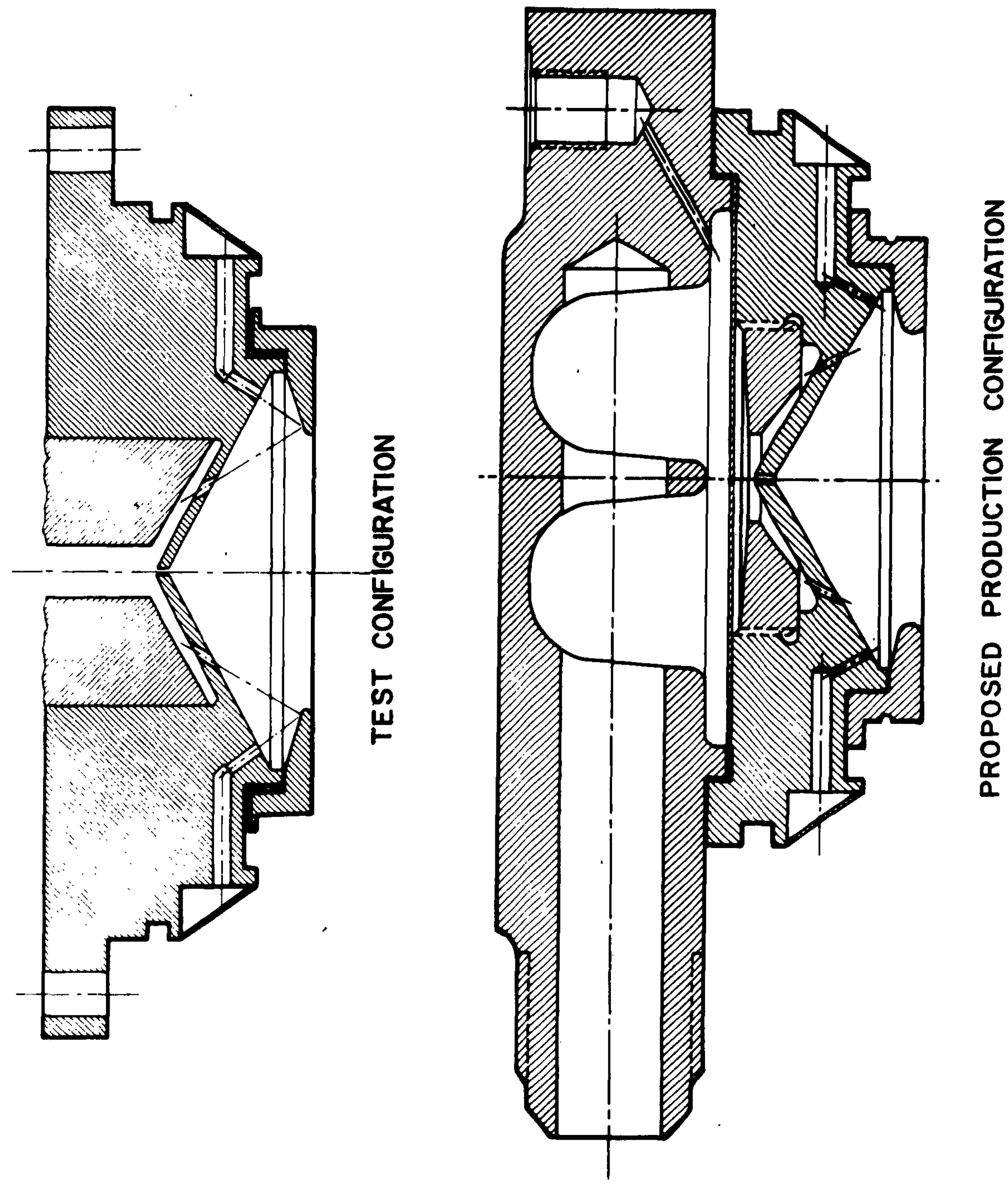

Figure 23. Vernier Splash-Plate Injector

2. Determine injector performance
3. Determine thrust chamber operating characteristics

Forty-six tests were conducted at Component Test Laboratory-4 (CTL-4), (Fig. 24) between 15 April and 8 June 1963. During the first week of testing at CTL-4, a decision was made to run a parallel program at CTL-2, Cell 2B. This necessitated the design and buildup of a new test stand (Fig. 25) by CTL-2 personnel. Buildup and system checkouts were completed, and 32 tests were conducted between 4 June and 19 June 1963.

Each injector type was intended to be subjected to tests at thrust levels of 500 and 700 pounds. Oxidizer-to-fuel mixture ratios of 1.5, 1.7, 1.8, 1.9, and 2.1 were utilized at each thrust level. Although each injector was scheduled for 300 seconds of testing at each thrust and mixture ratio, some of the injectors did not complete the entire series of tests. Tables 10 and 11 summarize the test series.

Component Test Laboratory-4, Cell 26B

Four injectors were hot fired at Cell 26B for a total of 8805 seconds. These units included a P/N EO 119924 injector, a P/N EO 123830 injector, and two P/N EO 123864 injectors. Following test stand checkout and system blowdowns, three calibration and four duration tests were conducted with the P/N EO 119924 injector. The second duration test was cut because of erratic oxidizer flow, chamber pressure, and thrust. The reason for this erratic behavior was theorized to have been cavitation within the facility oxidizer orifice and gaseous oxygen formation in the 2-inch oxidizer supply line. A bleed was installed, the

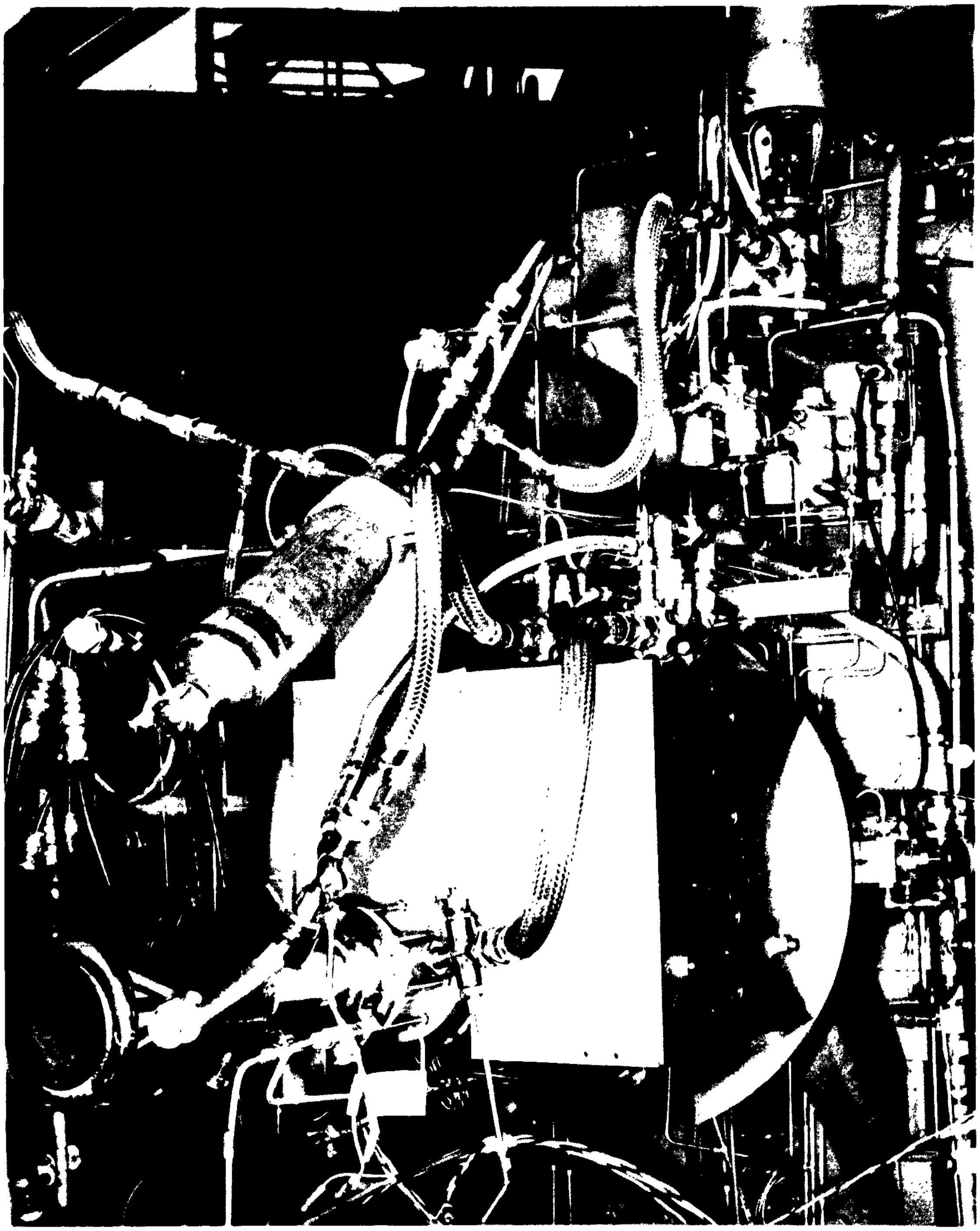

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Figure 24. Test Setup in Cell 26B, Component Test Laboratory-4

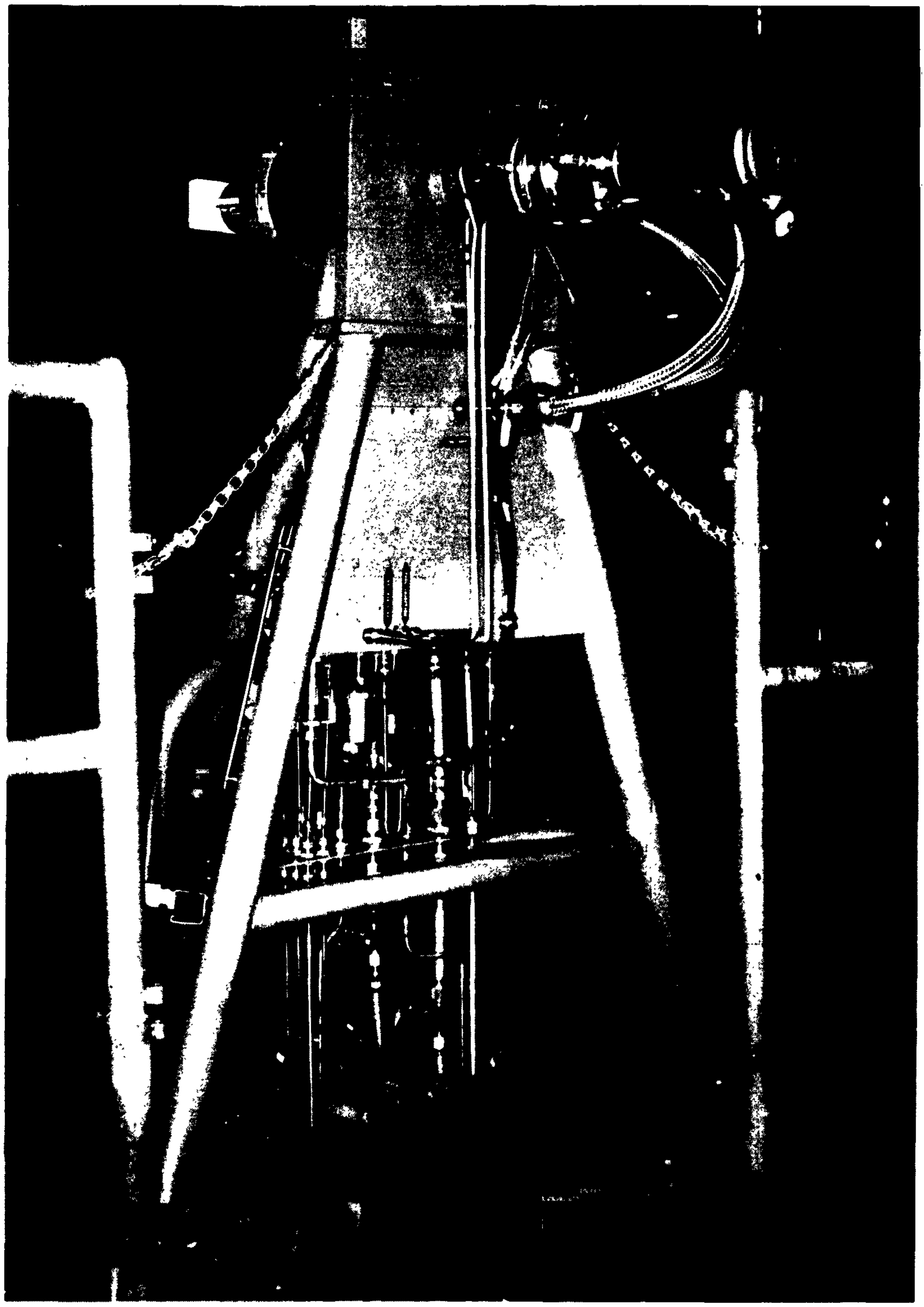

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Figure 25. Test Setup in Cell 2B, Component Test Laboratory-2

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SUMMARY OF THRUST CHAMBER TESTING A

Date, 1963	Injector Part No.	Injector Serial No.	Test No.	Targeted Value		Actual Value			Test Duration, seconds
				Thrust pounds	Mixture Ratio	Thrust, pounds	Mixture Ratio	Specific Impulse, seconds	
May 17	E0 119924	3139-1	030	500	1.8	--	1.099	--	1.1
May 17			031	500	1.8	--	1.892	--	4.0
May 18			032	500	1.8	--	1.802	--	29.3
May 18			033	500	1.8	359	1.891	126.7	301.5
May 22			034	700	1.8	682	1.847	211.3	170.0
May 22			035	700	1.7	709	1.831	200.4	302.5
May 23			036	700	1.8	694	1.721	203.5	323.5
May 25	E0 123830	4871	037	500	1.8	451	1.535	178.9	112.6
May 27			038	500	1.8	--	1.738	--	302.0
May 30			039	--	--	--	--	--	--
May 31			040	700	1.8	700	1.801	197.9	303.5
June 1			041	500	1.7	504	1.717	186.4	302.5
June 1			042	700	1.7	709	1.704	200.6	302.0
June 1			043	500	1.9	494	1.781	187.1	303.0
June 1			044	700	1.9	698	1.851	203.6	301.5
June 1			045	700	1.5	682	1.478	196.6	301.5
June 1			046	500	1.5	492	1.526	181.2	302.0
June 1			047	700	2.1	686	2.111	200.6	302.0
June 3			048	500	2.1	514	1.962	193.5	302.0
June 4	E0 123864	4866	049	700	1.8	504	1.631	196.7	4.4
June 5			050	500	1.8	562	1.677	212.4	302.5
June 6			051	700	1.8	752	1.670	223.3	311.5
June 6			052	500	1.7	561	1.713	208.1	300.0
June 6			053	700	1.7	738	1.638	219.2	301.5
June 6			054	500	1.9	560	1.854	214.4	302.0
June 7			055	700	1.9	748	1.790	226.4	302.5
June 7			056	700	1.5	723	1.422	213.0	301.5
June 7			057	500	1.5	533	1.455	196.7	301.5
June 8			058	700	2.1	752	1.959	224.0	301.5
June 8			059	500	2.1	541	1.984	209.5	301.0
June 8	E0 123864	4868	060	500	1.8	524	1.707	200.1	301.0
June 8			061	700	1.8	733	1.759	218.5	302.0
June 8			062	500	1.7	541	1.697	201.8	301.5
June 8			063	700	1.7	685	1.563	207.8	301.5
June 8			064	500	1.9	574	1.936	214.3	302.0

TABLE 10

CHAMBER TESTING AT COMPONENT TEST LABORATORY-4, CELL 26B

Specific Impulse, seconds	Test Duration, seconds	Cumulative Duration, seconds	Remarks
--	1.1	1.1	
--	4.0	5.1	
--	29.3	34.4	
126.7	301.5	335.9	
211.3	170.0	505.9	Test cut due to erratic instrumentation
200.4	302.5	808.4	
203.5	323.5	1131.9	Heavy thrust chamber erosion occurred during test;chamber not removed
178.9	112.6	112.6	
--	302.0	414.6	
--	--	--	Blowdown
197.9	303.5	718.1	
186.4	302.5	1020.6	Slight thrust chamber erosion occurred during test; chamber not removed
200.6	302.0	1322.6	
187.1	303.0	1625.6	
203.6	301.5	1927.1	
196.6	301.5	2228.6	
181.2	302.0	2530.6	
200.6	302.0	2832.6	
193.5	302.0	3134.6	
196.7	4.4	4.4	
212.4	302.5	306.9	
223.3	311.5	618.4	
208.1	300.0	918.4	
219.2	301.5	1219.9	
214.4	302.0	1521.9	
226.4	302.5	1824.4	
213.0	301.5	2125.9	
196.7	301.5	2427.4	
224.0	301.5	2728.9	
209.5	301.0	3029.9	Heavy thrust chamber throat erosion occurred during test
200.1	301.0	301.0	
218.5	302.0	603.0	
201.8	301.5	904.5	
207.8	301.5	1206.0	
214.3	302.0	1508.0	Heavy thrust chamber (above throat) erosion; one spot of erosion in combustion zone

TABLE 11

SUMMARY OF THRUST CHAMBER TESTING AT COMPONENT TE

Date, 1963	Injector Part No.	Injector Serial No.	Test No.	Targeted Value Thrust, pounds	Targeted Value Mixture Ratio	Actual Value Thrust, pounds	Actual Value Mixture Ratio	Actual Value Specific Impulse, seconds	Test Duration, seconds
June 4	Splash	Plate	010	700	1.8	674	1.787	198.5	3
June 4			011	700	1.8	738	1.742	204.8	302
June 5			012	500	1.8	527	1.795	183.9	298
June 7			013	500	1.8	492	1.759	190.8	392
June 8	EO 123829	4869	014	500	1.8	515	1.726	187.3	300
June 8			015	700	1.8	725	1.820	204.2	300
June 8			016	500	1.7	524	1.688	192.6	300
June 8			017	700	1.7	715	1.681	206.2	300
June 8			018	500	1.9	533	1.918	191.8	300
June 8			019	700	1.9	734	1.892	208.7	300
June 10			020	700	1.5	699	1.490	200.5	300
June 11			021	500	1.5	528	1.595	189.0	303
June 13			022	700	2.1	730	2.150	208.5	300
June 13			023	500	2.1	541	2.090	193.6	300
June 15	Splash	Plate	024	700	2.1	734	2.012	193.6	300
June 15			025	500	2.1	545	2.109	213.5	300
June 15	EO 123829	4867	026	500	1.8	533	1.849	196.2	300
June 15			027	700	1.8	748	1.859	206.5	300
June 15			028	500	1.7	521	1.811	192.0	300
June 15			029	700	1.7	720	1.700	204.3	300
June 15			030	500	1.9	518	1.880	191.6	300
June 15			031	700	1.9	726	2.040	201.0	300
June 17			032	--	--	--	--	--	68
June 17			033	700	1.5	705	1.560	195.2	285
June 17			034	500	1.5	486	1.490	184.0	302
June 17			035	700	2.1	698	2.200	201.0	308
June 17			036	500	2.1	486	2.250	177.0	300
June 18	Splash	Plate	037	700	1.7	701	1.660	201.4	300
June 19			038	700	1.5	696	1.440	192.1	300
June 19			039	500	1.5	492	1.430	172.0	300
June 19			040	500	1.9	516	1.802	186.8	300
June 19			041	700	1.9	722	1.815	204.0	300

TABLE 11

STING AT COMPONENT TEST LABORATORY-2, CELL 2B

e			
Specific Impulse, seconds	Test Duration, seconds	Cumulative Duration, seconds	Remarks
198.5	3	3	
204.8	302	306	
183.9	298	605	
190.8	392	997	
187.3	300	300	
204.2	300	600	
192.6	300	900	
206.2	300	1200	
191.8	300	1500	
208.7	300	1800	
200.5	300	2100	
189.0	303	2403	Removed injector to LOX clean
208.5	300	2703	
193.6	300	3002	Minor nickel erosion and one minor eroded spot upstream of throat
193.6	300	1355	
213.5	300	1655	
196.2	300	300	
206.5	300	600	
192.0	300	900	
204.3	300	1200	
191.6	300	1500	
201.0	300	1800	
--	68	1868	Cut due to warm LOX
195.2	285	2153	
184.0	302	2455	
201.0	308	2763	
177.0	300	3063	Inspection of thrust chamber post 36 revealed minor thrust chamber throat erosion (one spot) upstream of throat
201.4	300	1955	
192.1	300	2255	
172.0	300	2555	
186.8	300	2855	
204.0	300	3155	No thrust chamber erosion

orifice was changed, and no further problems of this manner occurred during the remainder of the tests on this unit.

Testing of the P/N EO 119924 injector was terminated after the fourth duration test because of heavy thrust chamber erosion (Fig. 26). Because the oxidizer tank pressure was increased to reach the planned mixture ratio, the cause of erosion has not been definitely established. However, calculation of transition mixture ratio showed no cause of thrust chamber erosion resulting from this shift in tank pressure. The thrust chamber inner-wall erosion was located 3 inches upstream of the throat and was through the wall. Minor nickel and parent metal erosion was evident at several other points. No evidence of erosion was detectable during the test or during close examination of the data. No further testing was attempted on this unit. The operating regime for the P/N EO 119924 injector is shown in Fig. 27.

Ten duration tests were completed on the P/N EO 123830 injector. The first test was terminated early because of the erratic parameters, and the 2-inch facility line was replaced by a 1-inch line to eliminate any problem with gaseous oxygen. The testing was continued with only a slight shift in the performance parameters. Minor thrust chamber erosion was evident after 700 seconds, but testing was continued after concluding that the erosion had been caused by a plugged orifice. No further erosion occurred during subsequent tests. The second P/N EO 123830 unit was not tested because of heavy streaking noted when the first chamber was sectioned and inspected following testing (Fig. 26). The operating regime of the P/N EO 123830 injector until the time of erosion is shown in Fig. 28.

