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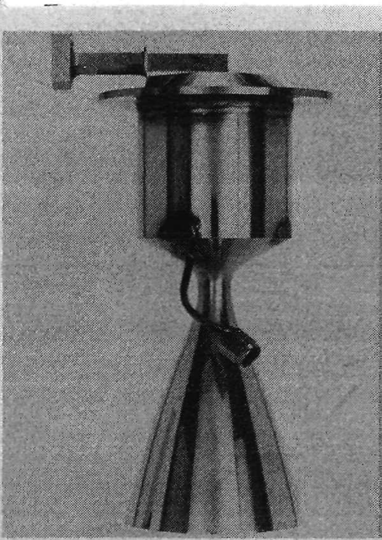
MARINER VENUS/MERCURY 1973

Mariner Venus/Mercury 1973
Rocket Engine Assembly
Final Report



ROCKET ENGINE ASSEMBLY

PREPARED FOR

JET PROPULSION LABORATORY
PASADENA, CALIFORNIA

BY

TRW
SYSTEMS GROUP
ONE SPACE PARK • REDONDO BEACH • CALIFORNIA

Mariner Venus/Mercury 73
Rocket Engine Assembly
Index Number 2010
November 10, 1972

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Prepared for Jet Propulsion Laboratory, Pasadena, California
by TRW Systems, Redondo Beach, California
Under Contract Number 953361

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1. SUMMARY

This final report covers the work conducted by TRW Systems for the Jet Propulsion Laboratory on Contract 953361 for the Fabrication and Test of Rocket Engine Assemblies (REA) for Mariner Venus/Mercury 1973.

The contract covered fabrication, assembly and Flight Acceptance (FA) test of seven (7) REA's including the Type Approval (TA) test of one engine and fabrication of one (1) additional kit consisting of detail parts for an engine ready for catalyst loading.

This report will not cover the engine (S/N 202) selected for TA testing since this engine is covered in the Type Approval Test Summary Report.

This report covers the flight engines S/N 201, 203, 204, 205, 206 and 207. The kit engine is S/N 208 and only the water flow calibration data is included for this engine.

The MV/M '73 Rocket Engine Assembly (REA) as shown in Figure 1-1 is a nominal 51 lbs thrust monopropellant engine. The injector assembly consists of a shower head type injector having eighteen (18) 0.026 in diameter injector holes. A 60 mesh screen is downstream of the injector with one layer of 20-30 fine mesh Shell 405 catalyst packed under pressure. Following the catalyst is a retention plate having circular annular areas enclosed with 60 mesh screens on each side. The main catalyst bed (also packed under pressure) consists of a uniform mixture of 75 percent Shell 405, 1/8 inch cylindrical pellets and 25 percent HA-3, 1/8 inch cylindrical pellets. The catalyst bed is retained by a 10 mesh screen and a baffle plate. The nozzle has a nominal throat area of 0.15 in^2 and a nozzle expansion ratio of 44:1.

A plug orifice is used on the inlet side of the injector as a trim orifice to calibrate the engine pressure drop.

Under steady state operation the specific impulse is not less than 228 lb-sec at 55 lb_f and 218.5 lb-sec at 10 lb_f thrust varying linearly between these limits. The characteristic velocity is not less than 4100 ft/sec at any thrust level.

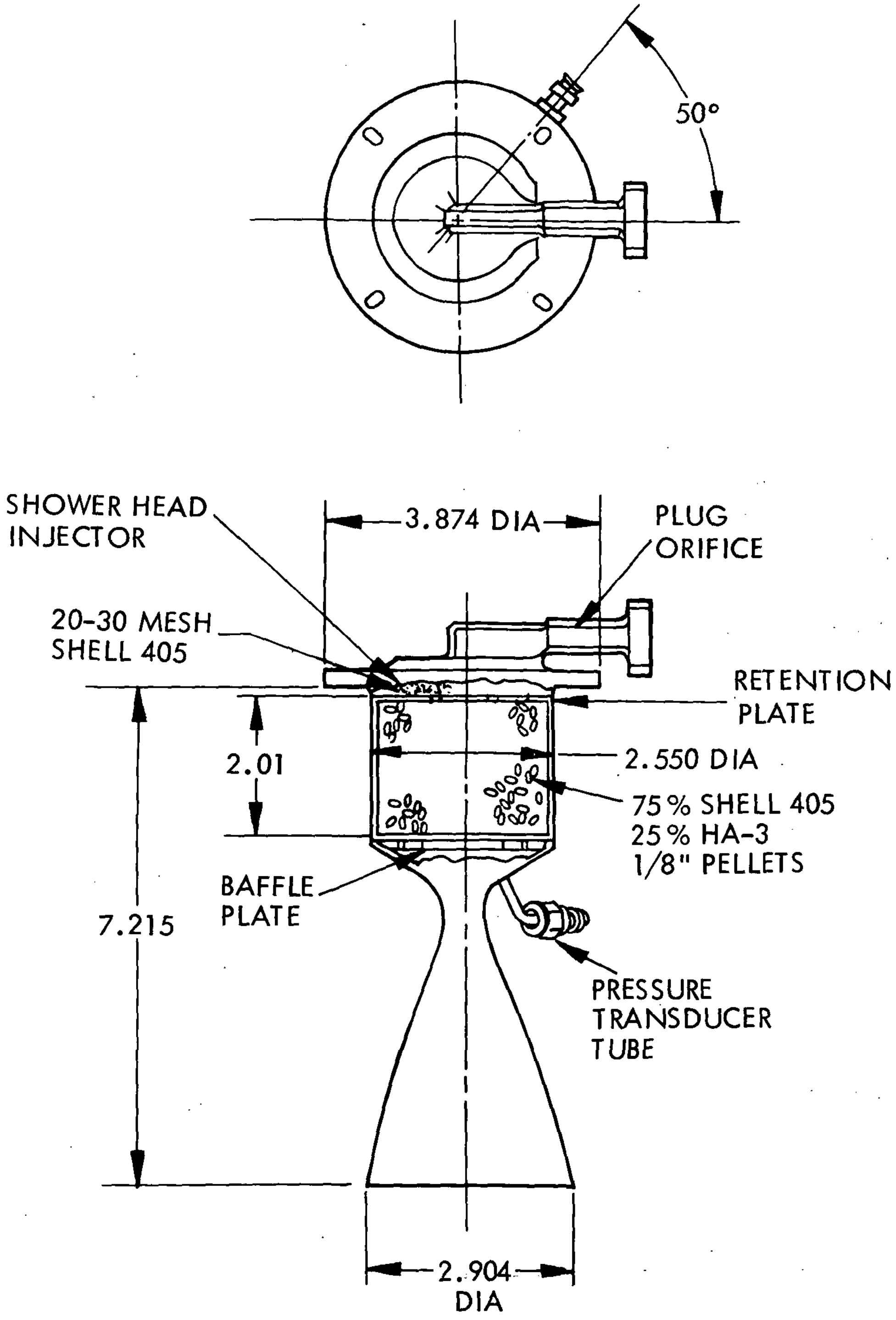

Figure 1-1. MV/M 73

Photographs of the MV/M 73 REA complete with the JPL-Furnished Marquardt value is shown in Figure 1-2.

All TA and FA testing were conducted as per the JPL Specification TS506207 entitled "Detail Specification for Rocket Engine Propulsion Subsystem Mariner Venus/Mercury 1973 Flight Equipment Type Approval and Flight Acceptance Tests." During the length of the contract the above specification was revised to a "A" revision and finally to a "B" revision.

A complete list of all software prepared by TRW Systems for the MV/M 73 REA Contract in addition to this final report is as follows:

MV/M 73 REA Quality Assurance & Reliability Program Plan

MV/M 73 REA Manufacturing Plan

MV/M 73 REA Configuration Control Plan

MV/M 73 REA TA Test Plan

MV/M 73 REA FA Test Plan

MV/M 73 REA Type Approval Test Summary Report

CTSP-1 Data Reduction and Performance Analysis Computer Program

Complete data package for each flight engine

TEST PROCEDURES

Title	Procedure Number
Rocket Engine Injector Water Flow Test, Flight Acceptance	JPL-EP507020
Injector Assembly, Rocket Engine, 10013197	JPL-EP507021
Assembly of Rocket Engine Welded Assembly, 10013198	JPL-EP507022
Rocket Engine, 10013199 or 10013198 Proof and Leak Test, Flight Acceptance	JPL-EP507023
MV/M '73 Rocket Engine 10013199 Vibration Test, Flight Acceptance	JPL-EP507024
MV/M '73 Rocket Engine 10013199 Vibration Test, Type Approval	JPL-EP507025

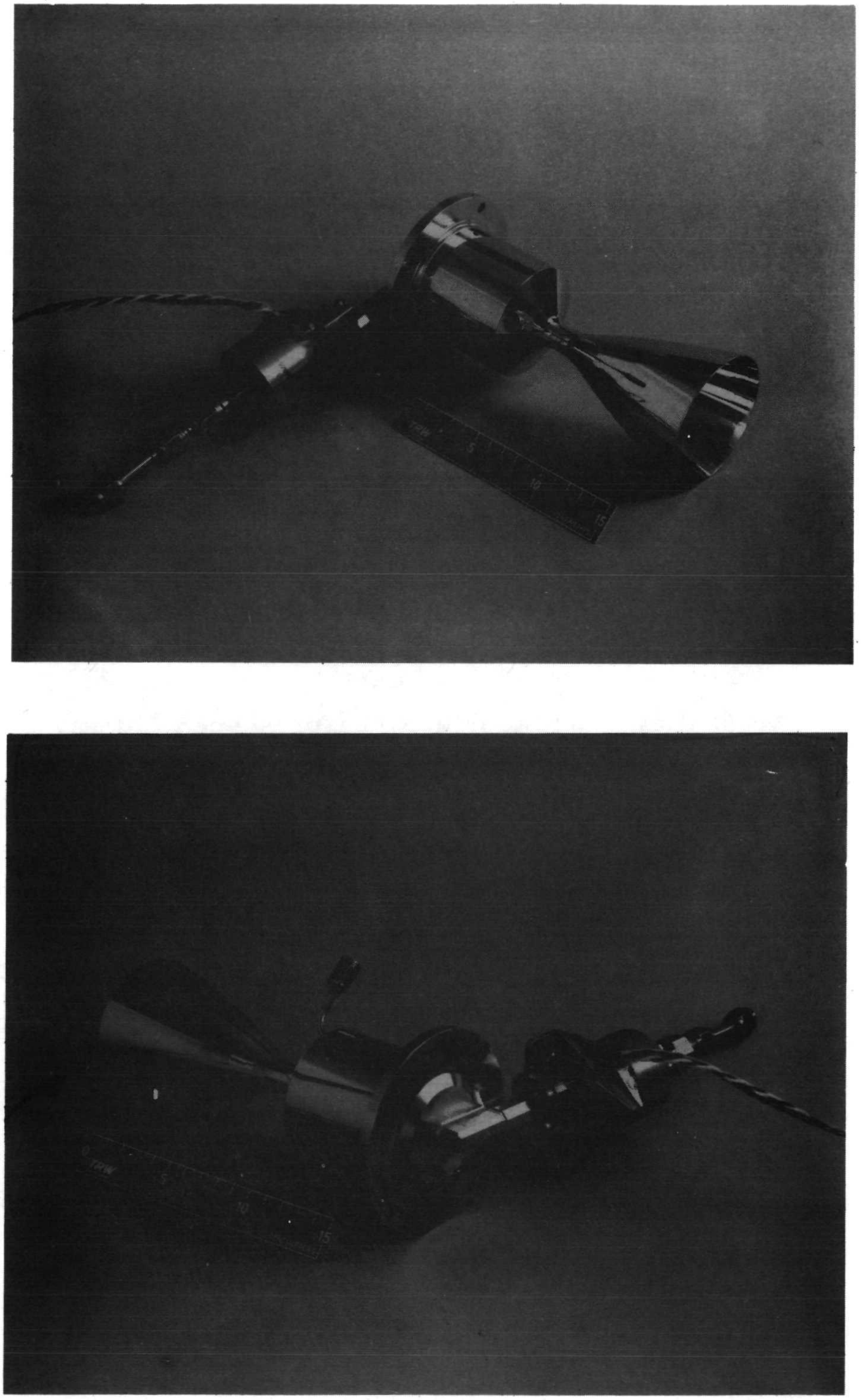

Figure 1-2. MV/M73 REA with JPL Furnished Marquardt Valve

TEST PROCEDURES (Continued)

Title	Procedure Number
Hot Firing Tests of Rocket Engine, 10013199 Flight Acceptance	JPL-EP507026
Hot Firing Tests of Rocket Engine, 10013199 Type Approval	JPL-EP507027

2. ORGANIZATION

The Mariner Venus/Mercury 1973 Rocket Engine Assemblies were fabricated, assembled, tested and delivered by a project organization specifically established for this activity within the Applied Technology Division (ATD) of TRW Systems. ATD is managed by A. F. Grant.

The MV/M73 project was conducted in the Combustion Systems Laboratory under the Energy Systems Operation headed by G. W. Elverum, Jr.

The key organization for the MV/M73 REA project is shown in Figure 2-1.

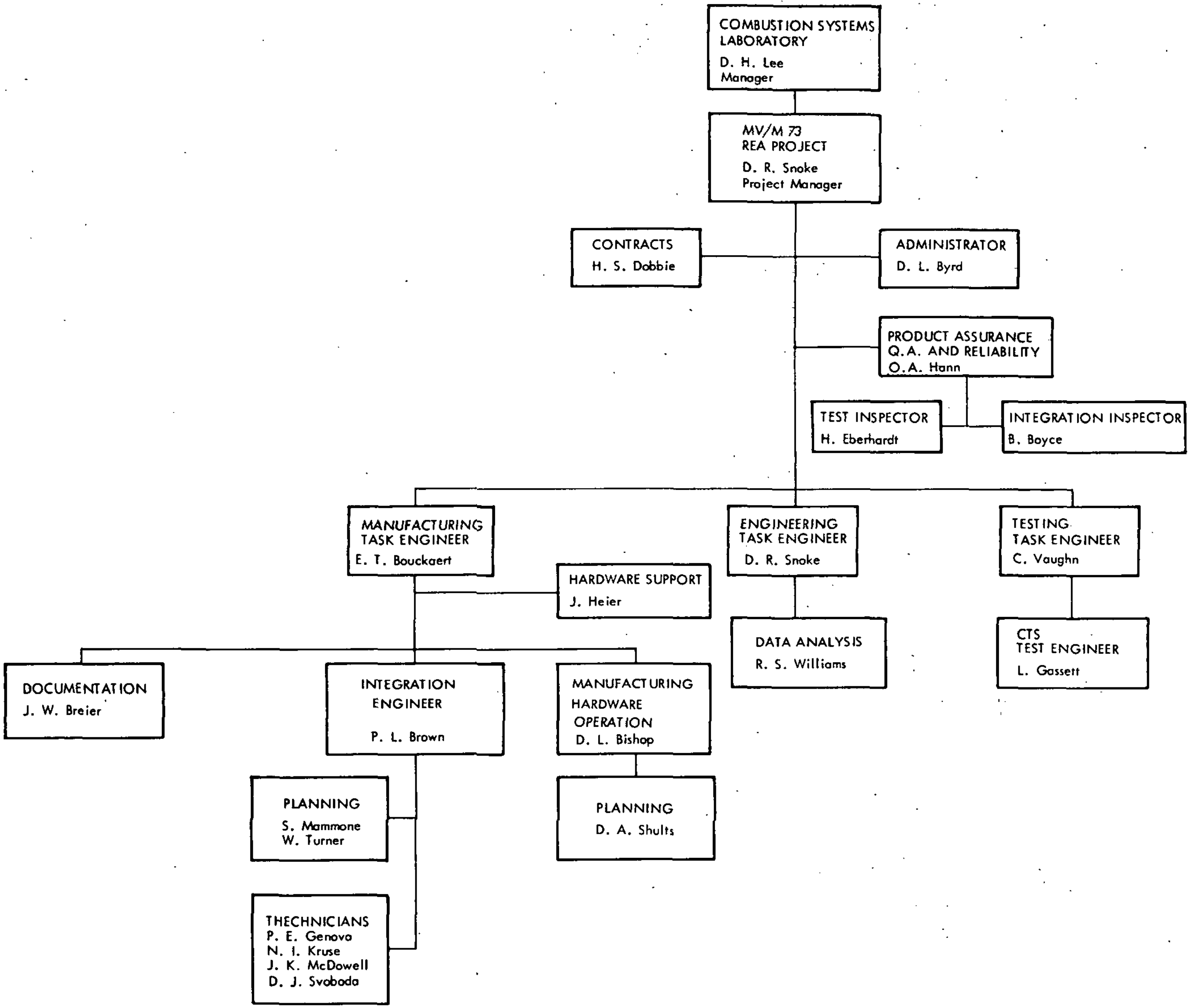

Figure 2-1. MV/M 73 REA Project Organization

3. HARDWARE INTEGRITY

The production and test program for the MV/M73 Rocket Engine was conducted in a manner to ensure a high level of product integrity. The quality assurance and reliability was conducted in accordance with the "MV/M 73 REA Quality Assurance and Reliability Program Plan" dated March 24, 1972. The methods utilized encompassed the use of approved assembly and test procedures used in conjunction with drawings and specifications. Specific events were preplanned and sequenced with reference to particular specification requirements on TRW standard shop work orders. Inspections were conducted at the conclusion of key events. Problems as they occurred were analyzed by the cognizant manufacturing, test and quality engineer for the improvement of methods to ensure conformance. As a result of these techniques the program quantities were manufactured and tested with no attrition. Defects were primarily of the cosmetic type during fabrication and minor test anomalies which were mostly due to test equipment malfunctions. None of the defects or anomalies resulted in the degradation of the rocket engine structural or functional characteristics.

4. FABRICATION AND ASSEMBLY DATA

The manufacturing of the REA's were carried out in accordance with the following plans which were prepared at the beginning of the contract and approved by JPL:

"MV/M 73 REA Manufacturing Plan" dated April 21, 1972

"MV/M 73 REA Configuration Control Plan" dated March 17, 1972

The REA's were fabricated and assembled at TRW Systems between February and August 1972. The parts list for all engines is shown in Figure 4-1.

The fabrication, assembly, and test flow chart used for the engines is shown in Figure 4-2.

The test procedures listed in Section 1 of this report were used for fabrication, assembly and test of all flight engines.

4.1 CATALYST SUMMARY

The injector on each flight engine was loaded with 19.0 to 19.3 grams of 20-30 mesh Shell 405. After loading the catalyst, a gap of 0.004 ± .001 inches remained between the injector body and retention plate. This gap was closed by applying a torque of 70 ± 10 inch-pounds on the JPL furnished weld fixture. A final torque of 85-90 in-lbs was then applied prior to welding.

Each shell was loaded with 201.5 to 211.9 grams of 75% Shell 405 1/8 inch cylindrical pellets and 25% HA-3 1/8 inch cylindrical pellets. After loading the catalyst into the shell a gap of 0.010 inches was measured between the injector and shell. A torque of 25 to 30 inch-pounds was then used on the weld fixture to close this gap and a final torque of 35 inch-pounds was used prior to welding.

Figure 4-3 indicates the amount of catalyst and torque used for each of the flight engines.

Part Number	Description	Qty	Next Assembly	Drawing Number
10013199-1	Rocket Engine Propulsion Subsystem		10040180	10013199 F
10013198-1	Rocket Engine Welded Assembly	1	10013199-1	10013198 H
10013191-1	Shell Welded Assembly Rocket Engine	1	10013198-1	10013191 G
10013187-1	Shell	1	10013191-1	10013187 C
10013188-1	Baffle	1	10013191-1	10013188 B
10013190-1	Tube Transducer	1	10013191-1	10013190 C
10013194-5	Screen Square Weave	1	10013191-1	10013194 C
AN 818-3C	Nut Coupling (3J Used)	1	10013191-1	---
NS 20819-3C	Sleeve (3J Used)	1	10013191-1	---
10013197-1	Injector Assembly Rocket Engine	1	10013198-1	10013197 K
10013194-6	Screen Square Weave	1	10013197-1	10013194 C
10013194-8	Screen Square Weave	1	10013197-1	10013194 C
10013194-9	Screen Square Weave	1	10013197-1	10013194 C
10013195-1	Body Injector	1	10013197-1	10013195 E
10013196-1	Orifice Plate Injector	1	10013197-1	10013196 C
10041433-1	Plate Retention Fine Catalyst	1	10013197-1	10041433 C
10045402-1	Plug, Orifice, Injector Propulsion Subsystem	1	10013197-1	10045402 A

Figure 4-1. Parts List for All Flight REA

Part Number	Description	Qty	Next Assembly	Drawing Number
Shell 405	Catalyst ABSG 20-30 Mesh	A/R	10013197-1	---
Shell 405	Catalyst 1/8 Pellets	A/R	10013198-1	---
BS 506210	Catalyst HA-3 1/8 x 1/8 Pellets	A/R	10013198-1	---

Figure 4-1. Parts List for All Flight REA (Continued)

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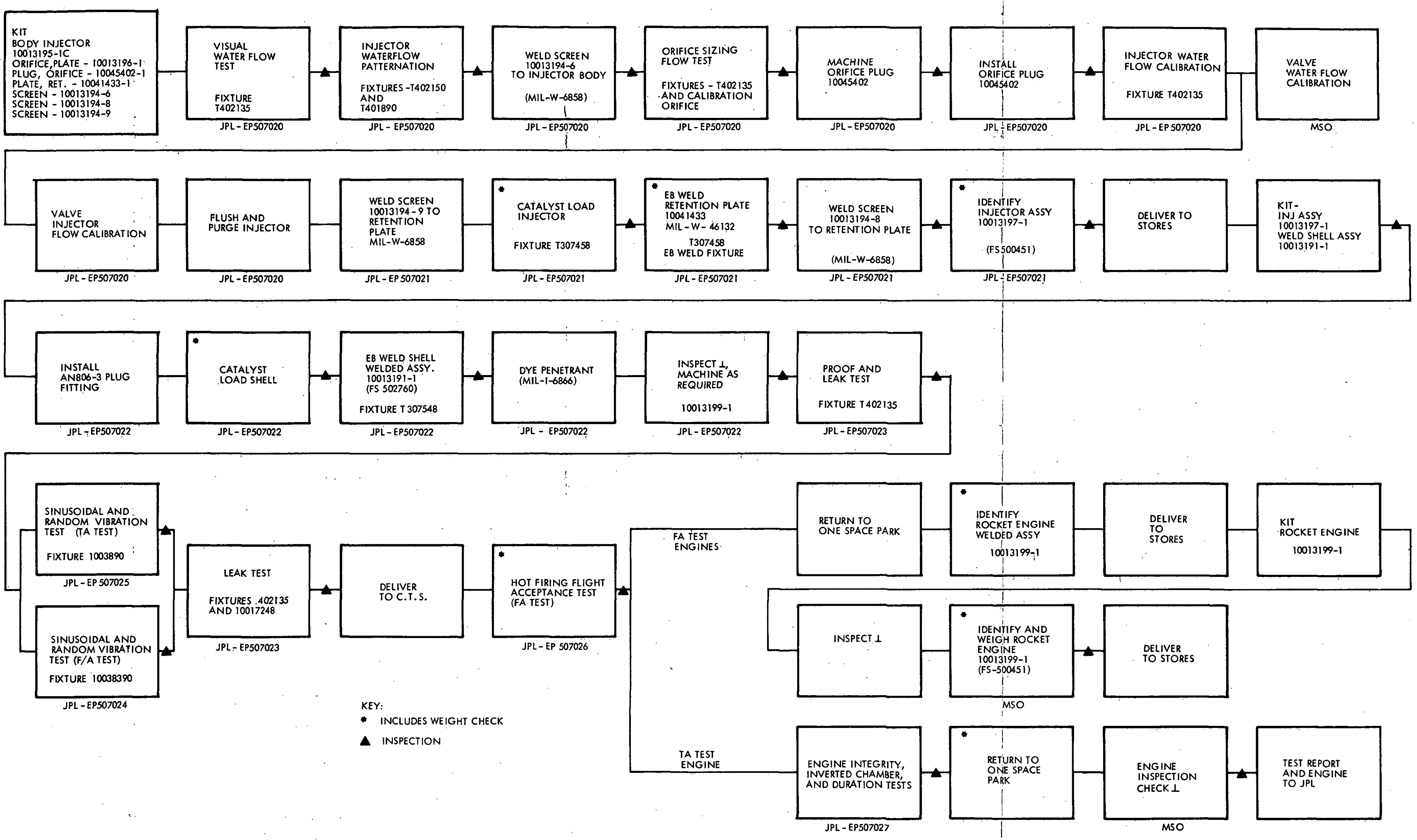

Figure 4-2. Rocket Engine Assembly Test Flow Chart

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Engine S/N	Injector			Shell		
	Catalyst Weight Grams	Torque in-lbs		Catalyst Weight Grams	Torque in-lbs	
		Close Gap	Final		Close Gap	Final
201	19.3	80	85	211.9	25	35
203	19.0	N.A.	85	201.5	N.A.	35
204	19.0	75	90	203.4	26	35
205	19.1	60	85	203.0	26	35
206	19.2	80	90	204.4	30	35
207	19.2	70	90	208.1	28	35

Figure 4-3. Catalyst Weight Summary

4.2 WEIGHT SUMMARY

Weight losses due to hot fire acceptance test and final weights of each flight engines are listed below:

Engine S/N	Weight Loss Due to FA Tests Grams	Final Weight Grams*
201	16.5	1181.1
203	10.6	1173.0
204	12.9	1168.1
205	13.6	1169.8
206	12.8	1163.0
207	14.3	1169.2

*Final weight prior to shipment; all plugs and closures removed.

5. FLIGHT ACCEPTANCE NONREACTIVE TESTS

5.1 WATER FLOW TESTS

The following water flow tests were conducted on the injectors prior to catalyst loading.

5.1.1 Visual Water Flow Test

The visual water flow test was conducted as per Procedure JPL EP-507020. The injectors were flowed at a water flow rate of 0.22 ± 0.005 lb/sec to visually verify that no holes were plugged and that no burrs are causing distorted flow. The test setup conformed to Figure 5-1 and is shown in the photograph in Figure 5-2.

5.1.2 Water Flow Patternation Test

The water flow patternation test was conducted on all injectors as per Procedure JPL EP-507020. The injectors were flowed with the orifice spray separator, JPL Drawing 10041448, at 0.16 ± 0.005 lb/sec. The test setup conformed to Figure 5-3 and is shown in the photograph in Figure 5-4. The separator outlet tubes were connected to 18 collector tubes of sufficient size to allow at least 5 seconds of continuous flow. The discharge volumes were measured and recorded in Figure 5-5. Maximum deviation of any tube both above and below the average volume was recorded. (The maximum allowable deviation from the average volume must be less than 20 percent.)

5.1.3 Injector Orifice Sizing

The orifice sizing was performed in accordance with Procedure JPL EP-507020. After installing the screen Part No. 10013194-6 three orifices were flowed for each injector and from this data an orifice size was selected. The plug orifice (JPL Drawing 10045402) was to be sized to have a pressure drop across the injector of 95^{-0}_{+10} psi at a flow rate of 0.22 ± 0.002 lb/sec water. The size of orifice selected for each engine and the flow rate and pressure drop is shown in Figure 5-6.

5.1.4 Valve Calibration

Two flight type solenoid valves Part No. 10039802 were furnished by JPL. The valves were water flow calibrated several times during the program to check for performance changes.

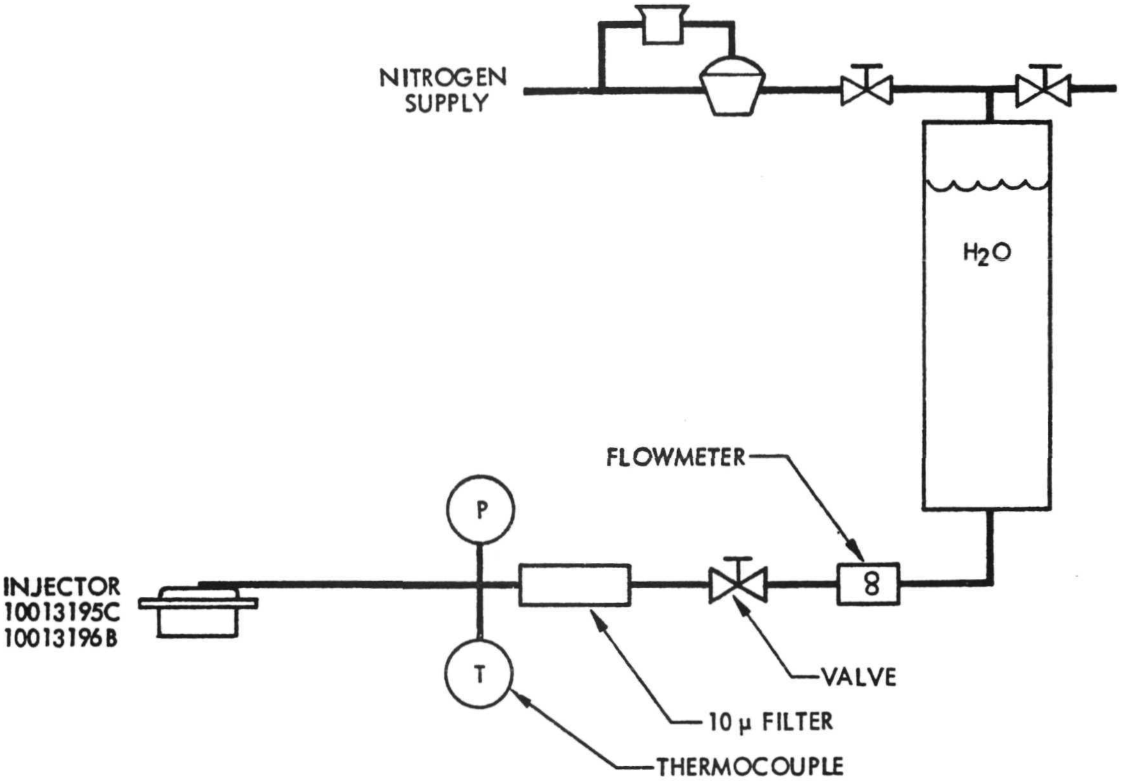


Figure 5-1. Visual Observation Injector Flow Pattern Test Setup

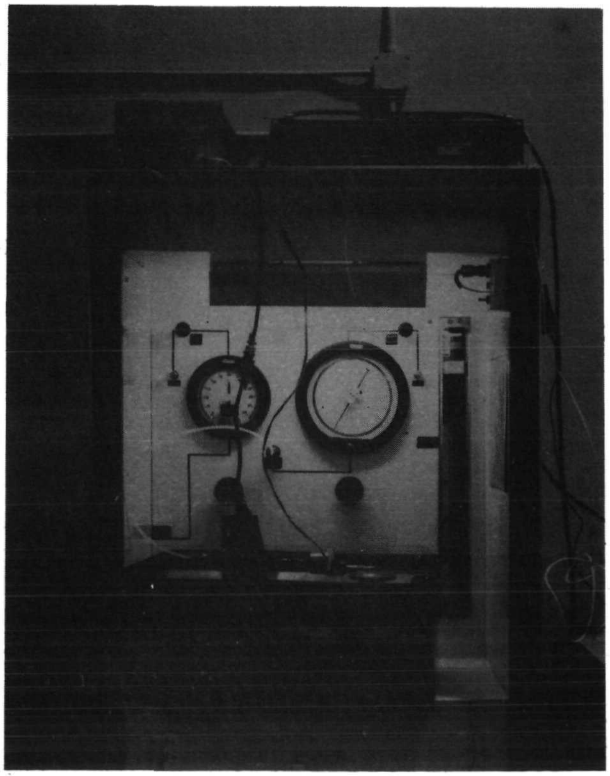


Figure 5-2. Photograph of Visual Pattern Test

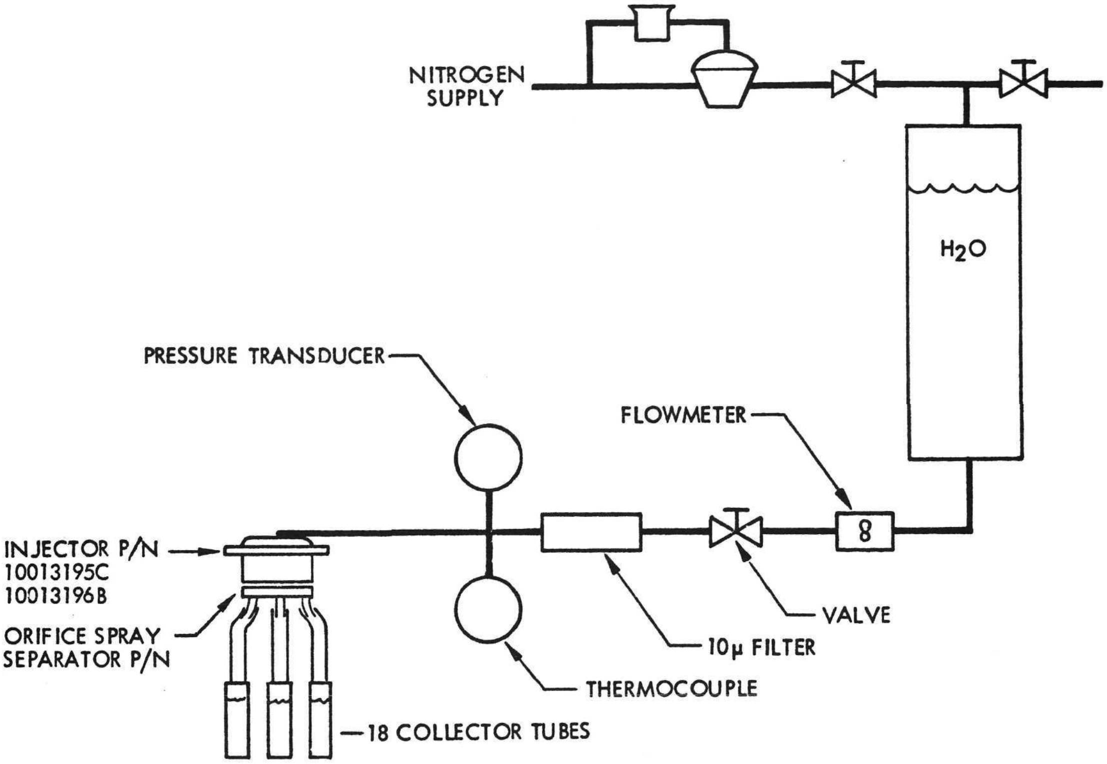


Figure 5-3. Injector Flow Distribution Test Setup

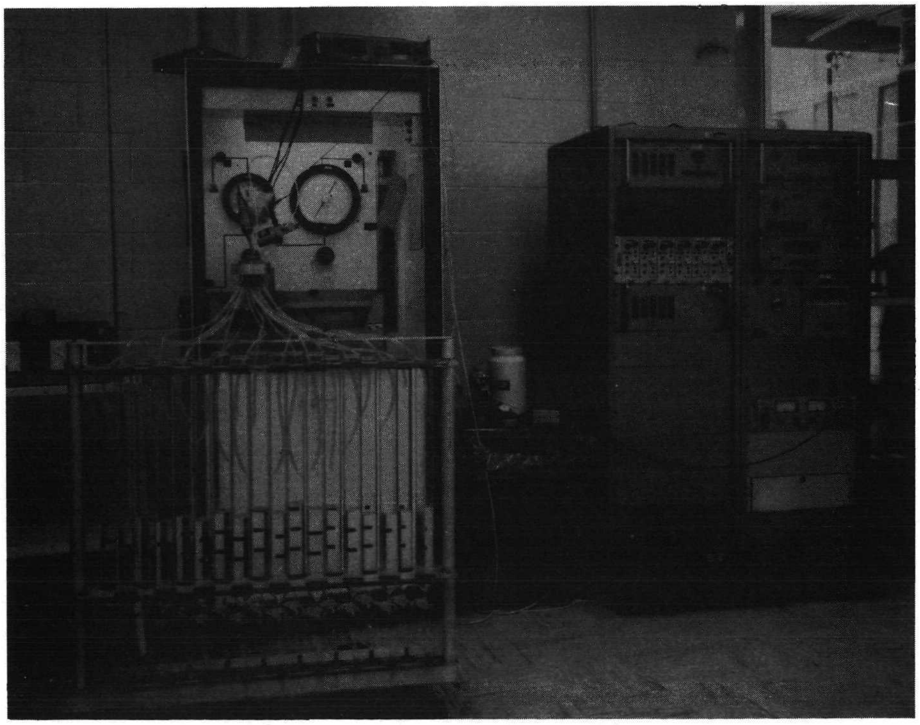


Figure 5-4. Photograph of Injector Flow Distribution Test

Burrette Graduate No.	S/N 201	S/N 203	S/N 204	S/N 205	S/N 206	S/N 207	S/N 208
1	3.1	8.3	7.2	2	2	2	1.6
2	3.1	6.6	9.3	2	2	2	1.6
3	3.1	6.6	9.3	2	4	2	1.6
4	11.1	10.1	7.2	2	6	2	5.7
5	11.1	8.3	9.3	2	6	4	1.6
6	11.1	6.6	5.2	2	2	2	7.7
7	4.7	5.5	2.8	0	2	2	4.5
8	4.7	2	4.8	2	2	2	.004
9	12.6	2	4.8	4	2	0	2.4
10	3.1	5.5	10.9	2	2	2	.004
11	4.7	5.5	5.2	2	2	6	2.4
12	4.7	2	4.8	2	2	6	1.6
13	4.7	2	4.8	2	0	2	1.6
14	4.7	3.84	6.8	2	2	4	2.4
15	4.7	2	.8	3	2	0	2.4
16	3.1	3.8	4.8	0	2	2	2.4
17	4.7	5.5	2.8	2	2	2	2.4
18	3.1	3.8	2.8	10.2	4	4	2.4

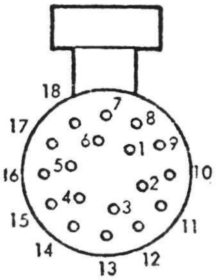


Figure 5-5. Water Flow Patternation Test Results (Deviation %)

Engine S/N	Orifice Diameter (in.)	Pressure Drop
201	0.0951	103.54 psi @ 0.215 lb/sec
203	0.0985	101.88 psi @ 0.22 lb/sec
204	0.0982	99.0 psi @ 0.22 lb/sec
205	0.1047	100.9 psi @ 0.22 lb/sec
206	0.0982	102.9 psi @ 0.22 lb/sec
207	0.0978	97.5 psi @ 0.22 lb/sec
208	0.0982	100.5 psi @ 0.22 lb/sec

Figure 5-6. Orifice Size and Injector Pressure Drop

The valves were S/N 0003 and 0004 and the test sequence and engine S/N used with each valve are as follows:

A. Valve S/N 0003 first calibration

Engine S/N 203	Valve S/N 0003	FA Test
Engine S/N 202	Valve S/N 0003	FA Test
Engine S/N 201	Valve S/N 0003	FA Test
Engine S/N 202	Valve S/N 0003	TA Test

B. Valve S/N 0003 second calibration

C. Valve S/N 0004 first calibration

Engine S/N 206	Valve S/N 0004	FA Test
Engine S/N 207	Valve S/N 0004	FA Test
Engine S/N 204	Valve S/N 0003	FA Test
Engine S/N 205	Valve S/N 0003	FA Test

D. Valve S/N 0003 third calibration

E. Valve S/N 0004 second calibration

Injector S/N 208 was water flowed with valve S/N 0004 twice, after both calibrations of valve S/N 0004.

The test setup for calibrating the valves conformed to Figure 5-7. The data and plots for the valve calibrations are shown in the following figures:

First calibration	Valve S/N 0003	Figures 5-8 and 5-9
First calibration	Valve S/N 0004	Figures 5-10 and 5-11
Second calibration	Valve S/N 0003	Figures 5-12 and 5-13
Second calibration	Valve S/N 0004	Figures 5-14 and 5-15
Third calibration	Valve S/N 0003	Figures 5-16 and 5-17

The change in slope of the valve calibration curves is apparently a characteristic of the valve. See Appendix E for the calibration data and sizes of flow meters and pressure transducers used on the water flow tests.

5.1.5 Valve-Injector Combination Flow Calibration

The valve-injector combination for each engine was water flow calibrated in accordance with Procedure JPL EP-507020. The solenoid

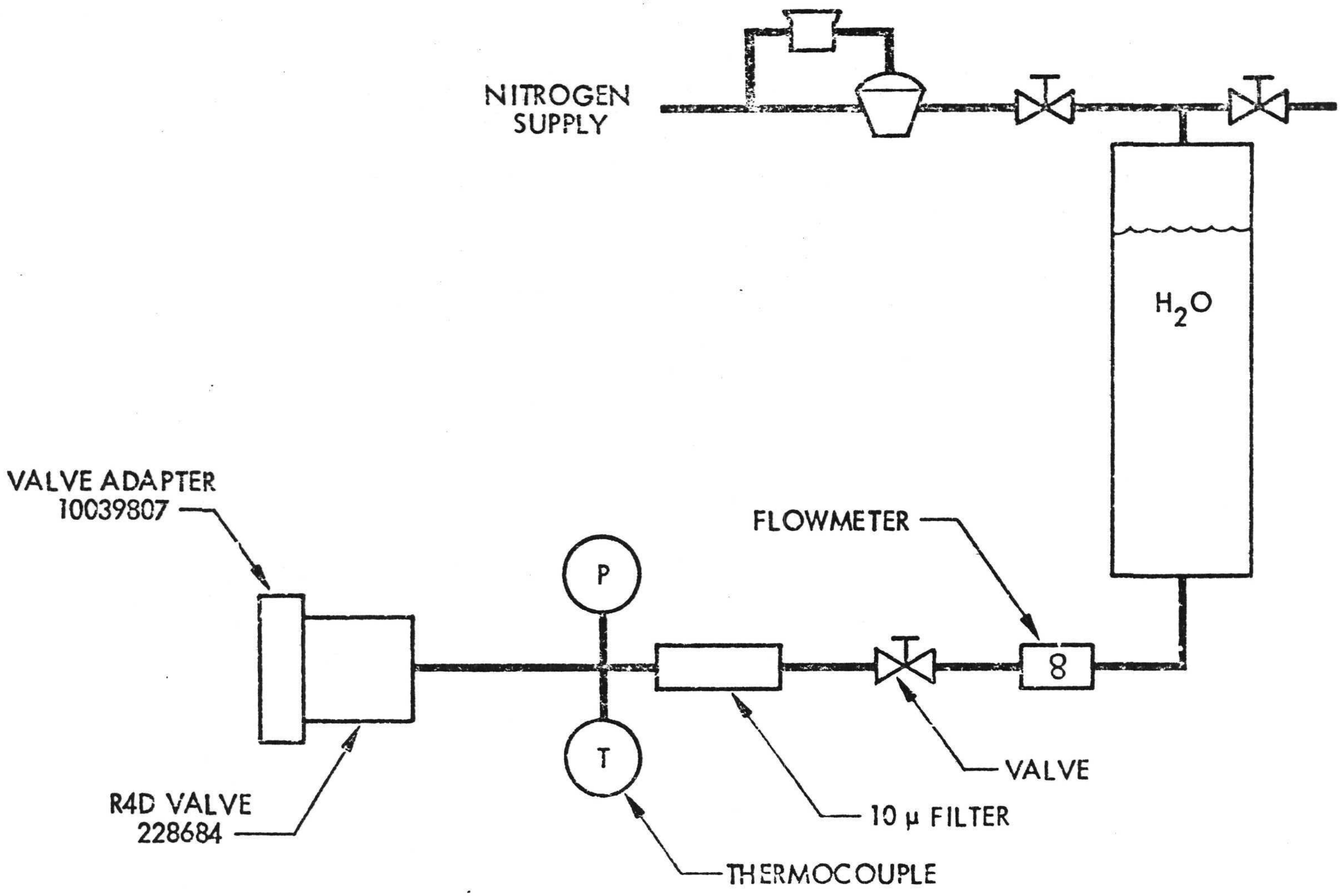


Figure 5-7. Valve Water Calibration

Water Flow Rate lb/sec	Inlet Water Temp. ^{O}F	Pressure Drop psig
.0397*	69	1.55
.0597*	69	3.71
.0802*	69	6.67
.1003	68	10.18
.1201	68	14.65
.1402	68	19.78
.1603	68	25.73
.1813	68	33.68
.2024	68	43.16
.2202	68	52.34
.2401	68	63.80
.2601	68	76.53
.2702	68	83.25
.2598	68	76.46
.2400	68	63.70
.2200	68	52.20
.2007	68	42.35
.1801	68	33.10
.1600	68	25.68
.1400	68	19.77
.1200	68	14.65
.1002	68	10.22
.0805*	69	6.72
.0605*	69	3.80
.0395*	69	1.58

*Flow Meter S/N Space T-MF-1 (Potter)
All others with Flow Meter S/N 32997 (Foxboro)
All pressures measured with Alinco S/N 34814

Figure 5-8. Valve S/N 0003 Water Flow First Calibration Data (April 21, 1972)

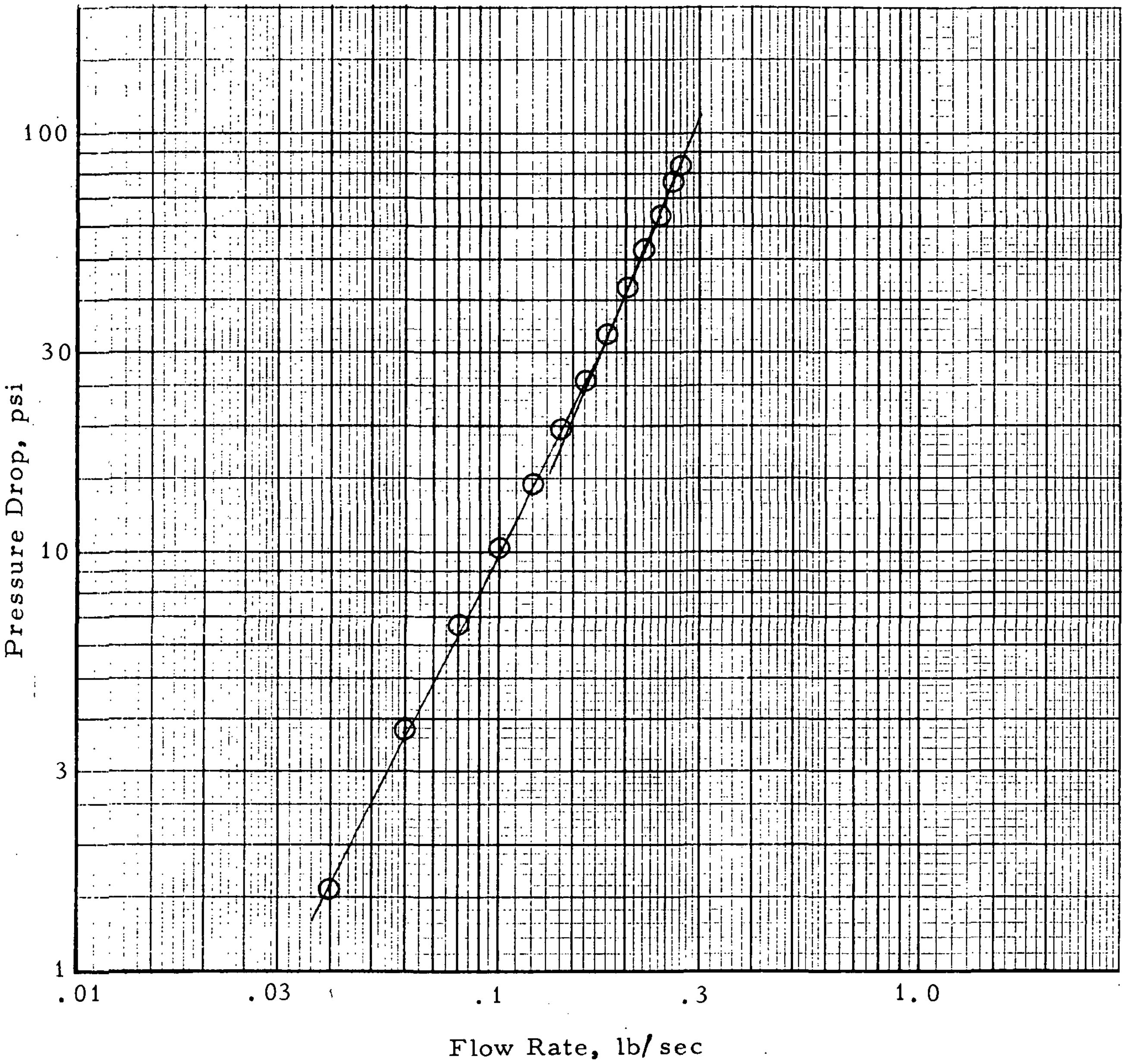


Figure 5-9. Valve S/N 0003 Water Flow First Calibration Data

Water Flow Rate lb/sec	Inlet Water Temp. ^{o}F	Pressure Drop psig
0.04*	72.8	1.6
0.06*	72.8	3.4
0.08*	72.8	6.1
0.10	72.8	9.4
0.12	72.8	13.3
0.14	72.8	18.0
0.16	72.8	23.1
0.18	72.8	29.8
0.20	72.8	37.8
0.22	72.8	48.8
0.24	72.8	60.1
0.26	72.8	71.4
0.27	72.8	78.3
0.26	72.8	71.2
0.24	72.8	59.0
0.22	72.8	49.2
0.20	72.8	38.5
0.18	72.8	30.0
0.16	72.8	23.3
0.14	72.8	18.0
0.12	72.8	13.6
0.10	72.8	10.1
0.08*	72.8	6.1
0.06*	72.8	3.5
0.04*	72.8	1.6

*Flow Meter S/N Space T-MF-1 (Potter)
All others with Flow Meter S/N 32997 (Foxboro)
All pressures measured with Alinco S/N 34814

Figure 5-10. Valve S/N 0004 Water Flow First Calibration Data (June 23, 1972)

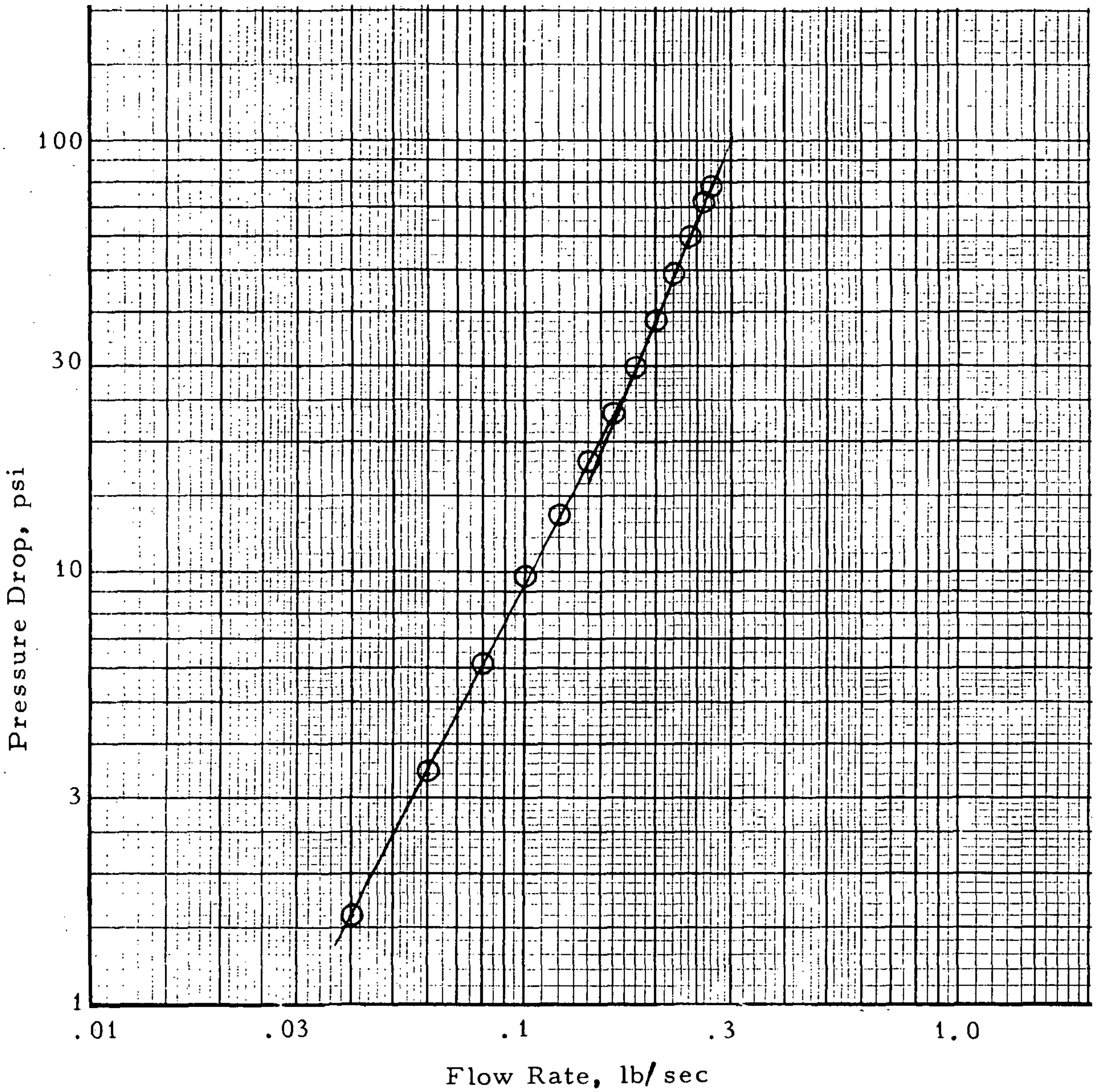


Figure 5-11. Valve S/N 0004 Water Flow First Calibration Data

Water Flow Rate lb/sec	Inlet Water Temp. ^{o}F	Pressure Drop psig
.0403*	74	1.77**
.0603*	74	3.89**
.0801*	74	6.84**
.1005*	74	10.80**
.120	73	15.06**
.140	73	20.46**
.160	73	26.63**
.180	73	34.30**
.200	73	43.46**
.221	73	53.70
.240	73	64.20
.260	73	74.40
.270	73	83.85
.260	73	76.90
.240	73	64.45
.220	73	54.00
.201	73	43.94**
.181	73	34.42**
.161	73	26.75**
.141	73	20.55**
.121	73	15.28**
.1010*	74	11.00**
.0808*	74	7.05**
.0600*	74	3.92**
.0406*	74	1.83**

*Flow Meter S/N Space T-MF-1 (Potter)
All other flows with Flow Meter S/N 32997 (Foxboro)

**Pressure measured with Taber S/N 661433
All others with Alinco S/N 34814

Figure 5-12. Valve S/N 0003 Water Flow Second Calibration Data (August 18, 1972)

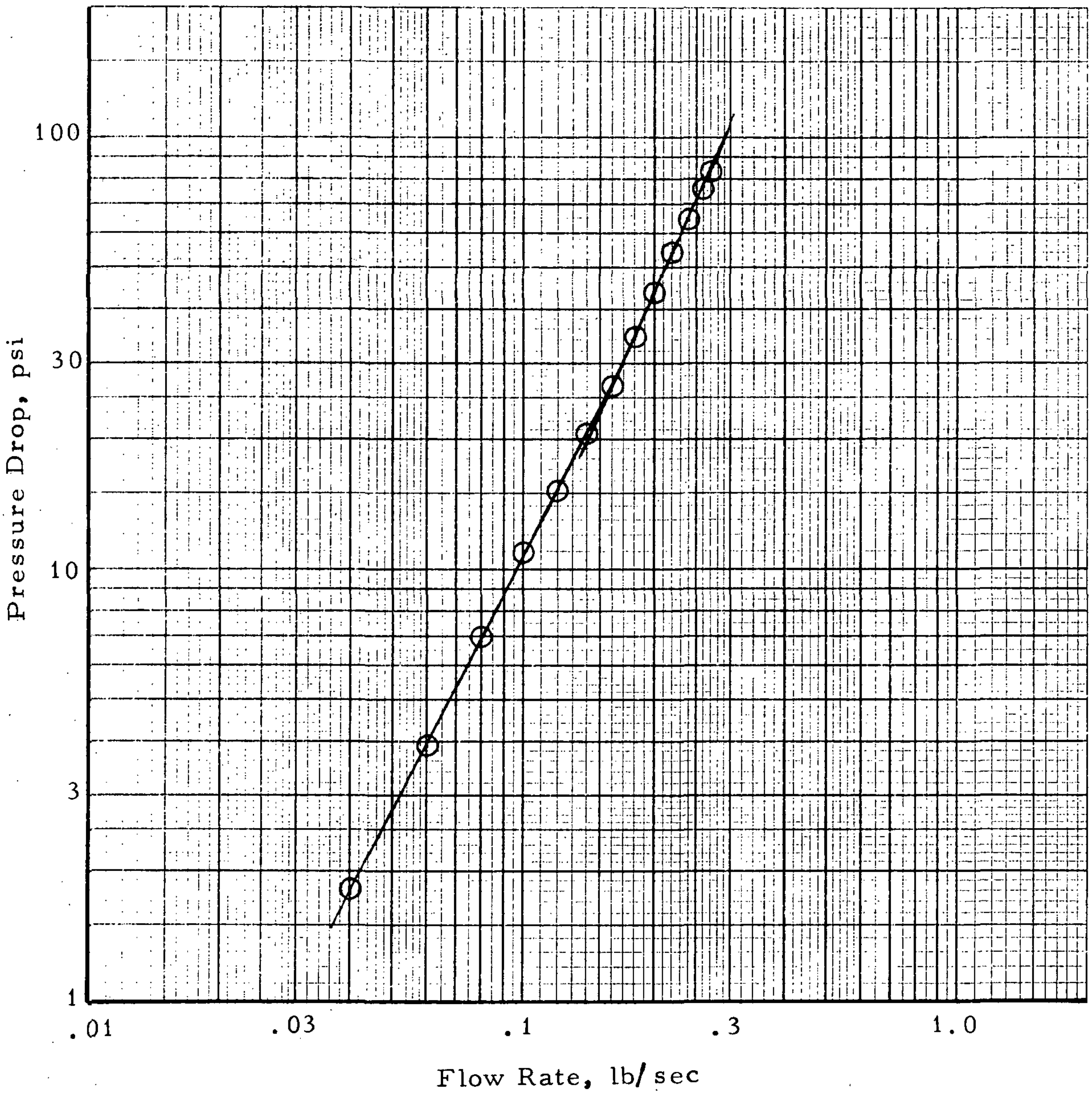


Figure 5-13. Valve S/N 0003 Water Flow Second Calibration Data

Water Flow Rate lb/sec	Inlet Water Temp. oF	Pressure Drop psig
.03953*	60	1.76**
.06031*	60	4.00**
.08014*	60	6.86**
.10094*	60	10.77**
.12005	60	14.49
.14218	60	19.95
.16106	60	25.34
.18203	60	32.86
.20096	60	41.16
.21906	60	50.85
.24120	60	63.2
.25954	60	74.5
.26943	60	81.6
.26089	60	75.3
.24105	63	63.0
.22101	63	52.5
.19982	60	41.55
.18097	60	33.20
.16103	60	25.33
.14114	60	19.81
.12086	60	14.52
.10064*	60	10.40**
.08036*	60	6.89**
.06042*	60	3.97**
.04096*	60	1.88**

*Flow Meter S/N Space T-MF-1 (Potter)
All other flows with Flow Meter S/N 32997 (Foxboro)

**Pressure measured with Taber S/N 661433
All others with Alinco S/N 34814

Figure 5-14. Valve S/N 0004 Water Flow Second Calibration Data (September 8, 1972)

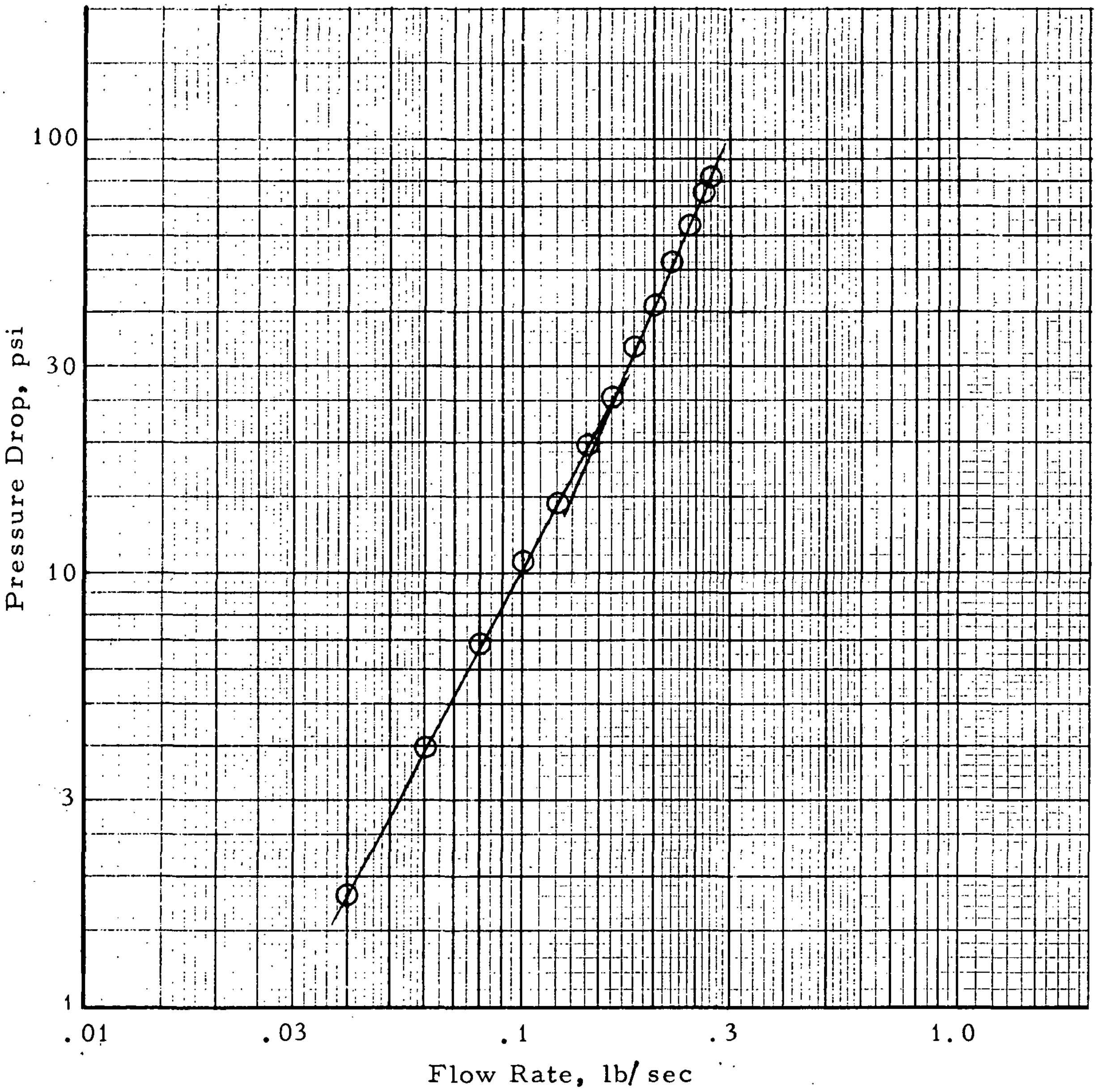


Figure 5-15. Valve S/N 0004 Water Flow Second Calibration Data

Water Flow Rate lb/sec	Inlet Water Temp. °F	Pressure Drop psig
.03924*	71.8	1.56**
.06001*	71.8	3.90**
.08182*	71.8	7.23**
.10327*	71.8	11.60**
.12061	71.8	15.46
.14246	71.8	21.24
.16237	71.8	27.28
.18147	71.7	34.52
.20208	71.7	44.00
.22186	71.7	55.20
.24092	71.6	65.60
.25959	71.6	77.50
.26979	71.5	85.10
.26011	71.5	77.70
.24067	71.5	65.57
.22001	71.5	54.20
.20141	71.5	43.95
.18144	71.6	35.00
.16173	71.6	26.98
.14136	71.7	20.48
.12027	71.7	14.98
.10173*	71.7	11.25**
.08056*	71.8	7.18**
.06017*	71.9	3.94**
.04159*	72.4	1.87**

*Flow Meter S/N Space T-MF-1 (Potter)
All other flows with Flow Meter S/N 32997 (Foxboro)

**Pressures measured with Taber S/N 661433
All other with Alino S/N 34814

Figure 5-16. Valve S/N 0003 Water Flow Third Calibration Data (September 8, 1972)

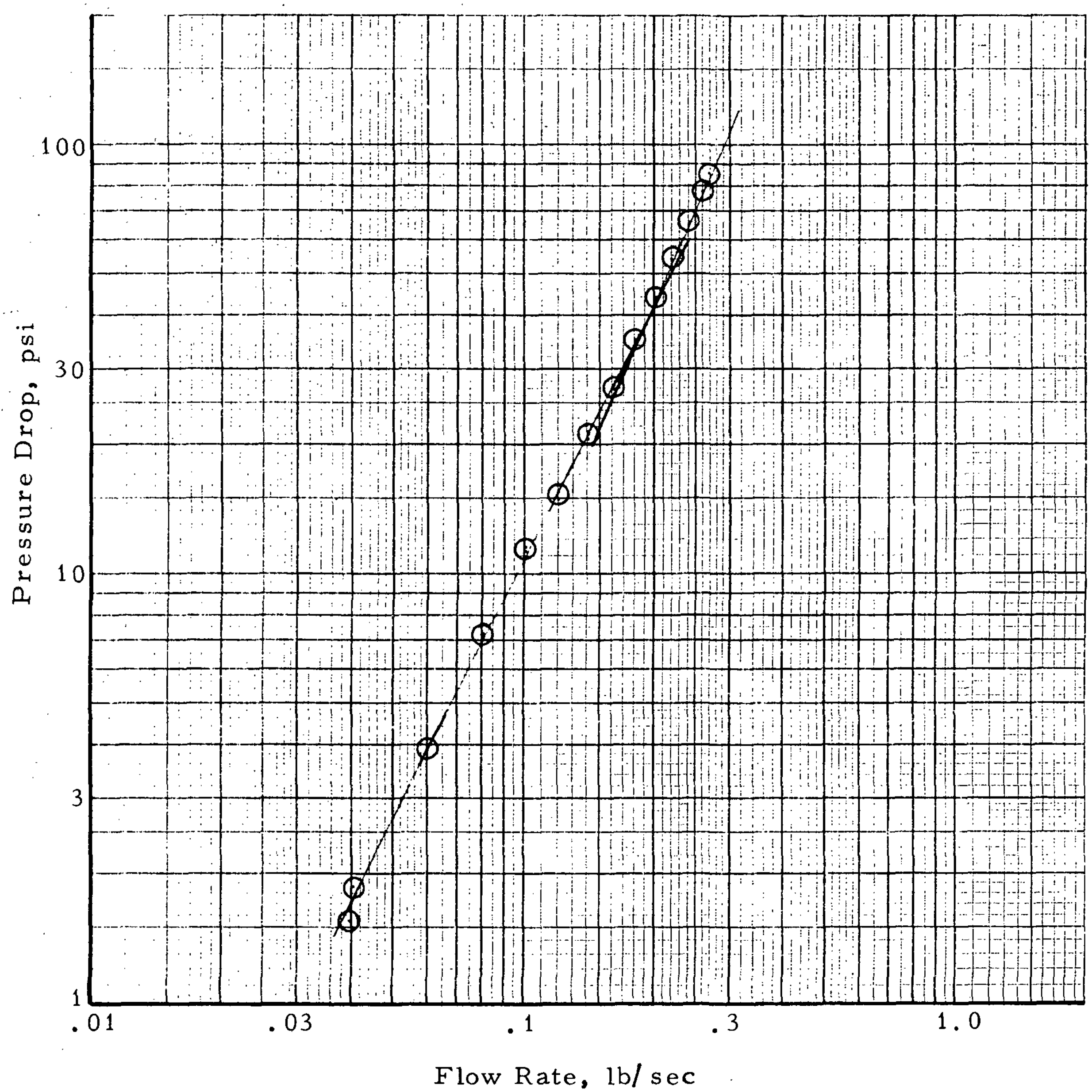


Figure 5-17. Valve S/N 0003 Water Flow Third Calibration

valve assembly Part No. 10039802 supplied by JPL with a propellant valve inlet adapter was attached to the injector-orifice combination. The combination was flowed over the range of 0.04 to 0.25 lb/sec with water. The total pressure drop versus flow rate was measured for each combination at a minimum of 12 points during increasing flow rate and at a minimum of 12 points during decreasing flow rate. The test setup was as shown in Figure 5-18. The data for each injector (201, 203, 204, 205, 206, 207 and two different tests on 208) is tabulated and plotted in Figures 5-19 through Figure 5-34.

5.1.6 Water Flow Bench - Instrumentation

During the water flow bench calibration of the MV/M '73 valves and injectors two error analyses were conducted. The first for pressure measurement and the second for flow measurement. The error analyses are presented in detail in Appendix "A" and will be summarized herein.

5.1.6.1 Pressure Measurement

The pressure measurement uncertainty estimate was obtained from five system level end to end calibrations conducted in a manner to simulate a worst-case test condition (i.e., comparison of transducer output to the calibration standard sixteen hours after initial adjustment of transducer zero and full scale output).

The results of this calibration shown in Figure 5-35 indicate a maximum nonlinearity of nearly 1 percent at 4 psia decreasing to approximately 0.2 percent at the full scale level. While these levels are within the specification requirement of ± 1 percent a second (0 to 50 psia) transducer was installed for lower range pressure measurements thereby assuring uncertainty of measurement well within specification requirements.

Two notes of significance regarding this data are warranted. First, the discontinuity in nonlinearity between 15 and 20 psi is attributed to the fact that two calibration standards were employed (0 to 15 psia and 0 to 300 psia). Second, the hysteresis exhibited is atypical of strain gauge transducers and the inconsistency of the hysteresis at low pressures relative to the full scale of the two calibration gauges is attributed to the calibration standards.