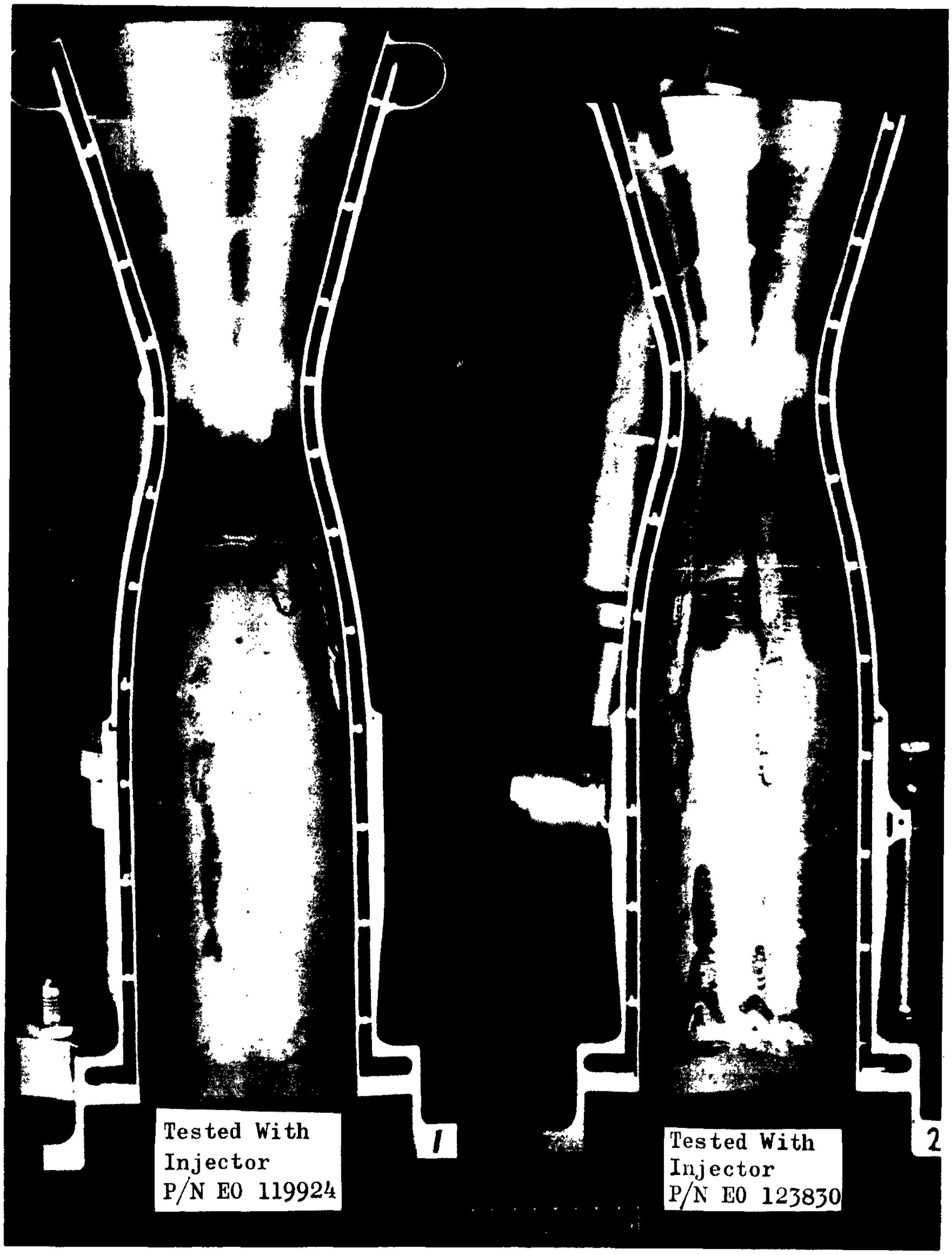

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Figure 26. Sectioned Vernier Engine Showing Thrust Chamber Erosion Resulting After Tests With Injectors P/N EO 119924 and P/N EO 123830

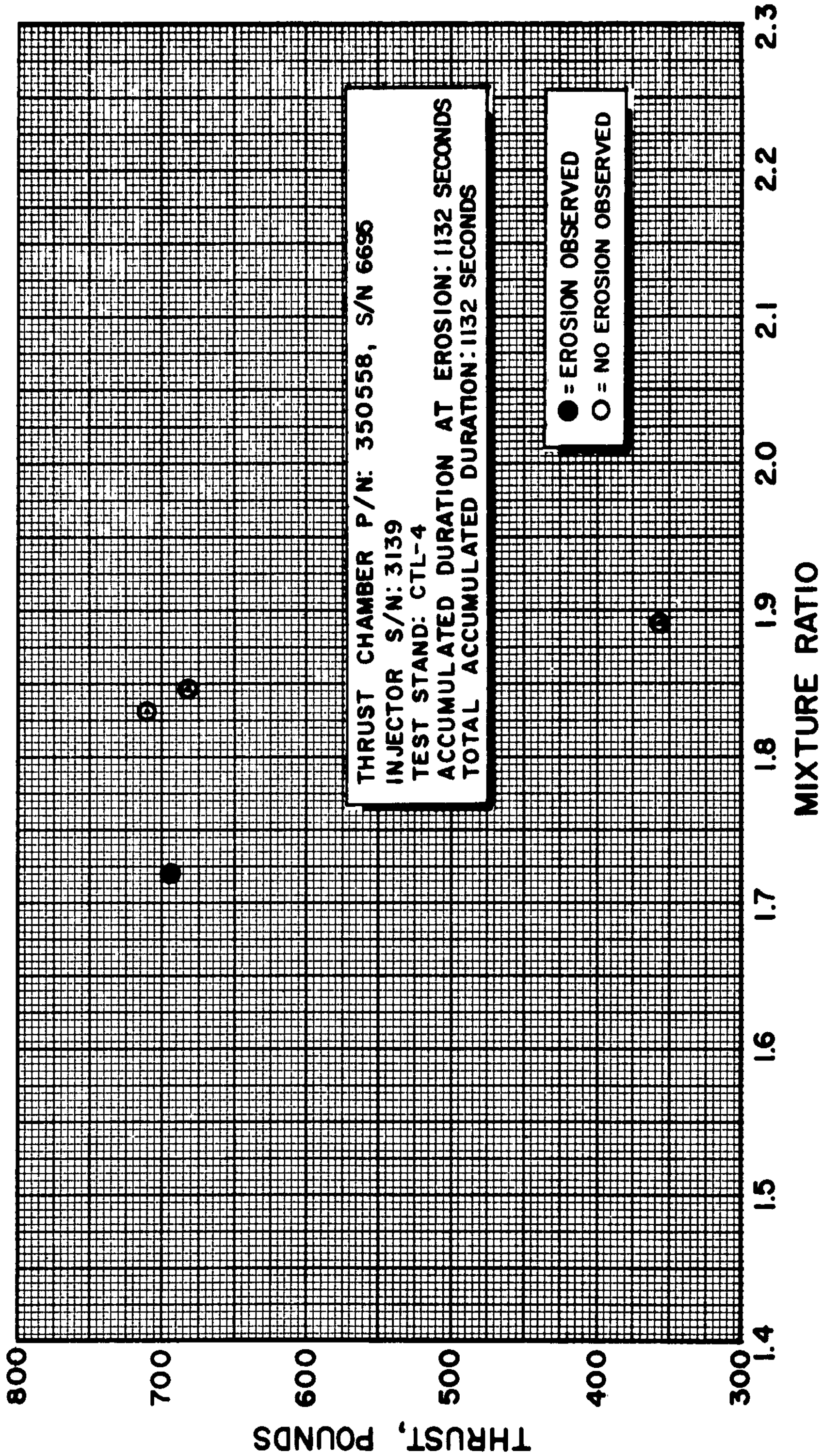

Figure 27. Operating Regime of Injector P/N EO 119924 Tested with Thrust Chamber S/N 6695

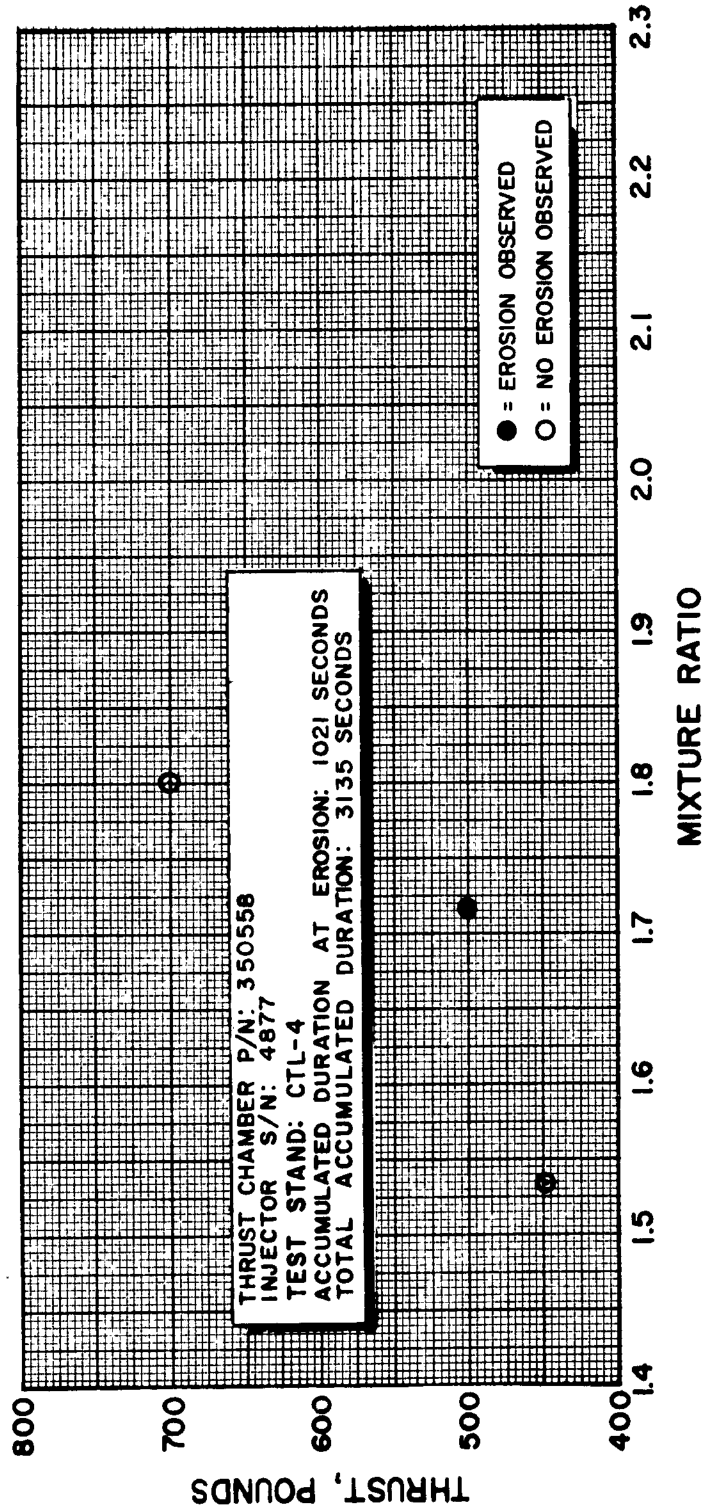

Figure 28. Operating Regime of Injector P/N EO 123830 Tested With Thrust Chamber S/N 6326

Ten duration tests for a total of 3030 seconds were completed on the first P/N EO 123864 unit before erosion was encountered. The erosion occurred at the highest mixture ratio (1.98) attained for the series. Posttest inspection revealed heavy thrust chamber erosion in the throat area through the inner wall. The operating regime of this unit is shown in Fig. 29. The second P/N EO 123864 unit was also tested because of the relatively good results with the first unit. However, only five tests for 1508 seconds were completed before thrust chamber erosion occurred at a mixture ratio of 1.94. This erosion, shown in Fig. 30, was similar to that experienced by the first unit. No further testing was conducted with the P/N EO 123864 configuration. The operating regime of the second P/N EO 123864 unit is shown in Fig. 31.

Component Test Laboratory-2, Cell 2B

Three units were hot fired in Cell 2B for a total of 9164 seconds. These included two P/N EO 123829 injectors and a prototype splash-plate injector.

Both units of the P/N EO 123829 configuration injector were subjected to the complete 3000-second test series before producing minor nickel erosion and one minor parent metal erosion upstream of the throat on the last test (Fig. 32). The thrust and mixture ratio values for the tests producing erosion on the two units were 541 pounds at 2.09 and 486 pounds at 2.25. The complete operation regimes of these units are shown in Fig. 33 and 34. Correlation of injector position to thrust chamber erosion determined that the erosion produced by the P/N EO 127829 injectors was not in line with an injector orifice set. It was concluded that the high mixture ratio operating condition, and not injector position or orifice plugging, was the probable cause of erosion.

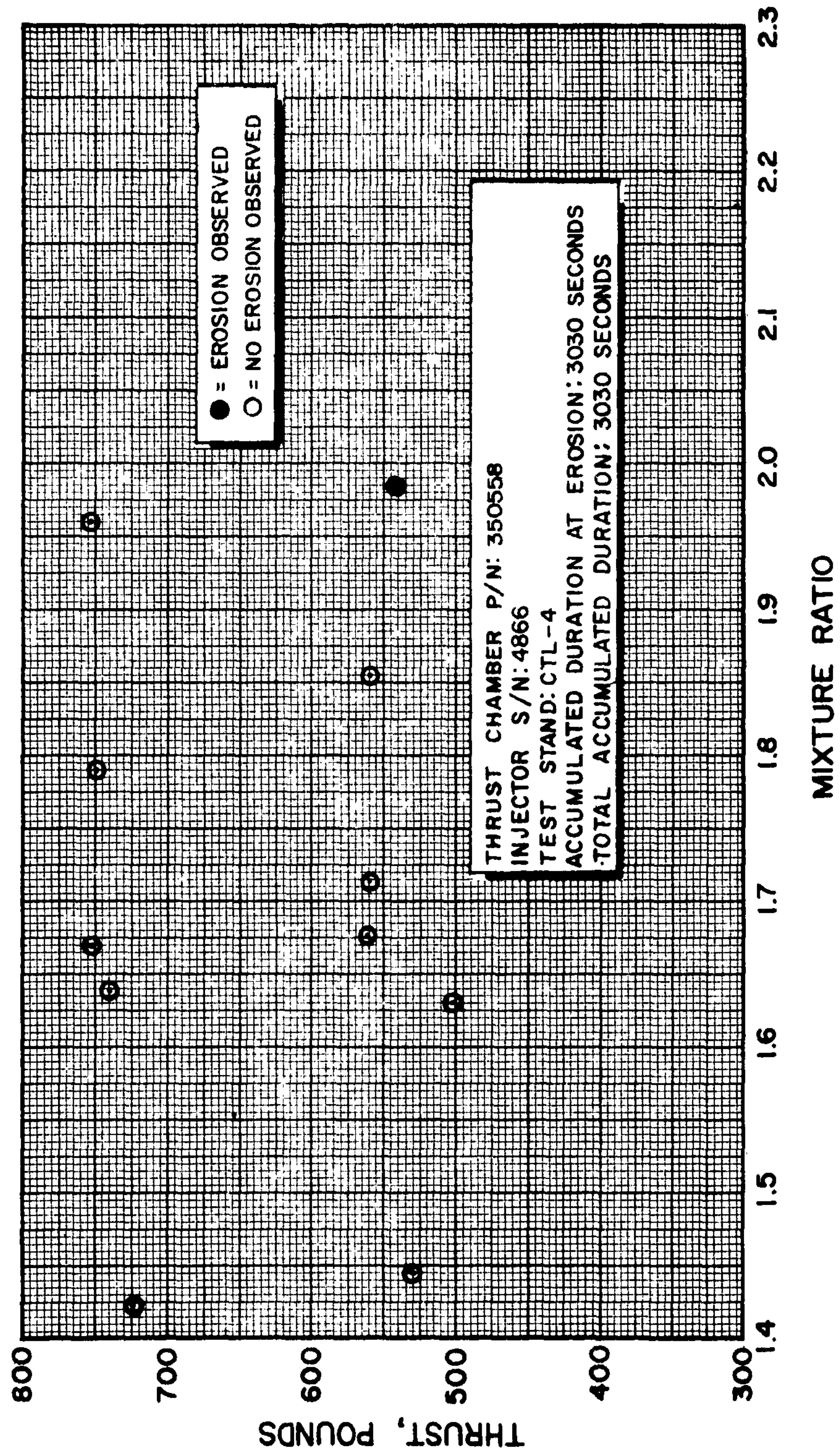

Figure 29. Operating Regime of Injector P/N EO 123864 Tested With Thrust Chamber S/N 6576

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Figure 30. Thrust Chamber Erosion After Tests With Second Unit of Injector P/N EO 123864

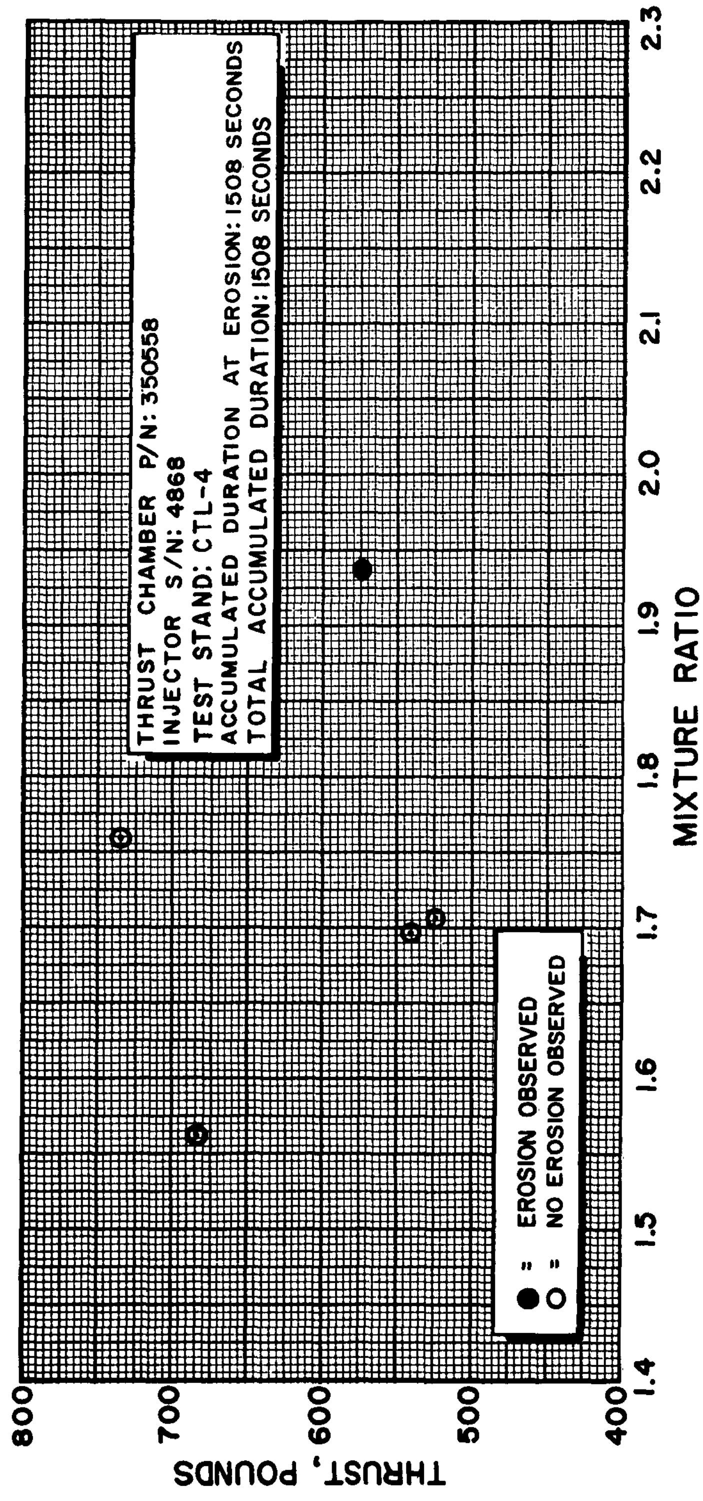


Figure 31. Operating Regime of Injector P/N EO 123829 Tested With Thrust Chamber S/N 6694

1BS35-9/4/63-C1G

Figure 32. Thrust Chamber Erosion After Tests With Injector P/N EO 123829

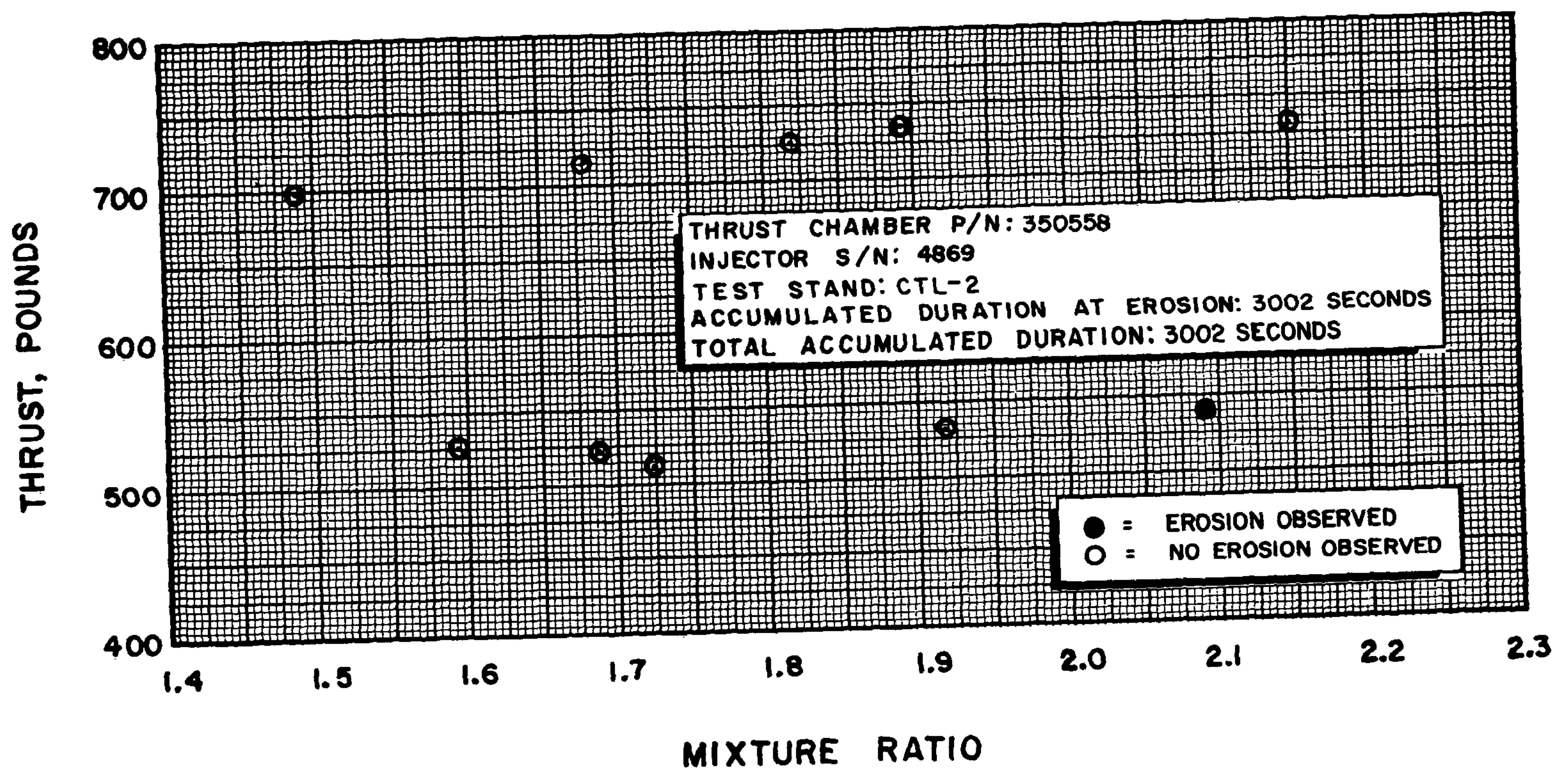


Figure 33. Operating Regime of Injector P/N E0 123829 Tested With Thrust Chamber S/N 6574