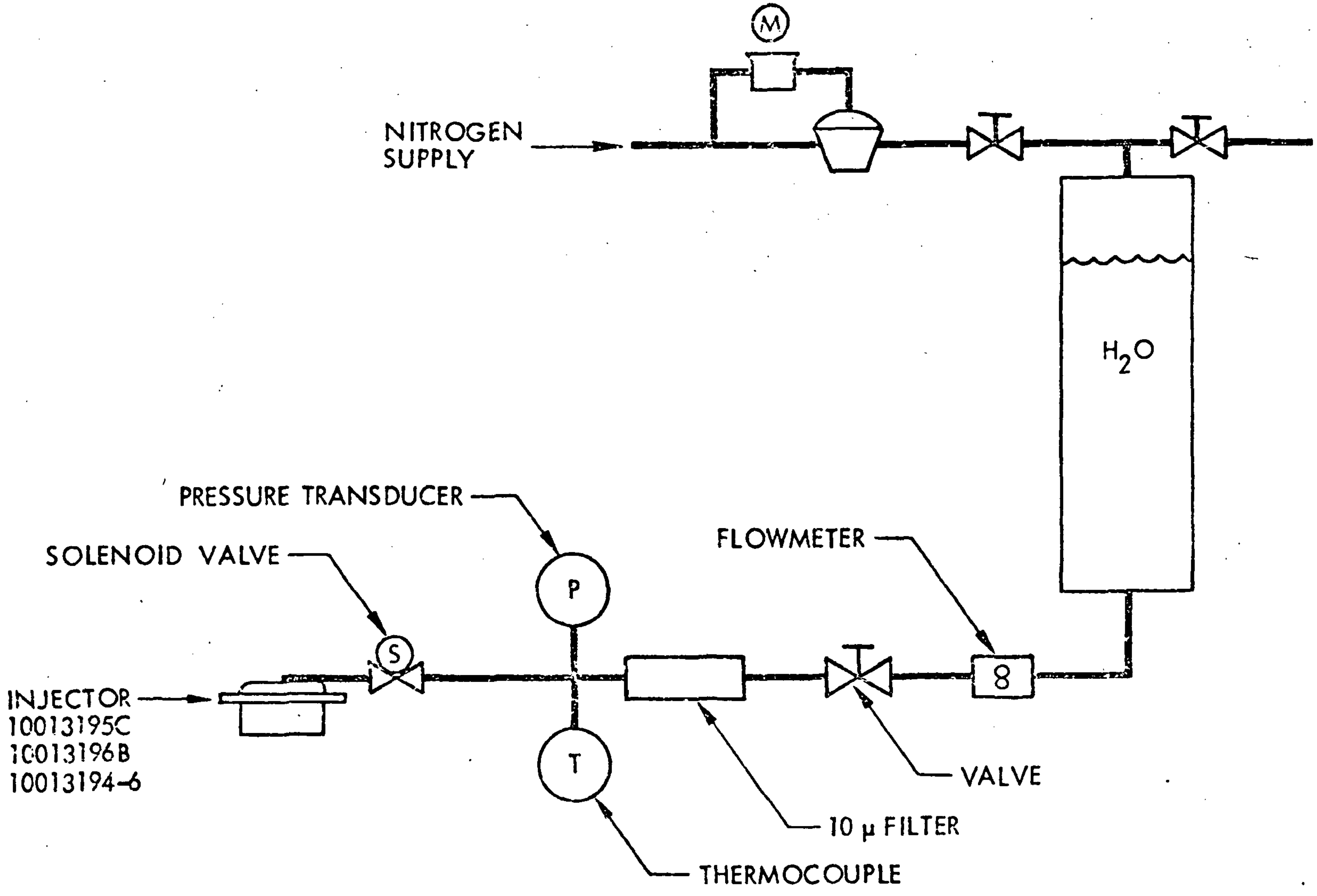


Figure 5-18. Valve-Injector Combination Calibration Test Setup

Water Flow Rate lb/sec	Inlet Water Temp. °F	Pressure Drop psig
.040	67	5.79
.061	67	12.52
.080	67	21.93
.100	67	34.43
.120	67	48.08
.140	67	64.51
.160	67	83.96
.180	67	105.48
.200	67	130.54
.220	67	157.32
.240	67	186.62
.260	67	225.64
.270	67	243.85
.260	67	224.42
.240	67	188.74
.220	67	158.87
.200	67	131.70
.180	67	106.22
.160	67	84.58
.140	67	64.50
.120	67	47.74
.100	67	34.38
.080	67	22.19
.060	67	12.38
.040	67	5.83

Flow Meter S/N 32997 (Foxboro)

Pressure Transducer Alinco S/N 34814

Figure 5-19. Valve-Injector Calibration Data, Injector S/N 201
Valve S/N 0003

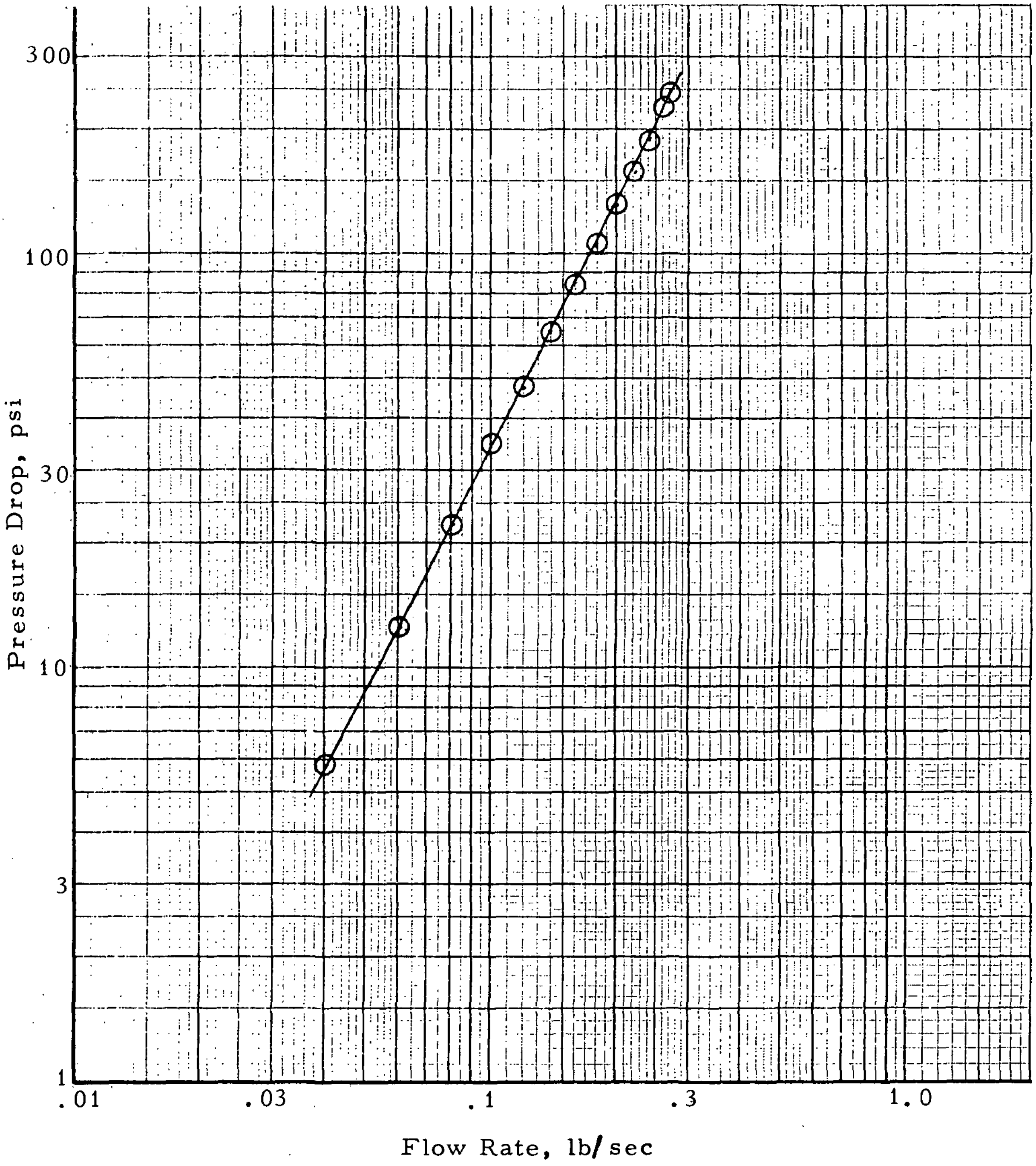


Figure 5-20. Valve-Injector Calibration Data, Injector S/N 201 Valve S/N 0003

Water Flow Rate lb/sec	Inlet Water Temp. ^{o}F	Pressure Drop psig
.0399	74	5.17
.0599	72	11.32
.0795	70	20.26
.100	69	31.89
.120	68	44.95
.140	68	61.09
.160	67	79.70
.180	67	99.89
.201	67	125.45
.219	67	148.67
.240	67	178.50
.260	67	211.79
.270	67	232.73
.260	67	214.55
.240	67	181.40
.220	67	152.24
.200	67	126.15
.180	68	101.67
.160	68	80.71
.120	68	45.81
.100	69	33.17
.080	69	20.66
.059	69	11.58
.040	69	5.47

Flow Meter S/N 32997 (Foxboro)

Pressure Transducer Alinco S/N 34814

Figure 5-21. Valve-Injector Calibration Data, Injector S/N 203
Valve S/N 0003

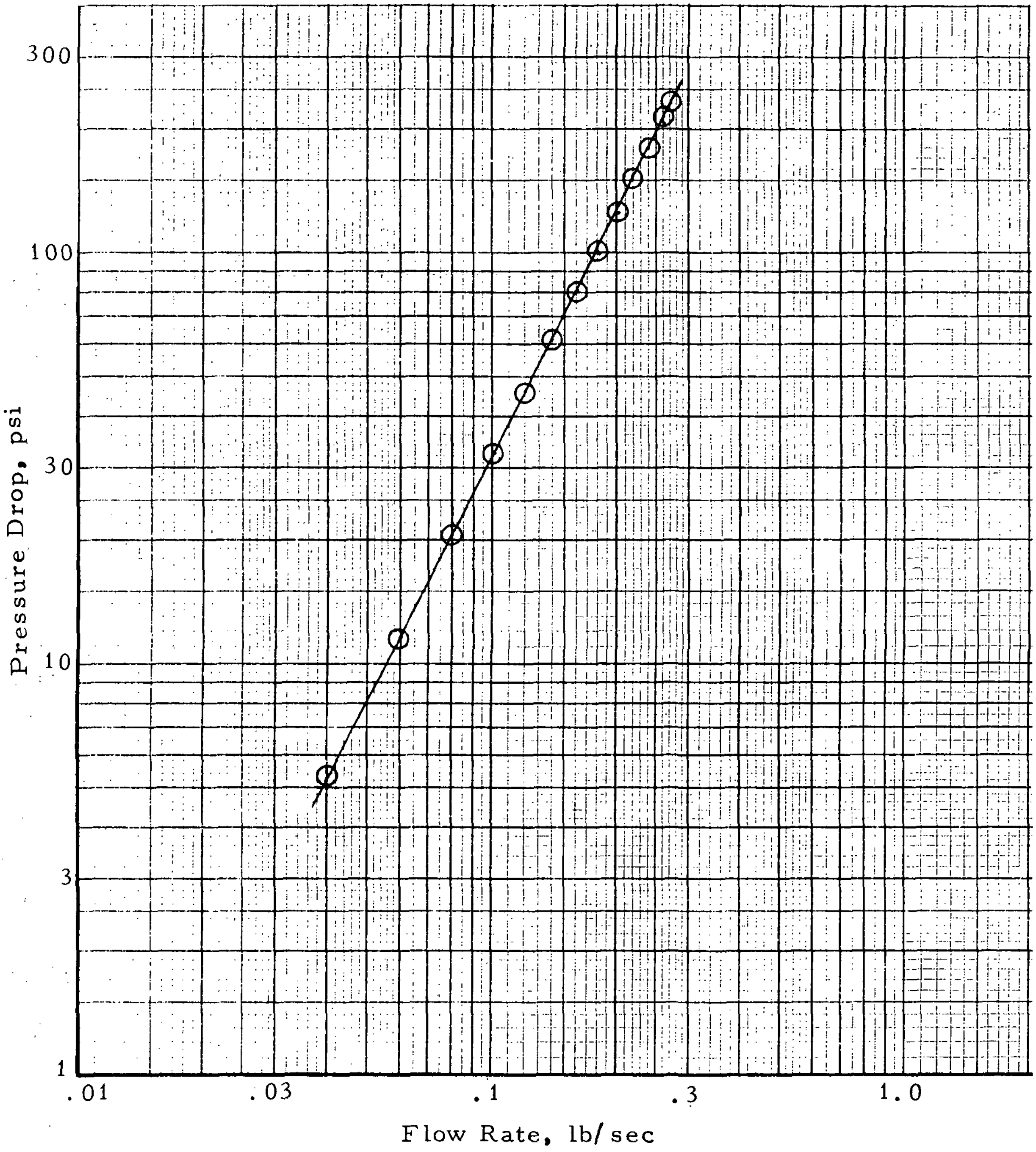


Figure 5-22. Valve-Injector Calibration Data, Injector S/N 203
Valve S/N 0003

Water Flow Rate lb/sec	Inlet Water Temp. ^{o}F	Pressure Drop psig
.040*	73	4.9
.060*	73	11.0
.080*	73	19.9
.100*	73	31.3
.12	73	43.4
.14	73	59.6
.16	73	77.1
.18	73	98.3
.20	73	121.8
.22	73	148.3
.24	73	176.4
.26	73	209.0
.27	73	226.0
.26	73	209.5
.24	73	177.2
.22	73	148.6
.20	73	121.0
.18	73	98.2
.16	73	77.7
.14	73	59.5
.12*	73	44.5
.10*	73	31.4
.08*	73	20.5
.06*	73	11.5
.04*	73	4.8

*Flow Meter S/N Space T-MF-1 (Potter)

All other flows with Flow Meter S/N 32997 (Foxboro)

All pressures with Alino S/N 34814

Figure 5-23. Valve-Injector Calibration Data, Injector S/N 204, Valve S/N 0003

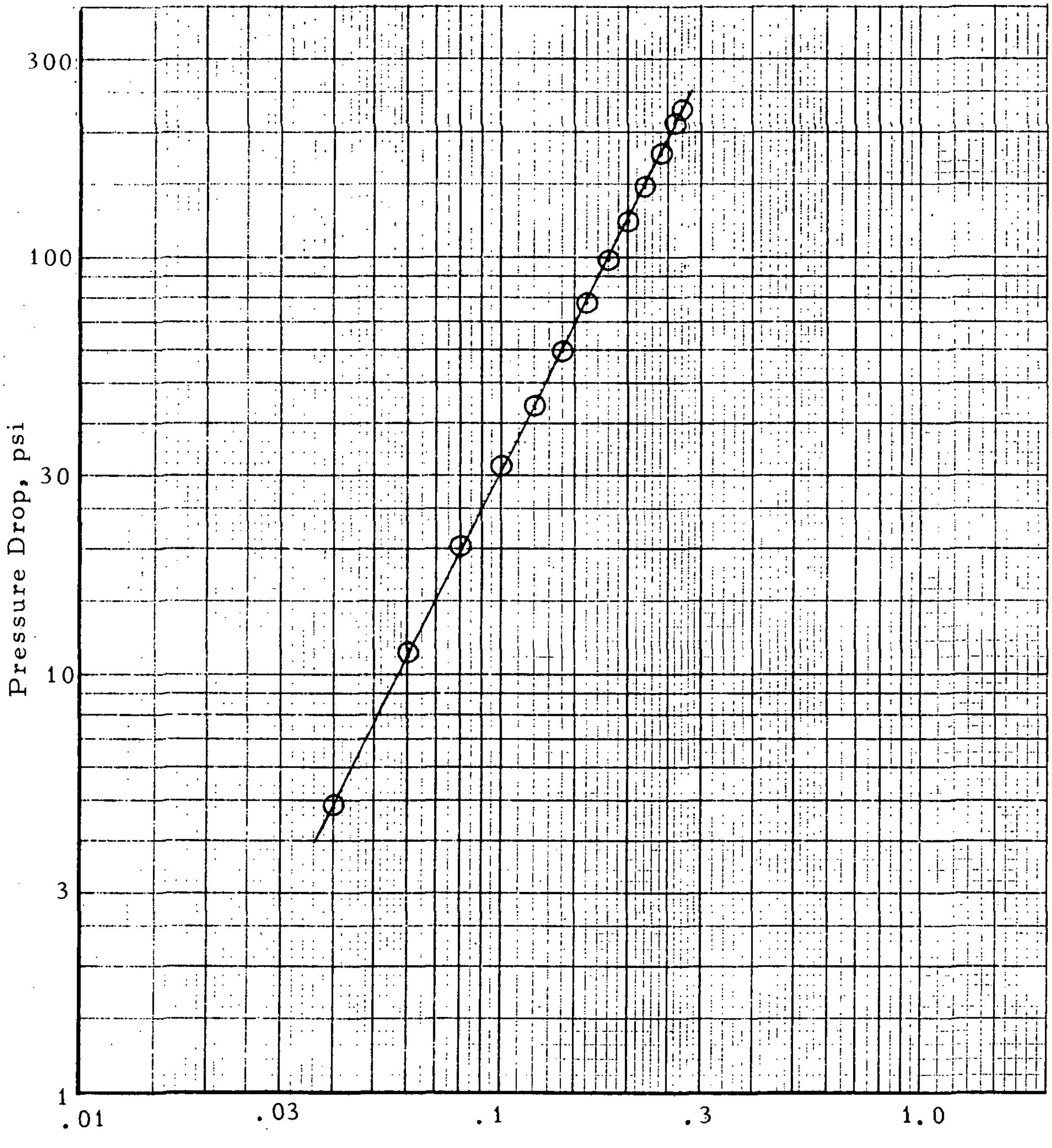


Figure 5-24. Valve-Injector Calibration Data, Injector S/N 204
Valve S/N 0003

Water Flow Rate lb/sec	Inlet Water Temp. °F	Pressure Drop psig
.04 *	73	4.6
.06 *	73	11.5
.08 *	73	19.8
.10 *	73	31.0
.12	73	43.5
.14	73	58.4
.16	73	77.0
.18	73	96.5
.20	73	120.0
.22	73	148.7
.24	73	175.2
.26	73	208.0
.27	73	221.0
.26	73	206.0
.24	73	175.5
.22	73	148.0
.20	73	123.5
.18	73	97.4
.16	73	78.0
.14	73	60.0
.12	73	43.0
.10 *	73	31.0
.08 *	73	19.7
.06 *	73	11.6
.04 *	73	4.8

*Flow Meter S/N Space T-MF-1 (Potter)

All other flows with Flow Meter S/N 32997 (Foxboro)

All pressures with Alino S/N 34814

Figure 5-25. Valve-Injector Calibration Data, Injector S/N 205
Valve S/N 0003

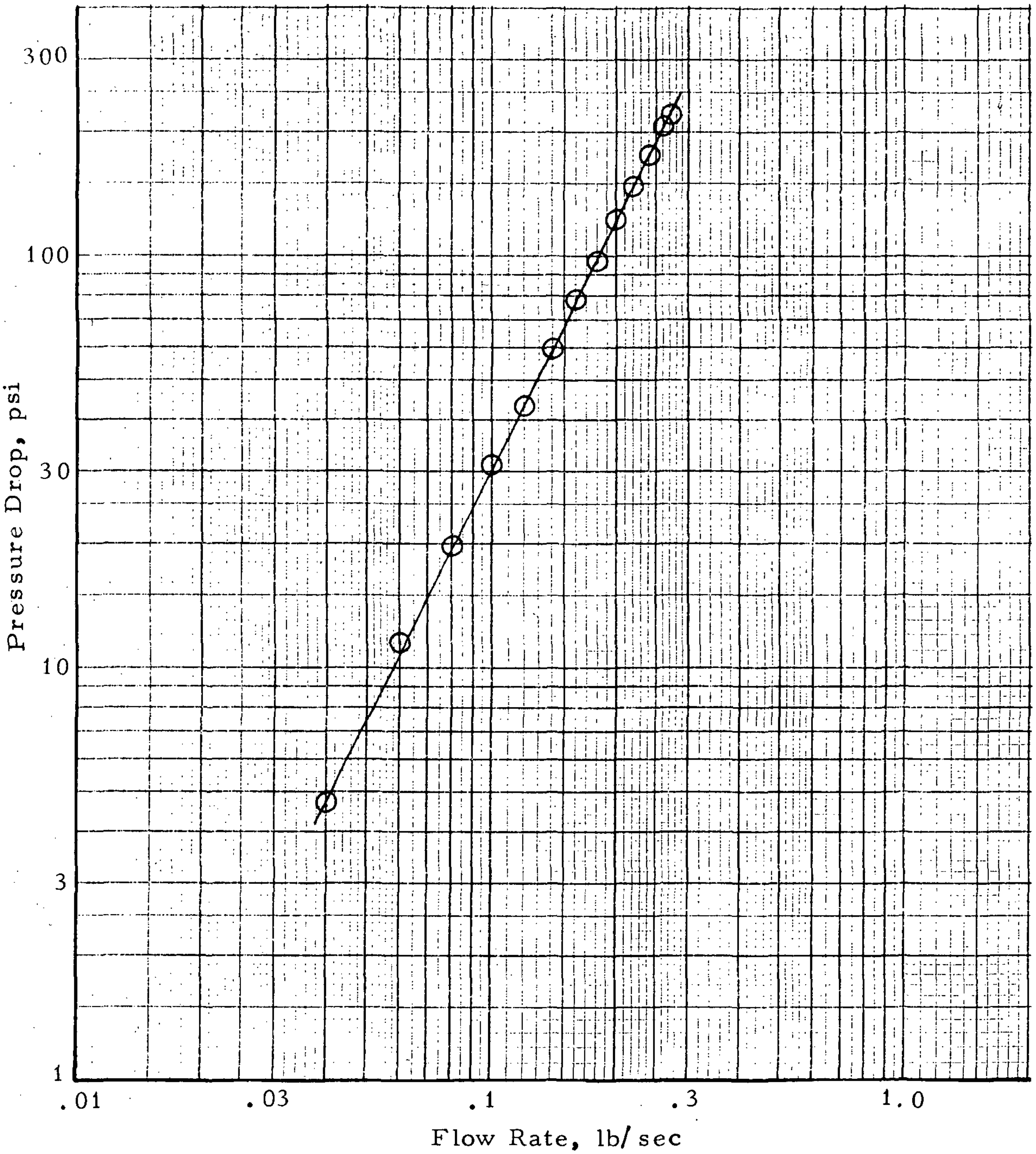


Figure 5-26. Valve-Injector Calibration Data, Injector S/N 205, Valve S/N 0003

Water Flow Rate lb/sec	Inlet Water Temp. ^oF (Avg.)	Pressure Drop psig
.041 *	73.8	4.8
.061 *	73.8	10.85
.080 *	73.8	19.11
.100 *	73.8	30.68
.120	73.4	42.7
.140	73.4	57.6
.160	73.4	76.2
.180	73.4	96.0
.200	73.4	118.8
.220	73.4	145.0
.240	73.4	171.0
.260	73.4	200.5
.270	73.4	220.5
.260	73.4	201.9
.240	73.4	170.5
.220	73.4	145.5
.200	73.4	119.6
.180	73.4	97.2
.160	73.4	77.5
.140	73.4	58.4
.121	73.4	43.85
.101 *	73.4	31.1
.080 *	73.8	19.3
.060 *	73.8	10.60
.041 *	73.8	4.75

*Flow Meter S/N Space T-MF-1 (Potter)

All other flows with Flow Meter S/N 32997 (Foxboro)

All pressures with Alino S/N 34814

Figure 5-27. Valve-Injector Calibration Data, Injector S/N 206
Valve S/N 0004

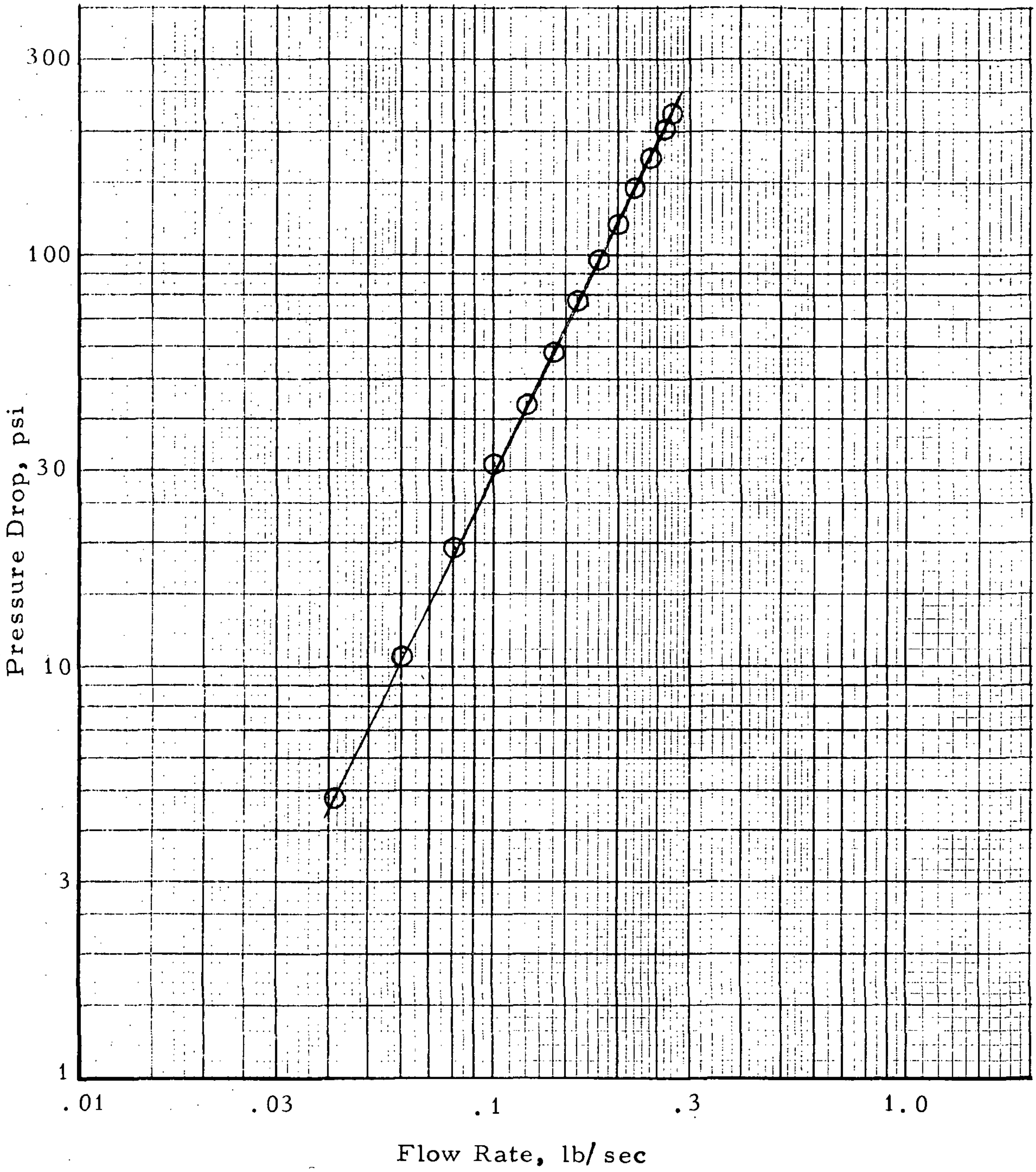


Figure 5-28. Valve-Injector Calibration Data, Injector S/N 206 Valve S/N 0004

Water Flow Rate lb/sec	Inlet Water Temp. ^{o}F (Avg.)	Pressure Drop psig
.040*	73.2	4.50
.060*	73.2	10.53
.080*	73.2	19.04
.100*	73.2	29.56
.119	73.0	41.06
.140	73.0	56.50
.160	73.0	73.60
.180	73.0	92.80
.200	73.0	114.50
.220	73.0	139.76
.240	73.0	165.12
.260	73.0	192.88
.270	73.0	209.30
.260	73.0	193.39
.240	73.0	165.50
.220	73.0	140.50
.200	73.0	115.10
.181	73.0	94.50
.160	73.0	74.19
.140	73.0	56.60
.120	73.0	41.80
.100*	73.2	29.60
.080*	73.2	18.59
.061*	73.2	10.57
.040*	73.2	4.65

*Flow Meter S/N Space T-MF-1 (Potter)

All other flows with Flow Meter S/N 32997 (Foxboro)

All pressures with Alino S/N 34814

Figure 5-29. Valve-Injector Calibration Data, Injector S/N 207
Valve S/N 0004

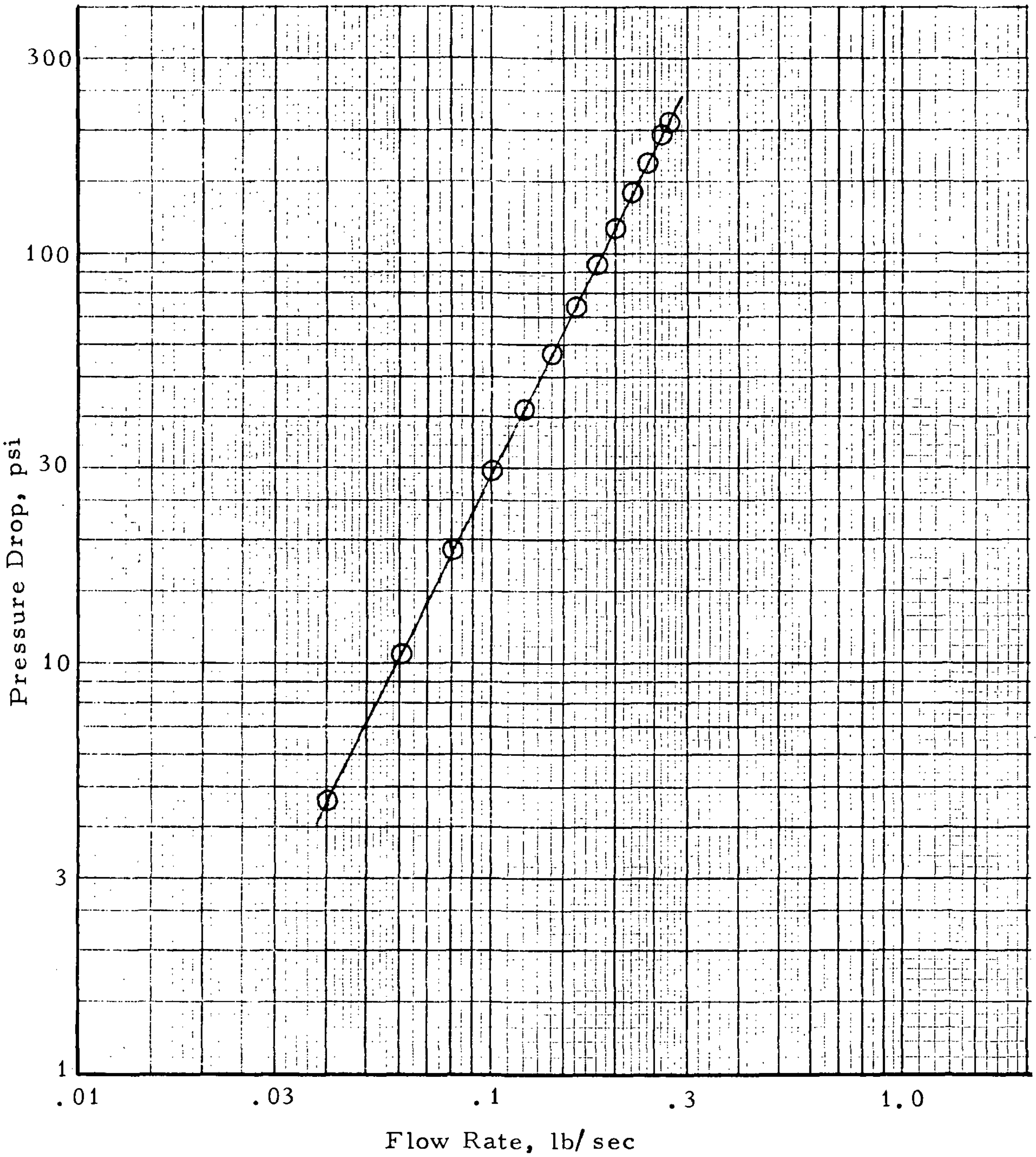


Figure 5-30. Valve-Injector Calibration Data, Injector S/N 207
Valve S/N 0004

Water Flow Rate lb/sec	Inlet Water Temp. °F (Avg.)	Pressure Drop psig
.040 *	70.8	4.75
.060 *	70.8	10.70
.080 *	70.8	18.93
.100 *	70.8	30.62
.120 *	70.8	43.61
.140	71.0	57.97
.159	71.0	75.71
.181	71.0	95.86
.200	71.0	117.50
.220	71.0	144.49
.240	71.0	169.39
.260	71.0	198.85
.270	71.0	216.75
.260	71.0	200.41
.240	71.0	169.45
.220	71.0	143.55
.200	71.0	119.30
.181	71.0	95.45
.160	71.0	76.00
.141	71.0	58.75
.120 *	70.8	43.61
.100 *	70.8	30.45
.080 *	70.8	19.72
.060 *	70.8	10.79
.041 *	70.8	4.89

*Flow Meter S/N Space T-MF-1 (Potter)

All other flows with Flow Meter S/N 32997 (Foxboro)

All pressures with Alino S/N 34814

Figure 5-31. Valve-Injector Calibration Data, Injector S/N 208 Valve S/N 0004 (First Calibration)

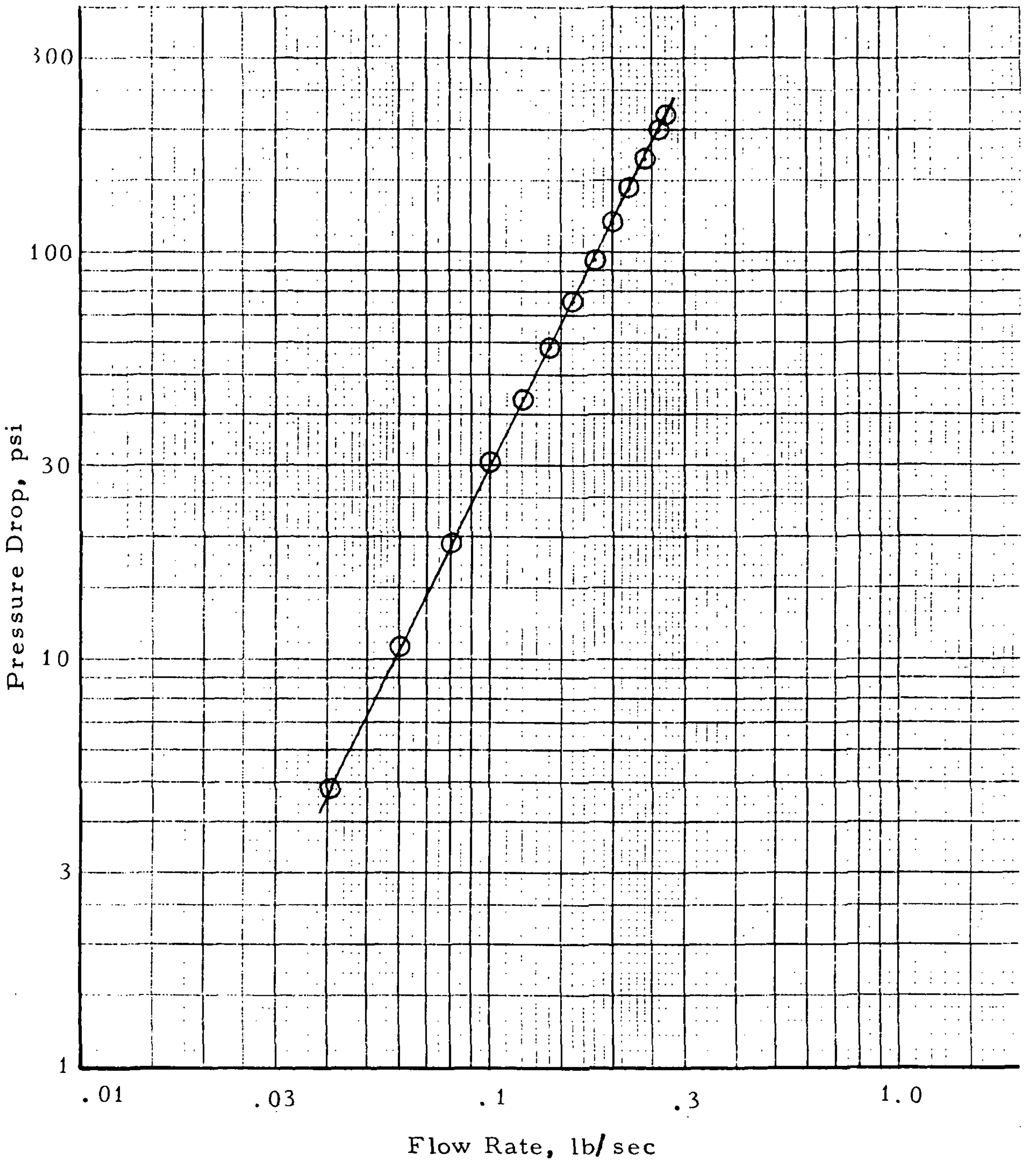


Figure 5-32. Valve-Injector Calibration Data, Injector S/N 208 Valve S/N 0004 (First Calibration)

Water Flow Rate lb/sec	Inlet Water Temp. °F	Pressure Drop psig
.03865*	67	4.71**
.06019*	67	11.0 **
.08148*	67	20.3 **
.10046*	67	31.1 **
.12097	66	43.82
.14130	66	59.80
.16015	66	76.50
.18067	67	97.1
.19994	67	118.8
.22225	67	146.7
.24119	67	171.6
.26066	67	202.3
.26950	67	218.9
.26040	68	202.3
.24056	68	172.5
.22069	68	147.0
.20111	68	120.8
.18119	68	97.9
.16064	68	77.2
.14065	68	59.5
.12056	68	43.57
.10134*	67	31.6 **
.08063*	67	19.8 **
.06076*	67	11.2 **
.04114*	67	5.2 **

*Flow Meter S/N Space T-MF-1 (Potter)
All others with Flow Meter S/N 32997 (Foxboro)
**Pressures measured with Taber S/N 661433
All others with Alinco S/N 34814

Figure 5-33. Valve-Injector Calibration Data, Injector S/N 208 Valve S/N 0004 (Second Calibration)