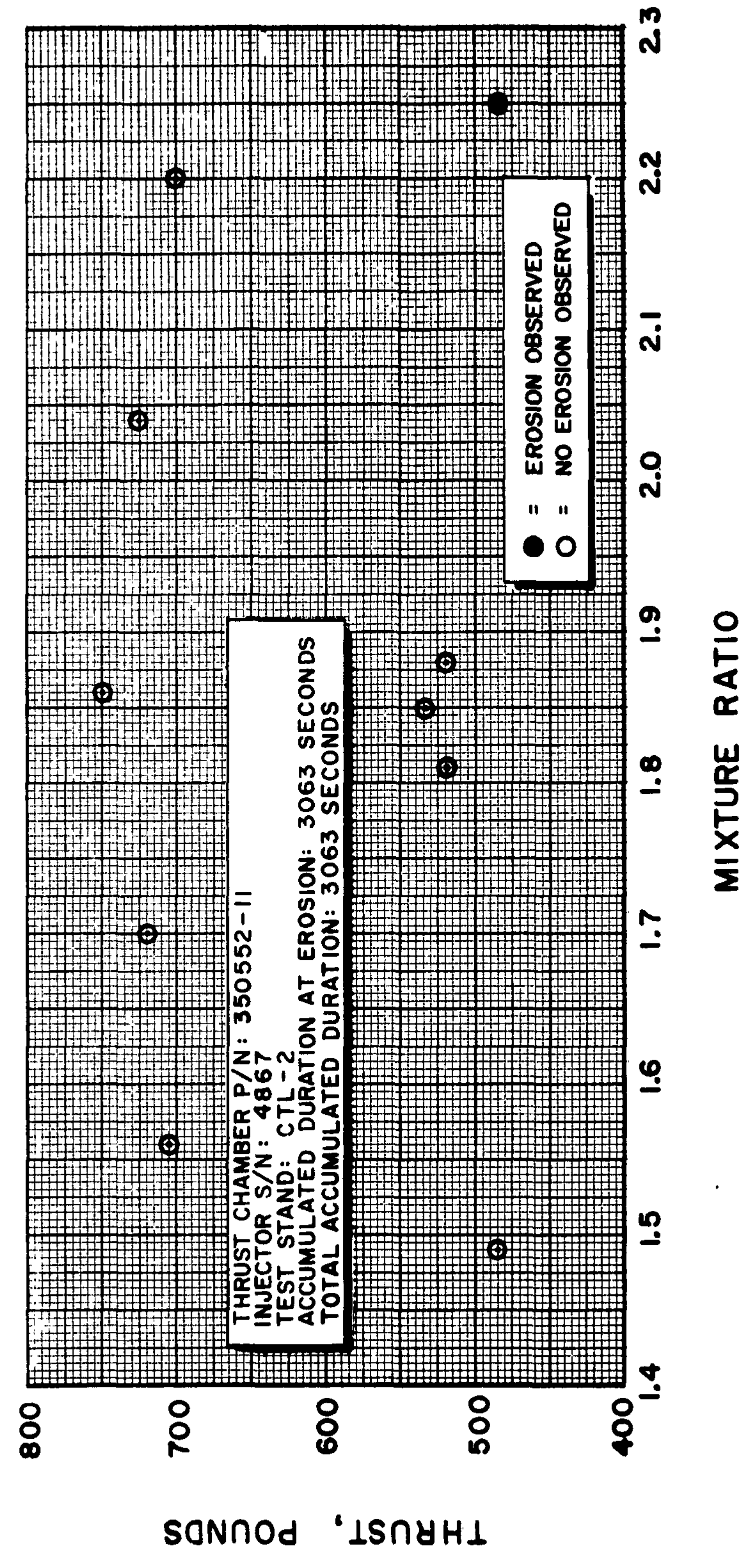


Figure 34. Operating Regime of Injector P/N EO 123829 Tested With Thrust Chamber S/N 6421

The splash-plate injector was tested for 3098 seconds at CTL-2, and no thrust chamber erosion was encountered. The operating regime of the splash-plate injector is shown in Fig. 35. The performance of this unit was comparable to the performance of the modified flat-face injector, but the test data indicated midtest performance shifts of a significantly greater magnitude than had occurred during the flat-face injector tests.

Carbon Buildup. Carbon buildup (Fig. 36) was found in the thrust chamber and on the injector face throughout the flat-face injector testing. Hard carbon up to 1/2-inch thick formed on the injector face upstream of the impinging propellant streams, and some pieces of carbon found in the test area showed the orifice pattern. The first three tests on each injector generally exhibited the heaviest carbon buildup, but random buildup was also evident during later tests. Soft carbon on the wall of the thrust chamber in line with each injector fuel orifice spoke gradually built up to a maximum thickness of 0.125 inch after several tests. Carbon buildup in the thrust chamber throat was not evident during the series.

A lesser degree of carbon buildup (Fig. 36) also was visible in the thrust chamber following splash-plate injector tests. Hard carbon on the wall at the injector end reached a 0.040-inch thickness, but decreased to zero thickness approximately 4 inches downstream. No carbon buildup was visible on the splash-plate injector face or in the thrust chamber throat, although it was assumed to have been in the throat as a result of the shifting performance and carbon particles found in the test area.

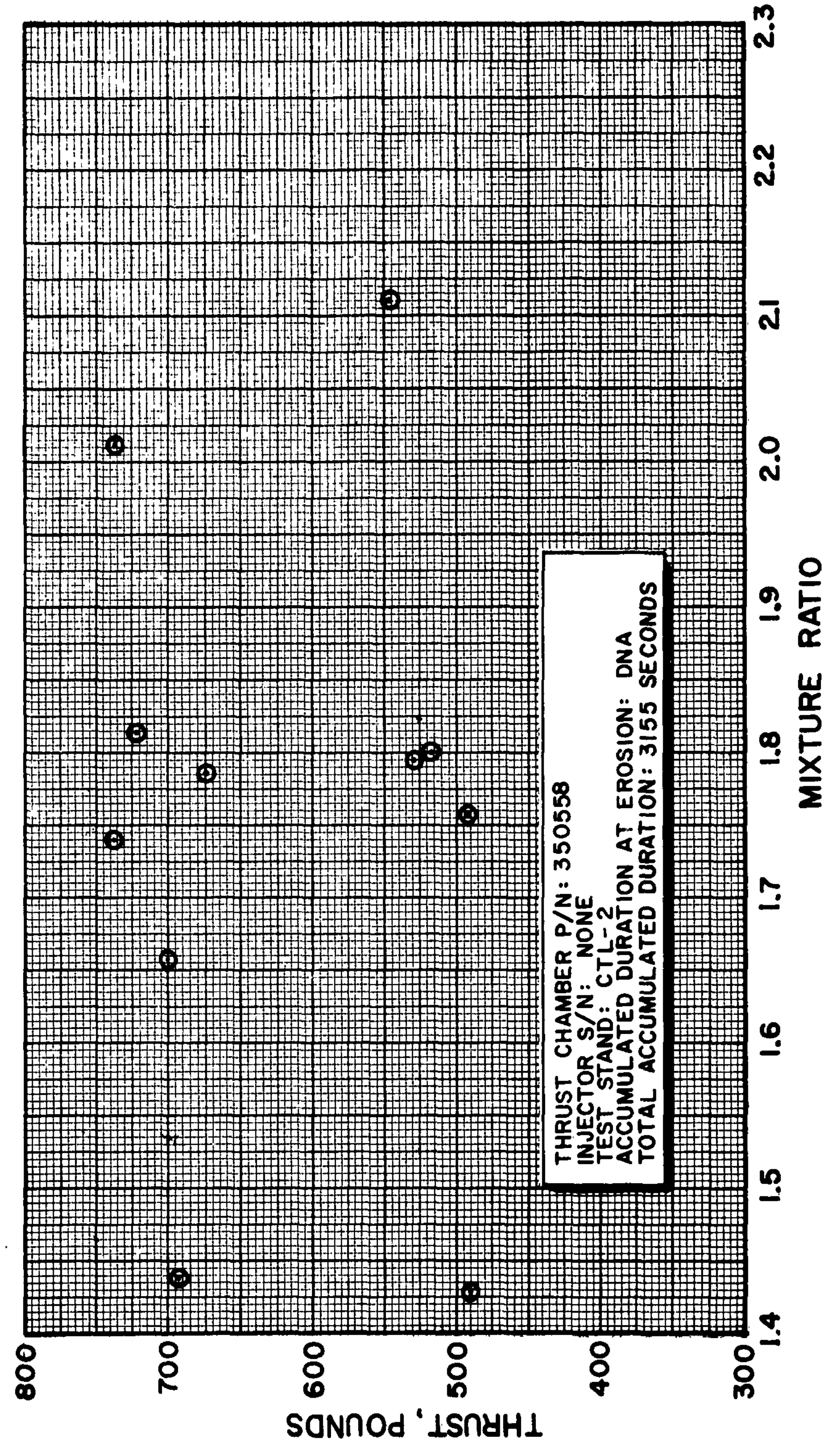


Figure 35. Operating Regime of Splash-Plate Injector Tested With Thrust Chamber S/N 6664

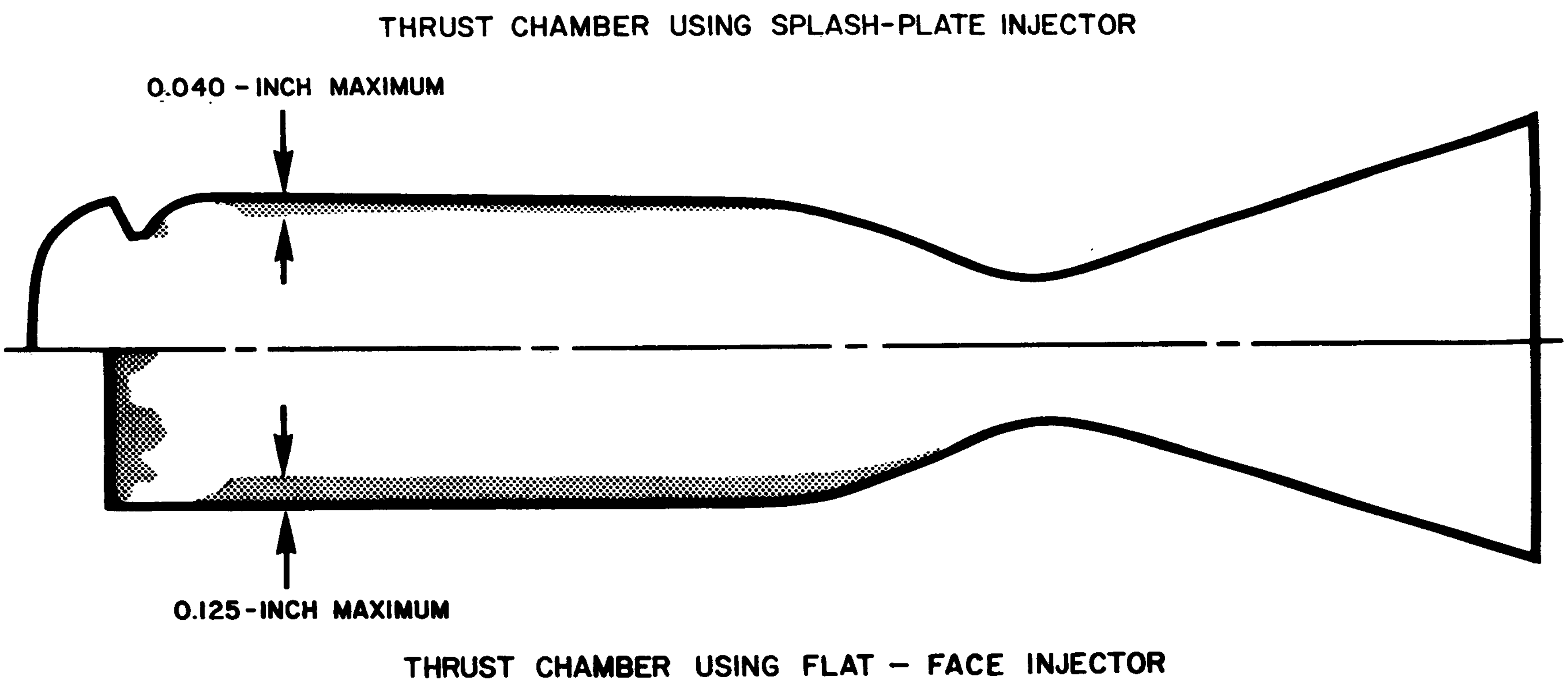


Figure 36. Typical Carbon Buildup During Tests With Splash-Plate and Flat-Face Injectors

A motion picture review from all tests showed random flashes in the exhaust. These flashes apparently were caused by burning carbon particles leaving the injector face and thrust chamber walls. No general correlation between the carbon particles and performance change could be established, but flashes were seen in the exhaust flame in conjunction with a significant performance shift during three tests with the splash-plate injector.

The carbon buildup on the wall of the thrust chamber was a result of the localized fuel-rich condition. Buildup on the face of the injector is thought to have been caused by the localized operating temperature of 1400 to 1800 F in conjunction with the cool injector face. No hardware damage was caused by the carbon buildup.

Performance Shifts. Two characteristics of the standard vernier injector at the 830-pound tank-fed thrust level was shifting performance during a test and nonrepeatability from test to test. Data from production tests indicated occasional mixture ratio changes of 0.2 and specific impulse shifts of as much as 4 seconds within any 1-second interval.

These shifts typically were noted as a continuous increase or decrease of all parameters interrupted by an occasional sudden shift in the opposite direction. The frequency of these shifts was not consistent, but generally averaged less than one shift per 30-second period with an operational deviation from the mean of 1.5% on all parameters in most extreme cases.

The cause of this shifting was thought to be carbon deposition in the throat. Calculations based on a constant thrust coefficient indicated a carbon buildup of 0.015 inch would be required.

During the downrated vernier test series, performance shifts were noted with each of the injector types. These consisted of gradual increases in chamber pressure and injection pressures, decreases in thrust and total flow, and a relatively constant mixture ratio until a sudden reverse shift occurred.

Performance shifts occurred during approximately 80% of the tests with the flat-face injectors. The frequency of occurrence was at least two shifts per duration run, with the first shift occurring within 50 seconds after the start of each test. The thrust shift mean in most cases was 1.0% with a deviation of ±0.5%. Total flow change averaged 1.4 ±0.4%. Data from several runs showed a decreasing chamber pressure, which is the opposite of the usual trend, but an investigation of this condition showed it to be caused by carbon blocking the chamber pressure tap.

Shifts also occurred during each of the 10 tests using the splash-plate injector. The frequency of occurrence averaged four shift per test with a thrust range of 1 to 5%. Three of the worst shifts encountered during different tests were 15, 17, and 35 pounds of thrust. The shifts were sudden and explosive in nature. In each case, examination of the test film coverage showed flashes of burning carbon leaving the chamber at the time of the shift. At the time of the 35-pound-thrust shift, total flow had decreased from 2.77 to 2.52 lb/sec. Concurrent mixture ratio and specific impulse variations were 0.2 and 5.0 seconds, respectively.

To determine if oxidizer temperature and gaseous nitrogen dilution had a significant effect on the performance shifts, three closely controlled tests were conducted on a P/N EO 123829 injector. These tests consisted of emptying the oxidizer tank, purging it with clean, dry nitrogen gas, retanking the oxidizer, bleeding to -285 F, and starting the test within 3 minutes of tank pressurization. One performance shift occurred during the three tests.

One performance shift also occurred during two subsequent tests which were conducted under normal conditions which allowed for oxidizer temperatures as high as -270 F. This appears to indicate that the observed performance shifts were not related to the quality of oxidizer in the supply tank.

Vibration Characteristics

Accelerometer measurements were recorded and a sonic analysis was made to define the predominant frequencies of the P/N EO 123829 and splash-plate injectors. The results of this study showed only high-frequency vibrations at levels of 2 to 4 g (rms) during stable mainstage. No detrimental frequencies existed during the operation of either injector.

The splash-plate injector exhibited questionable cutoff transients in the form of 8 to 10 g (rms) pulsations at cutoff. These decreased to 0 g (rms) within approximately 100 milliseconds.

Injector Performance

Figure 37 represents site specific impulse of four of the five injector configurations tested. Because of limited testing, the P/N EO 119924 injector was not included. The standard injector curve is included

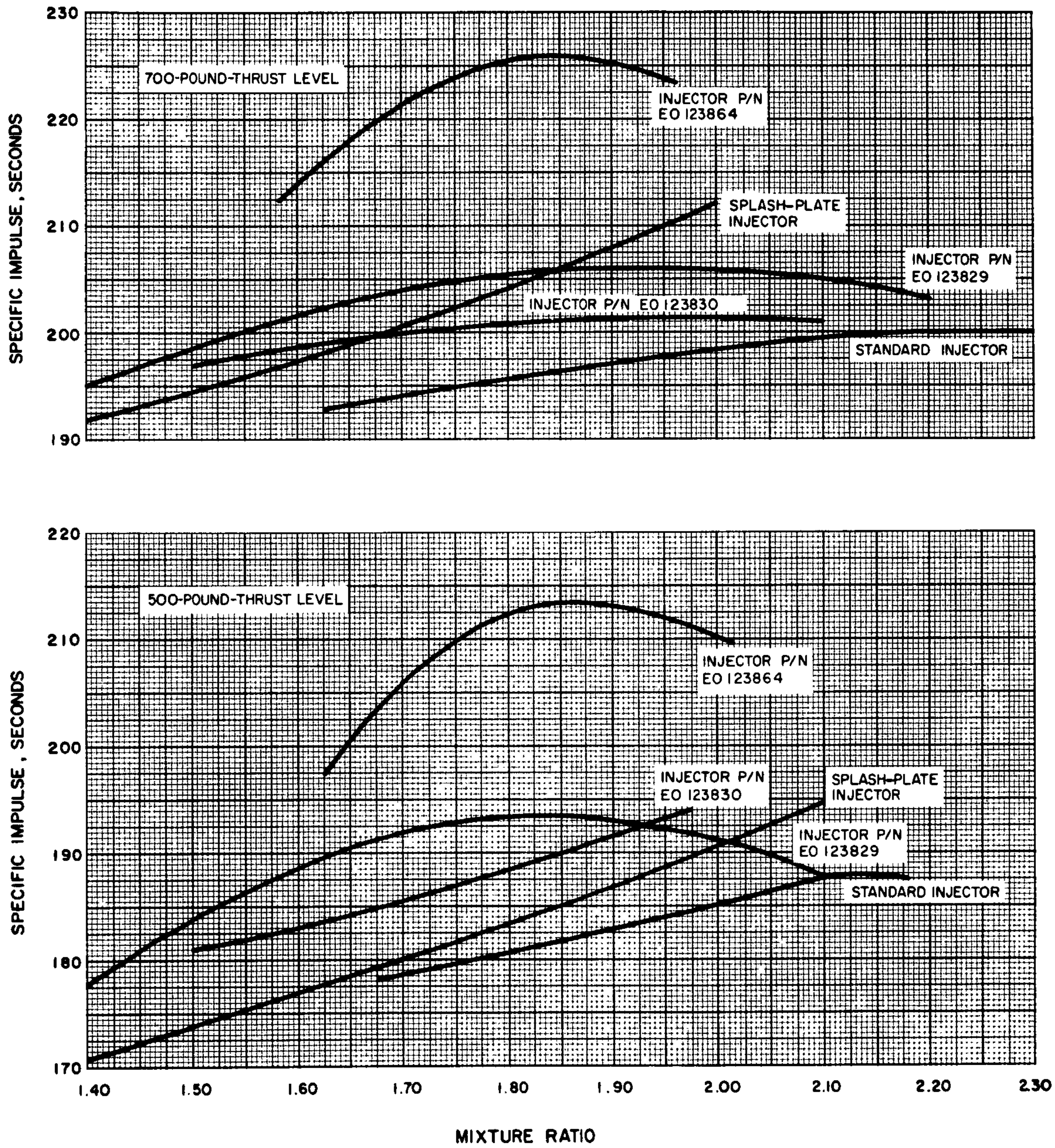


Figure 37. Site Specific Impulse at Various Mixture Ratios

for comparison purposes. Each curve was determined by a "least squares curve fit" program. Data points were omitted for clarity.

Injector Selection for Engine Testing

The component test phase of the modified vernier injector program indicated that, of the four flat-face injector types tested, only the P/N EO 123829 configuration appeared to offer a significantly reduced probability of thrust chamber erosion in comparison with the standard injector. The erosion experienced with the two tested P/N EO 123829 injectors occurred outside what would be considered the normal operating regime for the vernier system. All other characteristics of the injector/thrust chamber combination demonstrated during the thrust chamber assembly tests were satisfactory. The splash-plate injector characteristics during the thrust chamber assembly tests were also considered suitable for further evaluation, but only one prototype unit had been tested and changes would have had to be made to some aspects of the dome inlet and injector LOX inlet to achieve a successful production configuration. (Fig. 23, page 78) On the basis of these considerations it was recommended that the P/N EO 123829 injector be committed to the vernier engine system tests and that production configuration units of the splash-plate design be fabricated to serve as backup units.

VERNIER ENGINE TEST PHASE

PROGRAM DESCRIPTION

The engine test phase of the modified injector test program was conducted using six P/N EO 123829 injectors and one splash-plate injector in conjunction with nine thrust chambers. Only three YLR101-NA-15 vernier engines were available so six YLR101-NA-13 vernier engines were modified to operate at the low thrust level.

Ten tests were conducted with each unit. The first test was a calibration test of 30 seconds duration to obtain the data necessary to target the various thrust and mixture ratio levels. Tests 2 through 10 were scheduled to be conducted under the conditions summarized in Table 12.

The first P/N EO 123829 injector unit completed the test series with no recorded thrust chamber erosion (Fig. 38) but erosion was found in the combustion zone during disassembly. At the time of this discovery, seven tests had already been completed on the second test unit. This unit was immediately disassembled, carbon was removed from the combustion zone, and erosion was noted in the combustion zone. The operating regime of this unit until the time that thrust chamber erosion was noted is shown in Fig. 39. As a result of this incident, the procedure for determining erosion was revised to encompass disassembly of the thrust chamber/injector combination and removal of combustion zone carbon.

The third unit tested operated in the regime indicated in Fig. 40 until the time of initial erosion.

TABLE 12

SCHEDULED MIXTURE RATIO AND THRUST FOR TESTS CONDUCTED WITH MODIFIED VERNIER INJECTOR

Test No.	Mixture Ratio, o/f	Thrust, pounds	
		Tank-Fed Performance Level	Pump-Fed Performance Level
2	1.8	525	675
3	1.8	475	625
4	1.8	575	575
5	1.6	525	675
6	1.6	475	625
7	1.6	575	575
8	2.0	525	675
9	2.0	475	625
10	2.0	575	575

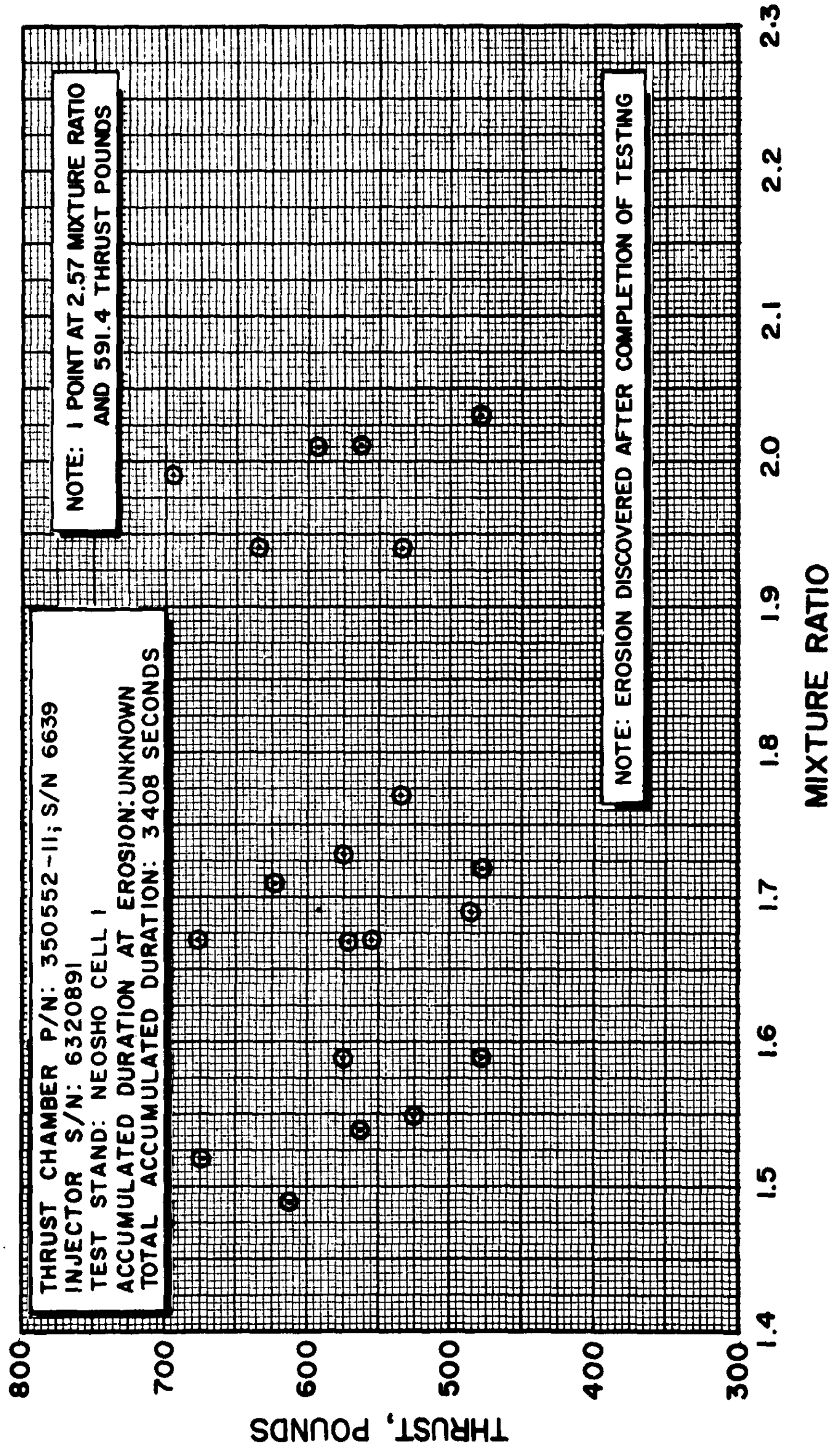


Figure 38. Operating Regime of Injector P/N EO 123829 Tested With Engine S/N 3401.

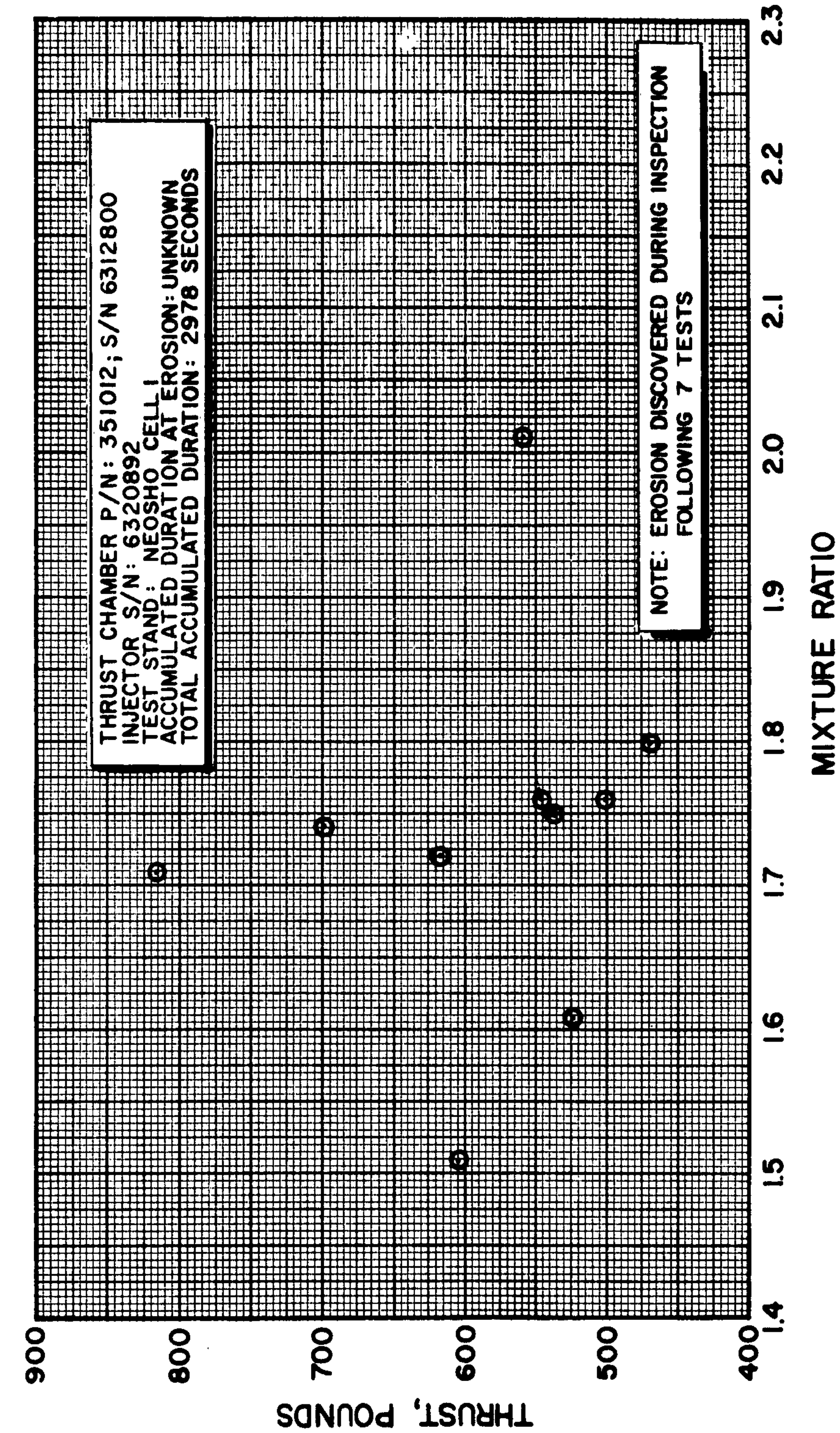


Figure 39. Operating Regime of Injector P/N EO 123829 Tested With Engine S/N 3501-2

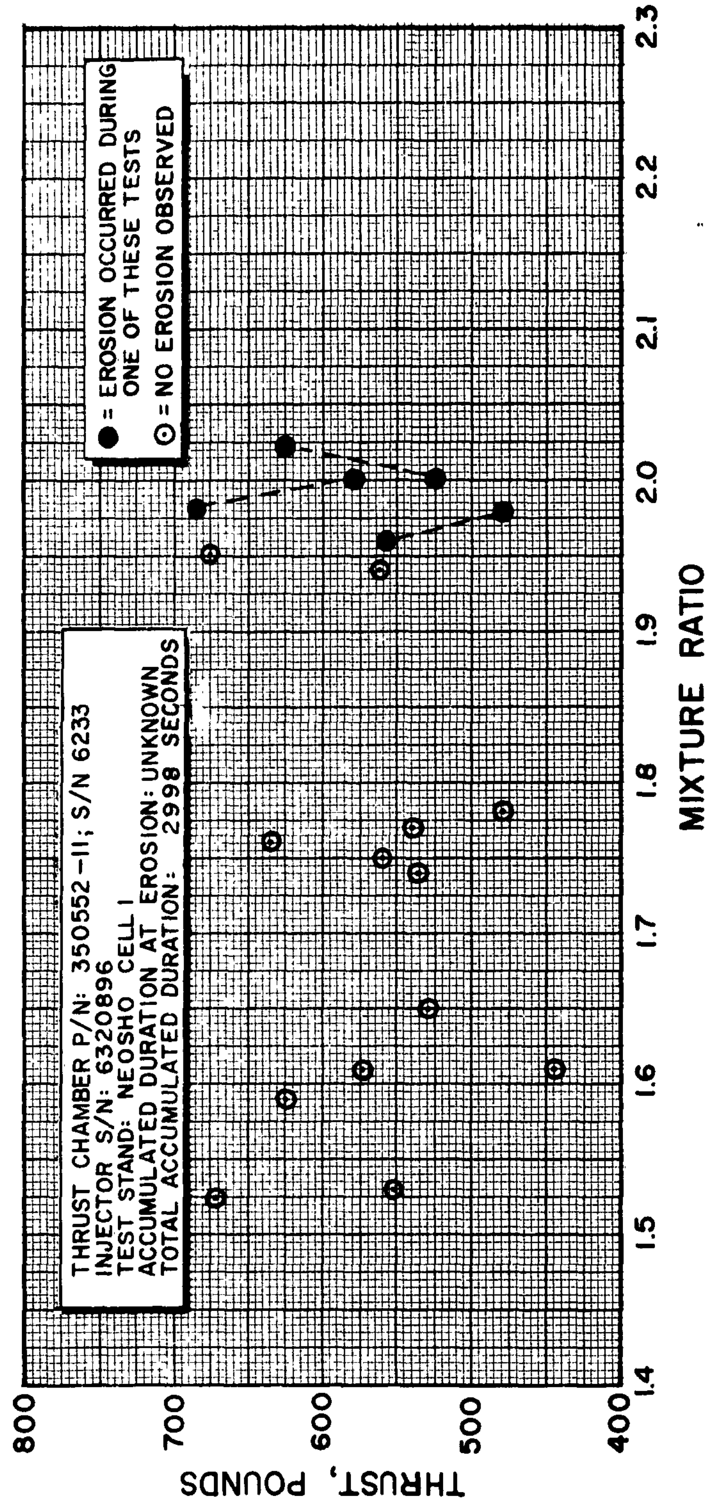


Figure 40. Operating Regime of Injector P/N EO 123829 Tested With Engine S/N 3401-2.

The occurrence of erosion on the first two units, coupled with the damage on the third unit in the high mixture ratio operating range, resulted in the splash-plate unit being used on the next vernier engine assembly. The operating regime of this unit until the time of initial thrust chamber erosion is shown in Fig. 41. In addition to the unsatisfactory erosion pattern exhibited by this injector, large thrust variations were experienced as the result of heavy carbon formations at the thrust chamber throat. Testing of the splash-plate unit was discontinued.

A review of the operating regimes and damage patterns of the first three P/N EO 123829 injectors appeared to indicate that thrust chamber erosion might be eliminated if operation at the 525-pound thrust level was restricted to mixture ratios of below approximately 1.9.

To evaluate the validity of this conclusion, three additional P/N EO 123829 injectors were tested under the conditions summarized in Table 13. The tests on these injectors were completely satisfactory with no occurrences of thrust chamber erosion. The operating regimes of these units are shown in Fig. 42 through 44.

After the sixth P/N EO 123829 injector had been tested, it was decided to retest one of the first three injectors which had previously produced erosion at a mixture ratio above 1.9. These new tests were conducted at the revised performance levels to obtain a comparison of the two test series and to eliminate the possibility that the erosion during the first series was related to a defective injector rather than the operating regime. Two tests were conducted with this injector before it was determined that the thrust chamber was not of production quality and could not be used for an accurate comparison.

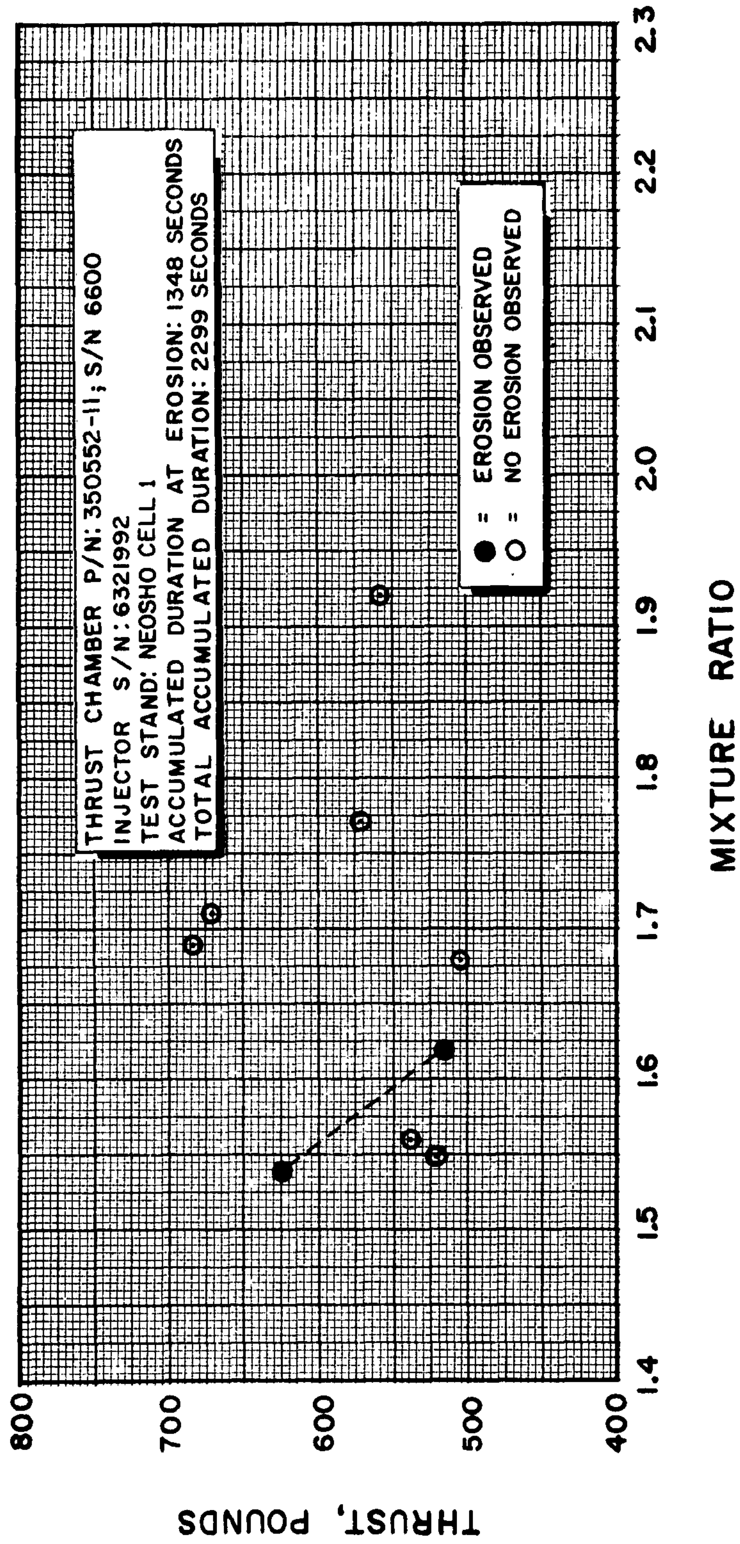


Figure 41. Operating Regime of Splash-Plate Injector P/N 99-308305 Tested With Engine S/N 3402

TABLE 13

REVISED SCHEDULE OF MIXTURE RATIO AND THRUST FOR TESTS CONDUCTED WITH MODIFIED VERNIER INJECTOR

Test No.	Mixture Ratio, o/f	Thrust, pounds	
		Tank-Fed Performance Level	Pump-Fed Performance Level
2	1.65	525 ±25	Approximately 610
3	1.65	525 ±25	Approximately 610
4	1.65	525 ±25	Approximately 610
5	1.5	525 ±25	Approximately 610
6	1.5	525 ±25	Approximately 610
7	1.5	525 ±25	Approximately 610
8	1.8	525 ±25	Approximately 610
9	1.9	525 ±25	Approximately 610
10	2.0	525 ±25	Approximately 610

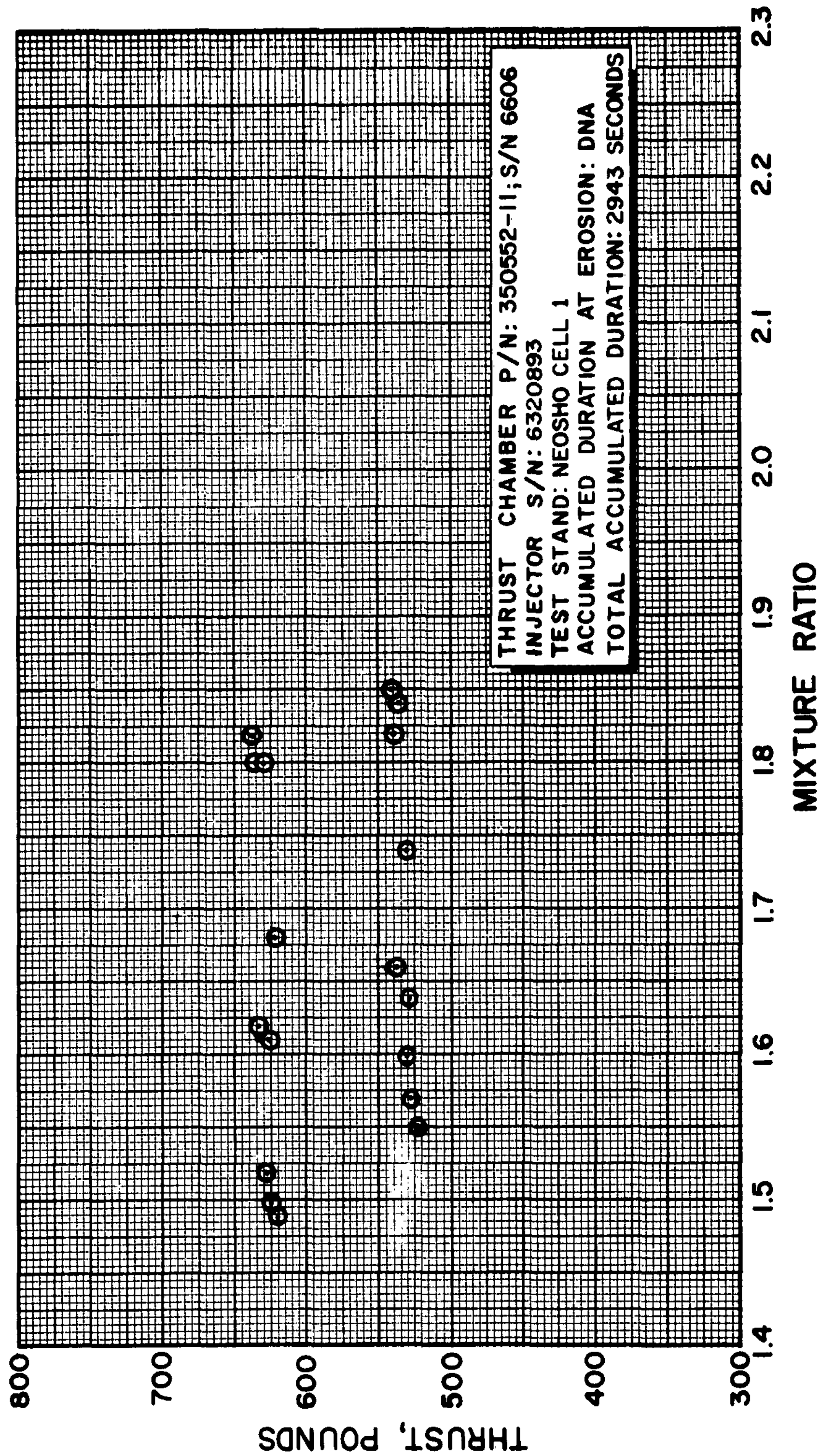


Figure 42. Operating Regime of Injector P/N EO 123829 Tested With Engine S/N 3401-3

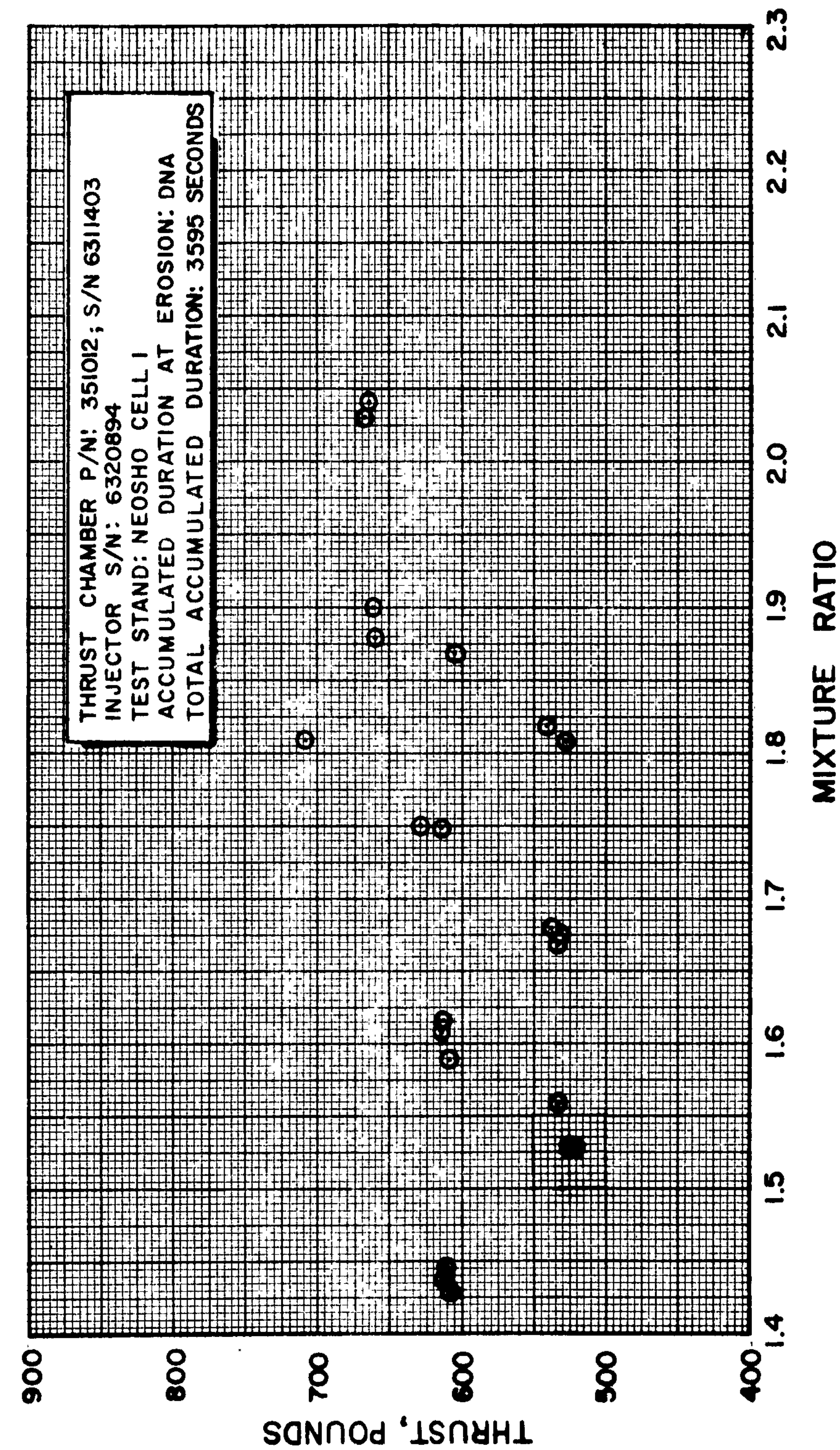


Figure 43. Operating Regime of Injector P/N EO 123829 Tested With Engine S/N 3501-3.