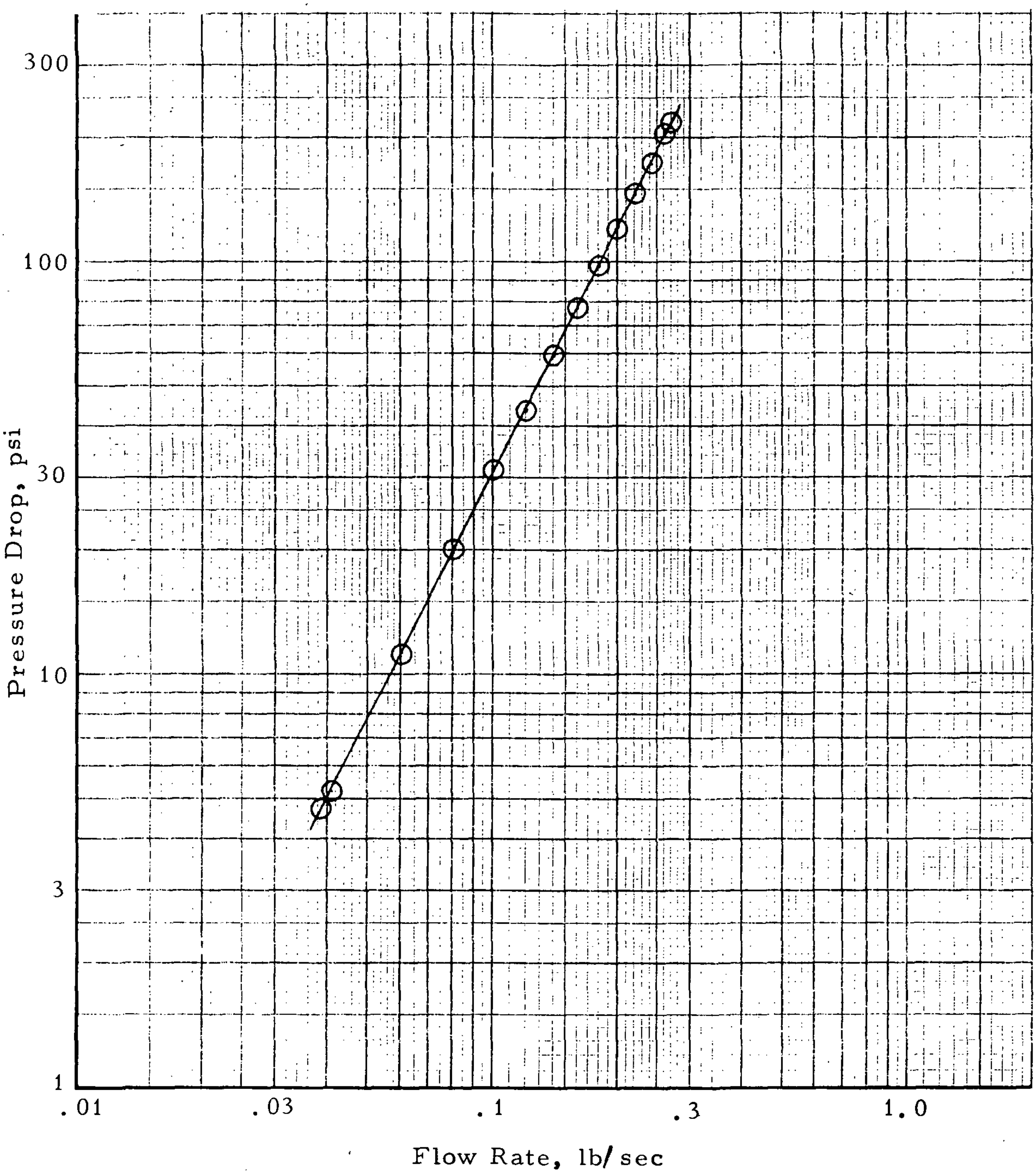


Figure 5-34. Valve-Injector Calibration Data, Injector S/N 208 Valve S/N 0004 (Second Calibration)

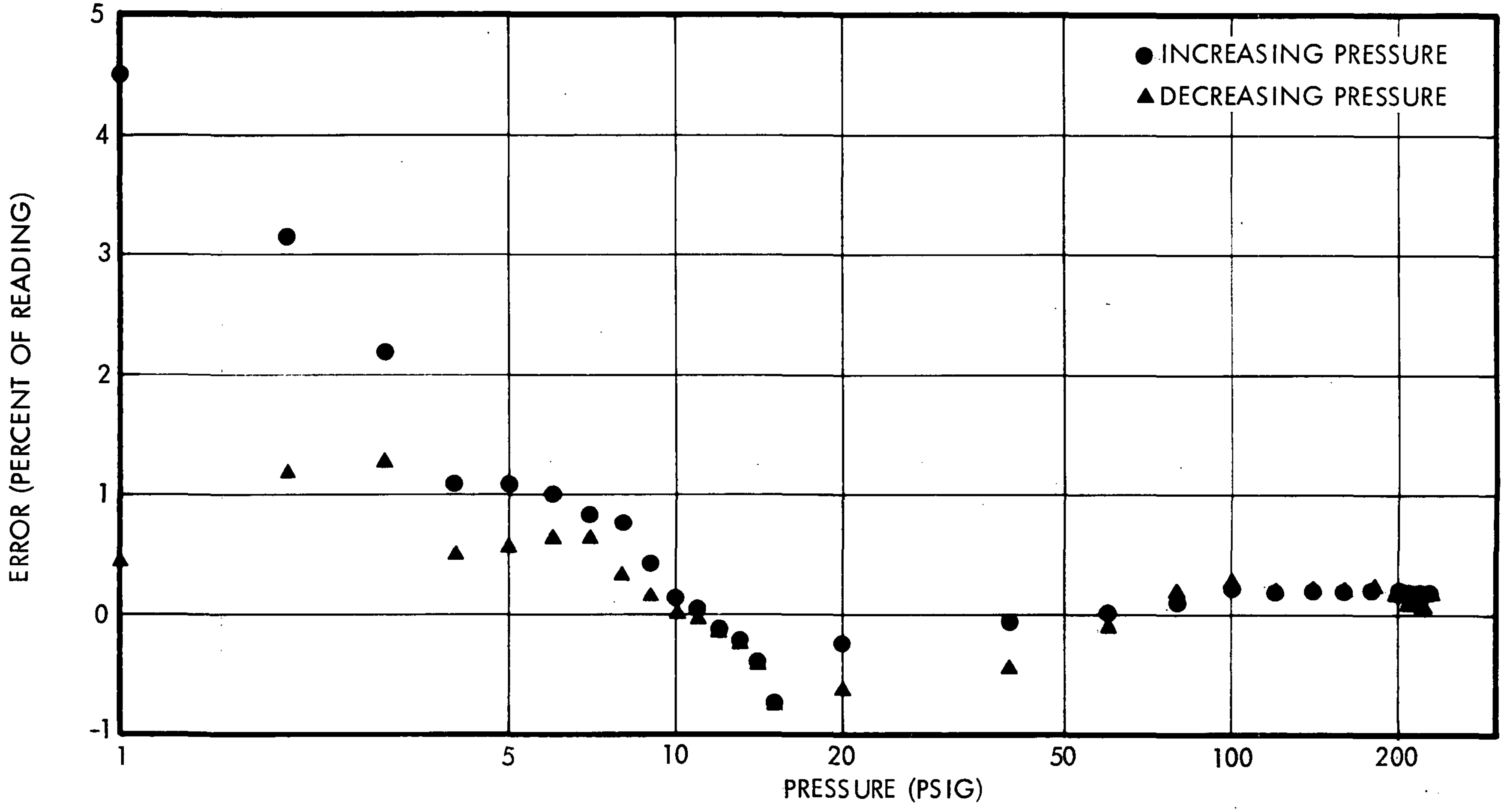


Figure 5-35. Water Flow Bench Pressure Measurement Calibration

5.1.6.2 Flow Measurement

The analysis of water flow measurement was also made on a worst case basis. The components of uncertainty developed as a percent of the lowest flow rate (0.04 lbm/sec) are: flow meter calibration conversion factor (K-Bar) shift, electronic counter accuracy and the effect of temperature variations on the volume to mass conversion factor (K-Bar).

The flowmeters calibrations were conducted at a maximum of 3 month intervals by an independent firm using NBS certified equipment and MIL Standard Procedures. A value of 0.5 percent, which actually represents greater than twice the maximum shift in any point occurring in consecutive three month calibrations, was assigned for this uncertainty source. In general, the shifts observed are less than 0.25 percent for flow rates greater than 35 percent of full range. Since TRW used two flowmeters for flow measurement and neither was used below the 35 percent point the estimate of ± 0.5 percent can be considered conservative.

The uncertainty attributed to the electronic counter has two components. These are (1) time base stability which over the TRW 12 week calibration cycle is 0.0024 percent and (2) a ±1 count error in the display which constitutes an error of ±0.025 percent at the 0.04 lbm/sec flow rate. The sum of these two components, 0.027 percent, represents the total uncertainty attributable to this source.

Finally, the conversion factor for volume to mass units was based on a 70°F water temperature, thereby introducing an error, if the water temperature is allowed to vary over the specification range of ± 5 degrees. This error source, which is simply the difference in water density from 70°F at the two extremes amounts to ± 0.064%.

The sum of the components of uncertainty for each source results in an overall estimate of ± 0.591 percent at the 0.04 lbm/sec flow rate. Since the major contributer to the total (i.e., flowmeter calibration uncertainty) decreases with increasing flow rate the specification requirement for flow measurement is asserted to be satisfied over the entire flowmeter range.

5.2 PROOF AND LEAK TEST

The proof test was conducted on each engine as per Procedure JPL EP-507023 after engine assembly and flange machining. The engine assemblies were subjected to a proof pressure test using GN_2. Pressure test fixture, Part No. 10001238-2, and injector inlet adapter fitting, was installed as shown in Figure 5-36. A pressure of 450 psig was applied and held for 5 minutes then reduced to 0 psig. This cycle was repeated a total of three times for each engine.

The leak test was conducted prior to and after vibration tests as per Procedure JPL EP-507023. The engines were subjected to a leak cycle check using Helium as a pressurizing agent. Pressure test fixture, Part No. 10001238-2 and injector inlet fitting, was installed as shown on Figure 5-36. The leak check was performed for 12 minutes at 300 psig using a helium leak detector, and leakage was to not exceed 10^{-6} scc/sec on the injector to shell interface and the PC tube to shell weld joint. All the engines passed this test.

5.3 VIBRATION TESTS

All flight engines were subjected to the TA vibration requirements and were conducted as per Procedure JPL EP-507025. Each engine was mounted and instrumented as shown in Figure 5-37 and the tests were conducted under ambient conditions.

The first flight engine to be vibrated was S/N 203 and the vibration requirements were as per JPL Spec TS506207A. The specified sinusoidal vibration spectrum and random vibration spectrum for this first engine is shown in Figure 5-38 and 5-39 respectively.

The remaining of the engines were vibrated as per JPL Spec TS506207B. The senusoidal vibration spectrum as per the "B" revision specification is shown in Figure 5-40. Sweep rate was 3 octaves per minute and the frequency sweep was 5 to 2000 Hz and back to 5 Hz. The amplitude levels specified were applied separately to each of the three mutually perpendicular axes, one of which lies along the longitudinal axis of the engine. The random vibration spectrum is shown in Figure 5-41. The vibration was applied to the three mutually perpendicular axis one of which lies on the longitudinal axis of the engine. Duration of the test was 20 seconds per axis.

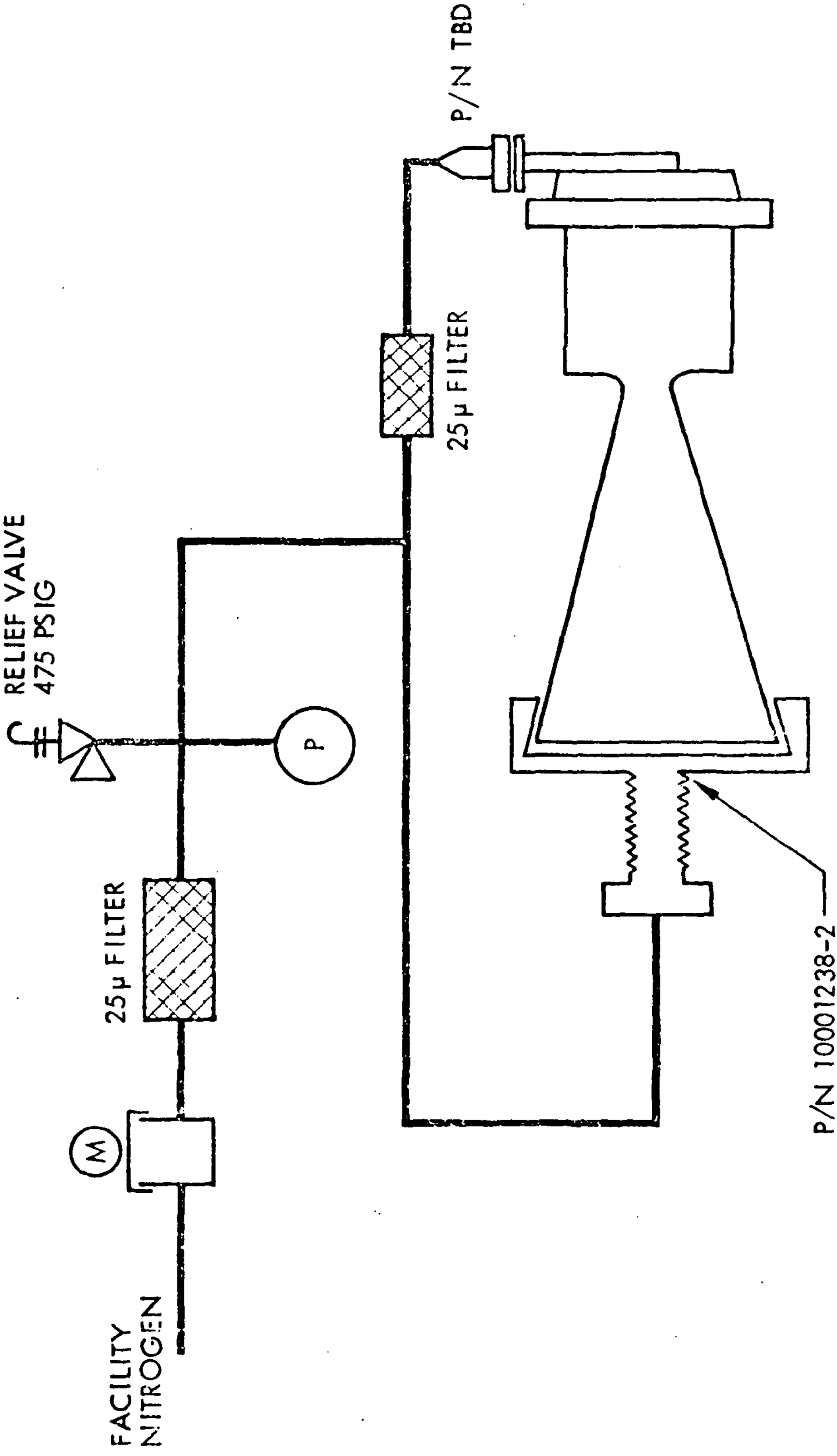


Figure 5-36. Engine Proof and Leak Test

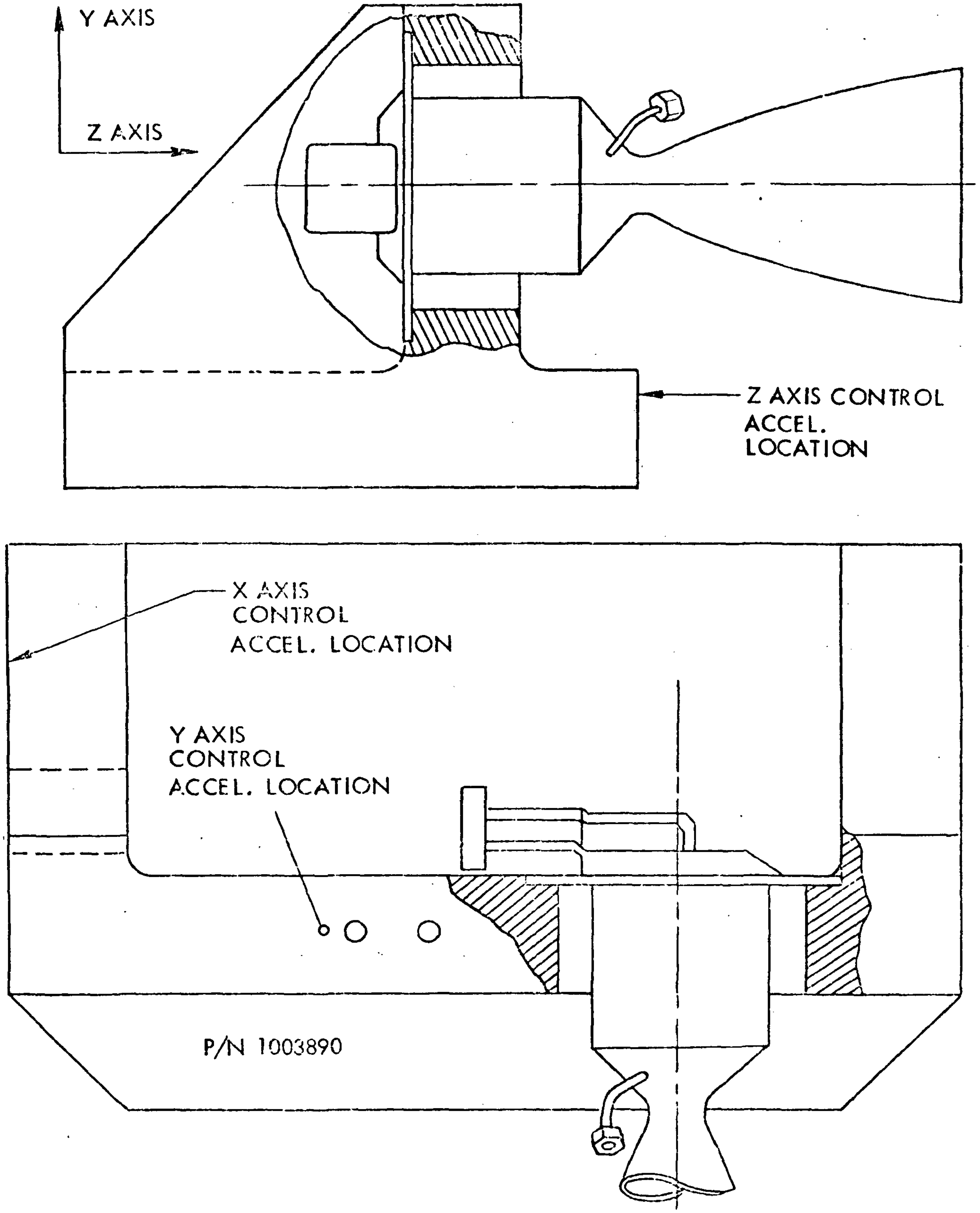


Figure 5-37. Axis Designation and Test Configuration

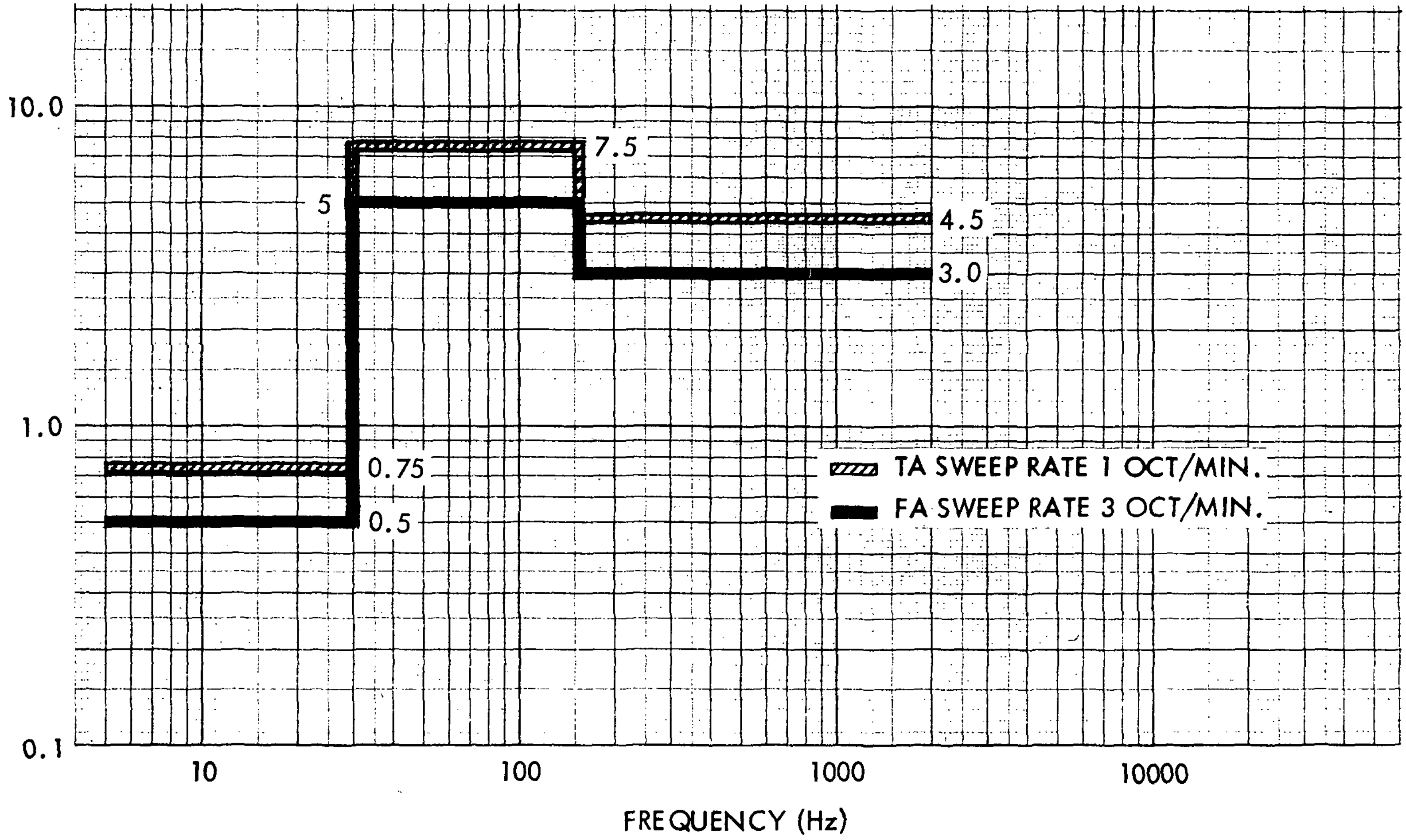


Figure 5-38. Sinusoidal Vibration Spectrum

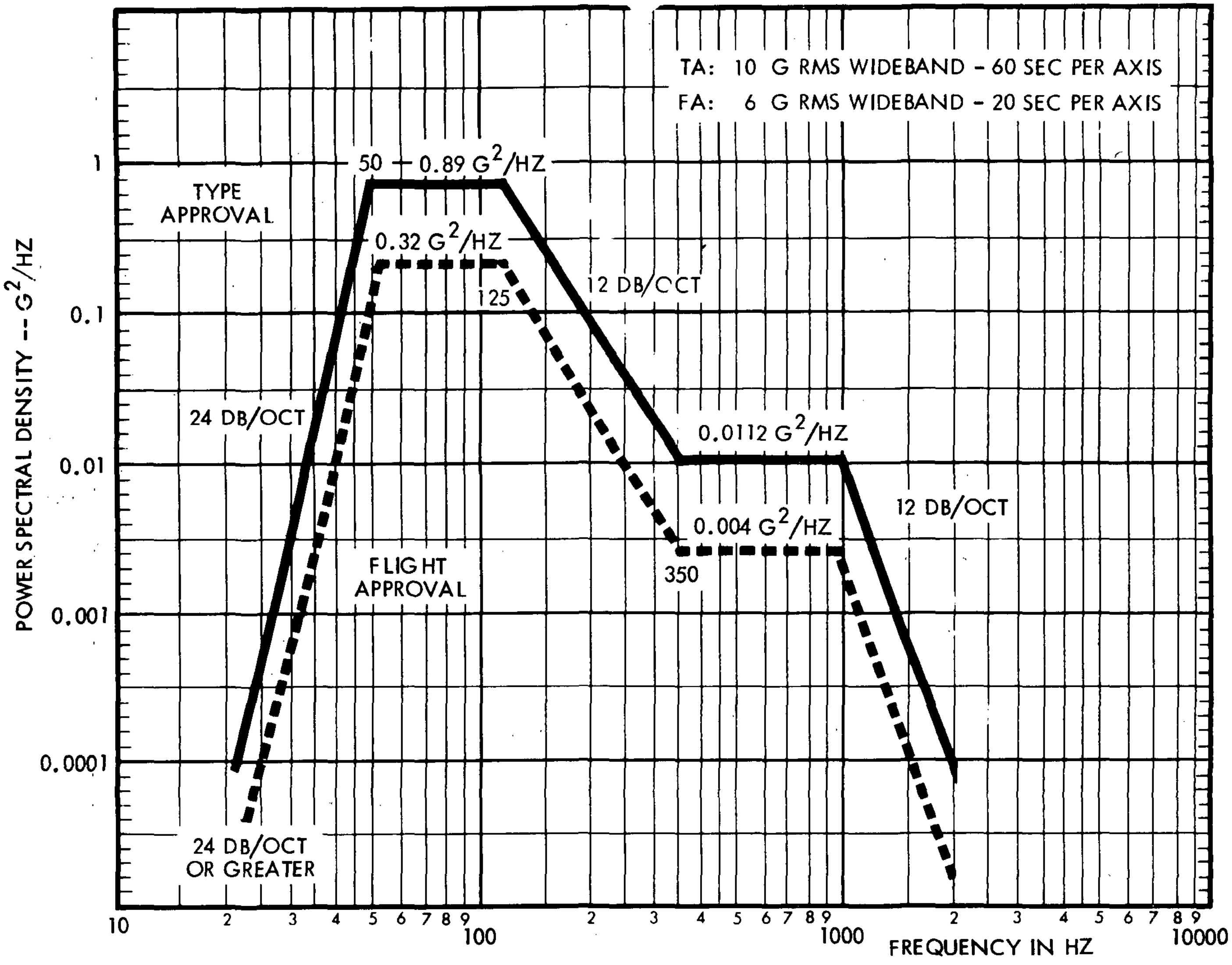


Figure 5-39. Random Vibration Spectrum

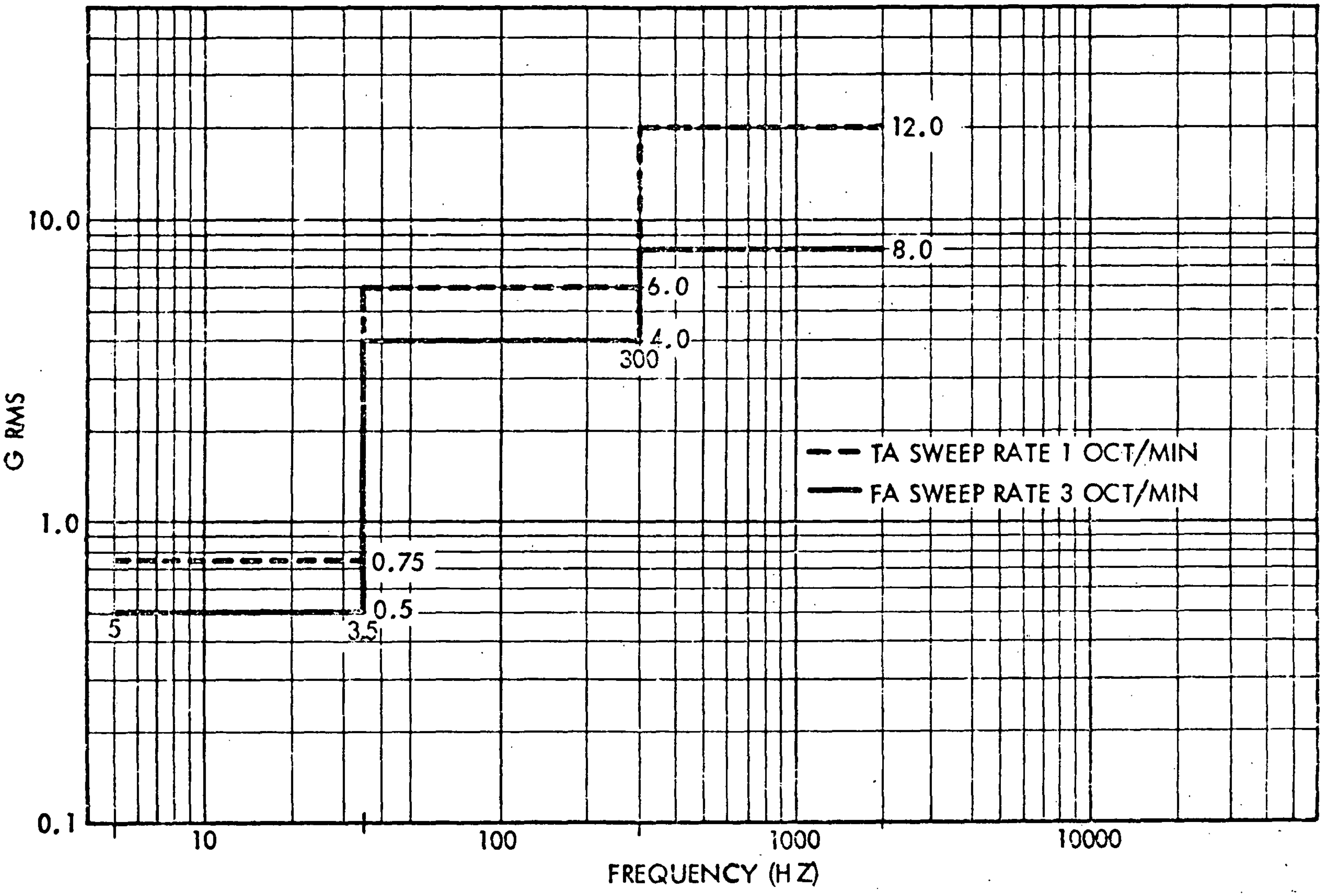
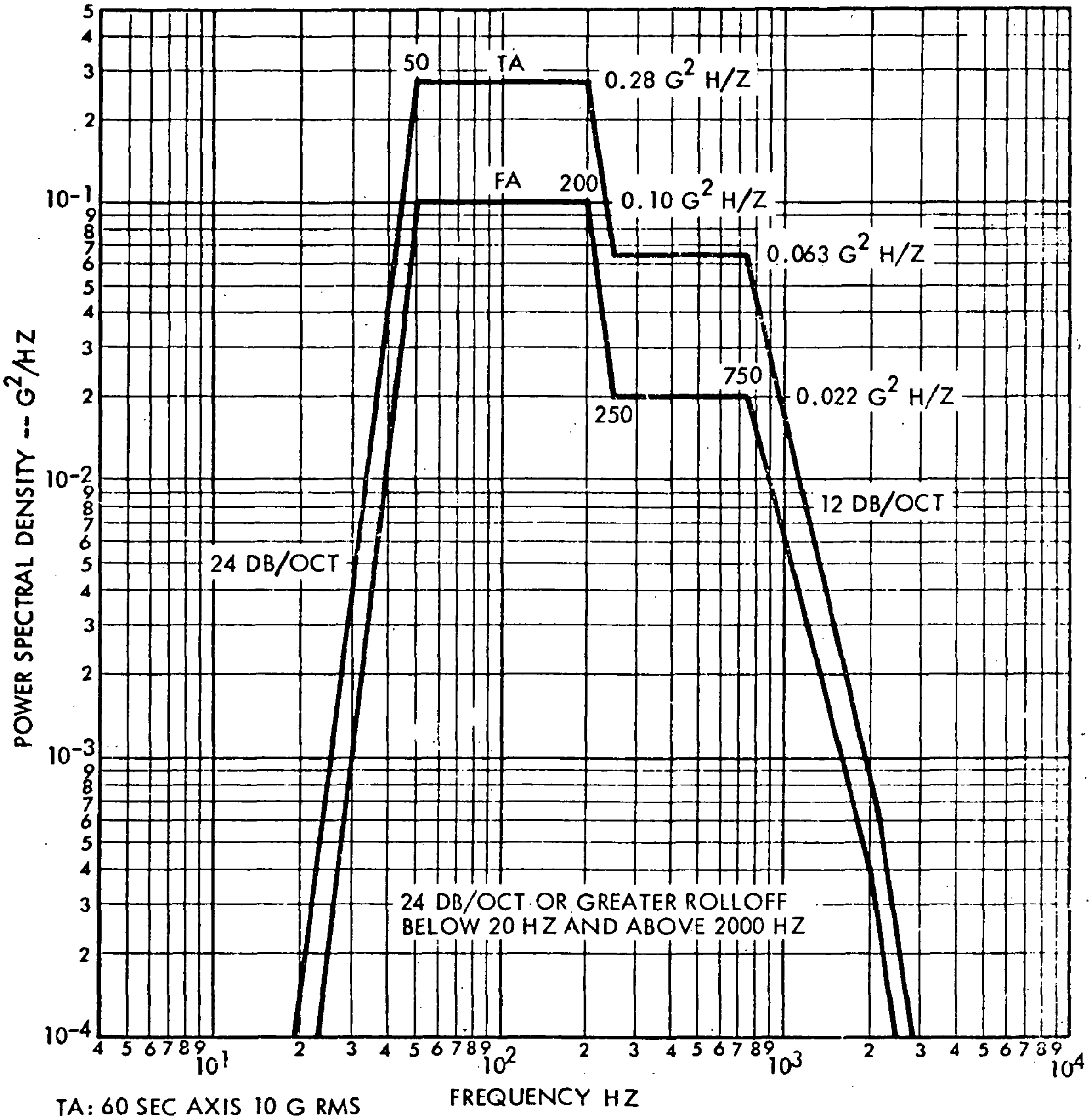


Figure 5-40. Sinusoidal Vibration Spectrum



TA: 60 SEC AXIS 10 G RMS
FA: 20 SEC AXIS 6 G RMS

Figure 5-41. Random Vibration Spectrum

A photograph of an engine mounted in the vibration fixture is shown in Figure 5-42.

The sinusoidal and random vibration data plots for the various flight approval engines are shown in the following figures:

Engine S/N 203	Figures 5-43 through 5-67
Engine S/N 201	Figures 5-68 through 5-74
Engine S/N 204	Figures 5-75 through 5-83
Engine S/N 205	Figures 5-84 through 5-92
Engine S/N 206	Figures 5-93 through 5-101
Engine S/N 207	Figures 5-102 through 5-110

All above tests were performed in Building M-1 Environmental Laboratory of TRW Systems Group between May and August of 1972.

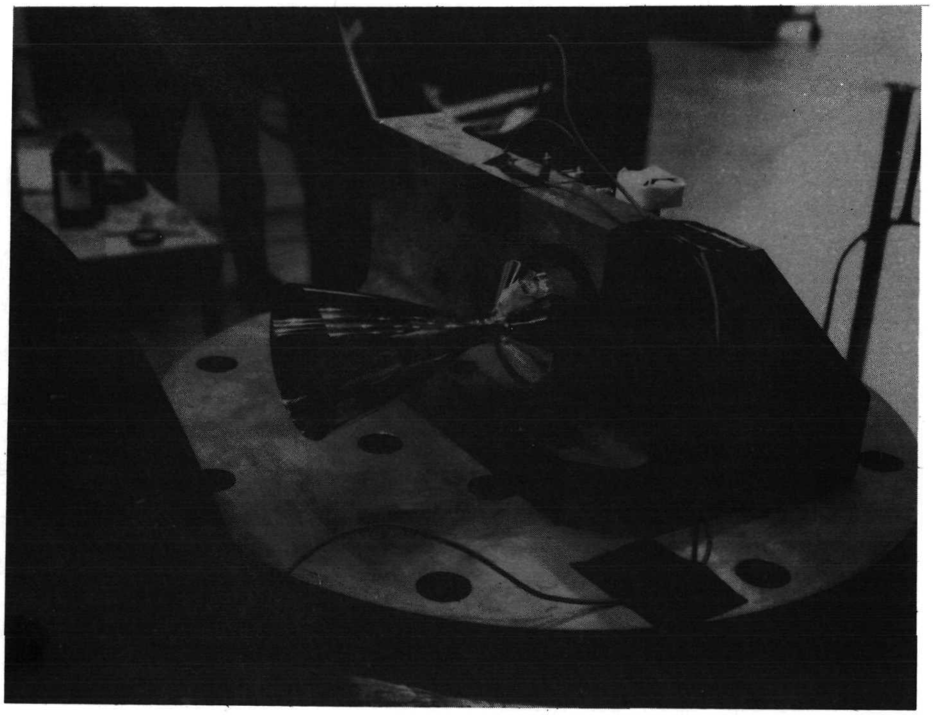
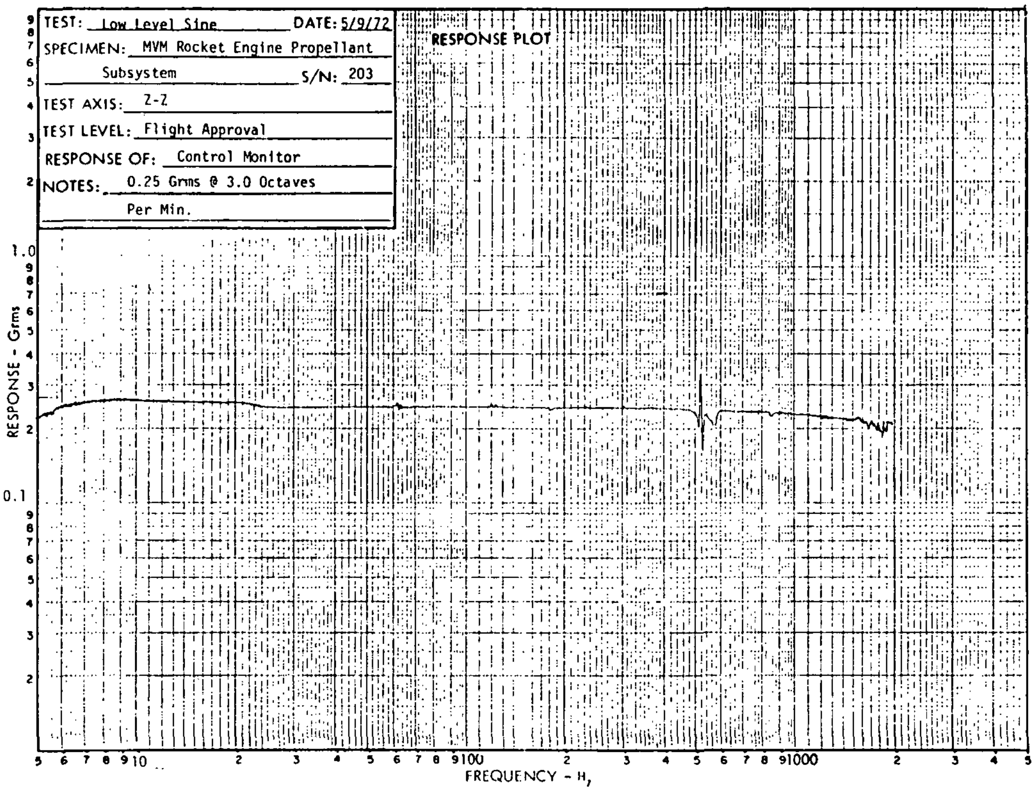


Figure 5-42. Engine S/N 203 Mounted in Vibration Fixture



TEST: Low Level Sine DATE: 5/9/72

SPECIMEN: MVM Rocket Engine Propellant Subsystem S/N: 203

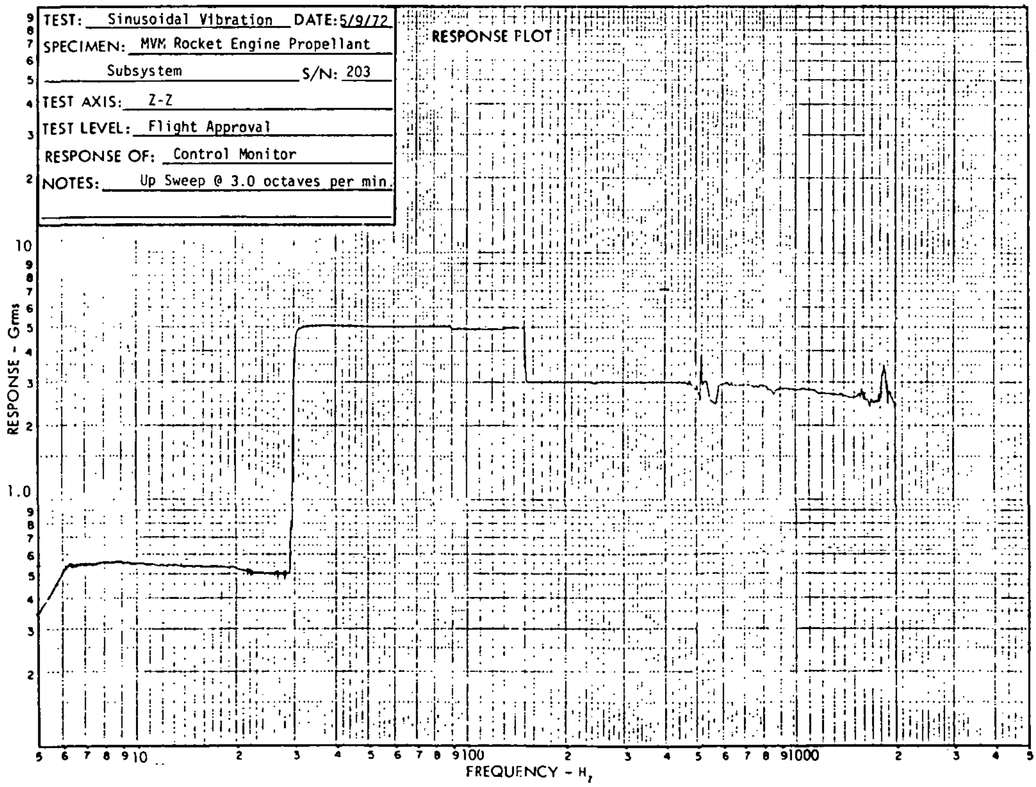
TEST AXIS: Z-Z

TEST LEVEL: Flight Approval

RESPONSE OF: Control Monitor

NOTES: 0.25 Grms @ 3.0 Octaves Per Min.

Figure 5-43



TEST: Sinusoidal Vibration DATE: 5/9/72

SPECIMEN: MVM Rocket Engine Propellant Subsystem S/N: 203

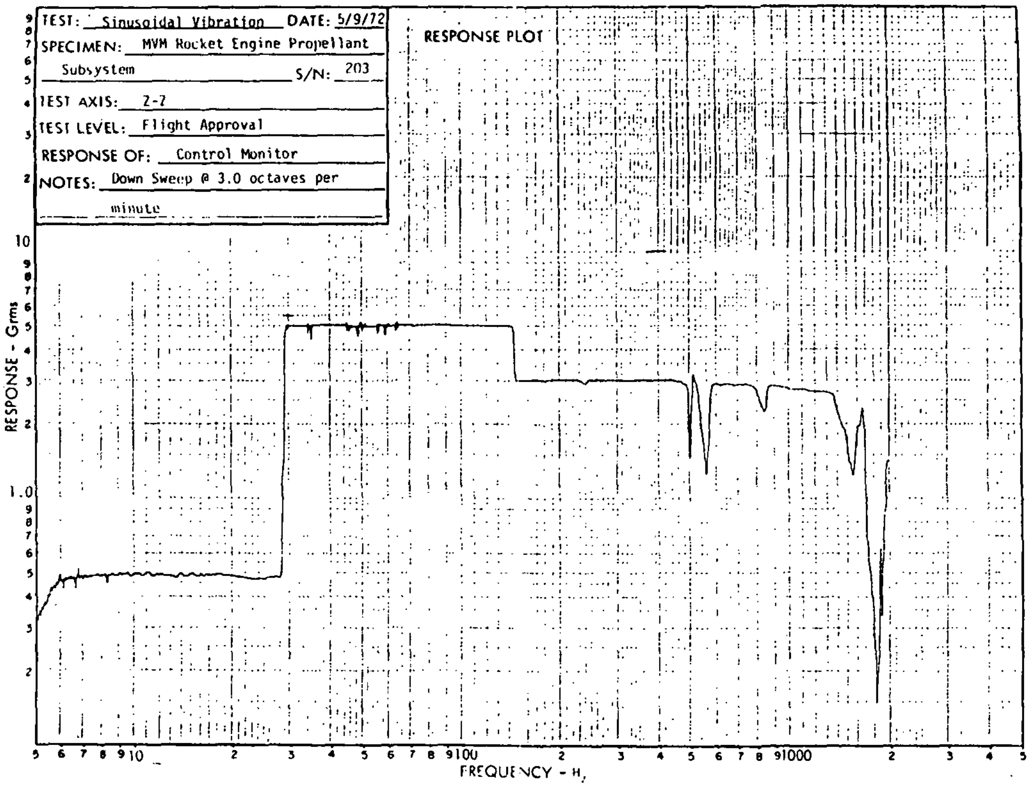
TEST AXIS: Z-Z

TEST LEVEL: Flight Approval

RESPONSE OF: Control Monitor

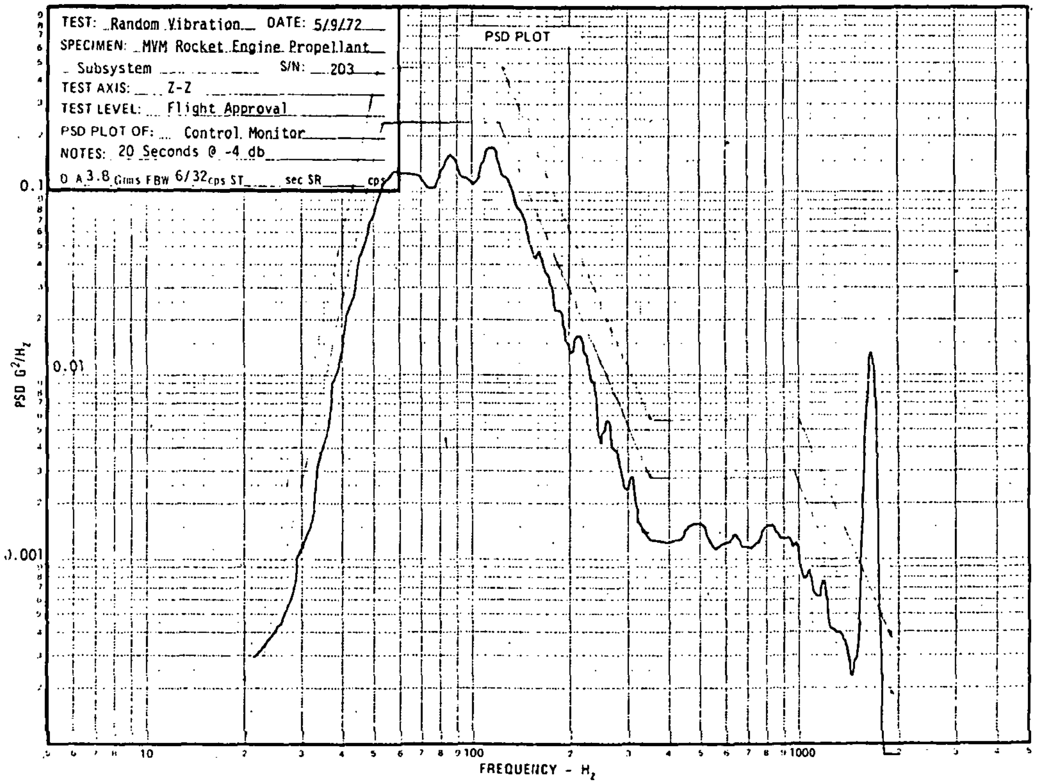
NOTES: Up Sweep @ 3.0 octaves per min.

Figure 5-44



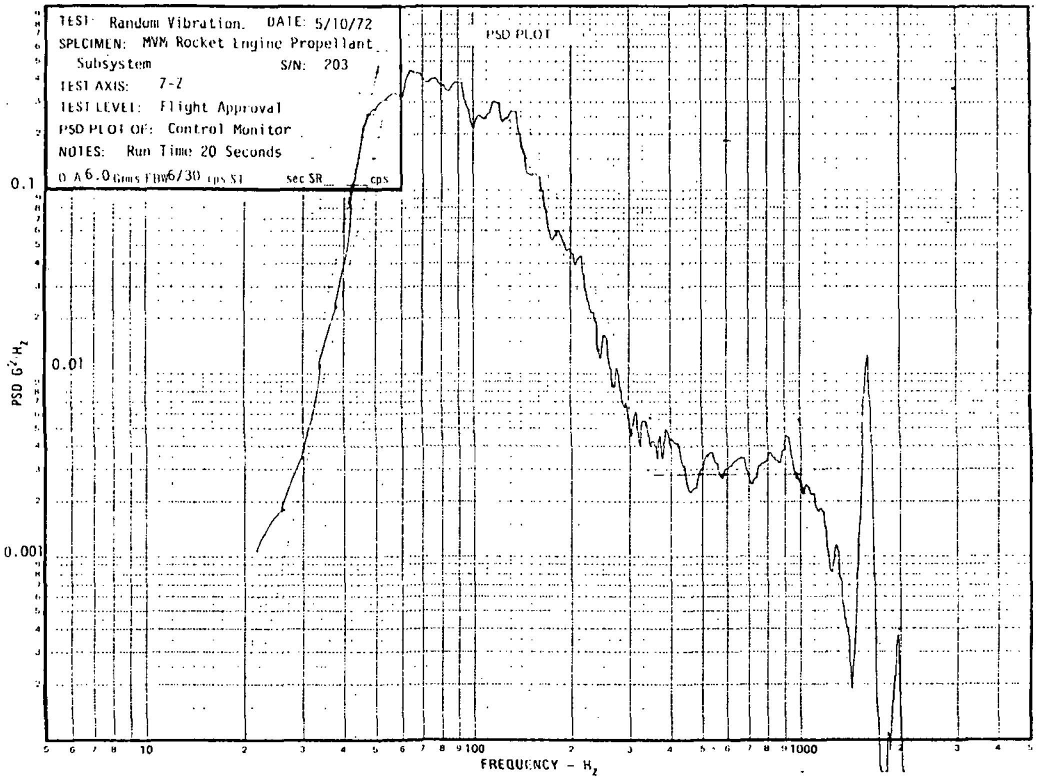
TEST: Sinusoidal Vibration DATE: 5/9/72
SPECIMEN: MVM Rocket Engine Propellant Subsystem S/N: 203
TEST AXIS: Z-Z
TEST LEVEL: Flight Approval
RESPONSE OF: Control Monitor
NOTES: Down Sweep @ 3.0 octaves per minute

Figure 5-45



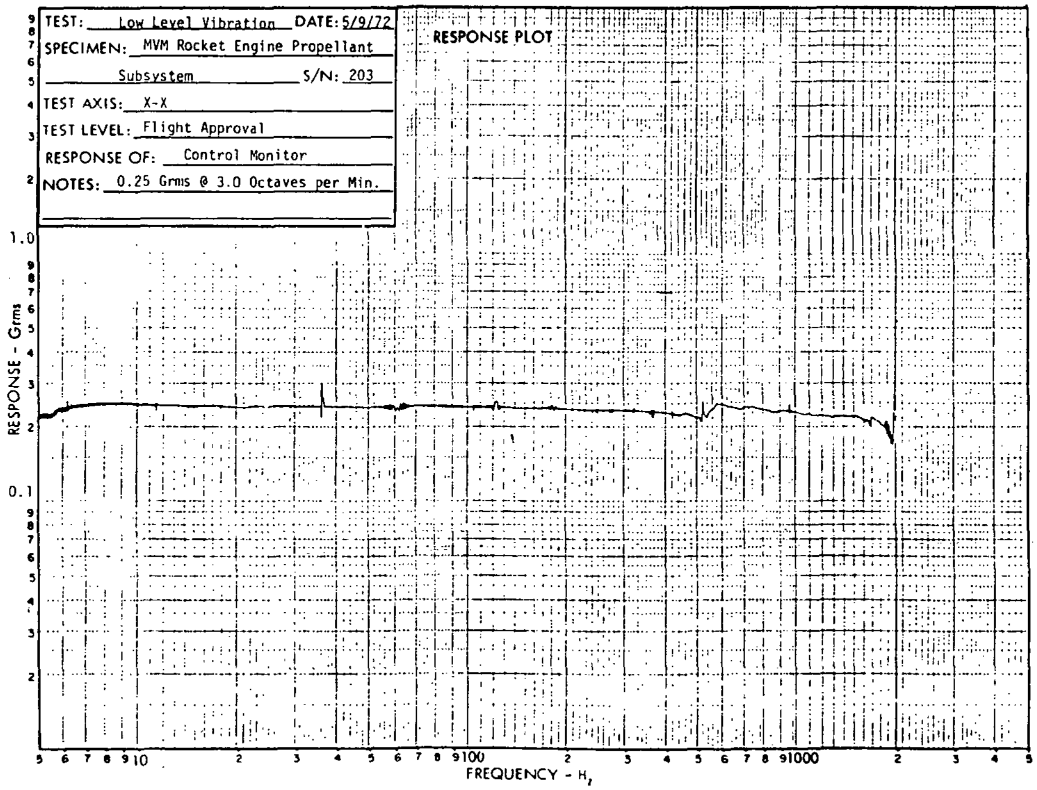
TEST: Random Vibration DATE: 5/9/72
SPECIMEN: MVM Rocket Engine Propellant Subsystem S/N: 203
TEST AXIS: Z-Z
TEST LEVEL: Flight Approval
PSD PLOT OF: Control Monitor
NOTES: 20 Seconds @ -4 db
O A 3.8 Grms FBW 6/32 cps ST____ sec SR____ cps

Figure 5-46



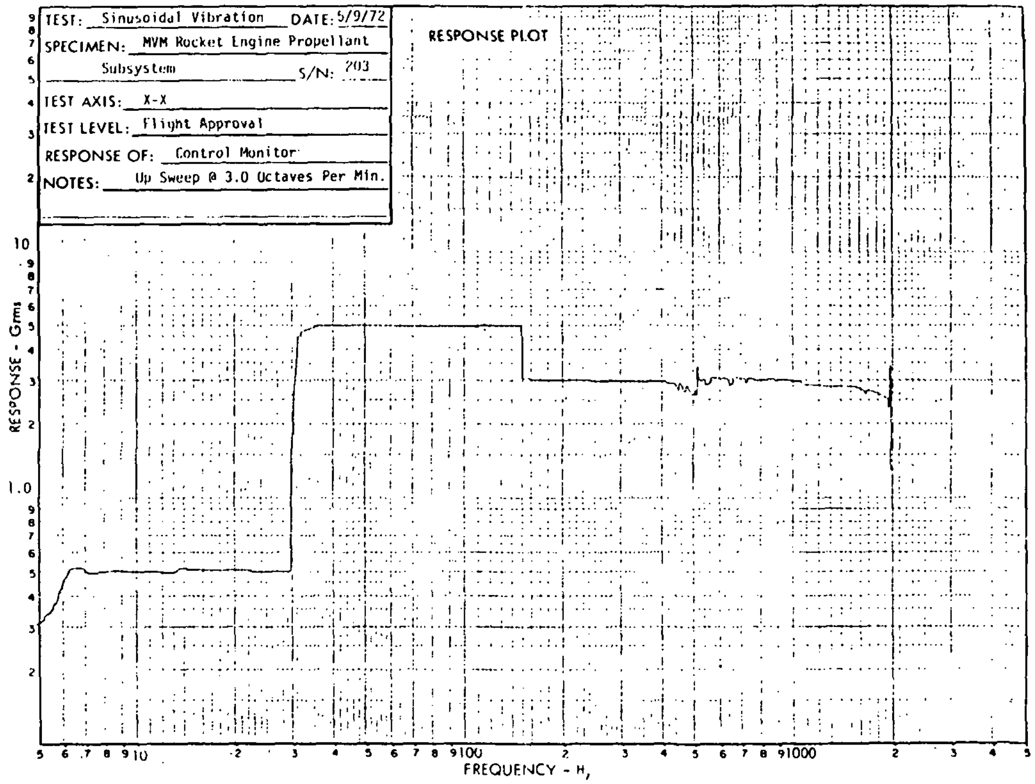
TEST: Random Vibration. DATE: 5/10/72
SPECIMEN: MVM Rocket Engine Propellant
Subsystem S/N: 203
TEST AXIS: Z-Z
TEST LEVEL: Flight Approval
PSD PLOT OF: Control Monitor
NOTES: Run Time 20 Seconds
O A 6.0 Grms FBW 6/30 cps ST sec SR cps

Figure 5-47



TEST: Low Level Vibration DATE: 5/9/72
SPECIMEN: MVM Rocket Engine Propellant
Subsystem S/N: 203
TEST AXIS: X-X
TEST LEVEL: Flight Approval
RESPONSE OF: Control Monitor
NOTES: 0.25 Grms @ 3.0 Octaves per Min.

Figure 5-48


TEST: Sinusoidal Vibration DATE: 5/9/72

SPECIMEN: MVM Rocket Engine Propellant Subsystem S/N: 203

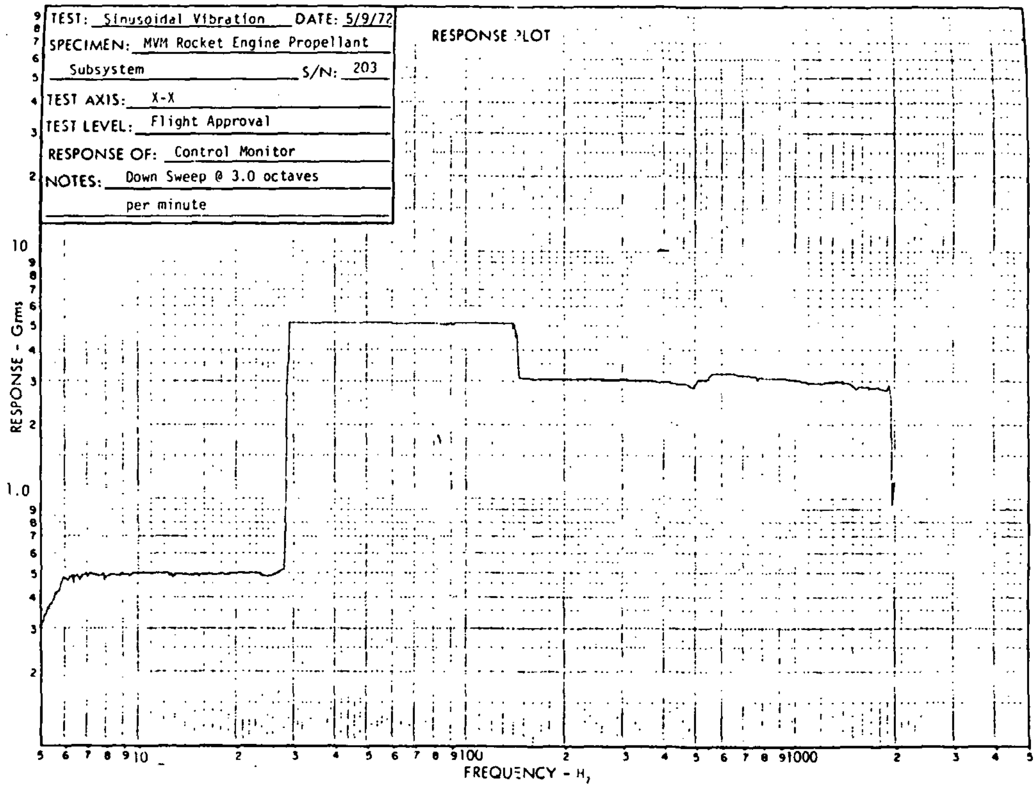
TEST AXIS: X-X

TEST LEVEL: Flight Approval

RESPONSE OF: Control Monitor

NOTES: Up Sweep @ 3.0 Octaves Per Min.

Figure 5-49


TEST: Sinusoidal Vibration DATE: 5/9/72

SPECIMEN: MVM Rocket Engine Propellant Subsystem S/N: 203

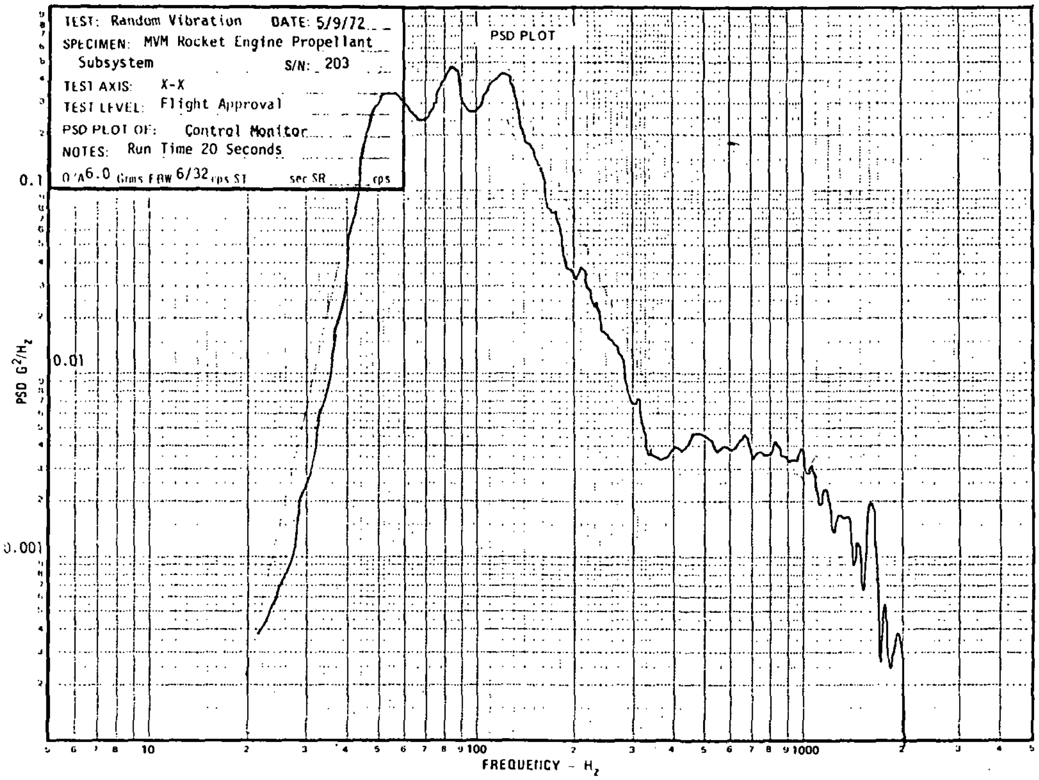
TEST AXIS: X-X

TEST LEVEL: Flight Approval

RESPONSE OF: Control Monitor

NOTES: Down Sweep @ 3.0 octaves per minute

Figure 5-50



TEST: Random Vibration DATE: 5/9/72

SPECIMEN: MVM Rocket Engine Propellant Subsystem S/N: 203

TEST AXIS: X-X

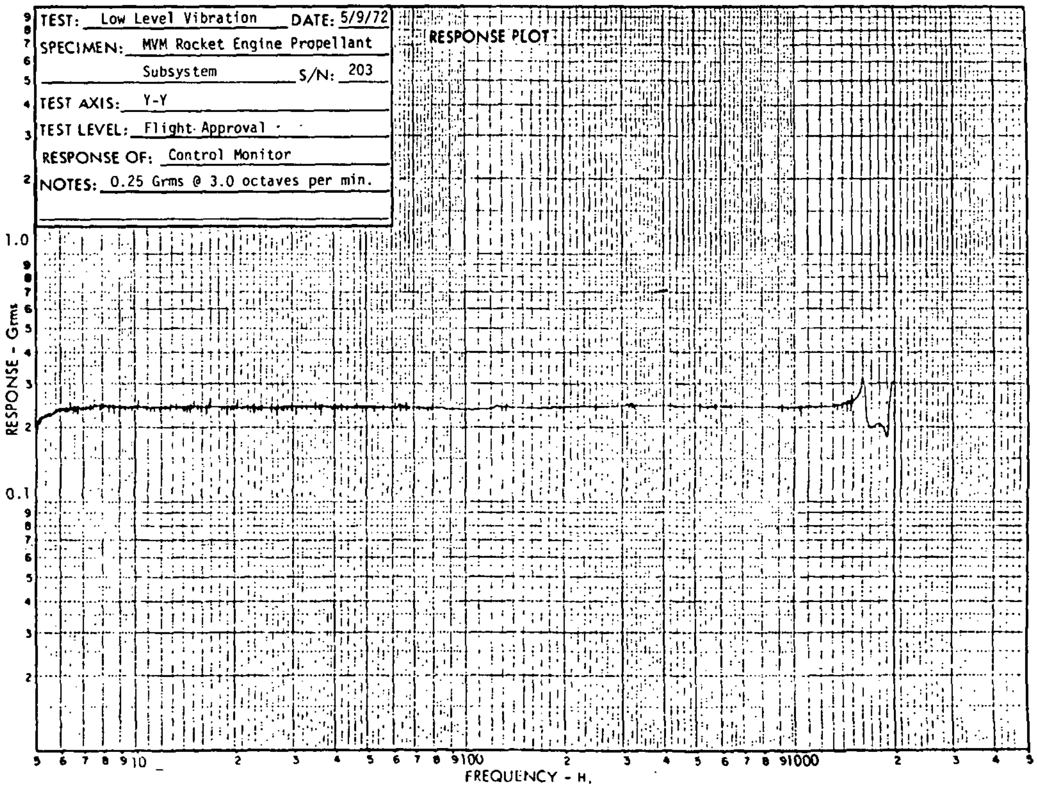
TEST LEVEL: Flight Approval

PSD PLOT OF: Control Monitor

NOTES: Run Time 20 Seconds

O/A 6.0 Grms EBW 6/32 cps ST sec SR cps

Figure 5-51



TEST: Low Level Vibration DATE: 5/9/72

SPECIMEN: MVM Rocket Engine Propellant Subsystem S/N: 203

TEST AXIS: Y-Y

TEST LEVEL: Flight Approval

RESPONSE OF: Control Monitor

NOTES: 0.25 Grms @ 3.0 octaves per min.

Figure 5-52

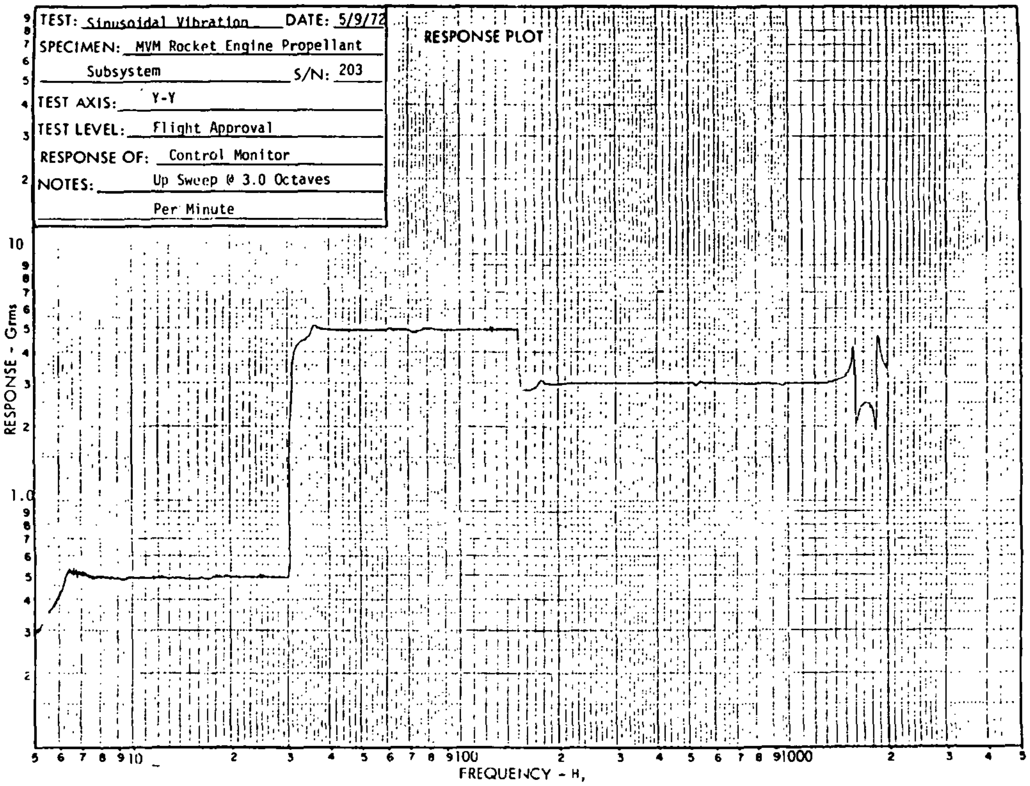

TEST: Sinusoidal Vibration DATE: 5/9/72
SPECIMEN: MVM Rocket Engine Propellant Subsystem S/N: 203
TEST AXIS: Y-Y
TEST LEVEL: Flight Approval
RESPONSE OF: Control Monitor
NOTES: Up Sweep @ 3.0 Octaves Per Minute

Figure 5-53

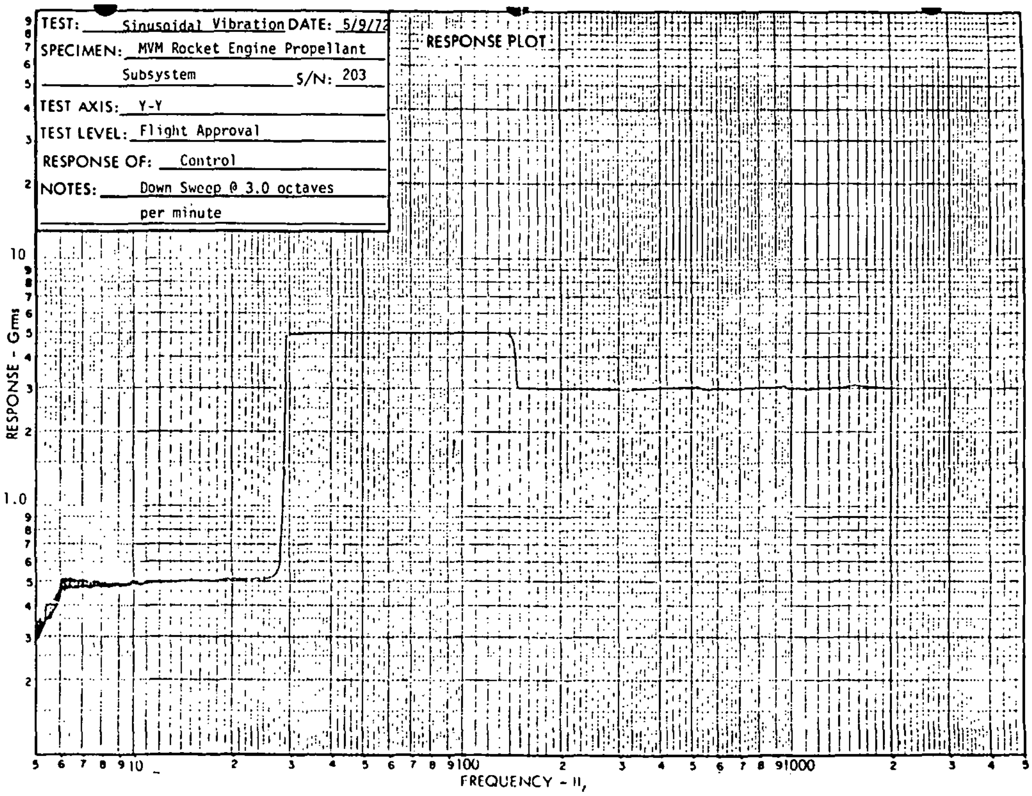

TEST: Sinusoidal Vibration DATE: 5/9/72
SPECIMEN: MVM Rocket Engine Propellant Subsystem S/N: 203
TEST AXIS: Y-Y
TEST LEVEL: Flight Approval
RESPONSE OF: Control
NOTES: Down Sweep @ 3.0 octaves per minute

Figure 5-54

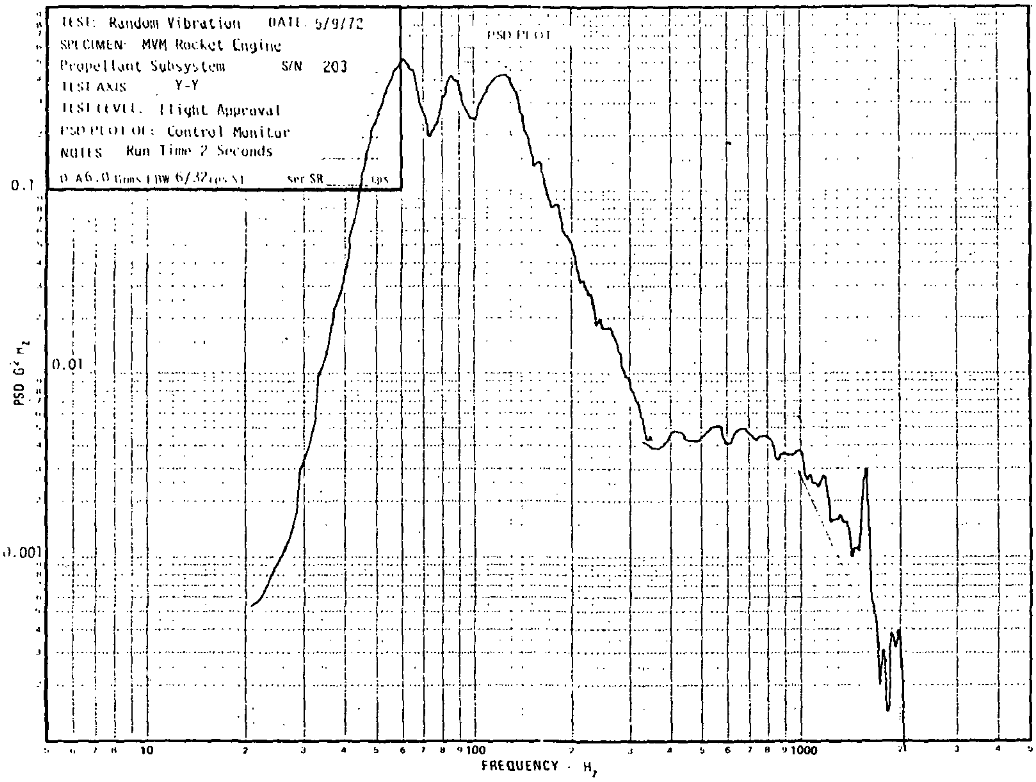

TEST: Random Vibration DATE: 5/9/72
SPECIMEN: MVM Rocket Engine
Propellant Subsystem S/N 203
TEST AXIS Y-Y
TEST LEVEL: Flight Approval
PSD PLOT OF: Control Monitor
NOTES Run Time 2 Seconds
0 A 6.0 Grms EBW 6/32 cps SI sec SR ____ cps