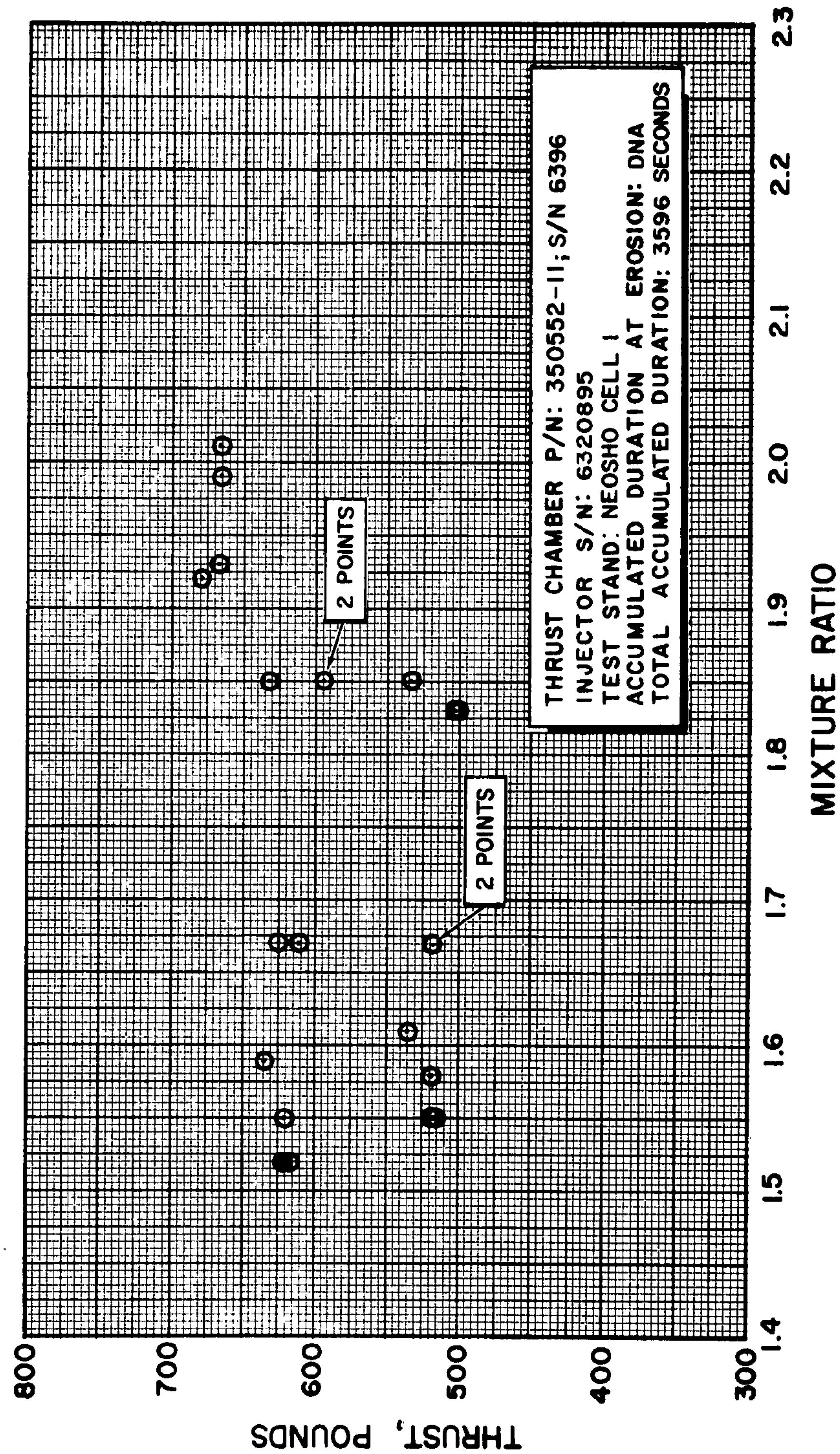


Figure 44. Operating Regime of Injector P/N EO 123829 Tested With Engine S/N 3402-2

The thrust chamber was changed, and a complete series of nine tests was conducted (Table 13). No thrust chamber erosion occurred. The operating regime of this unit is shown in Fig. 45.

TEST FACILITY

Component Test Stand 8 at the Neosho facility was slightly modified for the vernier engine test program. This stand had been previously used for Phase II testing of the YLR101-NA-15 MD 1 engine at the 777-pound thrust level. As part of the modification, temperature bulbs were incorporated to measure LOX and fuel injection temperatures, and all vernier engine pressure transducers were short coupled. Figures 46 through 49 show a YLR101-NA-15 engine on the test stand with all instrumentation installed.

Vernier engine test stands use a bypass system in the LOX and fuel facility lines to obtain both tank- and pump-fed performance levels without changing supply tank pressures during a test. The bypass systems on Test Stand 8 had been orificed to supply tank- and pump-fed inlet pressures and flows at the 777-pound thrust level. This facility orificing was not changed because it was determined that this system would approximate pump-fed operation using the new injector design.

When the performance values were changed, an attempt was made to reorifice the bypass system to hold the mixture ratio constant between the tank-fed and pump-fed levels. Because of the method used in reorificing the system, this objective was not attained.

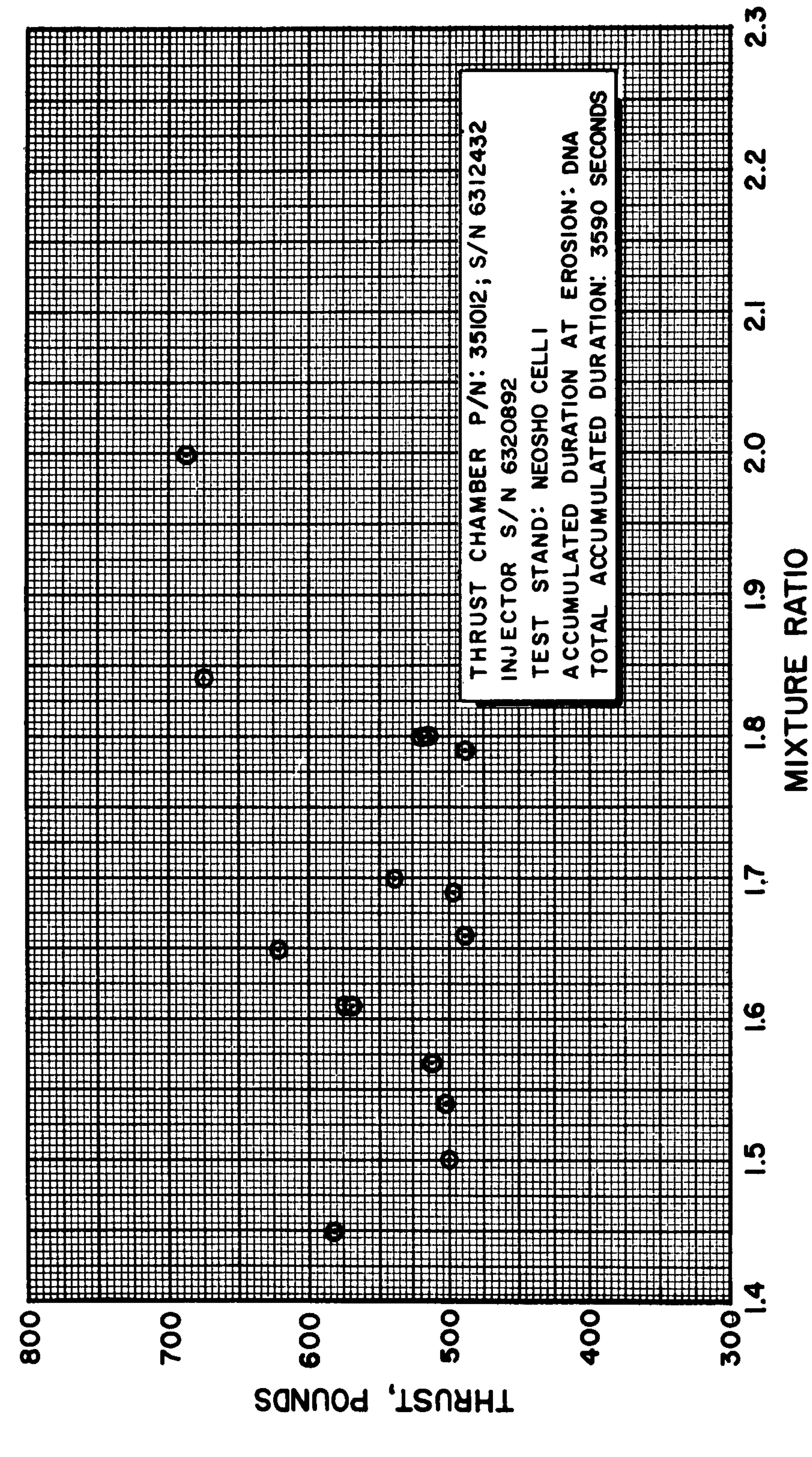
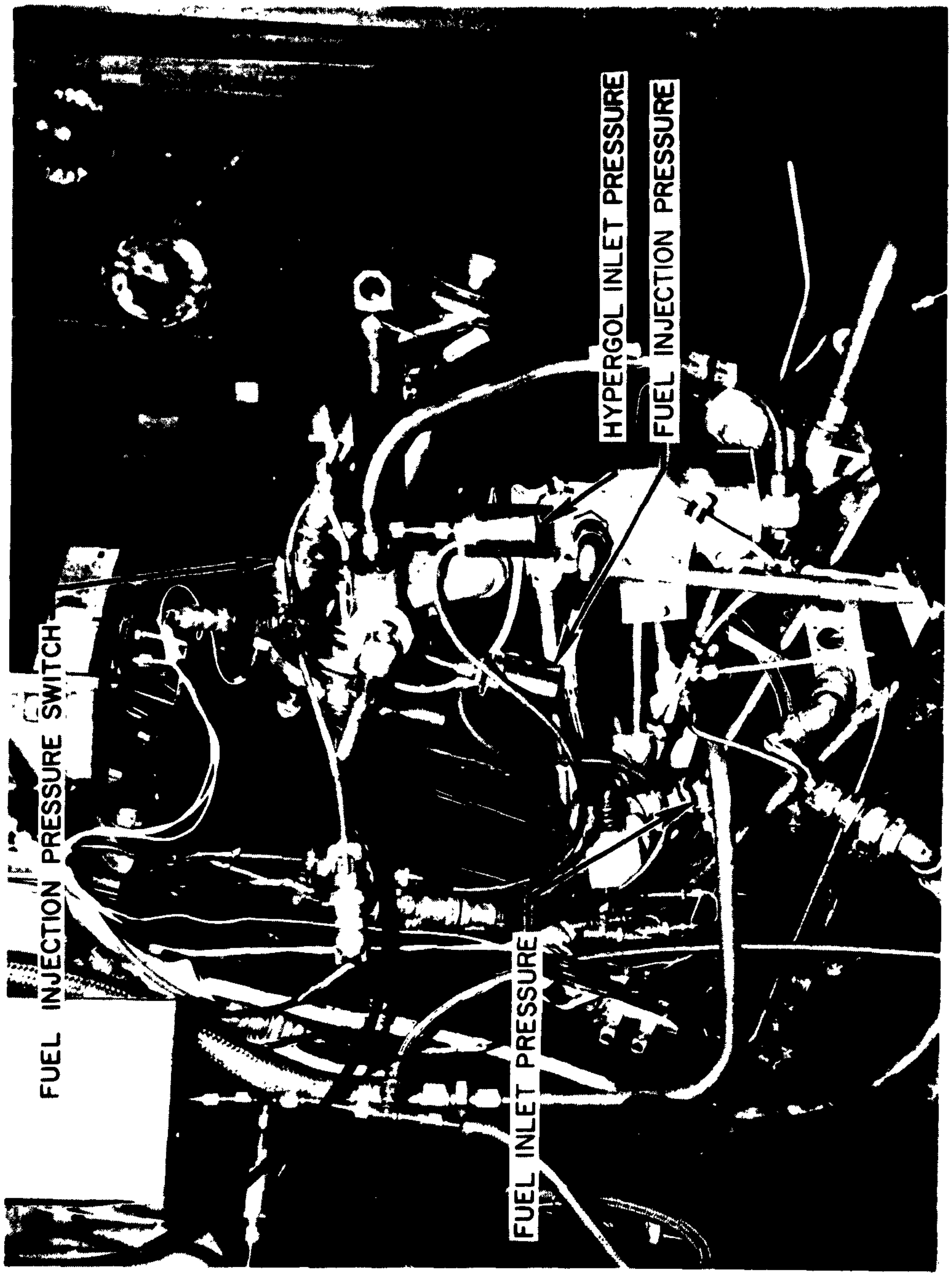
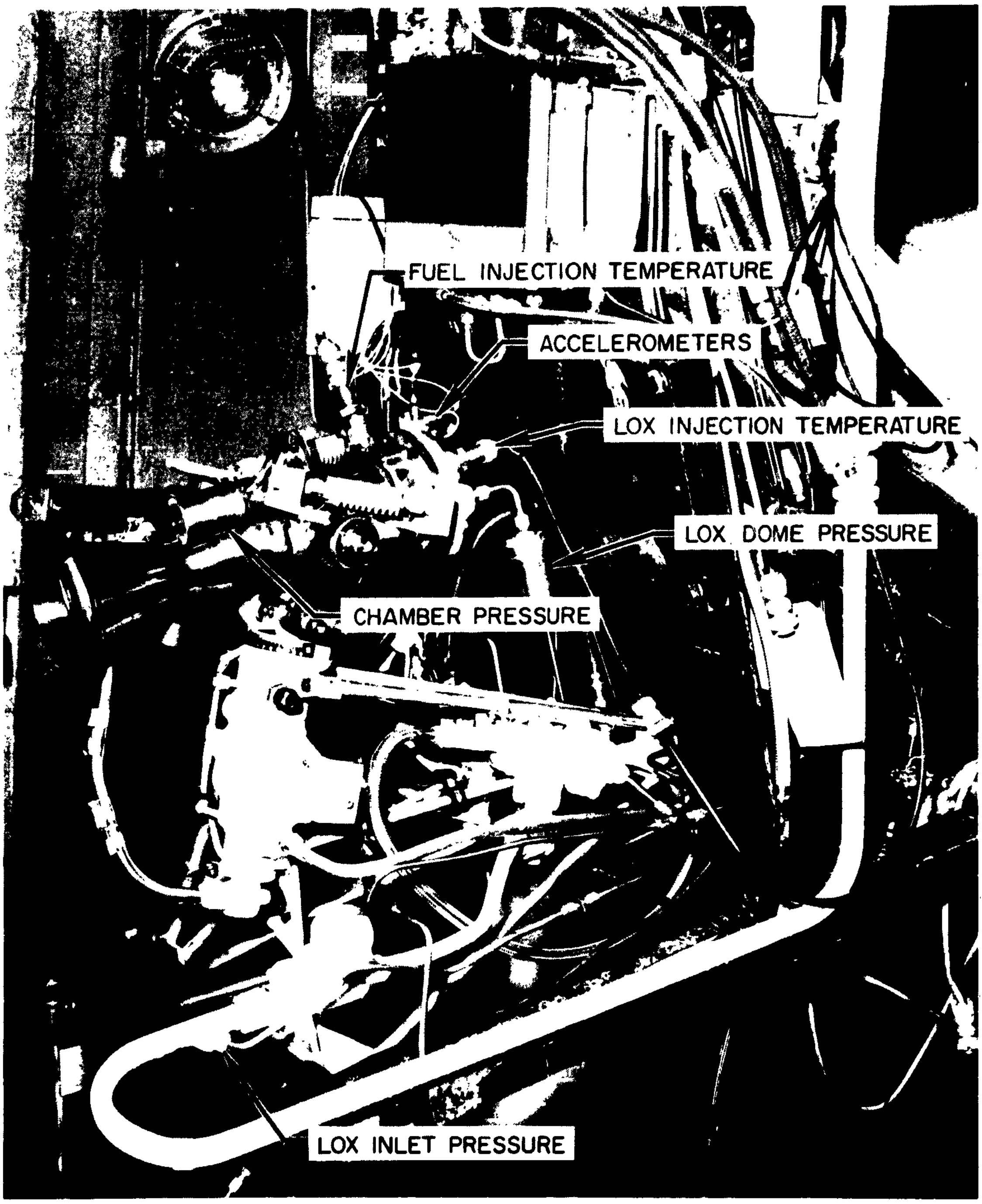


Figure 45. Operating Regime of Injector P/N EO 123829 Tested With Engine S/N 3503



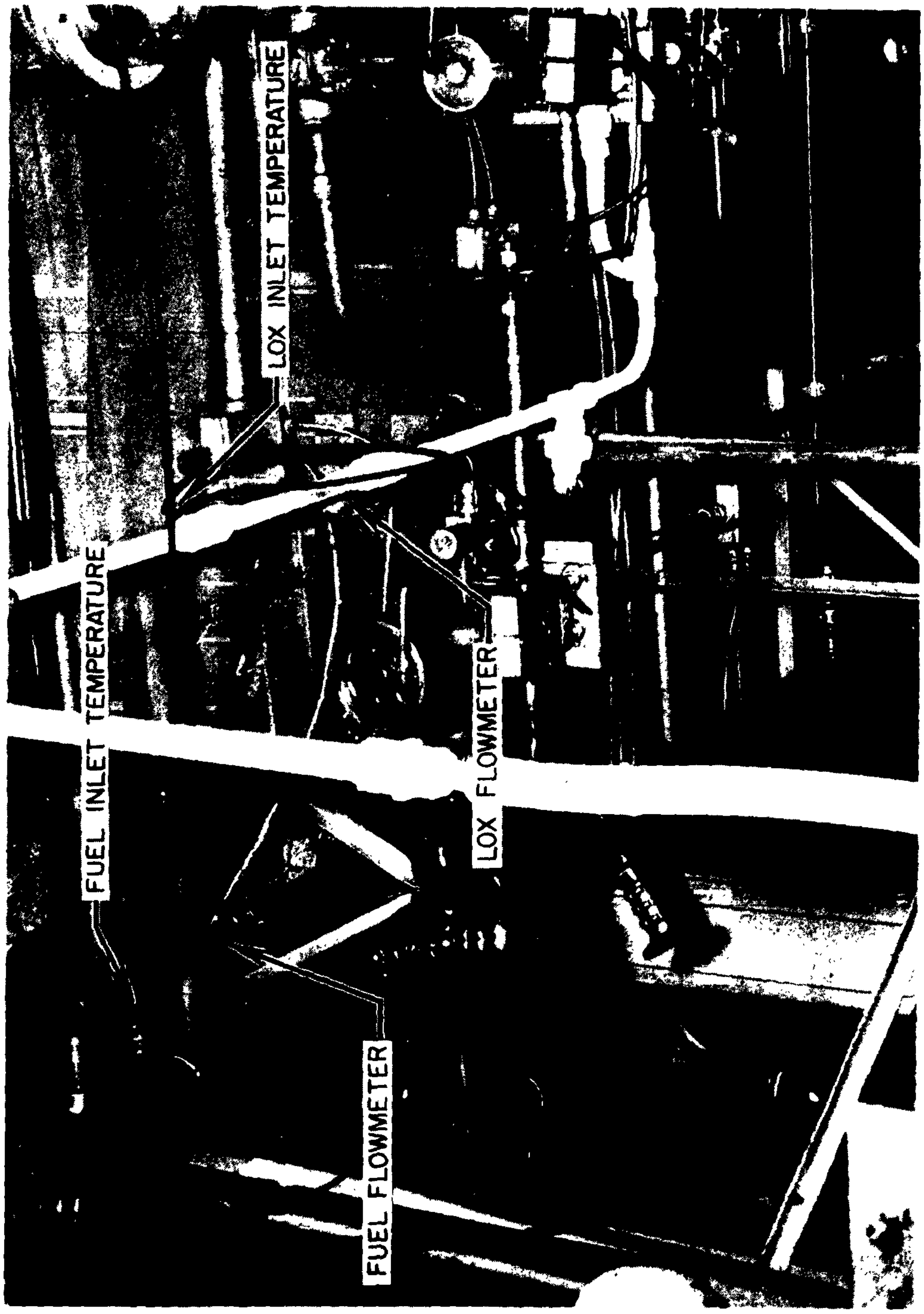
6NG32-8/7/63-N1C

Figure 46. Downrated Vernier Engine on Neosho Test Stand 8, View A



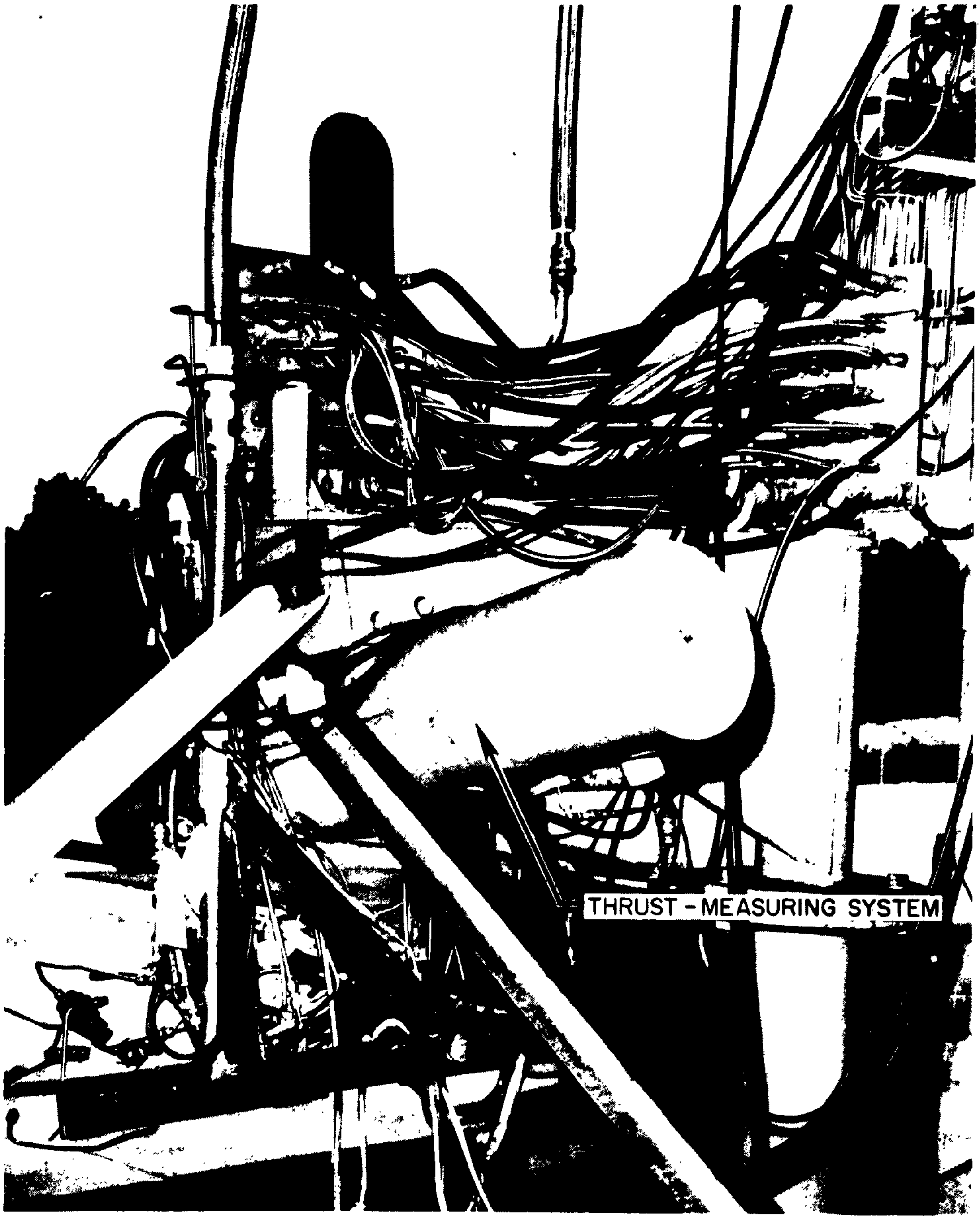
6NG32-8/7/63-N1A

Figure 47. Downrated Vernier Engine on Neosho Test Stand 8, View B



6NG32-8/7/63-N1B

Figure 48. Propellant Flowmeters and Inlet Temperatures Taps Used During Downrated Vernier Engine Tests on Neosho Test Stand 8



6NG32-8/7/63-NlD

Figure 49. Thrust-Measuring System Used During Downrated Vernier Engine Tests on Neosho Test Stand 8

TEST SUMMARY

The complete test series previously described consisted of 87 tests conducted at the Neosho facility on nine vernier engine systems. One splash plate and six P/N EO 123829 injectors were used. Each injector was subjected to the variations in thrust and mixture ratio previously stated, and the actual tank- and pump-fed values attained at the site are tabulated in Table 14. The facility tank pressures were difficult to calculate during the first test on the first two engines (S/N 3401 and 3501-2). This had been expected, but not to the degree encountered, and was the reason for requiring the calibration tests of only 30 seconds duration. It was determined that the difficulty in calculating the required facility tank pressures was caused by errors in the estimated engine LOX pressure losses for the YLR101-NA-13 engine (modified for the low thrust level) and the YLR101-NA-15 engine.

TRANSIENT PERFORMANCE

Start transient data from the modified injector program were compared with data obtained from the Phase II program, and it was found that only two engine sequence timings had shifted significantly. The fuel injection pressure switch actuated 244 milliseconds sooner at the 525-pound thrust level than at the 777-pound thrust level.because of the difference in pressure settings between the two switches, and the time from start signal to 90% thrust was 1.0 second longer at the 525-pound thrust level than at the 777-pound thrust level because of the LOX injection temperature characteristic during thrust buildup. This was previously detailed in the description of the Phase I tests. The LOX injection temperature primarily is an over-all engine parameter and not a characteristic of the injector only.

1

TABLE

SUMMARY OF MODIFIED VERNIER I

Injector Type	Injector Serial Number	Engine Serial No.	Engine Model	Test Number	Duration, seconds	Cumulative Duration, seconds	Tank-Fed
							Mixture Ratio
E0 123829	6320891	3401	Modified YLR101-NA-13	8948	11.5	11.5	-
				49	34.5	46.0	2.57
				50	378.8	424.8	1.77
				51	336.0	760.8	1.72
				52	338.0	1098.8	1.73
				53	333.8	1432.6	1.55
				54	331.7	1764.3	1.59
				55	330.7	2095.0	1.59
				56	332.5	2427.5	1.69
				57	328.5	2756.0	1.94
				58	327.3	3083.3	2.03
				59	326.5	3409.8	2.01
E0 123829	6320892	3501-2	YLR101-NA-15	8960	35.1	35.1	2.01
				61	21.1	56.2	1.76
				62	9.9	66.1	-
				63	331.5	397.6	1.75
				64	328.3	725.9	1.80
				65	327.6	1053.5	1.74
				66	339.1	1392.6	1.61
				67	326.9	1719.5	1.59
				68	102.1	1821.6	1.61
				69	328.5	2150.1	1.58
				70	176.5	2326.6	1.98
				71	327.6	2654.2	1.99
				72	327.9	2982.1	1.97

2

TABLE 14

IODIFIED VERNIER INJECTOR TESTING AT NEOSHO

Tank-Fed Site Values		Pump-Fed Site Values		Remarks
Mixture Ratio	Thrust, pounds	Mixture Ratio	Thrust, pounds	
-	-	-	-	LOX flow recorder malfunctioned
2.57	591	-	-	Calibration test
1.77	536	1.74	626	
1.72	479	1.70	562	
1.73	575	1.67	675	
1.55	526	1.49	613	
1.59	480	1.42	552	
1.59	575	1.52	673	
1.69	487	1.67	571	
1.94	534	1.94	633	
2.03	482	2.01	563	
2.01	594	1.99	694	Erosion spot noted upstream of nozzle after cleaning
2.01	561	-	-	Approximate values; LOX and fuel leaks
1.76	503	-	-	Approximate values; LOX and fuel leaks
-	-	-	-	LOX leak at yaw housing flex line
1.75	538	1.72	619	
1.80	471	1.76	546	
1.74	699	1.71	815	
1.61	525	1.51	604	Erosion at converging portion of chamber at 12:00 o'clock position
1.59	473	1.51	536	
1.61	565	1.51	650	
1.58	575	1.50	667	Erosion spot below injector face at 3:00 o'clock position
1.98	527	1.93	603	
1.99	476	1.92	540	
1.97	581	1.94	678	

1

TABLE 1

(Continue

Injector Type	Injector Serial Number	Engine Serial No.	Engine Model	Test Number	Duration, seconds	Cumulative Duration, seconds	Tank-Fed S
							Mixture Ratio
EO 123829	6320896	3401-2	Modified YLR101-NA-13	8973	34.3	34.3	1.73
				74	329.1	363.4	1.78
				75	329.5	692.9	1.78
				76	327.8	1020.7	1.94
				77	328.3	1349.0	1.65
				78	327.8	1676.8	1.59
				79	331.7	2008.5	1.61
				80	328.9	2337.4	2.00
				81	328.3	2665.7	1.98
				82	332.5	2998.2	2.00
Splash Plate	6321992	3402	Modified YLR101-NA-13	8983	32.0	32.0	1.68
				84	329.6	361.6	1.76
				85	330.0	691.6	1.64
				86	328.5	1020.1	1.77
				87	327.5	1347.6	1.62
				88	327.2	1674.8	1.60
				89	327.5	2002.3	1.62
				90	296.5	2298.8	2.01
EO 123829	6320893	3401-3	Modified YLR101-NA-13	8991	329.4	329.4	1.64
				92	329.8	659.2	1.67
				93	329.9	989.1	1.74
				94	328.0	1317.1	1.60
				95	327.6	1644.7	1.55
				96	327.6	1972.3	1.57
				97	329.0	2301.3	1.82
				98	328.1	2629.4	1.85
				99	329.0	2958.4	1.84

TABLE 14

(Continued)

Tank-Fed Site Values		Pump-Fed Site Values		
Mixture Ratio	Thrust, pounds	Mixture Ratio	Thrust, pounds	Remarks
1.73	536	-	-	Calibration test; discoloration streaks in throat area
1.78	539	1.76	633	Discoloration spots below injector face area on thrust chamber
1.78	480	1.76	560	
1.94	562	1.95	674	Melted plating streak at 5:00 o'clock position in combustion chamber
1.65	530	1.59	623	
1.59	464	1.53	552	
1.61	575	1.53	669	Possible erosion spot 1/2 inch below injector face at 6:00 o'clock position
2.00	525	2.02	623	
1.98	480	1.96	557	Plating streak increased slightly
2.00	577	1.98	683	
1.68	505	1.71	505	Calibration test
1.76	550	1.71	670	1/4-inch-thick carbon buildup in throat
1.64	447	1.56	540	Plating streak in throat at 8:00 o'clock position
1.77	572	1.69	684	
1.62	519	1.54	625	Streak extended to 6:00 o'clock position
1.60	465	1.52	555	Heavy carbon buildup in throat
1.62	573	1.50	684	Heavy carbon buildup in throat; performance changed
2.01	535	1.97	618	Throat area burned through
1.64	530	1.61	625	
1.67	538	1.62	632	
1.74	531	1.68	621	
1.60	532	1.52	627	
1.55	523	1.49	620	
1.57	528	1.50	624	
1.82	539	1.80	634	
1.85	541	1.82	636	
1.84	536	1.80	629	Plating streaks in throat area and combustion area

1

TABLE

(Contin

Injector Type	Injector Serial Number	Engine Serial No.	Engine Model	Test Number	Duration, seconds	Cumulative Duration, seconds	Tank-Fed
							Mixture Ratio
E0 123829	6320894	3501-3	YLR101-NA-15	8001	328.5	328.5	1.68
				02	328.9	657.4	1.67
				03	328.1	958.5	1.68
				04	326.7	1312.2	1.53
				05	327.0	1639.2	1.53
				06	326.2	1965.4	1.56
				07	327.8	2293.2	1.87
				08	326.9	2620.1	1.83
				09	325.3	2945.4	1.82
				10	325.2	3270.6	2.05
				11	324.1	3594.7	1.90
E0 123829	6320895	3402-2	Modified YLR101-NA-13	8012	327.1	327.1	1.63
				13	326.2	653.3	1.70
				14	325.9	979.2	1.70
				15	326.6	1305.8	1.57
				16	326.9	1632.7	1.60
				17	326.9	1959.6	1.57
				18	327.3	2286.9	1.87
				19	327.4	2614.3	1.86
				20	327.2	2941.5	1.86
				21	327.1	3268.6	1.96
				22	327.1	3595.7	2.02
E0 123829	6320892	3403	Modified YLR101-NA-13	8023	327.0	327.0	1.67
				24	326.5	653.5	1.70

TABLE 14
(Continued)

Tank-Fed Site Values		Pump-Fed Site Values		Remarks
Mixture Ratio	Thrust, pounds	Mixture Ratio	Thrust, pounds	
1.68	539	1.62	616	
1.67	536	1.61	614	Plating streak at 7:00 o'clock position in thrust chamber
1.68	534	1.59	612	
1.53	531	1.44	616	
1.53	526	1.43	608	
1.56	534	1.45	613	Slight increase in streak
1.87	607	1.81	707	
1.83	532	1.76	617	
1.82	543	1.75	631	Additional plating streak
2.05	670	2.04	664	
1.90	662	1.90	663	
1.63	533	1.59	634	1/4-inch plating spot at 3:00 o'clock position on thrust chamber near injector face
1.70	518	1.67	613	Plating spot at 2:00 o'clock position on thrust chamber near injector
1.70	523	1.67	624	
1.57	518	1.52	620	
1.60	518	1.55	621	
1.57	515	1.52	617	
1.87	533	1.85	633	
1.86	506	1.85	596	
1.86	500	1.85	596	
1.96	674	1.93	667	
2.02	667	2.01	664	Plating spot 1 inch above converging section at 12:50 o'clock position
1.67	535	1.63	634	
1.70	533	1.63	635	Testing discontinued on engine; faulty hardware

2

TABLE 14

(Continued)

Injector Type	Injector Serial Number	Engine Serial No.	Engine Model	Test Number	Duration, seconds	Cumulative Duration, seconds	Tank-Fed Val	
							Mixture Ratio	Th
E0 123829	6320892	3503	YLR101-NA-15	8025	326.6	326.6	1.72	
				26	326.4	653.0	1.66	
				27	326.6	979.6	1.69	
				28	326.7	1306.3	1.51	
				29	326.6	1632.9	1.81	
				30	326.6	1959.5	1.56	
				31	325.7	2285.2	1.59	
				32	325.3	2610.5	1.80	
				33	327.4	2937.9	1.82	
				34	326.7	3264.6	1.87	
				35	325.6	3590.2	2.02	

1

TABLE 14
(Continued)

Tank-Fed Values		Pump-Fed Site Values		
Mixture Ratio	Thrust, pounds	Mixture Ratio	Thrust, pounds	Remarks
1.72	542	1.65	623	
1.66	489	1.61	571	
1.69	499	1.61	574	Plating spot at 9:00 o'clock position in throat
1.51	501	1.45	583	
1.81	491	1.77	561	
1.56	506	1.49	588	Two plating spots at 1:00 o'clock position in thrust chamber converging section
1.59	515	1.50	592	Plating streak at 9:00 o'clock position near throat
1.80	521	1.72	598	
1.82	519	1.74	596	Copper sulfate test made on thrust chamber; no erosion
1.87	668	1.86	667	Small plating streak in throat
2.02	677	2.01	672	Small additional plating streak in throat

2

Cutoff impulse values obtained during the modified injector program agree with the original value of 80 ±25 lb-sec obtained during Phase I testing (without the cutoff delay circuit). The P/N E0 123829 and splash-plate injectors both exhibited cutoff characteristics similar to those of the P/N 350604 injector.

STEADY-STATE PERFORMANCE

Tank-fed performance for each engine test was read after 25 seconds of engine operation. These data were reduced to rated values of 525 pounds thrust and 1.8 mixture ratio at standard temperature and pressure. The averages of this rated tank-fed data for the P/N E0 123829 and the splash-plate injectors are shown in Table 15. The rated tank-fed data for the P/N 350604 injector obtained from Phase I testing have been included in Table 15 for comparison. The P/N E0 123829 injector demonstrated a specific impulse increase of 5 seconds at the tank-fed performance level. This increase in performance was also evident in characteristic velocity. The splash-plate injector had a specific impulse comparable to the P/N 350604 injector, but had a somewhat lower characteristic velocity.

During steady-state operation, performance shifts were experienced periodically throughout the test program. These shifts were of three types:

1. During the tank-fed portion of Test 8954, while engine S/N 3401 was operating at a 1.59 mixture ratio and 480 pounds of thrust, combustion instability in the form of a 500-cycle buzz occurred. This progressively became more

pronounced until the performance shifted (Fig. 50). The engine continued to buzz and remained at the lower performance level until pump-level performance was signalled. The buzz then disappeared and no further shifts occurred throughout the balance of the test. The same type of shift occurred with engine S/N 3401-2 during the tank-fed performance of Test 8978. Although engine S/N 3501-2 also was operated at a similar low thrust and mixture ratio level during Test 8967 and buzzed during the tank-fed portion of the test, no performance shift occurred.

2. Figure 51 shows the performance shifts that occurred sporadically throughout the engine test series with the splash-plate injector. A heavy carbon buildup in the throat of the thrust chamber was observed after Test 8984 (Fig. 52). It was considered likely that carbon of this type building up and breaking away caused the performance shifts during the splash-plate injector tests.

3. Performance shifts comparable to those obtained at the 1000-pound thrust level with the P/N 350604 injector occurred sporadically throughout the test series on the P/N EO 123829 injector (Fig. 53). The cause of these shifts is not as easily traced as the previous two. Injector hole patterns found in carbon particles after the tests showed that the carbon had built up on the face of the injector. During posttest inspections, carbon particles also were found adhering to the face of the injector. Removal of one injector revealed two triangular-shaped pieces of carbon at the junction of the injector and thrust chamber. These carbon pieces

TABLE 15

RATED TANK-FED PERFORMANCE OF DOWNRATED VERNIER ENGINE USIN
SPLASH PLATE AND P/N EO 123829 INJECTORS

Injector Type	Thrust, pounds	Mixture Ratio	Specific Impulse, seconds	Characteristic Velocity, ft/sec	Thrust Coefficient	Chambe Pressu psia
350604	525*	1.8*	180.1*	4919*	1.178*	212.
EO 123829	525	1.8	185.8	5019	1.191	212.
Splash Plate	525	1.8	180.5	4760	1.221	205.

*Rated value obtained during Phase I testing

1

TABLE 15

-FED PERFORMANCE OF DOWNRATED VERNIER ENGINE USING
;PLASH PLATE AND P/N EO 123829 INJECTORS

ecific pulse, conds	Characteristic Velocity, ft/sec	Thrust Coefficient	Chamber Pressure, psia	Propellant Weight Flowrate, lb/sec	
				Oxidizer	Fuel
80.1*	4919*	1.178*	212.2*	1.87*	1.04*
85.8	5019	1.191	212.0	1.816	1.009
80.5	4760	1.221	205.9	1.870	1.039

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2

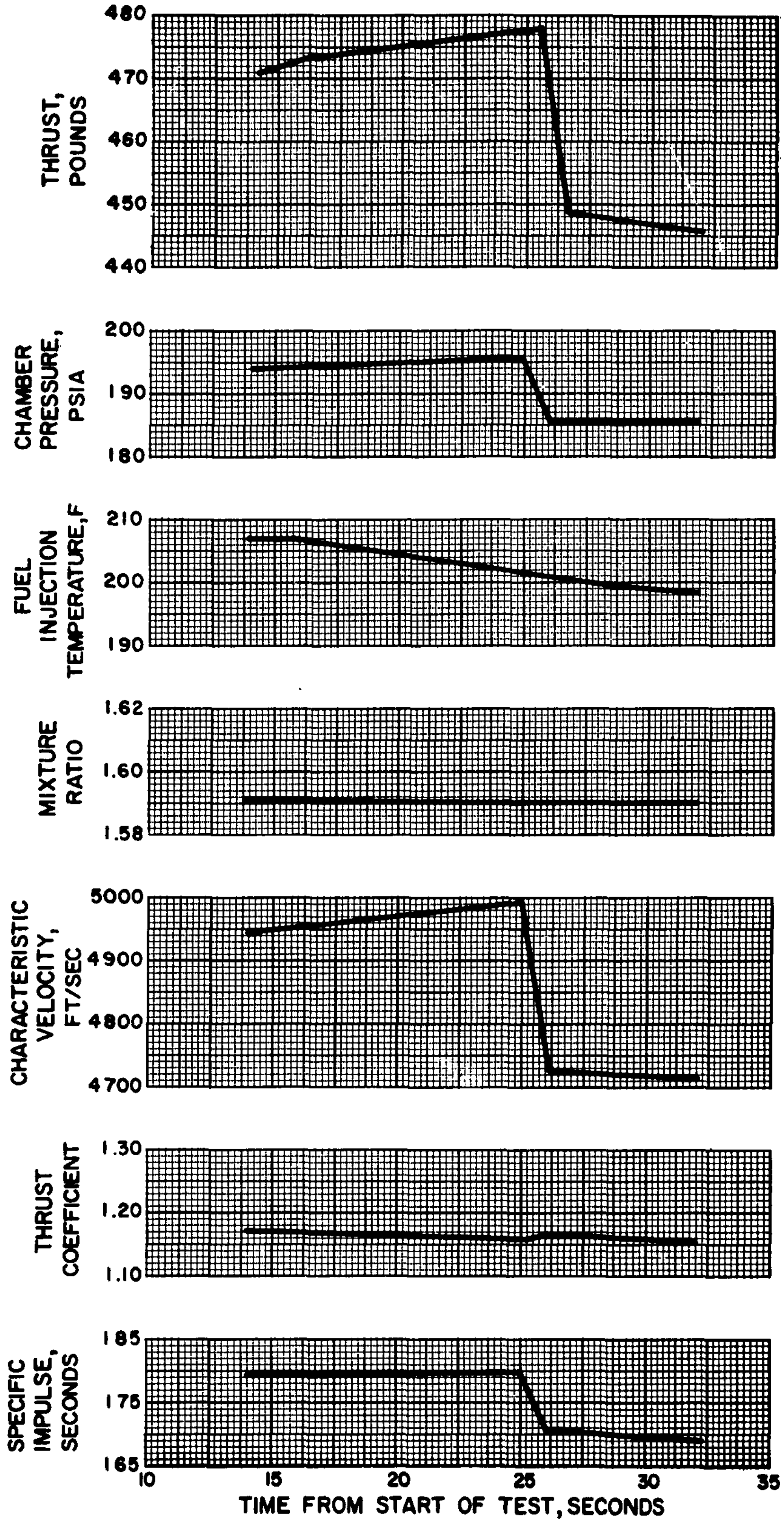

Figure 50. Engine S/N 3401 Performance Shift Caused by Buzzing During Run No. 8954 Using Injector P/N EO 123829, S/N 6320891