Figure 5-55

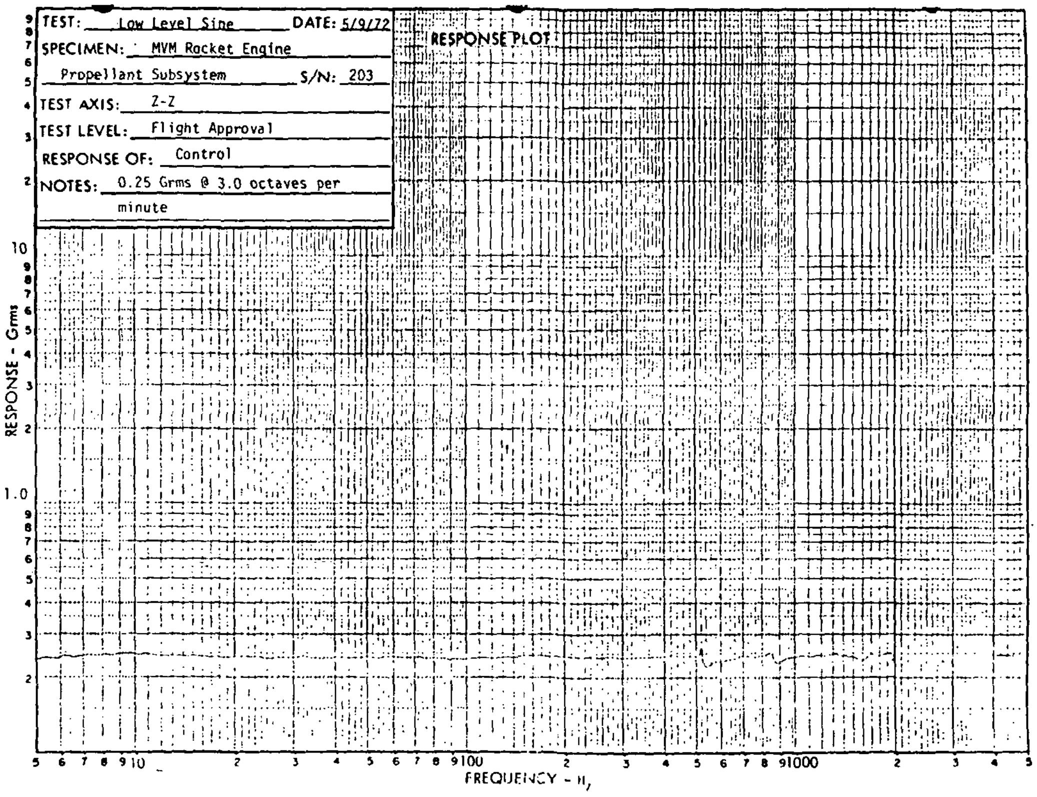
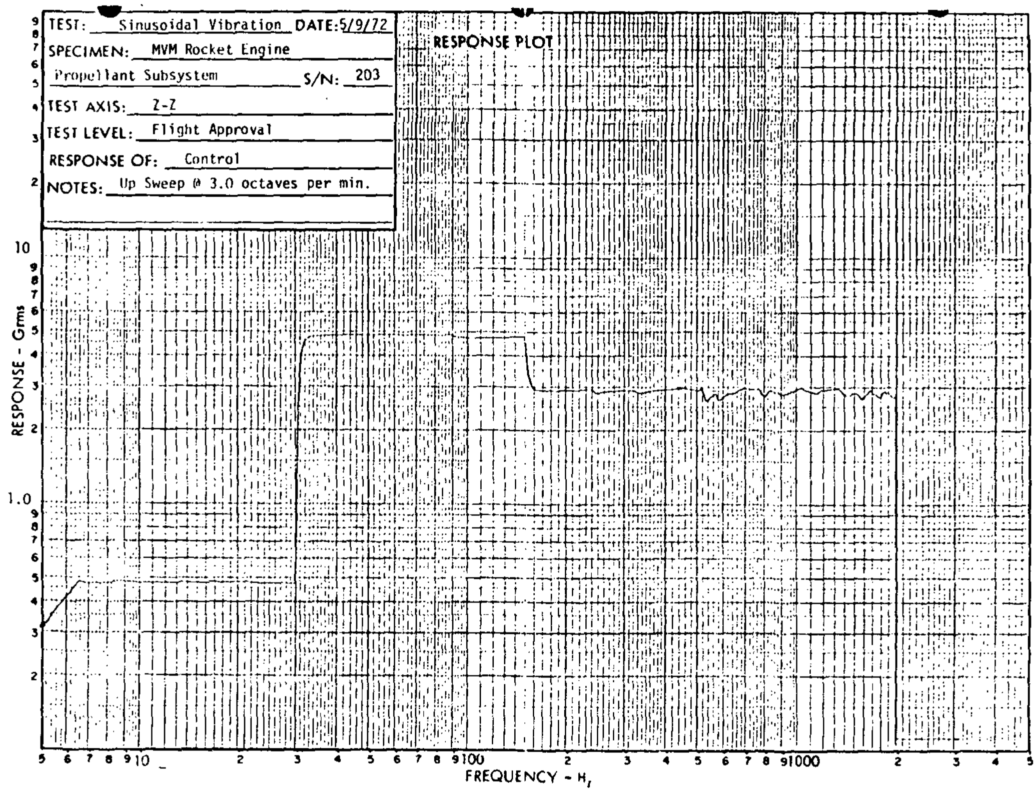

TEST: Low Level Sine DATE: 5/9/72
SPECIMEN: MVM Rocket Engine
Propellant Subsystem S/N: 203
TEST AXIS: Z-Z
TEST LEVEL: Flight Approval
RESPONSE OF: Control
NOTES: 0.25 Grms @ 3.0 octaves per minute

Figure 5-56



TEST: Sinusoidal Vibration DATE: 5/9/72

SPECIMEN: MVM Rocket Engine Propellant Subsystem S/N: 203

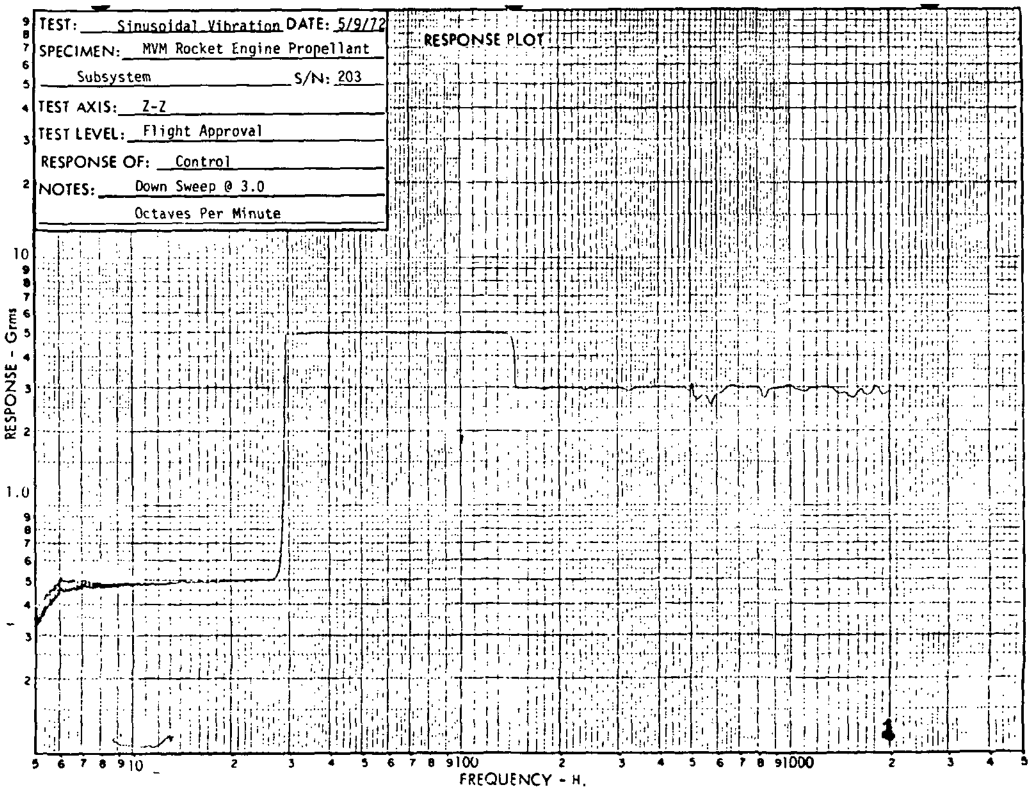
TEST AXIS: Z-Z

TEST LEVEL: Flight Approval

RESPONSE OF: Control

NOTES: Up Sweep @ 3.0 octaves per min.

Figure 5-57



TEST: Sinusoidal Vibration DATE: 5/9/72

SPECIMEN: MVM Rocket Engine Propellant Subsystem S/N: 203

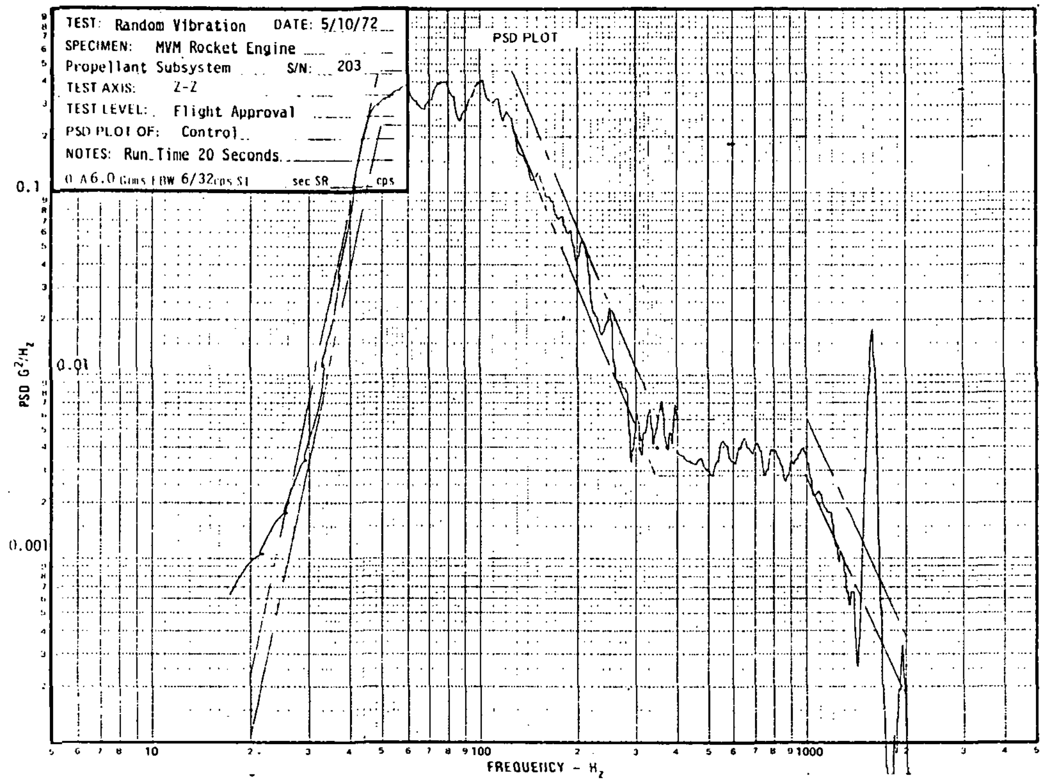
TEST AXIS: Z-Z

TEST LEVEL: Flight Approval

RESPONSE OF: Control

NOTES: Down Sweep @ 3.0 Octaves Per Minute

Figure 5-58



TEST: Random Vibration DATE: 5/10/72

SPECIMEN: MVM Rocket Engine

Propellant Subsystem S/N: 203

TEST AXIS: Z-Z

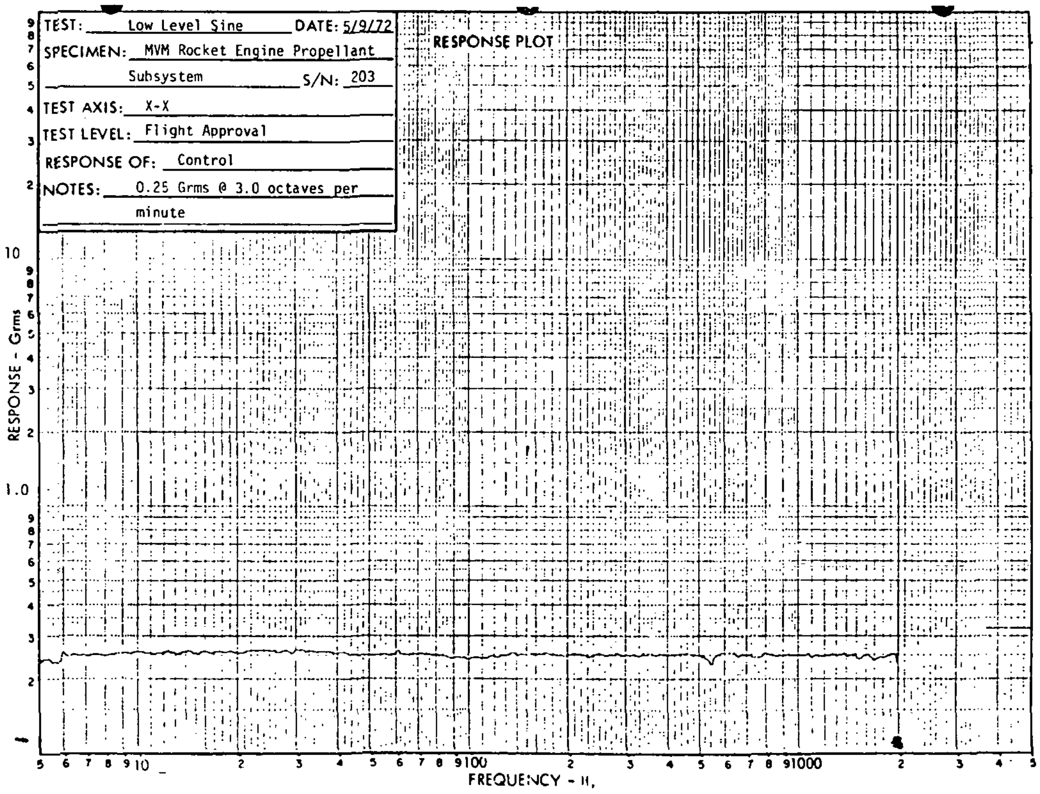
TEST LEVEL: Flight Approval

PSD PLOT OF: Control

NOTES: Run Time 20 Seconds

0 A 6.0 Grms FBW 6/32cps ST sec SR cps

Figure 5-59



TEST: Low Level Sine DATE: 5/9/72

SPECIMEN: MVM Rocket Engine Propellant Subsystem S/N: 203

TEST AXIS: X-X

TEST LEVEL: Flight Approval

RESPONSE OF: Control

NOTES: 0.25 Grms @ 3.0 octaves per minute

Figure 5-60

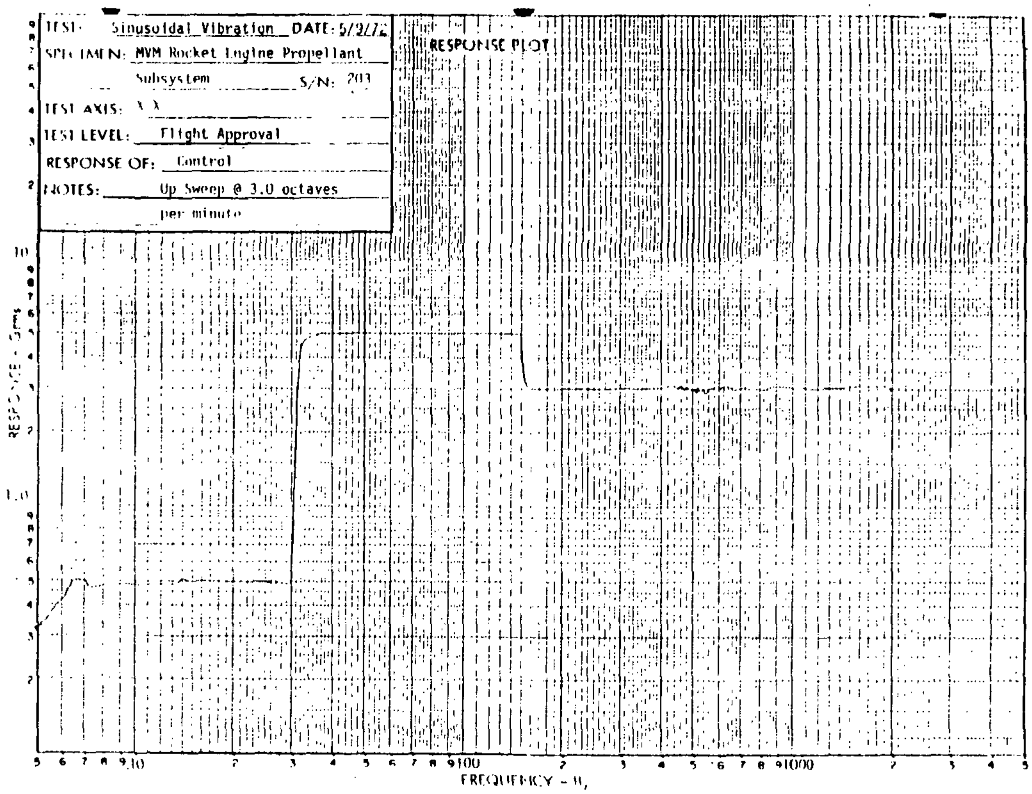

TEST: Sinusoidal Vibration DATE: 5/9/72
SPECIMEN: MVM Rocket Engine Propellant Subsystem S/N: 203
TEST AXIS: X-X
TEST LEVEL: Flight Approval
RESPONSE OF: Control
NOTES: Up Sweep @ 3.0 octaves per minute

Figure 5-61

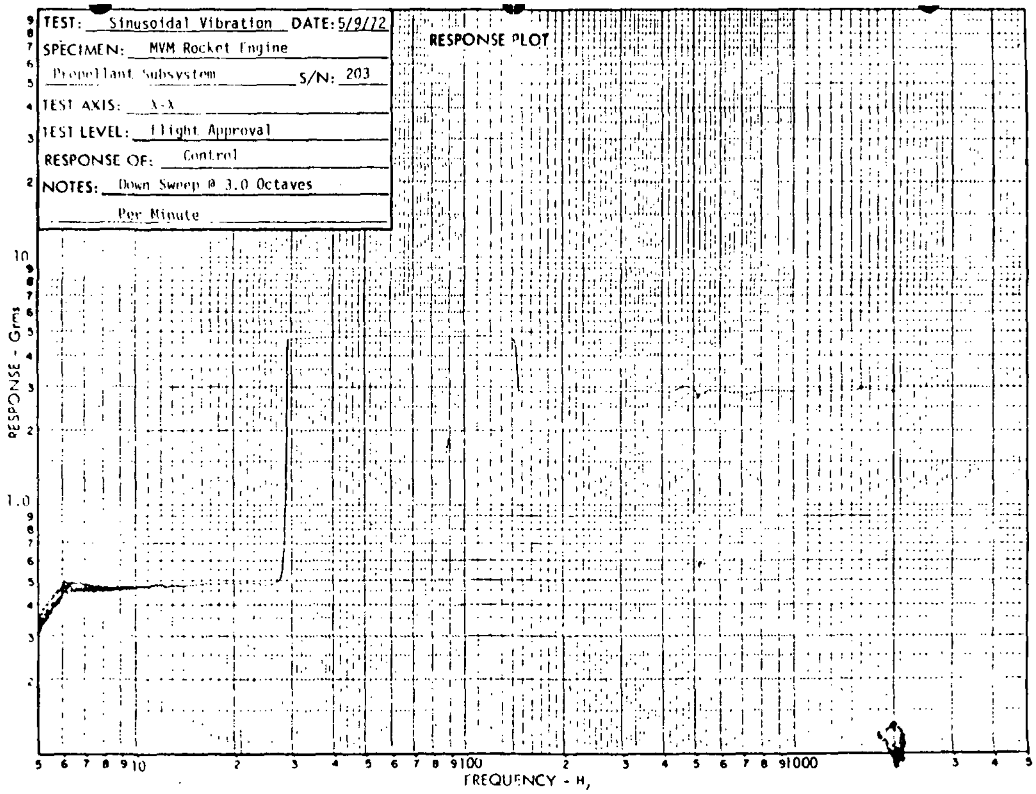

TEST: Sinusoidal Vibration DATE: 5/9/72
SPECIMEN: MVM Rocket Engine Propellant Subsystem S/N: 203
TEST AXIS: X-X
TEST LEVEL: Flight Approval
RESPONSE OF: Control
NOTES: Down Sweep @ 3.0 Octaves Per Minute

Figure 5-62

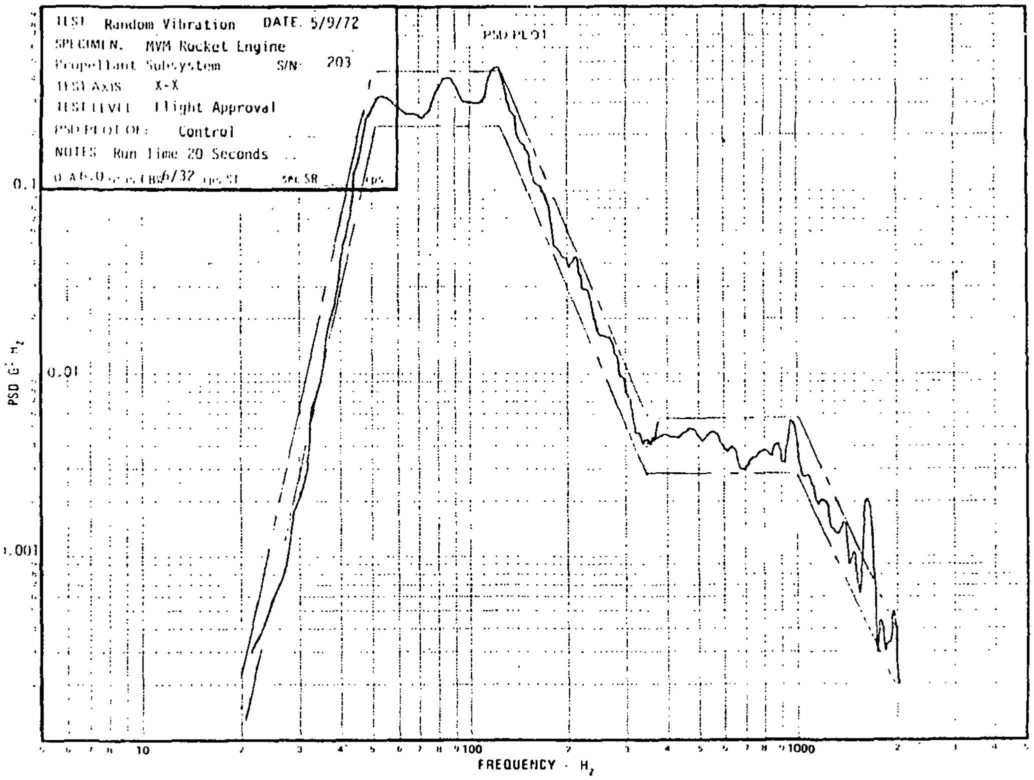

TEST Random Vibration DATE 5/9/72
SPECIMEN. MVM Rocket Engine
Propellant Subsystem S/N 203
TEST AXIS X-X
TEST LEVEL Flight Approval
PSD PLOT OF: Control
NOTES Run Time 20 Seconds
DAB 0 EBW 6/32 cps ST sec SR cps

Figure 5-63

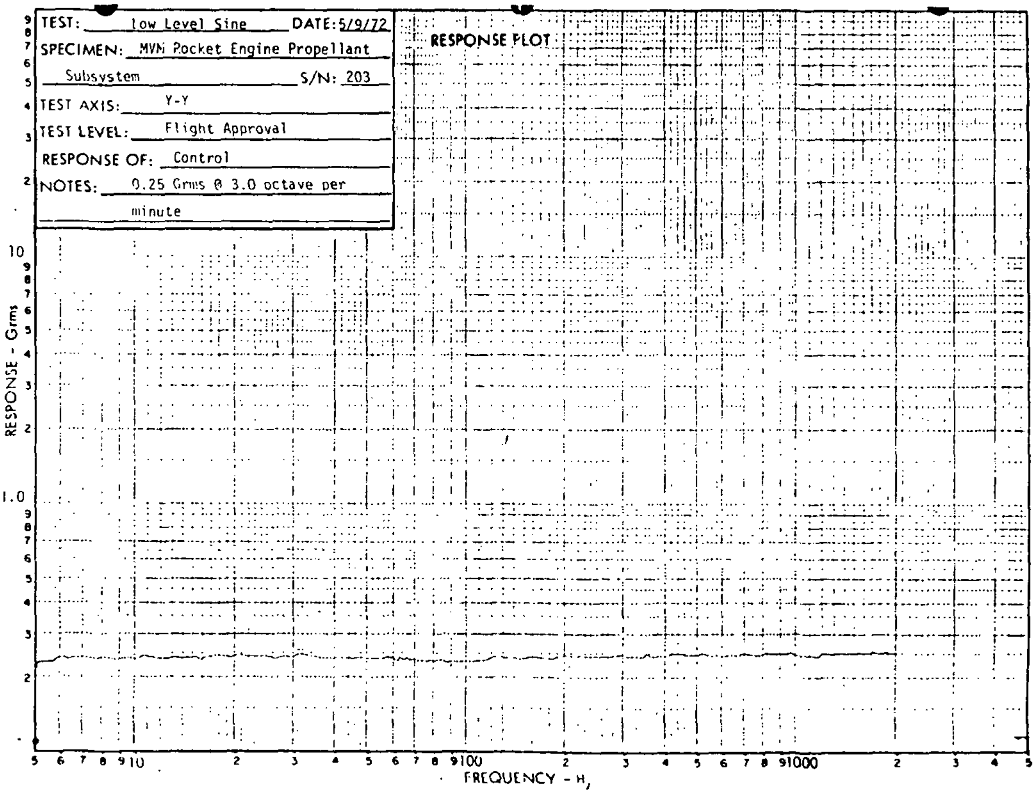
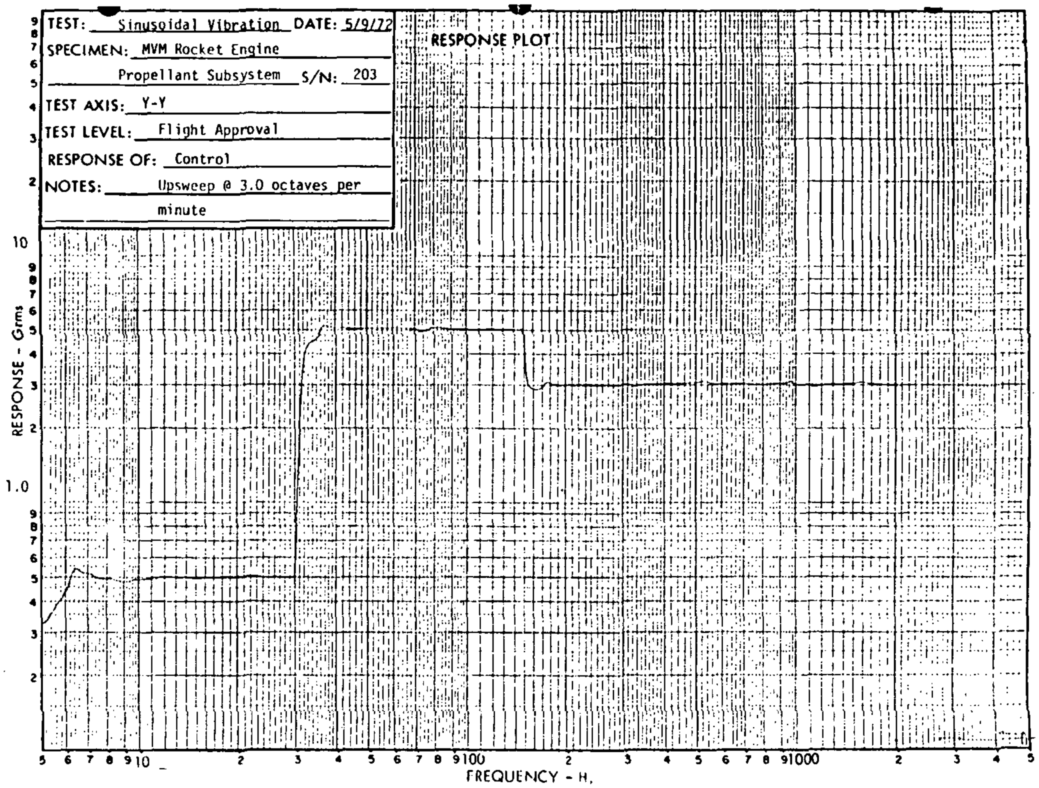
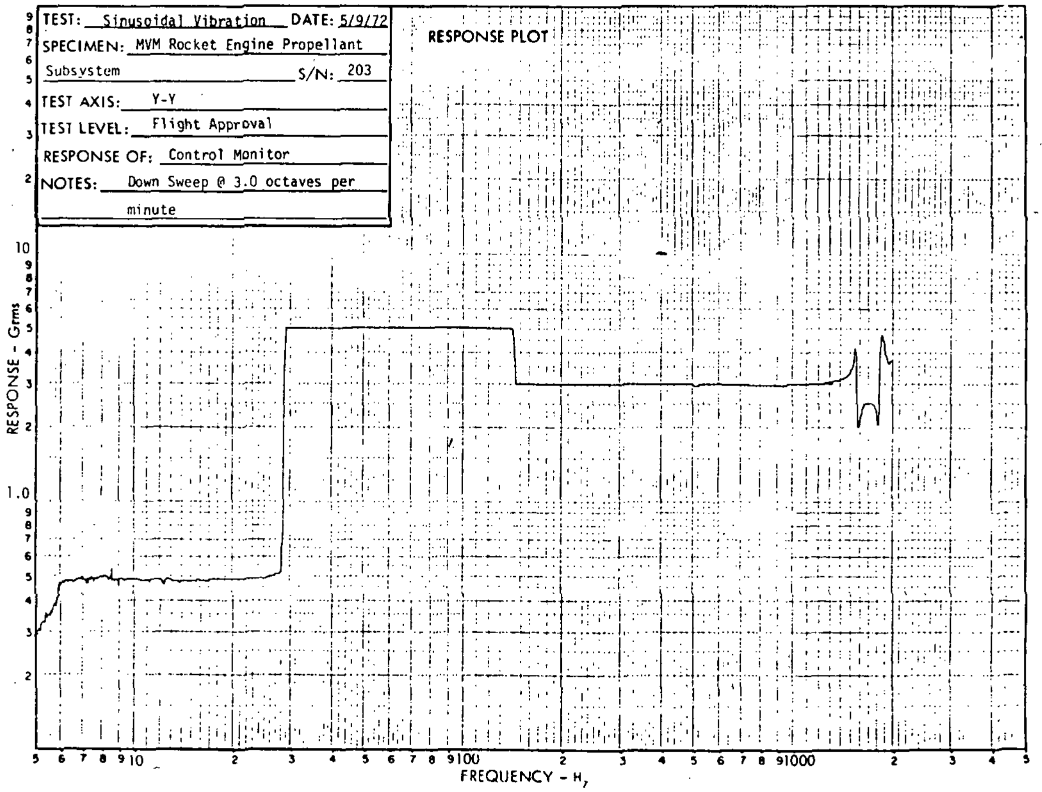

TEST: Low Level Sine DATE: 5/9/72
SPECIMEN: MVM Rocket Engine Propellant
Subsystem S/N: 203
TEST AXIS: Y-Y
TEST LEVEL: Flight Approval
RESPONSE OF: Control
NOTES: 0.25 Grms @ 3.0 octave per
minute

Figure 5-64



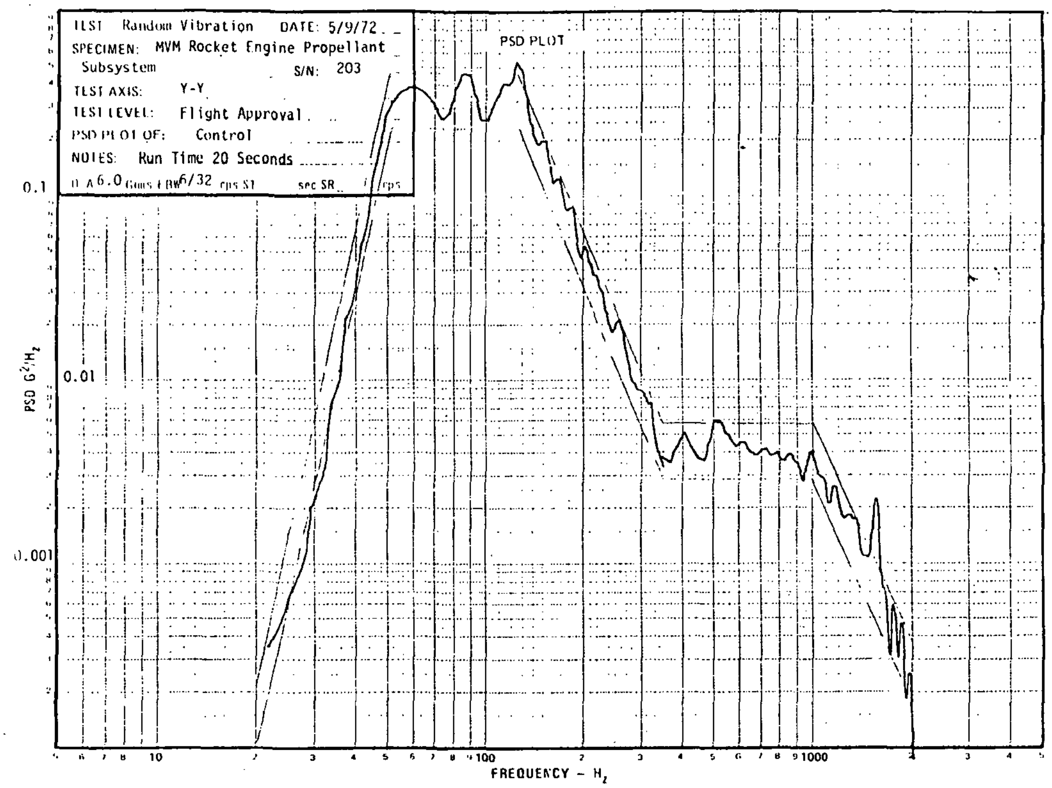
TEST: Sinusoidal Vibration DATE: 5/9/72
SPECIMEN: MVM Rocket Engine
Propellant Subsystem S/N: 203
TEST AXIS: Y-Y
TEST LEVEL: Flight Approval
RESPONSE OF: Control
NOTES: Upsweep @ 3.0 octaves per minute

Figure 5-65



TEST: Sinusoidal Vibration DATE: 5/9/72
SPECIMEN: MVM Rocket Engine Propellant
Subsystem S/N: 203
TEST AXIS: Y-Y
TEST LEVEL: Flight Approval
RESPONSE OF: Control Monitor
NOTES: Down Sweep @ 3.0 octaves per minute