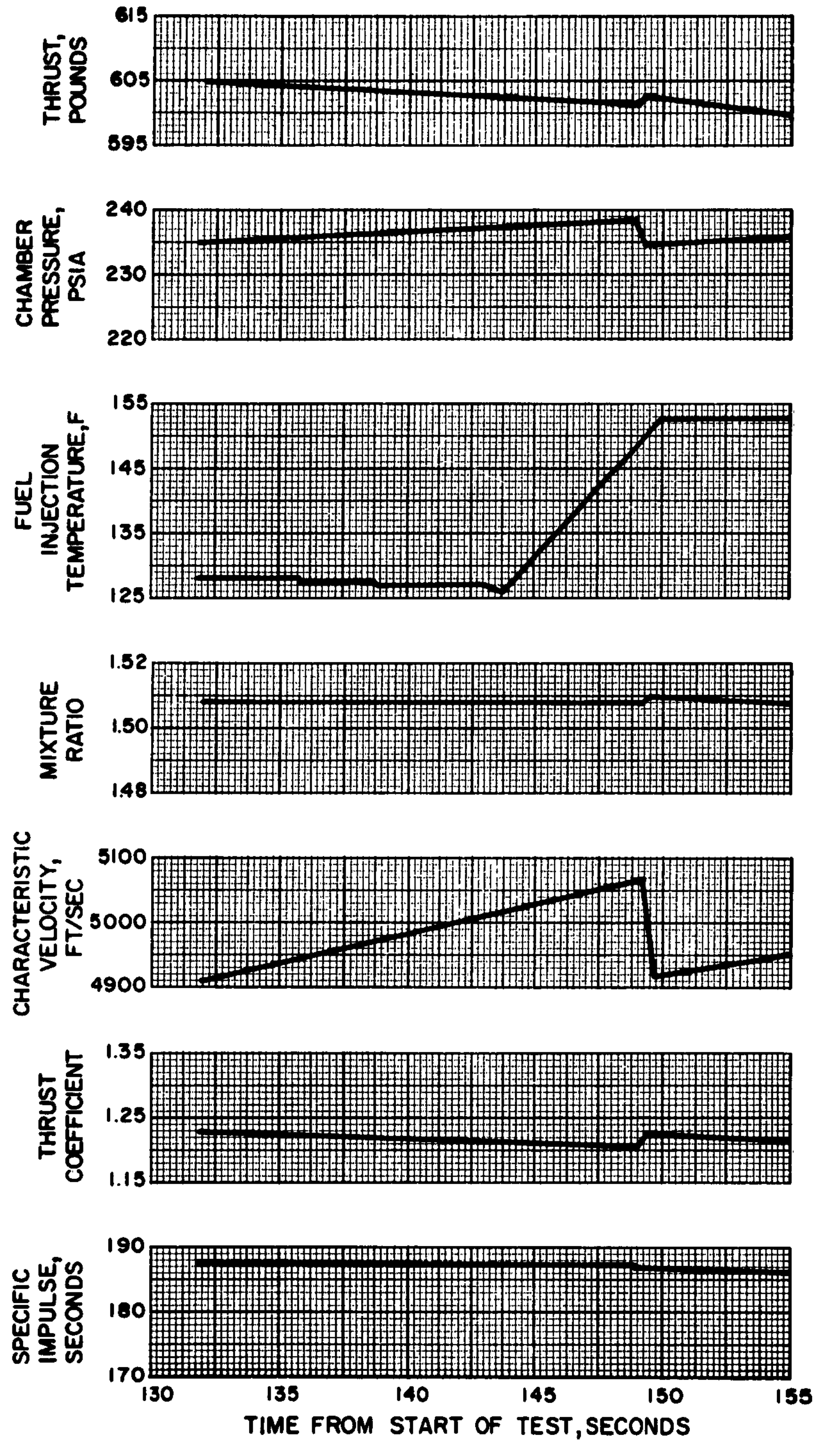

Figure 51. Engine 3402 Performance Shift Caused by Carbon Buildup in Thrust Chamber Throat During Run No. 8987 Using Splash-Plate Injector S/N 6321992

1CE35-9/24/63-C1A

Figure 52. Carbon Buildup in Thrust Chamber Throat After Test 8984

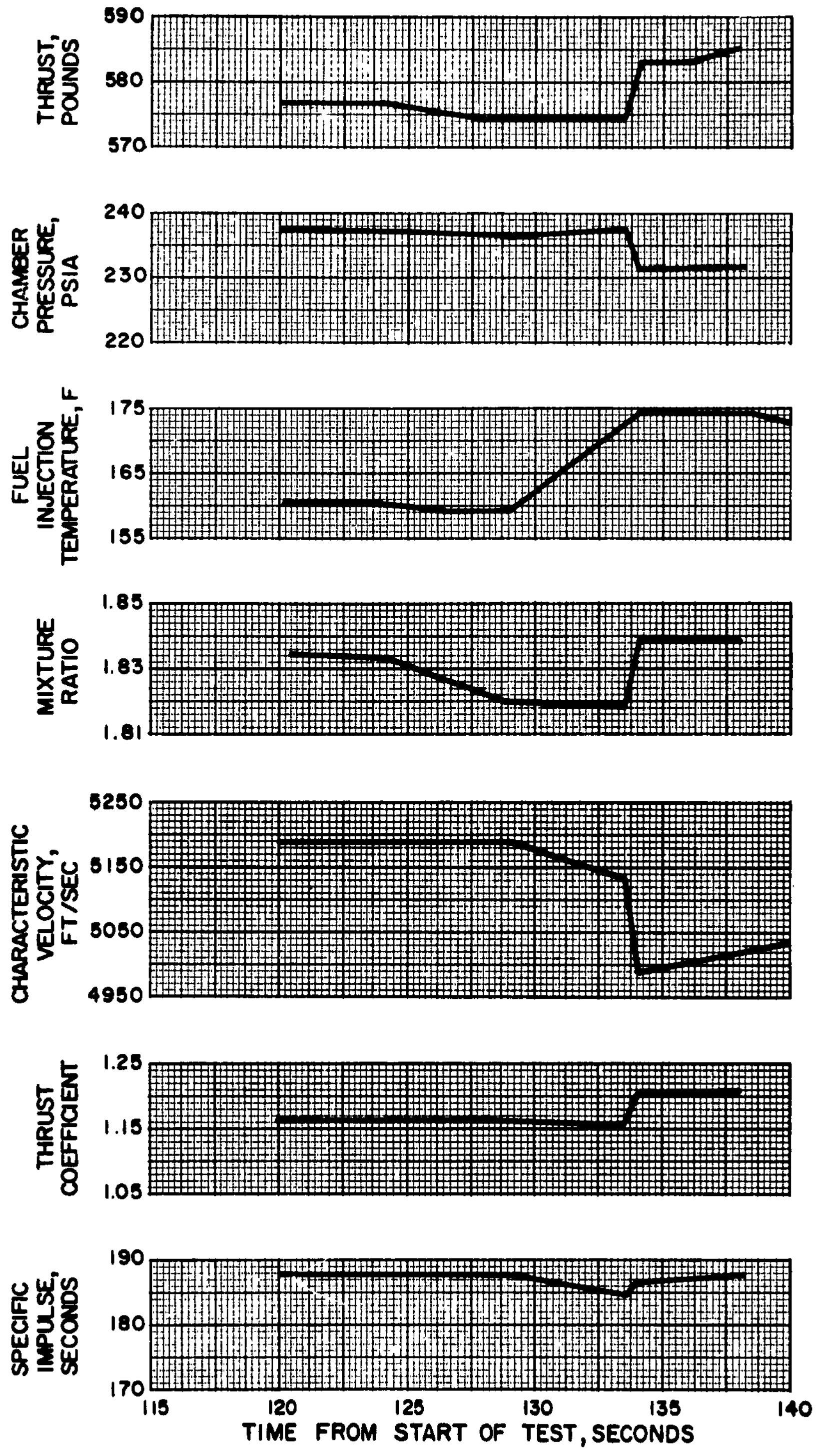

Figure 53. Engine S/N 3402-2 Performance Shift During Run No. 8019 Using Injector P/N E0 123829, S/N 6320895

showed the location of the outer fuel holes. The pieces were measured and are represented in Fig. 54. It is believed that carbon buildup and breaking away across the face of the injector may have caused changes in the impingement pattern which in turn produced the performance shifts.

HARDWARE CONDITION

Thrust chamber erosion or nickel-plating streaks in various forms occurred with each of the injectors tested during the modified injector vernier engine testing. At the beginning of the test program, the term "erosion" was used to describe any change in the thrust chamber wall. After the second engine tested, the term erosion was restricted to only those spots that were completely through the layer of nickel plating and into the parent metal of the thrust chamber. Because of the difficulty in visually determining whether a surface defect is into the parent material of a vernier thrust chamber that has been wiped clean, the first four "erosion" and "plating streaks" noted for the engines in Table 14 may be erroneous.

Although the wall of the first thrust chamber tested (engine S/N 3401) was only lightly coated with carbon, erosion was not detected until the thrust chamber was removed and cleaned. A subsequent test of the eroded area using an acid solution of copper sulphate showed that the erosion was into the parent metal. This solution turns exposed parent metal (type 4130 steel) to a copper color. As testing progressed, various means of detecting plating streaks and erosions were employed. These included wiping the carbon from the thrust chamber after every test, removing the injector periodically, and using the copper sulphate solution to check the spots that might be into the parent metal.

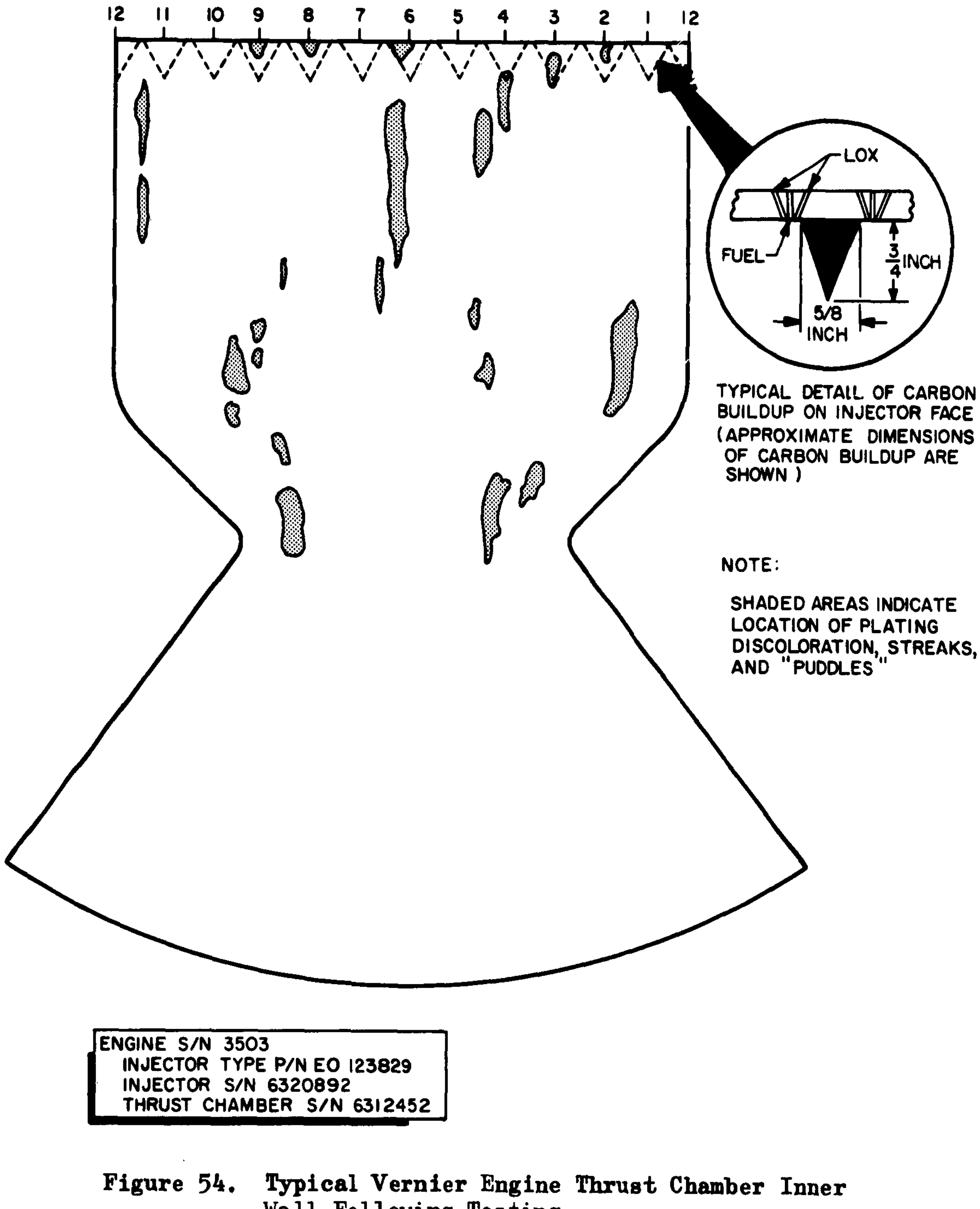

Figure 54. Typical Vernier Engine Thrust Chamber Inner Wall Following Testing

Following the test series on each engine, the thrust chamber was removed from the engine, cleaned to remove all carbon and oil, and tested with the copper sulphate solution. None of the last four thrust chambers, used with the P/N E0 123829 injector after lowering the nominal mixture ratio experienced erosions that were through to the parent metal. Figure 54 depicts the appearance of the interior of a typical thrust chamber after completion of testing. Discoloration of the plating, plating streaks, and plating "puddles" (especially near the injector face) were found.

The two triangles of carbon previously mentioned were examined; one was a solid triangle of carbon and the second had a round hole in the center. This hole fit exactly over a plating puddle. It cannot be determined if these carbon triangles formed completely around the thrust chamber wall as depicted in Fig. 54, but this is possible.

The fuel injection temperature randomly varied during all tests, with an amplitude of as much as 15 F. This variation in temperature could not be correlated with carbon buildup and breaking away except as noted in Fig. 51 and 53, but it does provide an indication that the temperature at the thrust chamber inner wall varied during the tests. Similar fuel injection temperature fluctuations previously were noted with the P/N 350604 injector during Phase I testing.

The splash-plate injector eroded only in the throat with no marks or plating streaks in the thrust chamber. The erosions in the throat were attributed to the heavy carbon buildup in that area (Fig. 52). The throat area was completely eroded away during operation at a 2.0 mixture ratio. Because of the good condition of the chamber wall, it is believed that no erosion of the throat would have occurred if the carbon had not built up. The reason for the carbon buildup in the chamber throat is not known. Component-level tests of the prototype splash-plate injector revealed midtest performance shifts which could have been caused by carbon buildup in the chamber throat, but no posttest indications of such a buildup were found.

APPENDIX A

FLOW TEST DATA USING GD/A LINES AND ORIFICES

The LOX and fuel start system missile propellant lines to be used with the YLR101-NA-15 vernier engines in SLV-3 Atlas missile were obtained from GD/A. These lines and the orificed elbows with various size orifices installed were calibrated at the Rocketdyne Canoga Park facility to provide data for vernier system performance balance calculations. The data obtained are presented in Fig. A-1 through A-8.

The orifices used had a 45-degree countersink on the downstream side. This resulted in greater efficiency. The orificing could be reversed at the time of installation, so data also were obtained with the orifices installed incorrectly (countersink on the upstream side of the orifice). Figures A-2, A-3, and A-4 show the results of improper orifice installation. Because of the extreme loss in orifice efficiency, it is recommended that these orifices be designed so that improper orifice installation is impossible.

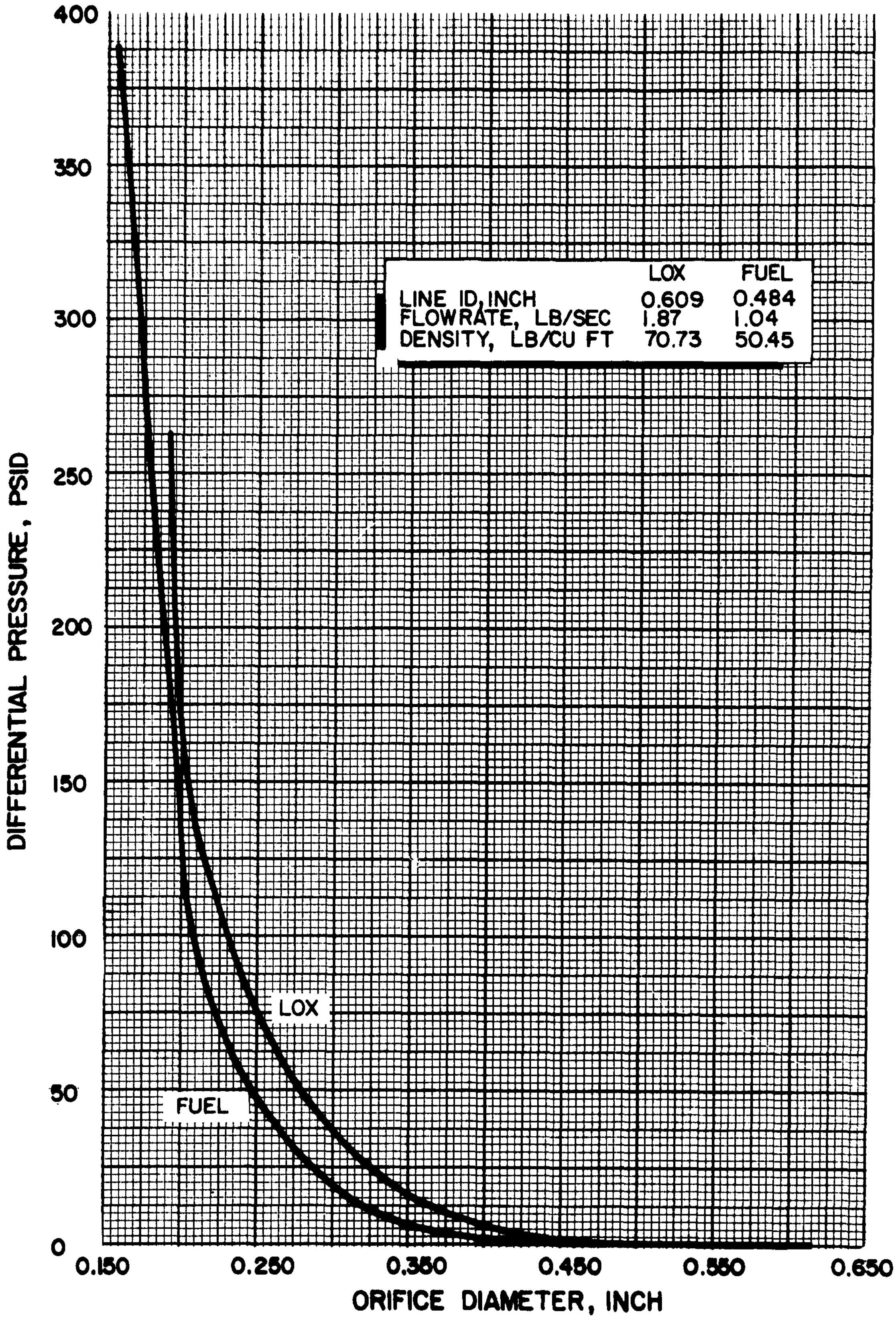

Figure A-1. Differential Pressure Through GD/A Orifices

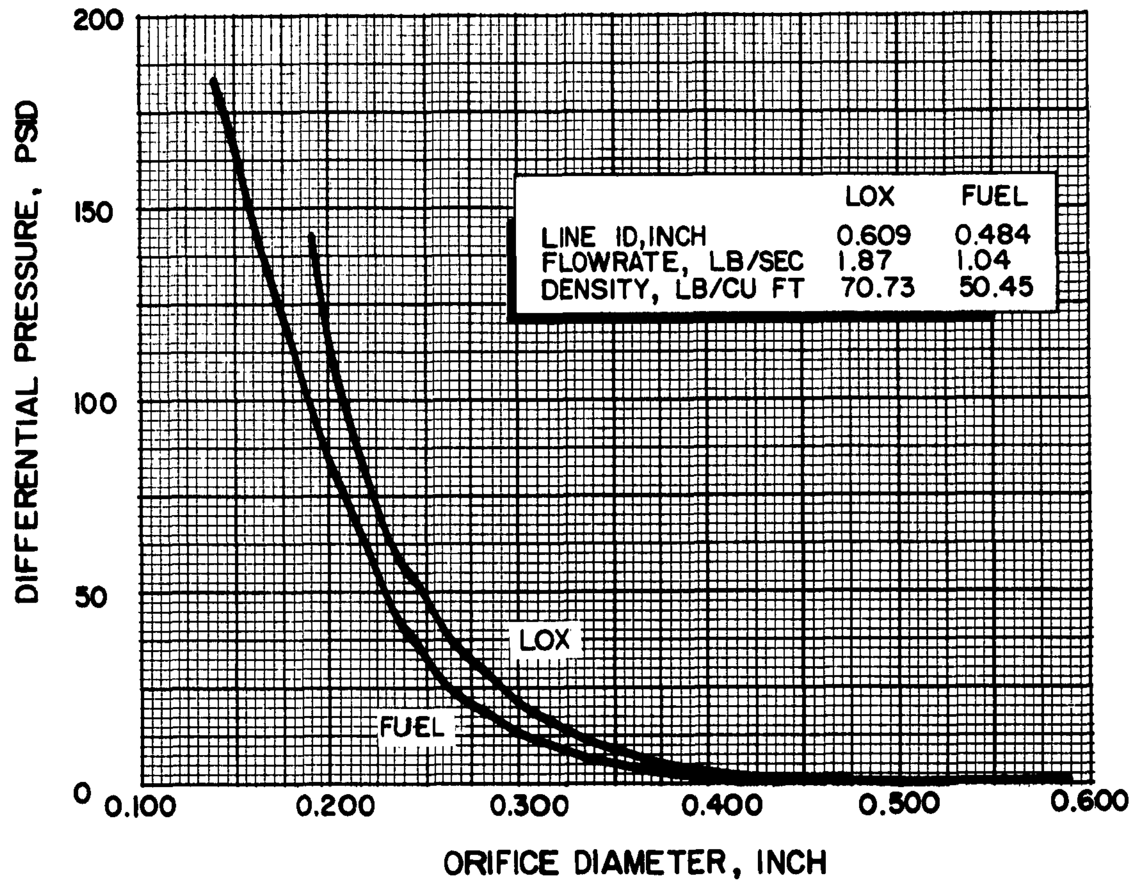

Figure A-2. Differential Pressure Through GD/A Orifices Reversed in Holders

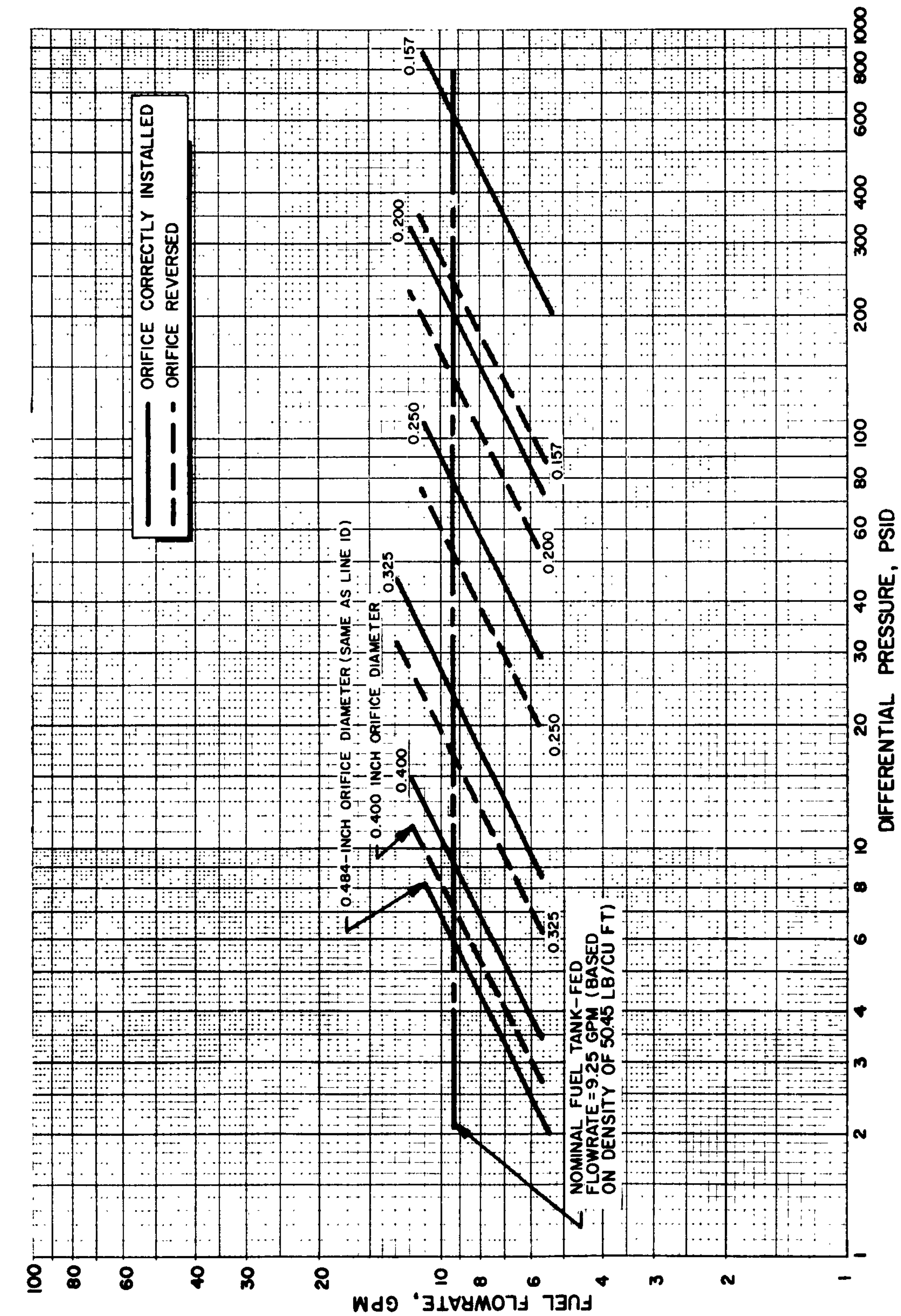

Figure A-3. LOX Flowrate Through GD/A Orifices at Various Differential Pressures

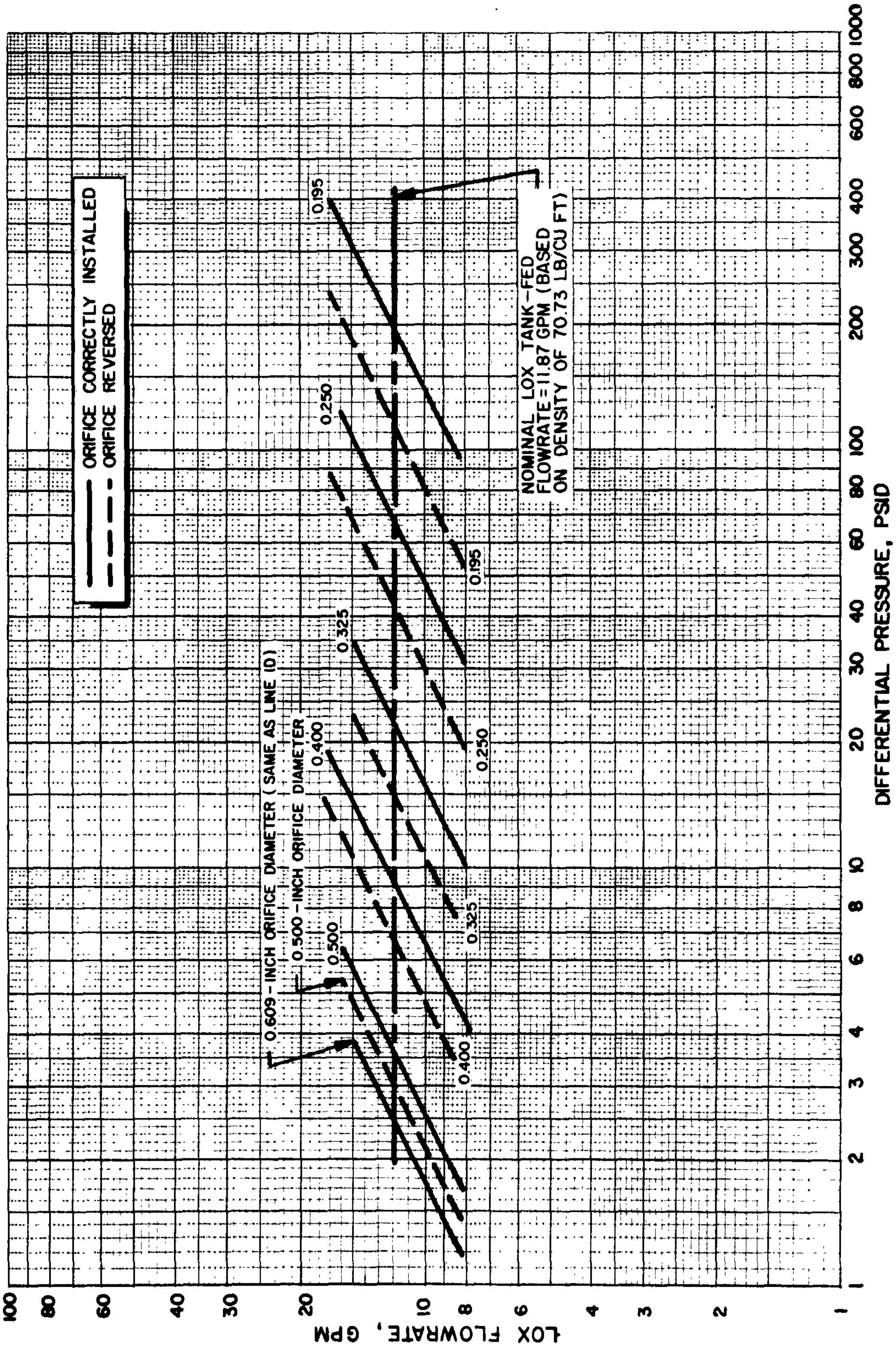

Figure A-4. Fuel Flowrate Through GD/A Orifices at Various Differential Pressures

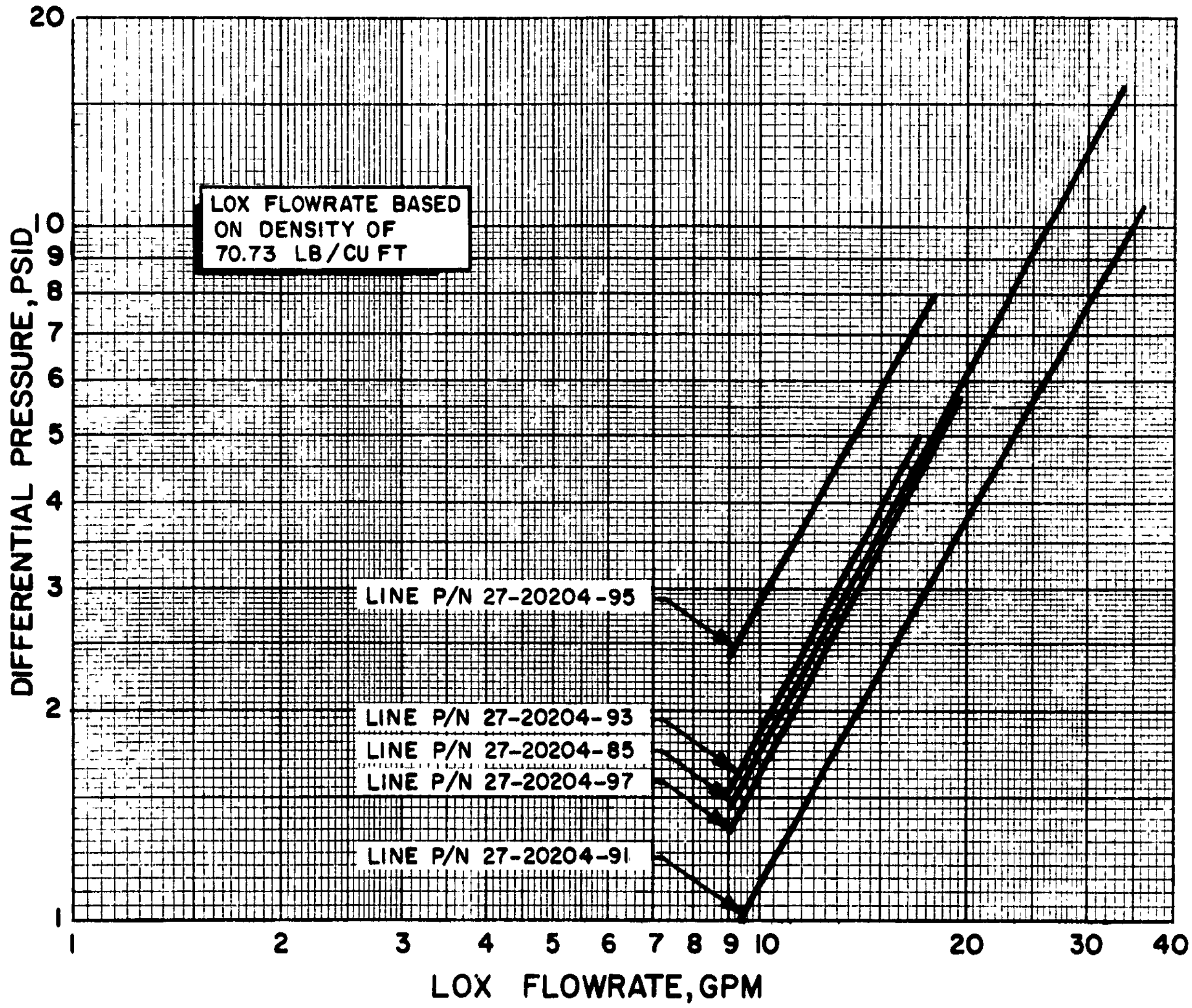

Figure A-5. Differential Pressure Through GD/A Start System Lines at Various LOX Flowrates

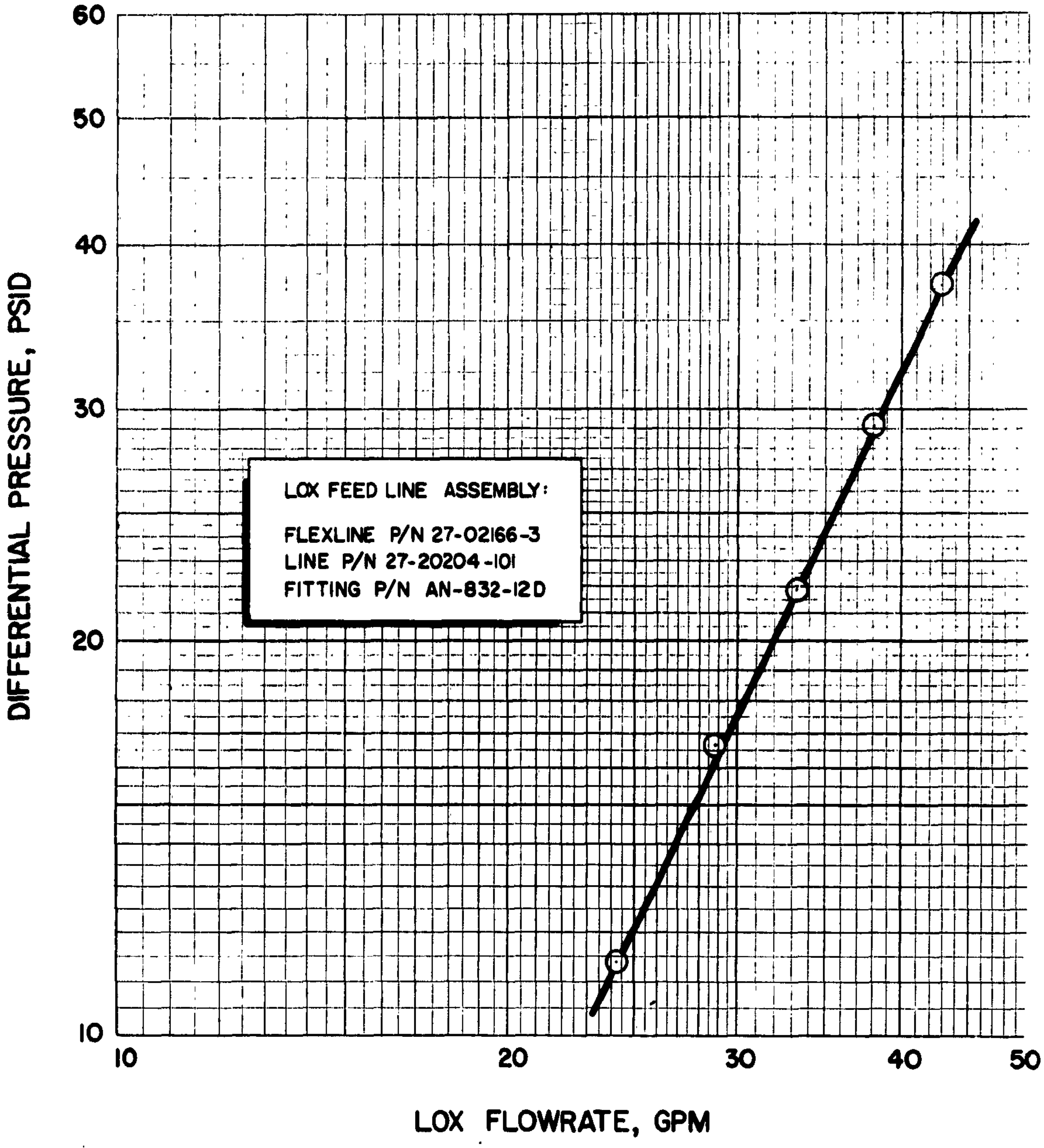

Figure A-6. Differential Pressure Through GD/A Vernier LOX Feed Line Assembly at Various LOX Flowrates

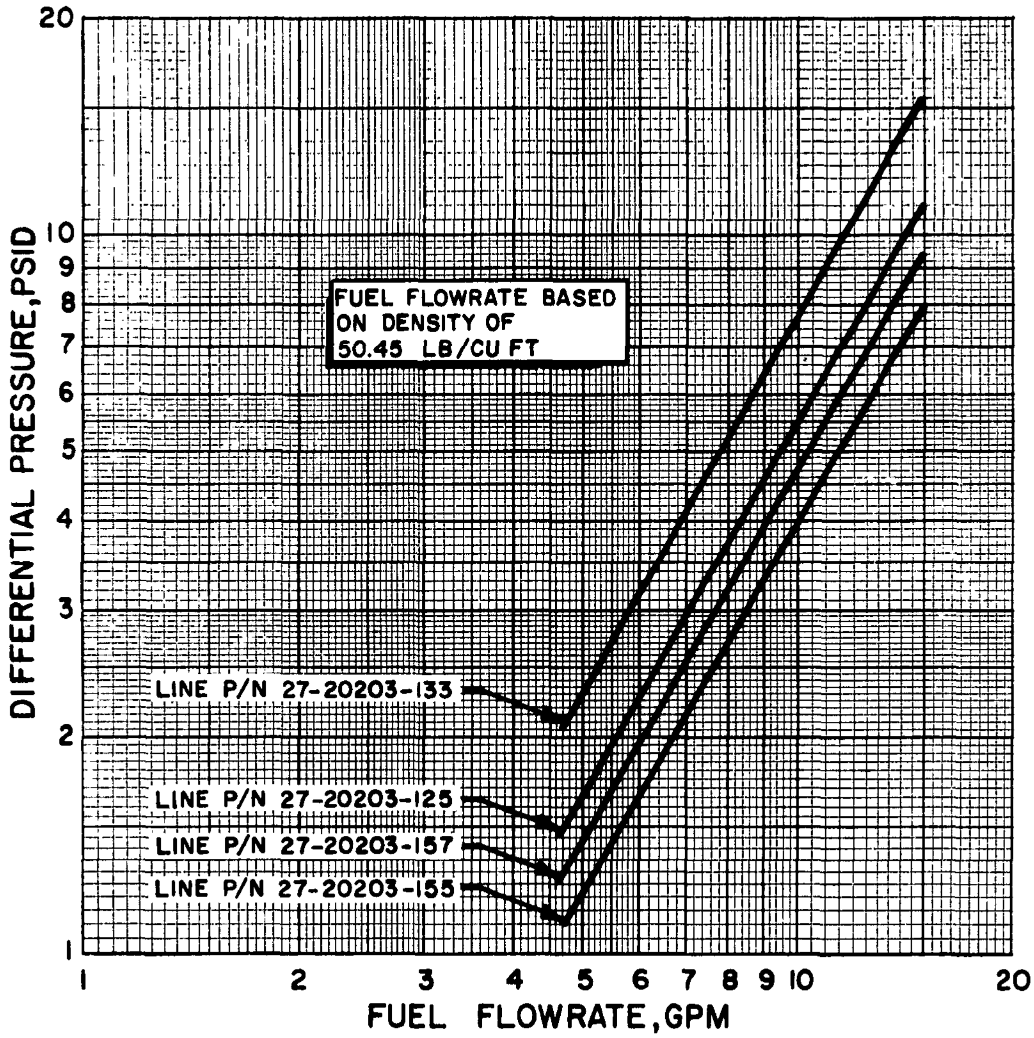

Figure A-7. Differential Pressure Through GD/A Start System Lines at Various Fuel Flowrates

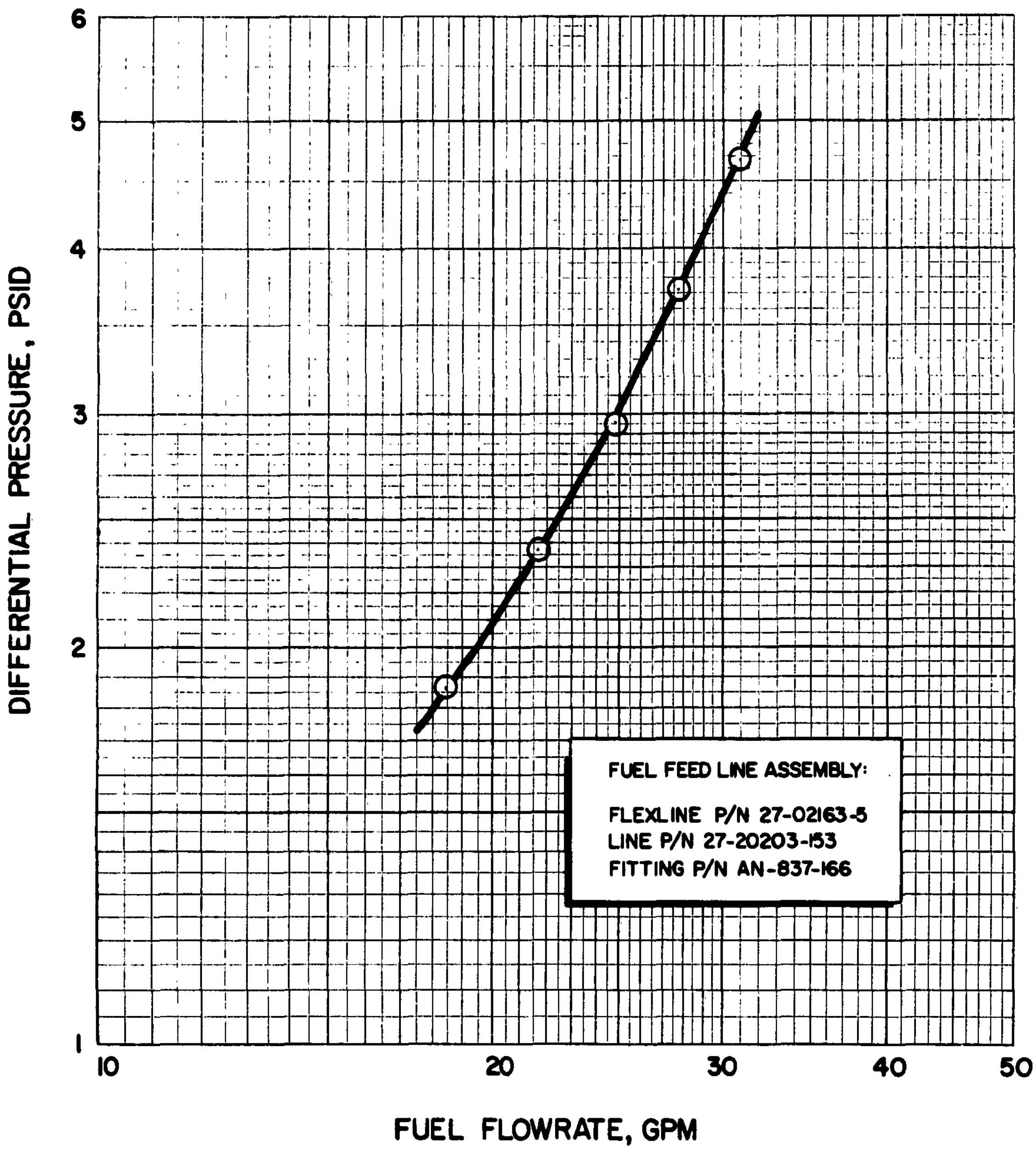

Figure A-8. Differential Pressure Through GD/A Vernier Fuel Feed Line Assembly at Various Fuel Flowrates

VERNIER INJECTOR PROPELLANT SIMULATION