Figure 5-66



TEST Random Vibration DATE: 5/9/72

SPECIMEN: MVM Rocket Engine Propellant Subsystem S/N: 203

TEST AXIS: Y-Y

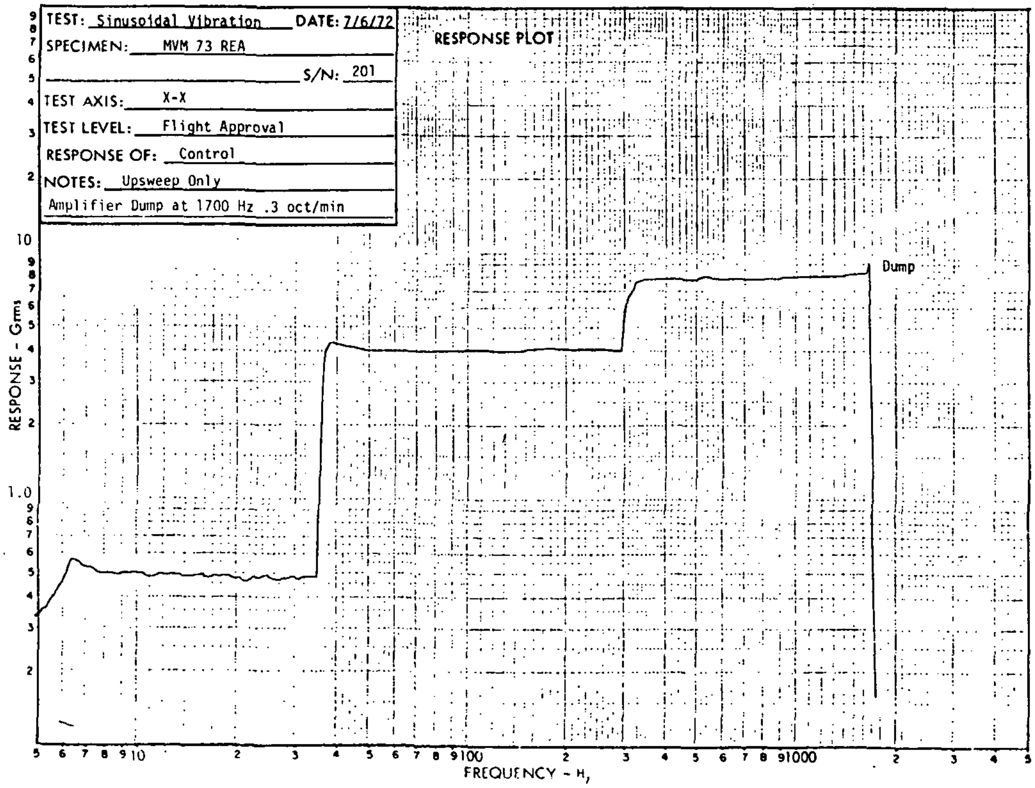
TEST LEVEL: Flight Approval

PSD PLOT OF: Control

NOTES: Run Time 20 Seconds

G A 6.0 Gms EBW 6/32 cps ST sec SR cps

Figure 5-67



TEST: Sinusoidal Vibration DATE: 7/6/72

SPECIMEN: MVM 73 REA

S/N: 201

TEST AXIS: X-X

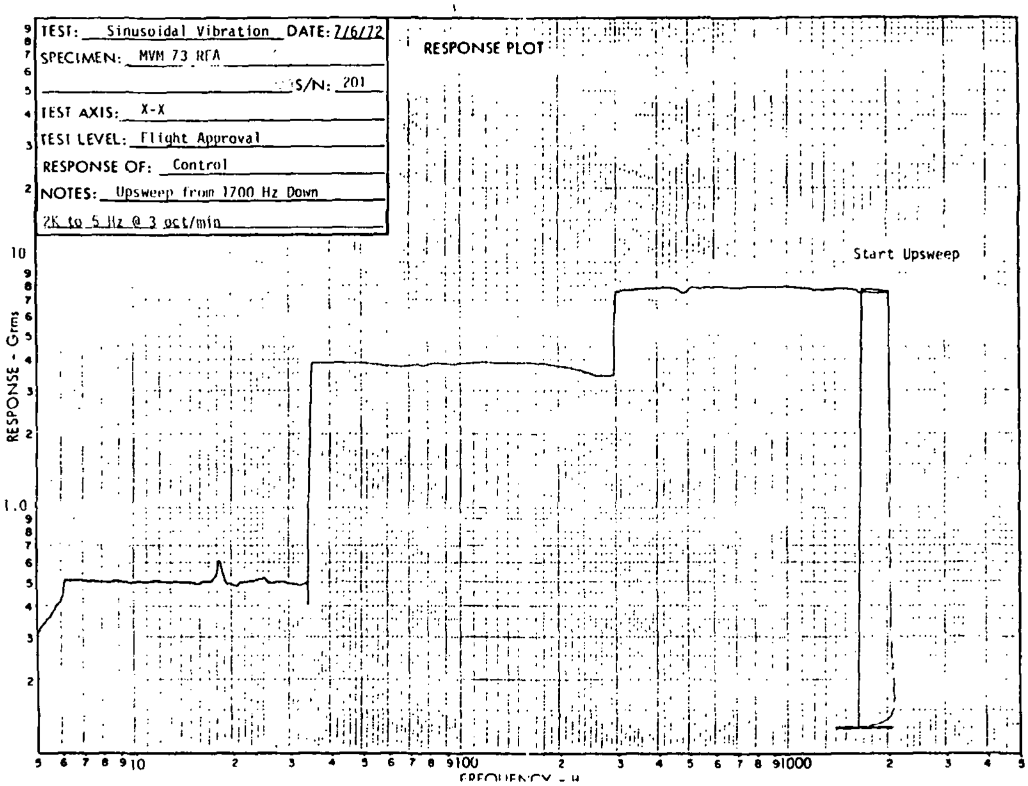
TEST LEVEL: Flight Approval

RESPONSE OF: Control

NOTES: Upsweep Only

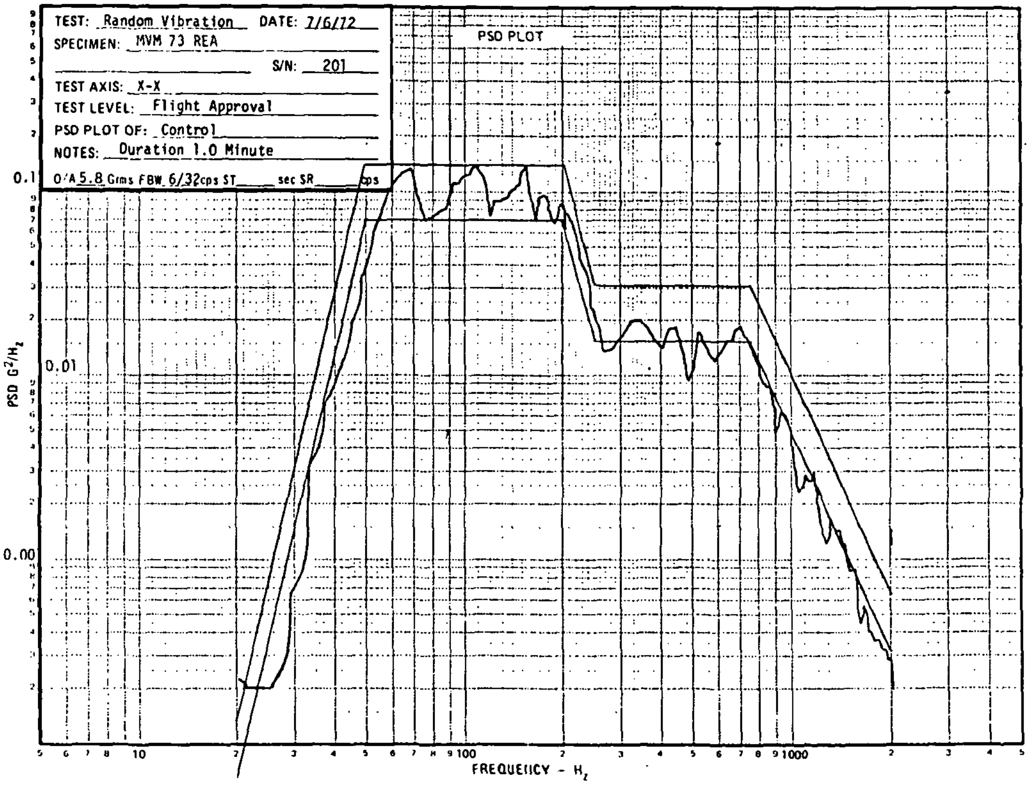
Amplifier Dump at 1700 Hz .3 oct/min

Figure 5-68



TEST: Sinusoidal Vibration DATE: 7/6/72
SPECIMEN: MVM 73 RFA
S/N: 201
TEST AXIS: X-X
TEST LEVEL: Flight Approval
RESPONSE OF: Control
NOTES: Upsweep from 1700 Hz Down
2K to 5 Hz @ 3 oct/min

Figure 5-69



TEST: Random Vibration DATE: 7/6/72
SPECIMEN: MVM 73 REA
S/N: 201
TEST AXIS: X-X
TEST LEVEL: Flight Approval
PSD PLOT OF: Control
NOTES: Duration 1.0 Minute
O'A 5.8 Grms FBW 6/32cps ST_____ sec SR_____ cps

Figure 5-70

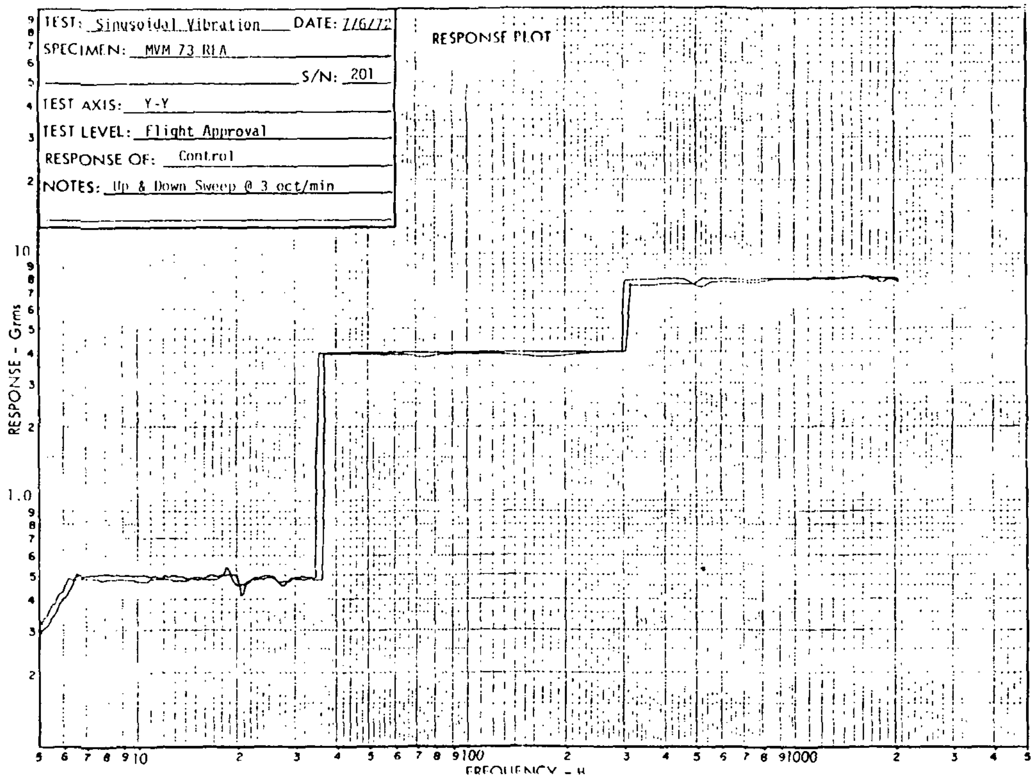

TEST: Sinusoidal Vibration DATE: 7/6/72
SPECIMEN: MVM 73 REA
S/N: 201
TEST AXIS: Y-Y
TEST LEVEL: Flight Approval
RESPONSE OF: Control
NOTES: Up & Down Sweep @ 3 oct/min

Figure 5-71

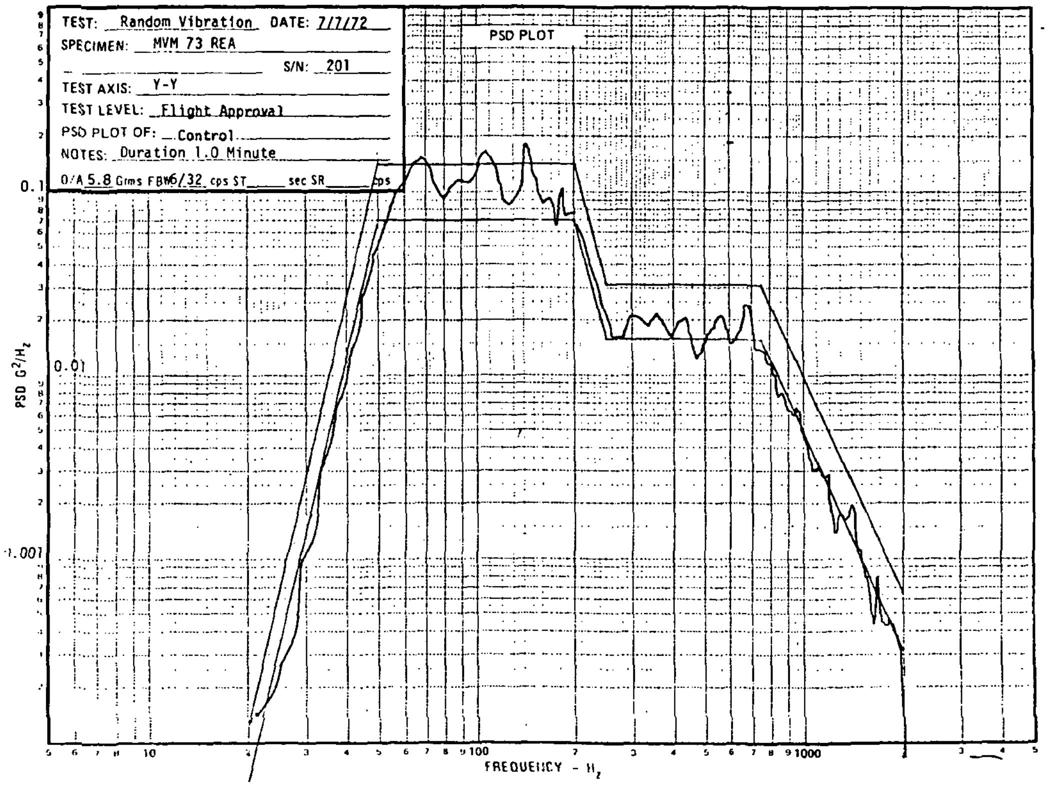

TEST: Random Vibration DATE: 7/7/72
SPECIMEN: MVM 73 REA
S/N: 201
TEST AXIS: Y-Y
TEST LEVEL: Flight Approval
PSD PLOT OF: Control
NOTES: Duration 1.0 Minute
O/A 5.8 Grms FBW6/32 cps ST ____ sec SR ____ cps

Figure 5-72

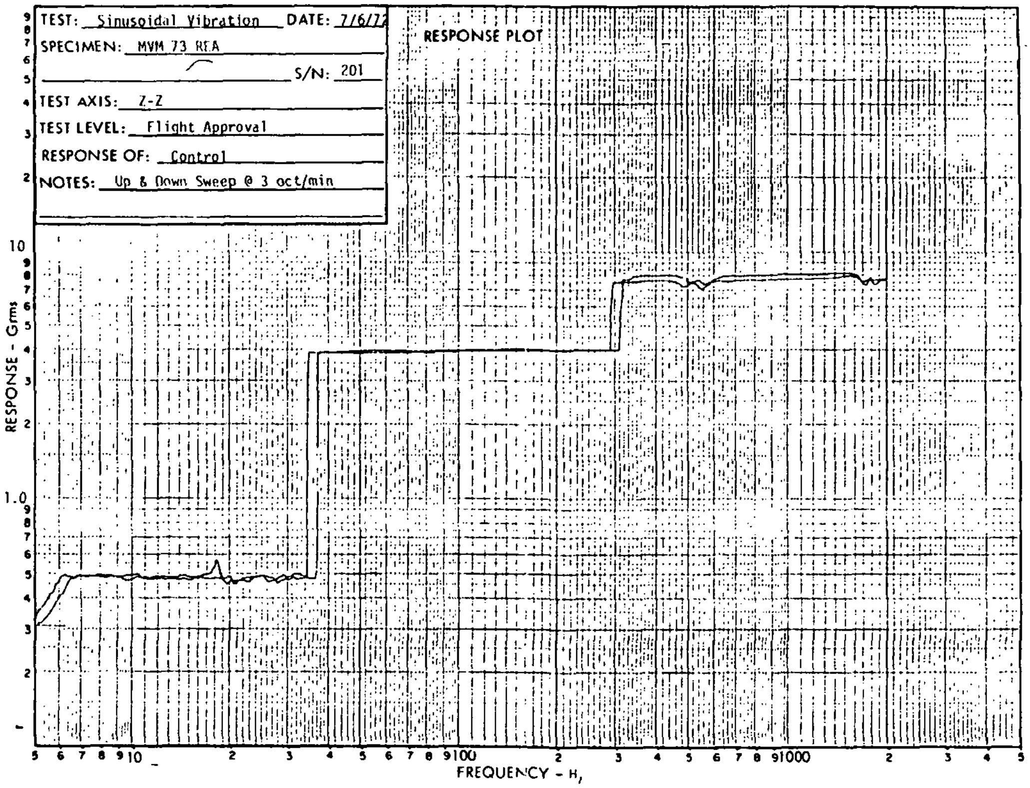

TEST: Sinusoidal Vibration DATE: 7/6/7
SPECIMEN: MVM 73 REA
S/N: 201
TEST AXIS: Z-Z
TEST LEVEL: Flight Approval
RESPONSE OF: Control
NOTES: Up & Down Sweep @ 3 oct/min

Figure 5-73

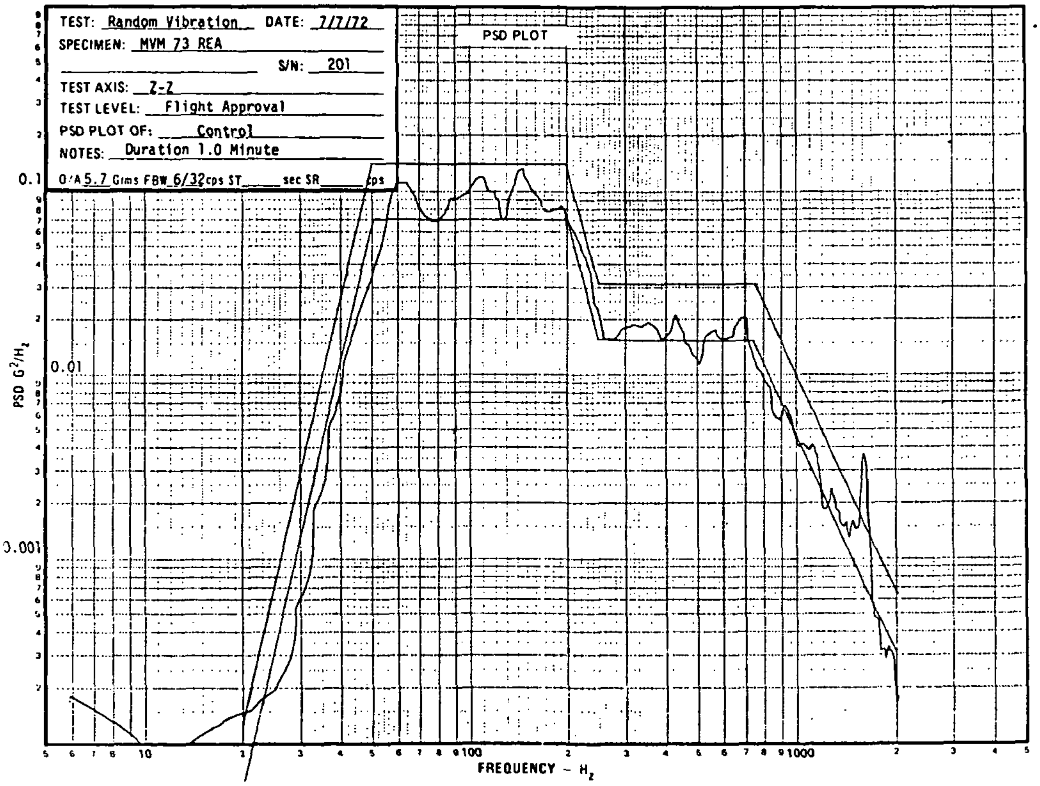

TEST: Random Vibration DATE: 7/7/72
SPECIMEN: MVM 73 REA
S/N: 201
TEST AXIS: Z-Z
TEST LEVEL: Flight Approval
PSD PLOT OF: Control
NOTES: Duration 1.0 Minute
O/A 5.7 Grms FBW 6/32cps ST____ sec SR____ cps

Figure 5-74

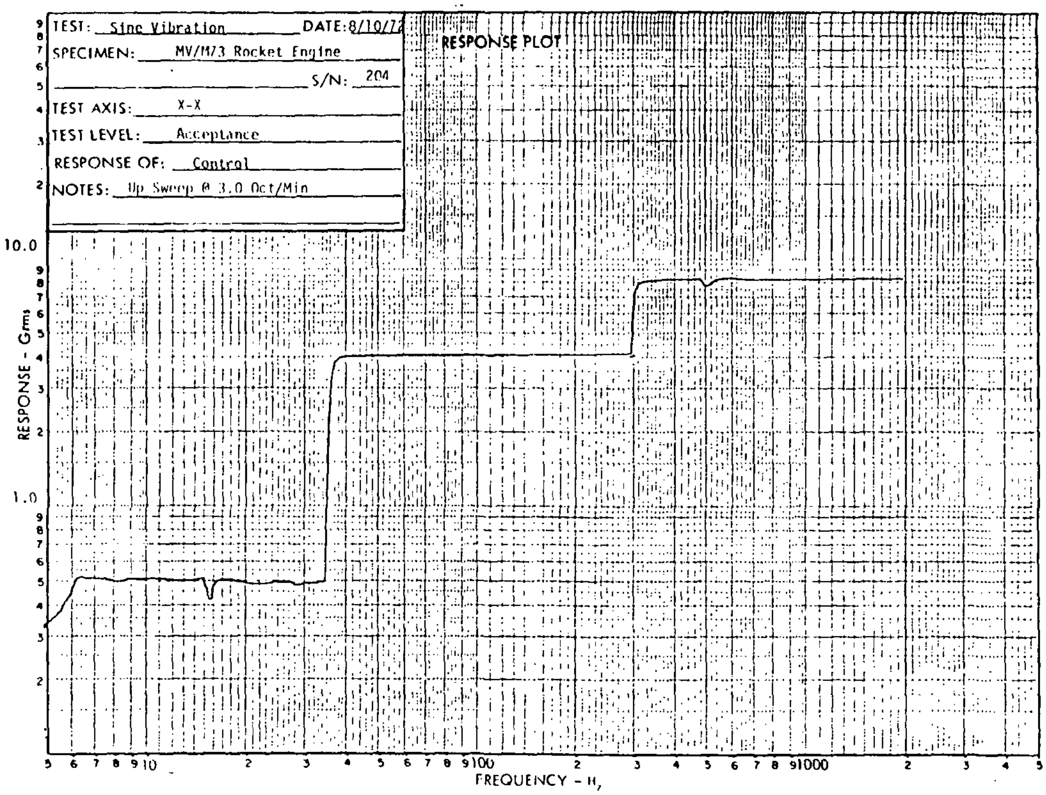

TEST: Sine Vibration DATE: 8/10/72
SPECIMEN: MV/M73 Rocket Engine
S/N: 204
TEST AXIS: X-X
TEST LEVEL: Acceptance
RESPONSE OF: Control
NOTES: Up Sweep @ 3.0 Oct/Min

Figure 5-75

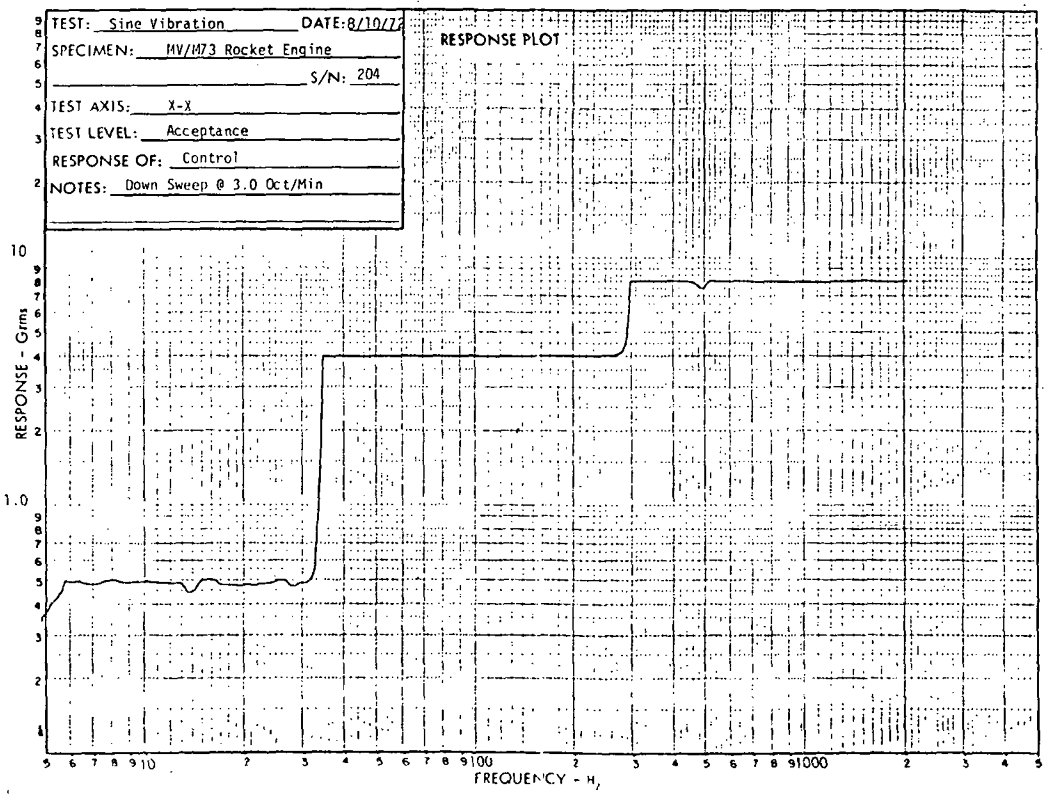
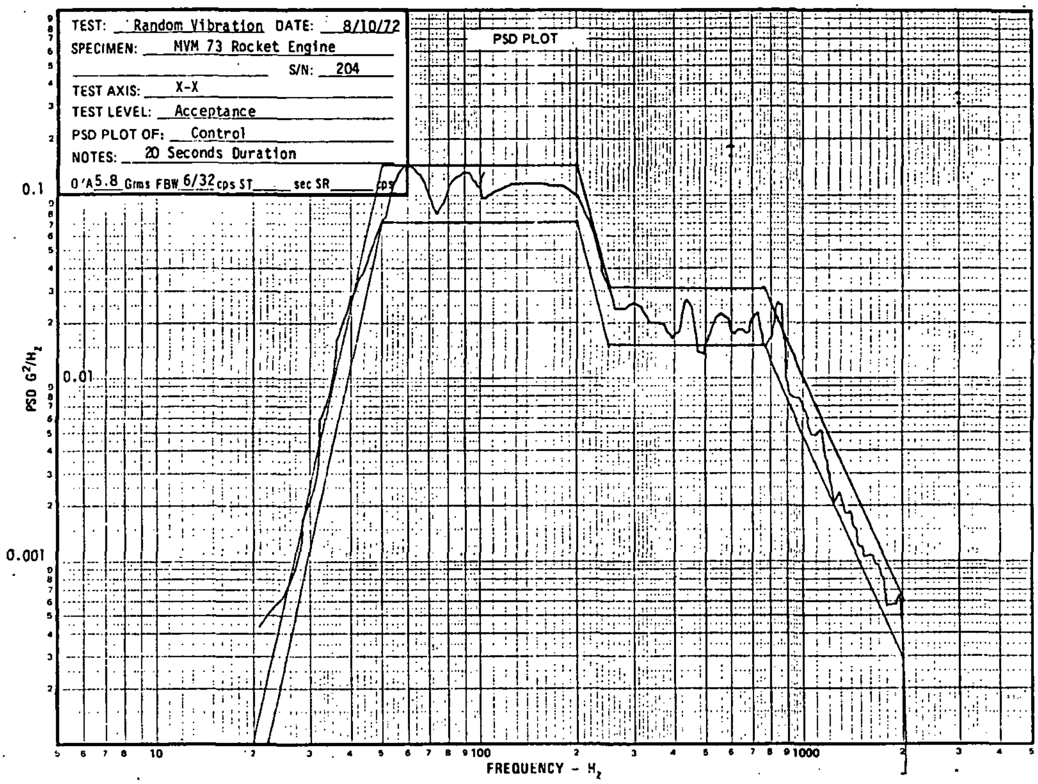
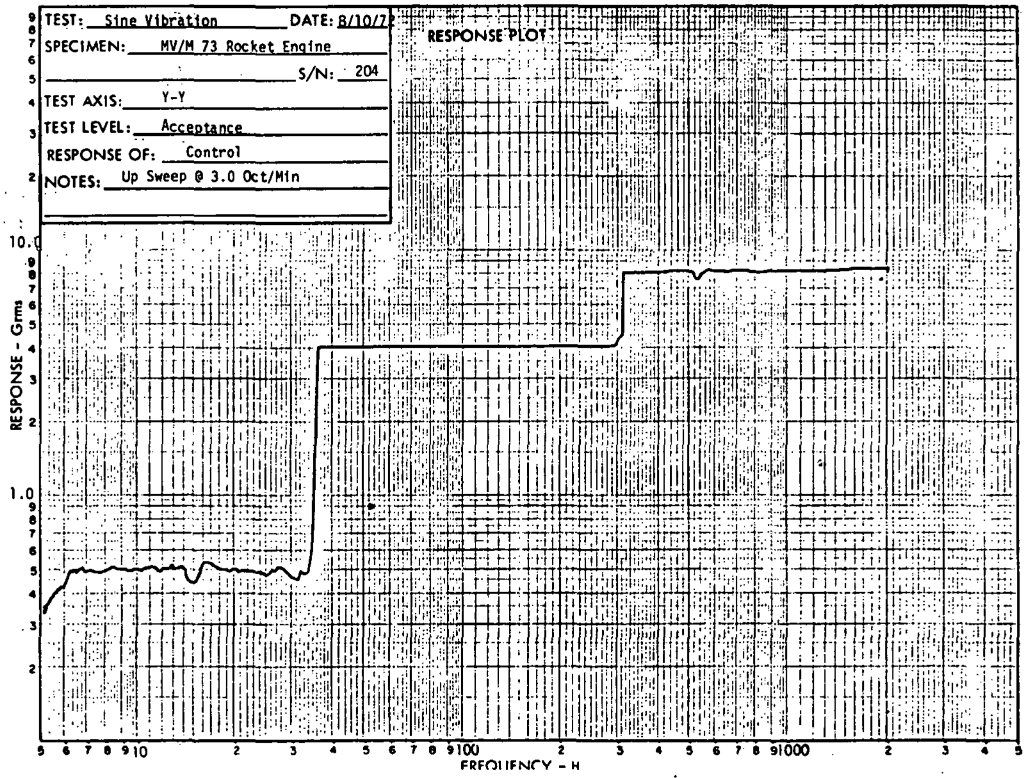

TEST: Sine Vibration DATE: 8/10/72
SPECIMEN: MV/M73 Rocket Engine
S/N: 204
TEST AXIS: X-X
TEST LEVEL: Acceptance
RESPONSE OF: Control
NOTES: Down Sweep @ 3.0 Oct/Min

Figure 5-76



TEST: Random Vibration DATE: 8/10/72
SPECIMEN: MVM 73 Rocket Engine
S/N: 204
TEST AXIS: X-X
TEST LEVEL: Acceptance
PSD PLOT OF: Control
NOTES: 20 Seconds Duration
O'A 5.8 Grms FBW 6/32 cps ST ____ sec SR ____ cps

Figure 5-77



TEST: Sine Vibration DATE: 8/10/72
SPECIMEN: MV/M 73 Rocket Engine
S/N: 204
TEST AXIS: Y-Y
TEST LEVEL: Acceptance
RESPONSE OF: Control
NOTES: Up Sweep @ 3.0 Oct/Min

Figure 5-78

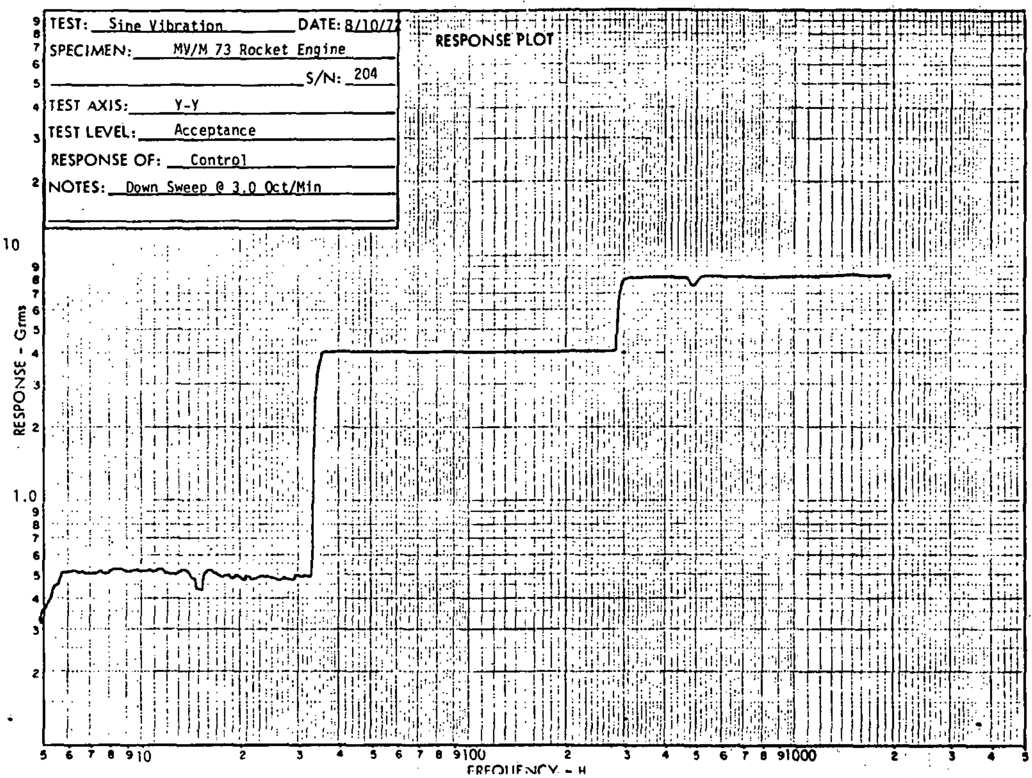

TEST: Sine Vibration DATE: 8/10/72
SPECIMEN: MV/M 73 Rocket Engine
S/N: 204
TEST AXIS: Y-Y
TEST LEVEL: Acceptance
RESPONSE OF: Control
NOTES: Down Sweep @ 3.0 Oct/Min

Figure 5-79

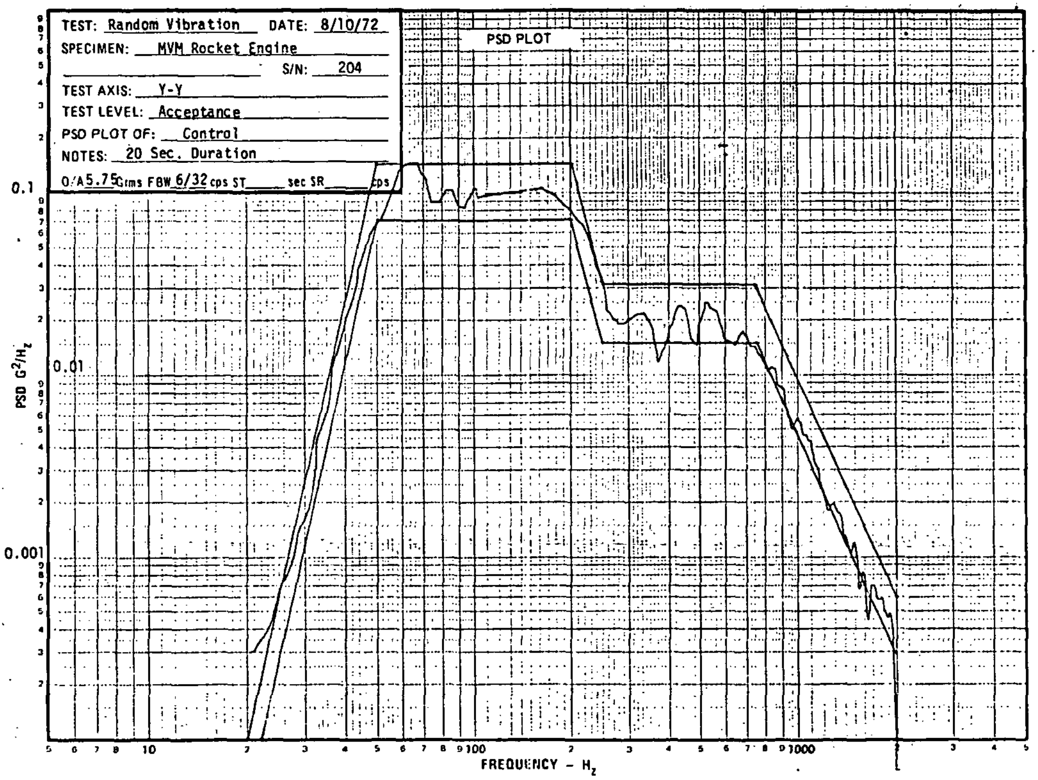

TEST: Random Vibration DATE: 8/10/72
SPECIMEN: MVM Rocket Engine
S/N: 204
TEST AXIS: Y-Y
TEST LEVEL: Acceptance
PSD PLOT OF: Control
NOTES: 20 Sec. Duration
O/A 5.75 Grms FBW 6/32 cps ST ____ sec SR ____ cps

Figure 5-80

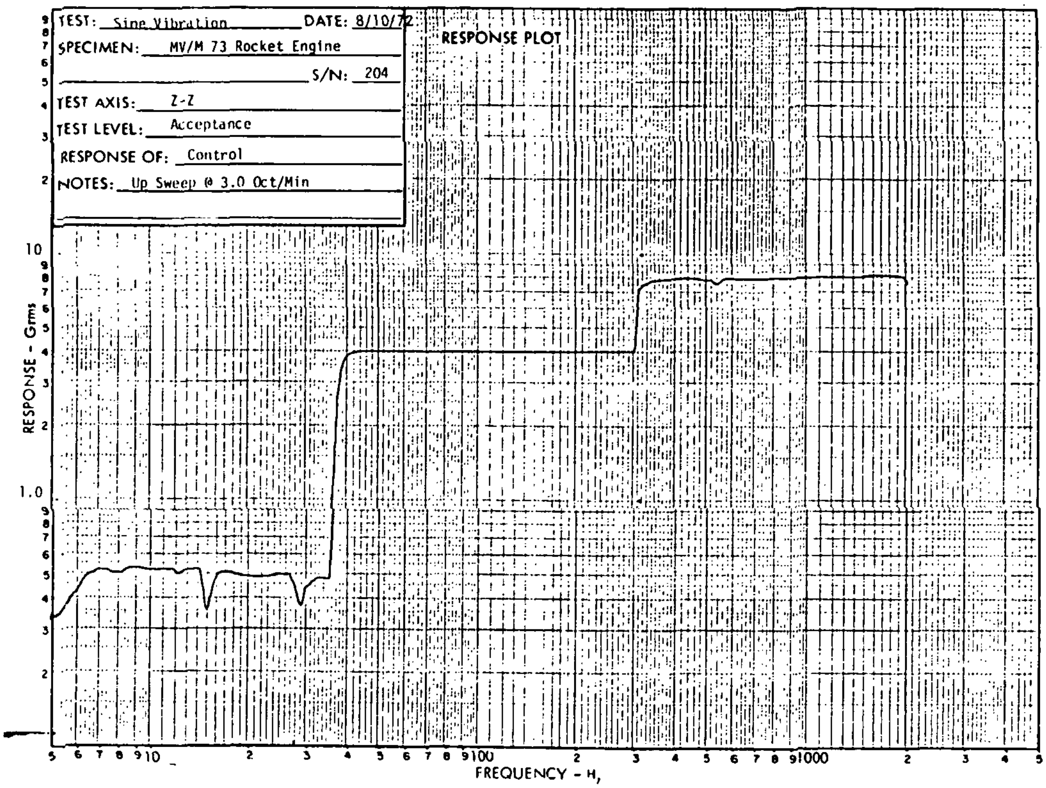

TEST: Sine Vibration DATE: 8/10/72
SPECIMEN: MV/M 73 Rocket Engine
S/N: 204
TEST AXIS: Z-Z
TEST LEVEL: Acceptance
RESPONSE OF: Control
NOTES: Up Sweep @ 3.0 Oct/Min

Figure 5-81

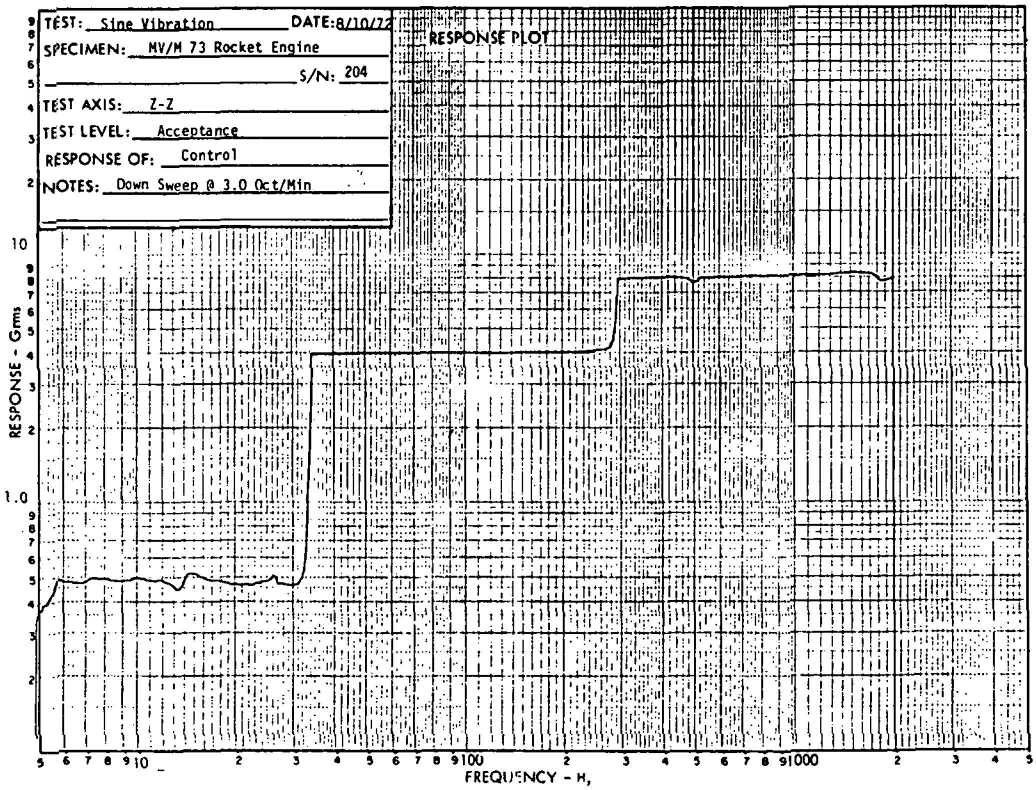
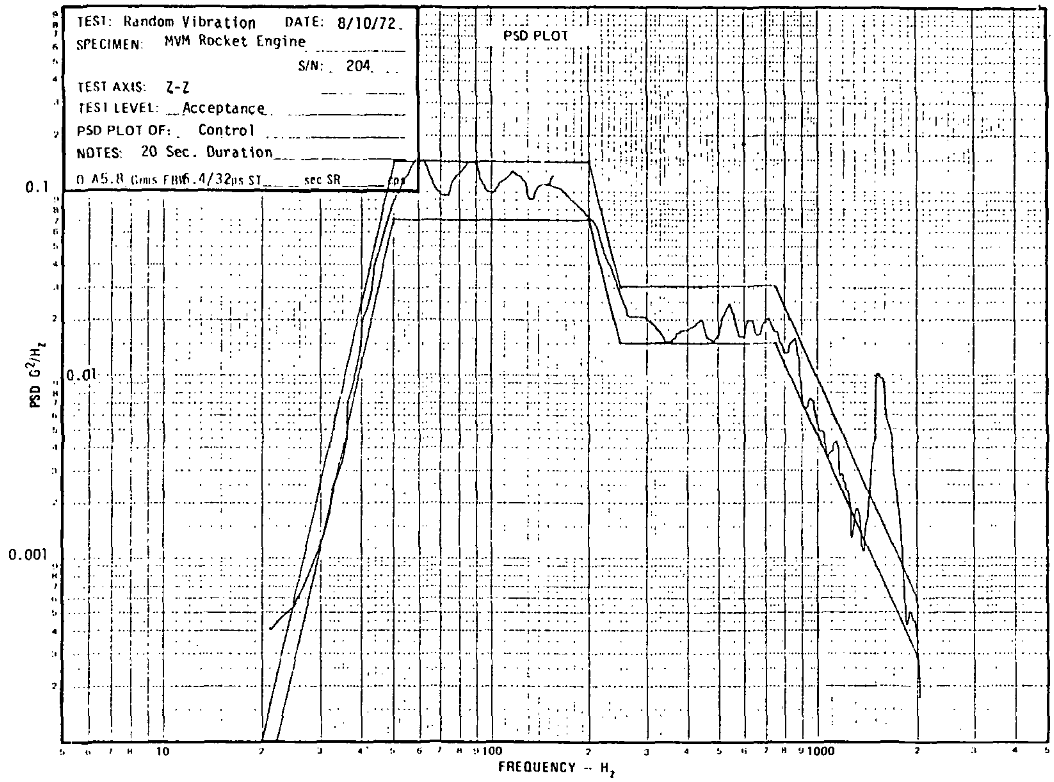

TEST: Sine Vibration DATE: 8/10/72
SPECIMEN: MV/M 73 Rocket Engine
S/N: 204
TEST AXIS: Z-Z
TEST LEVEL: Acceptance
RESPONSE OF: Control
NOTES: Down Sweep @ 3.0 Oct/Min

Figure 5-82


TEST: Random Vibration DATE: 8/10/72

SPECIMEN: MVM Rocket Engine

S/N: 204

TEST AXIS: Z-Z

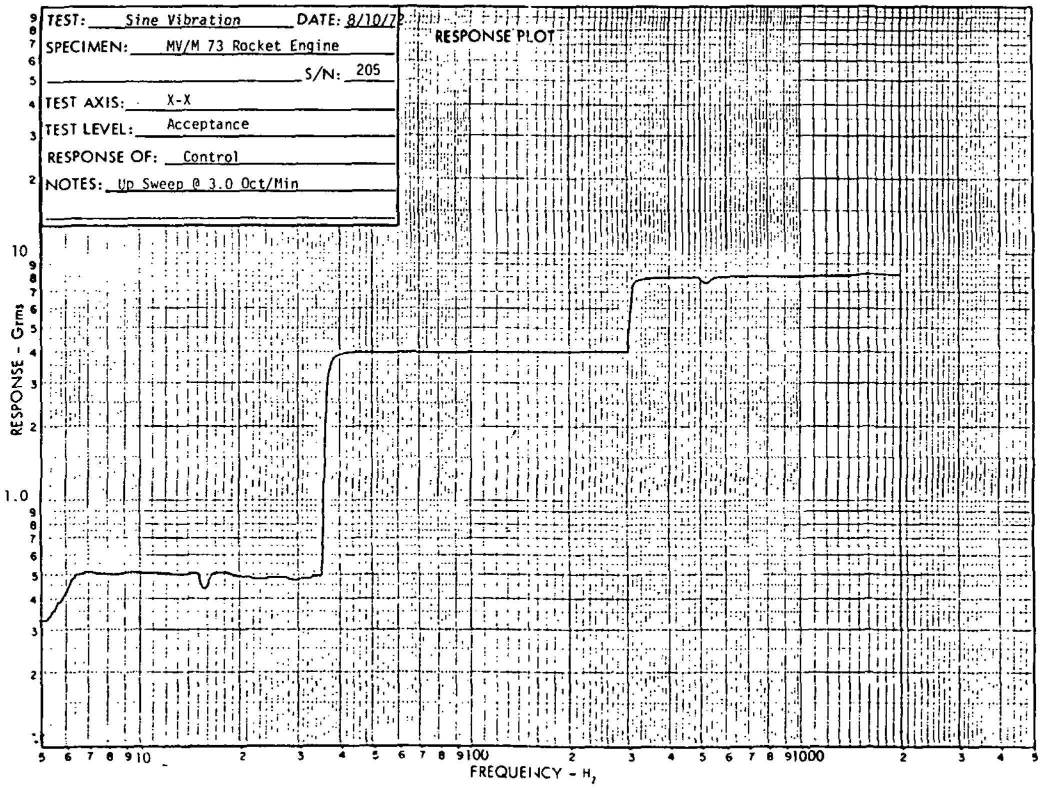
TEST LEVEL: Acceptance

PSD PLOT OF: Control

NOTES: 20 Sec. Duration

0 A5.8 Grms FBW6.4/32ps ST sec SR

Figure 5-83


TEST: Sine Vibration DATE: 8/10/72

SPECIMEN: MV/M 73 Rocket Engine

S/N: 205

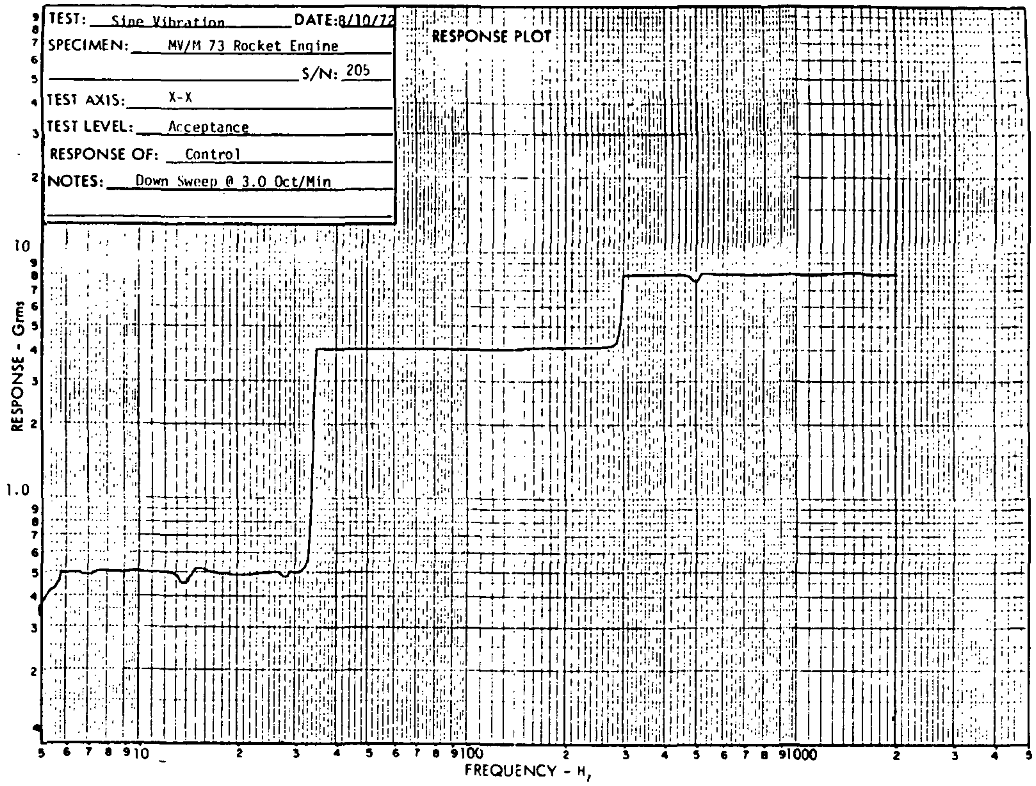
TEST AXIS: X-X

TEST LEVEL: Acceptance

RESPONSE OF: Control

NOTES: Up Sweep @ 3.0 Oct/Min

Figure 5-84



TEST: Sine Vibration DATE: 8/10/72

SPECIMEN: MV/M 73 Rocket Engine

S/N: 205

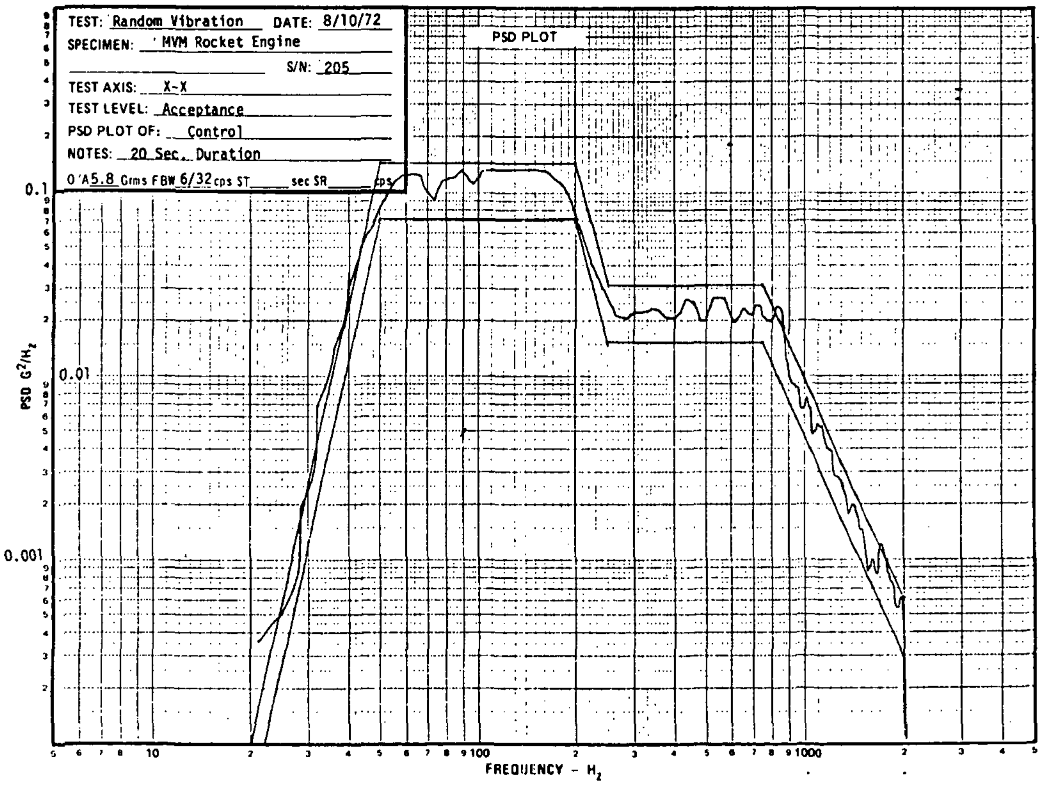
TEST AXIS: X-X

TEST LEVEL: Acceptance

RESPONSE OF: Control

NOTES: Down Sweep @ 3.0 Oct/Min

Figure 5-85



TEST: Random Vibration DATE: 8/10/72

SPECIMEN: MVM Rocket Engine

S/N: 205

TEST AXIS: X-X

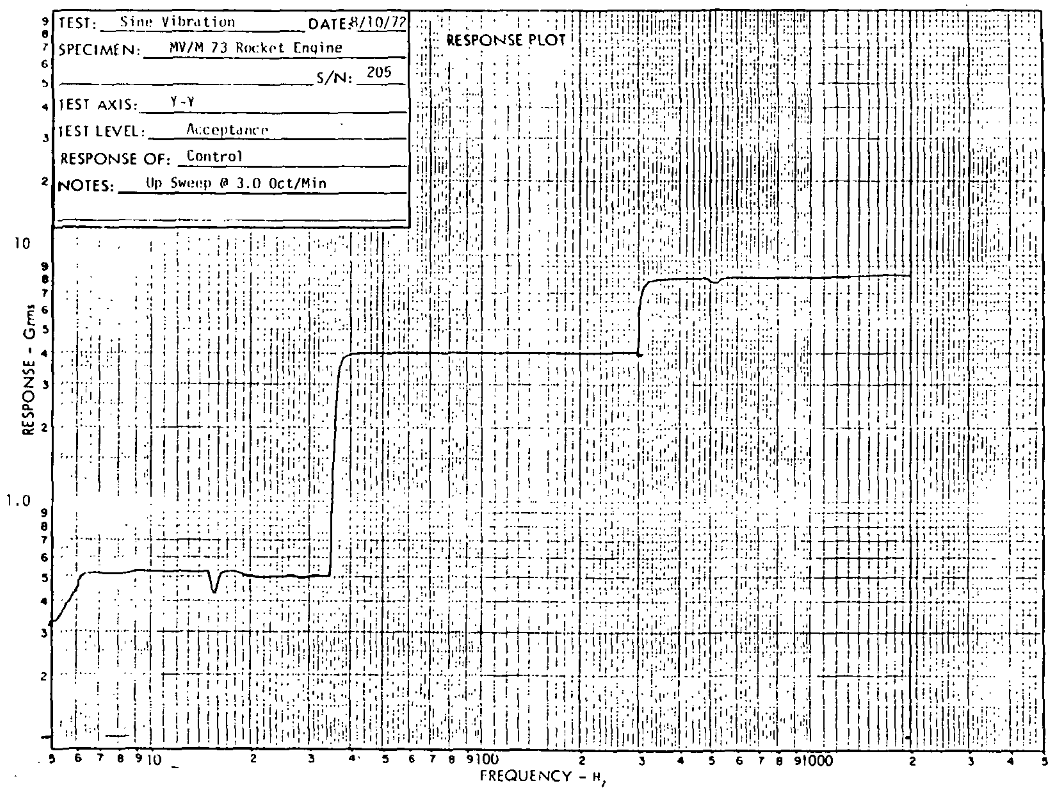
TEST LEVEL: Acceptance

PSD PLOT OF: Control

NOTES: 20 Sec. Duration

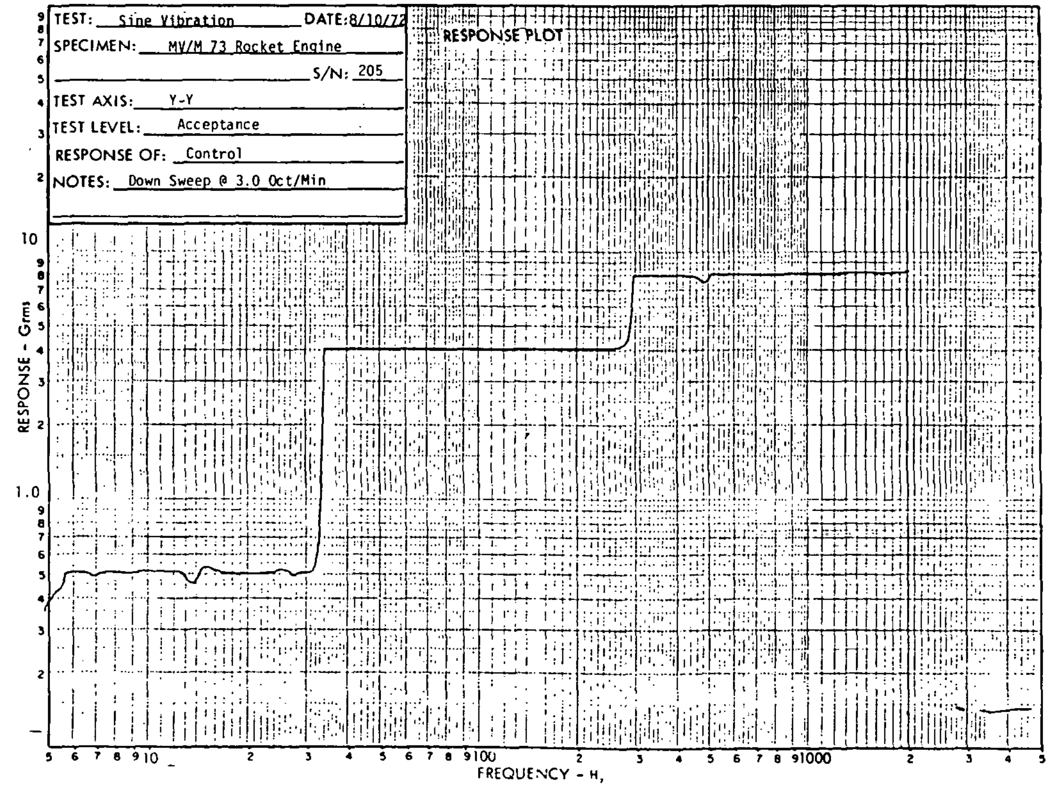
O'A 5.8 Grms FBW 6/32 cps ST ____ sec SR ____ cps

Figure 5-86



TEST: Sine Vibration DATE: 8/10/72
SPECIMEN: MV/M 73 Rocket Engine
S/N: 205
TEST AXIS: Y-Y
TEST LEVEL: Acceptance
RESPONSE OF: Control
NOTES: Up Sweep @ 3.0 Oct/Min

Figure 5-87



TEST: Sine Vibration DATE: 8/10/72
SPECIMEN: MV/M 73 Rocket Engine
S/N: 205
TEST AXIS: Y-Y
TEST LEVEL: Acceptance
RESPONSE OF: Control
NOTES: Down Sweep @ 3.0 Oct/Min

Figure 5-88

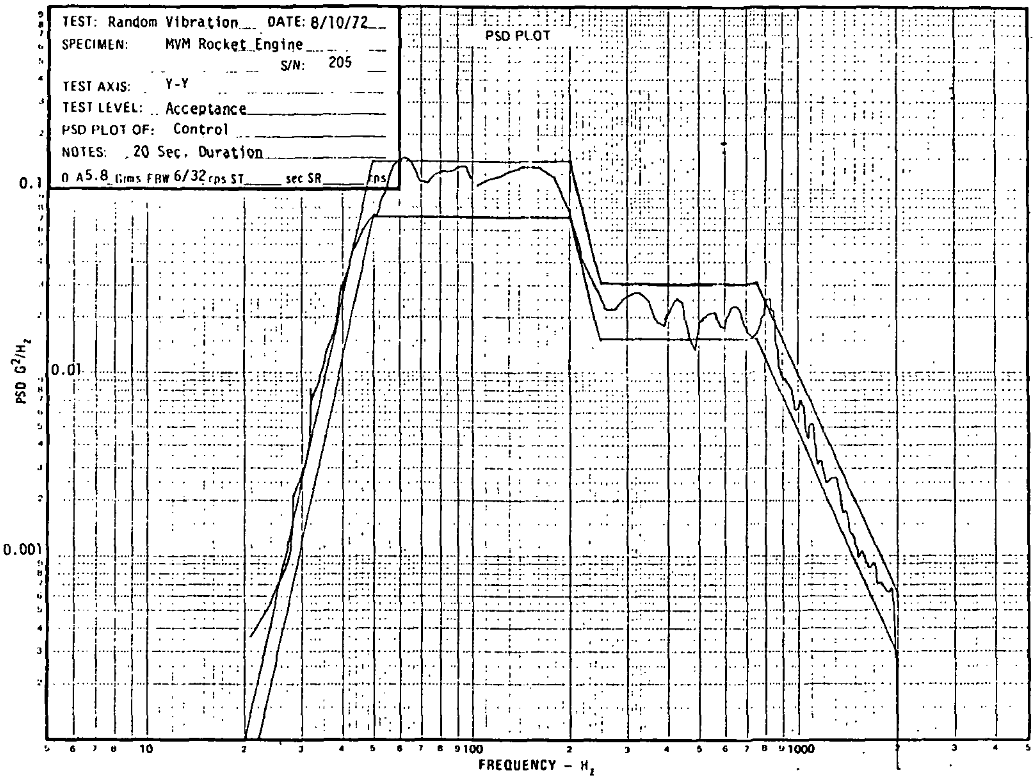

TEST: Random Vibration DATE: 8/10/72
SPECIMEN: MVM Rocket Engine
S/N: 205
TEST AXIS: Y-Y
TEST LEVEL: Acceptance
PSD PLOT OF: Control
NOTES: 20 Sec. Duration
0 A5.8 Grms FBW 6/32 cps ST ____ sec SR ____ cps

Figure 5-89

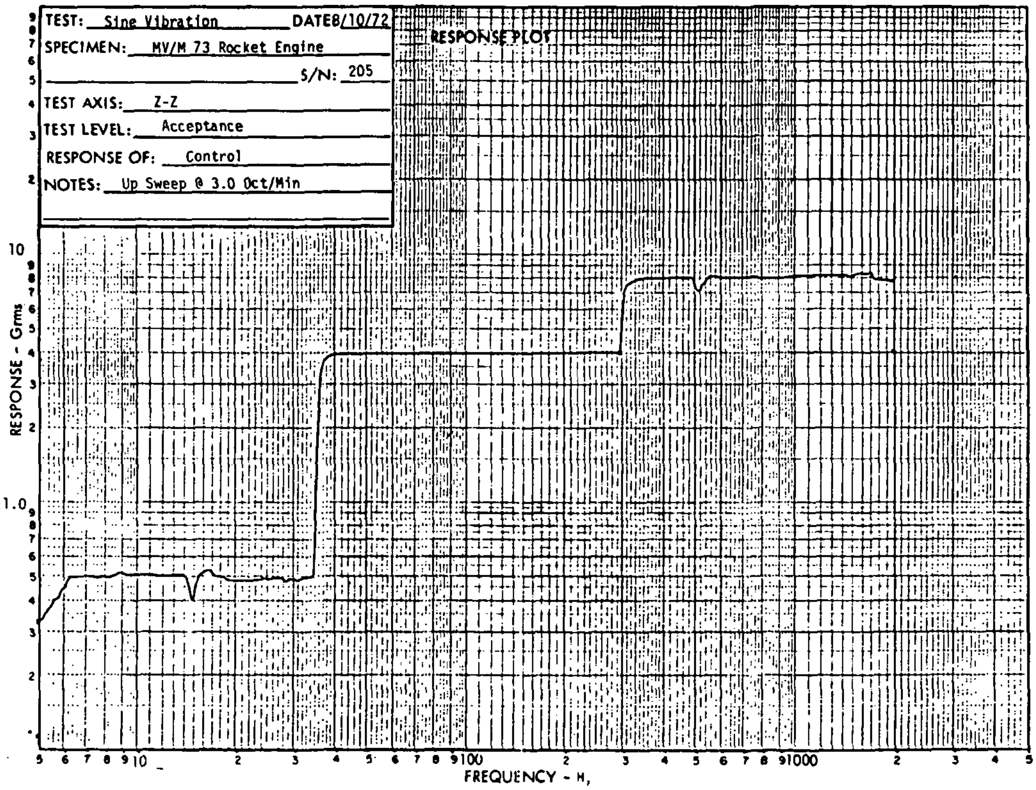
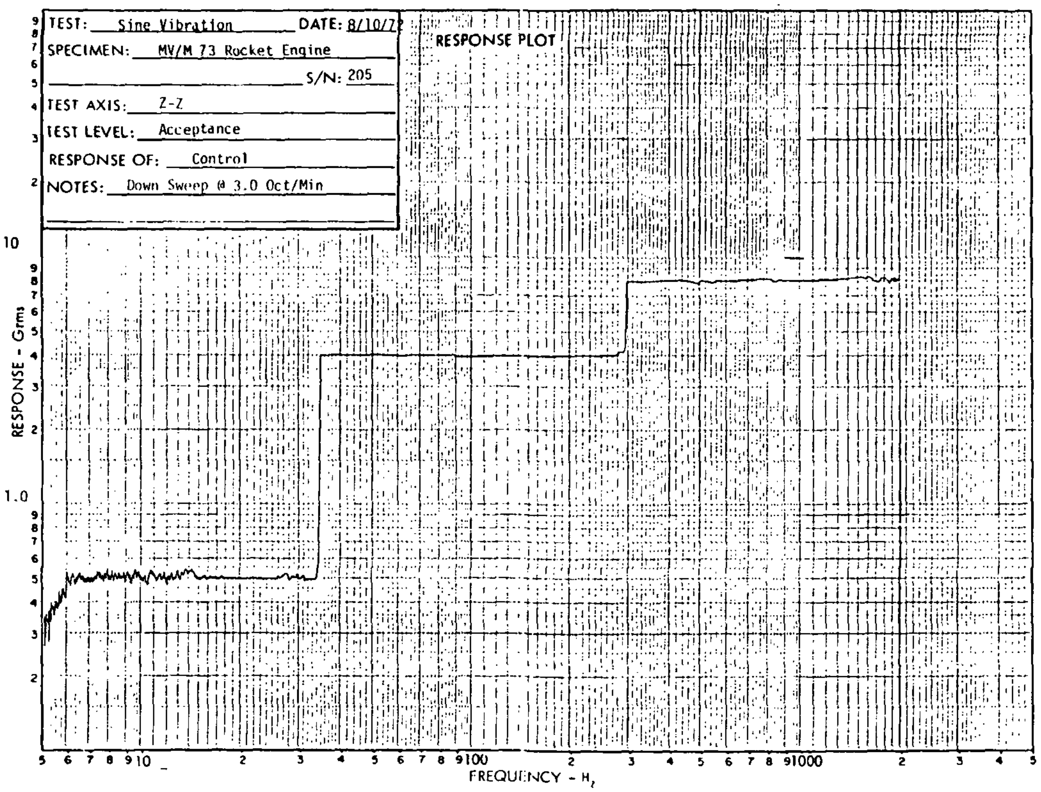

TEST: Sine Vibration DATE 8/10/72
SPECIMEN: MV/M 73 Rocket Engine
S/N: 205
TEST AXIS: Z-Z
TEST LEVEL: Acceptance
RESPONSE OF: Control
NOTES: Up Sweep @ 3.0 Oct/Min

Figure 5-90


TEST: Sine Vibration DATE: 8/10/7

SPECIMEN: MV/M 73 Rocket Engine

S/N: 205

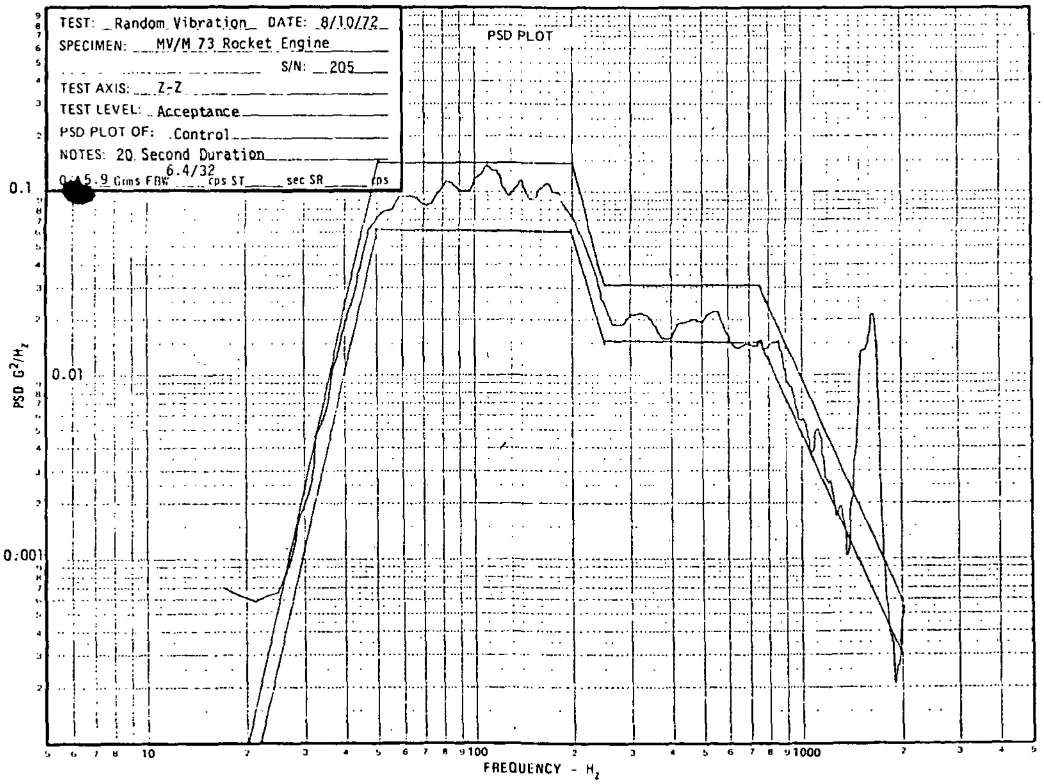
TEST AXIS: Z-Z

TEST LEVEL: Acceptance

RESPONSE OF: Control

NOTES: Down Sweep @ 3.0 Oct/Min

Figure 5-91


TEST: Random Vibration DATE: 8/10/72

SPECIMEN: MV/M 73 Rocket Engine

S/N: 205

TEST AXIS: Z-Z

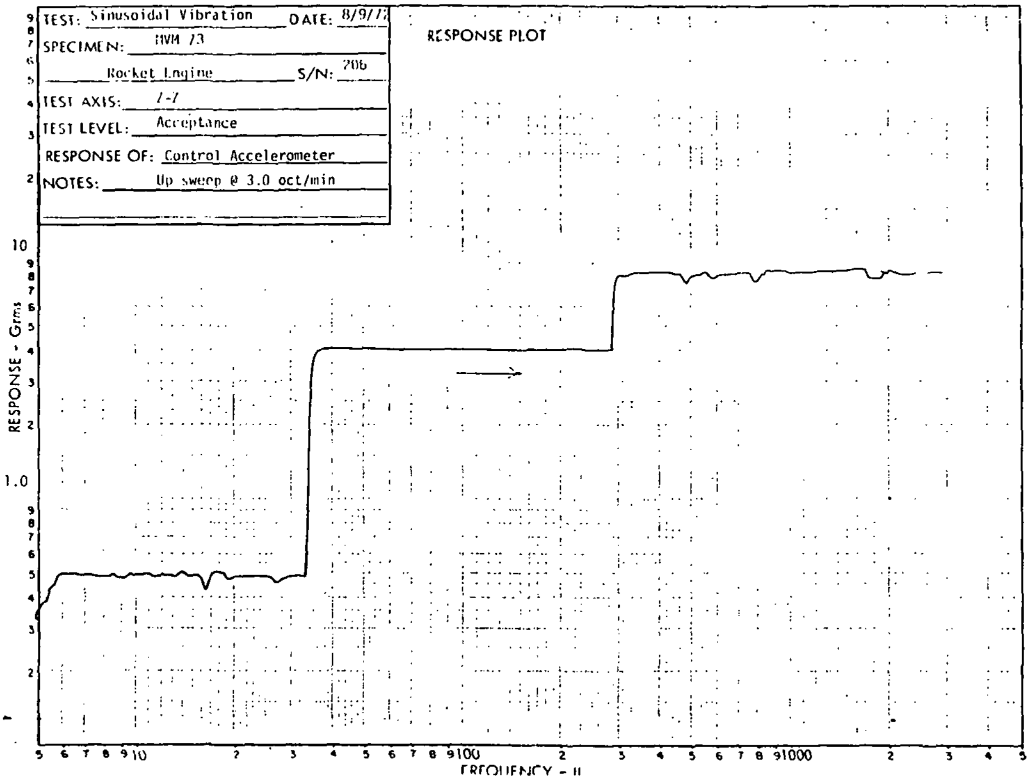
TEST LEVEL: Acceptance

PSD PLOT OF: Control

NOTES: 20 Second Duration

0[illegible]5.9 Grms FBW 6.4/32 cps ST sec SR cps

Figure 5-92



TEST: Sinusoidal Vibration DATE: 8/9/72

SPECIMEN: MVM 73

Rocket Engine S/N: 206

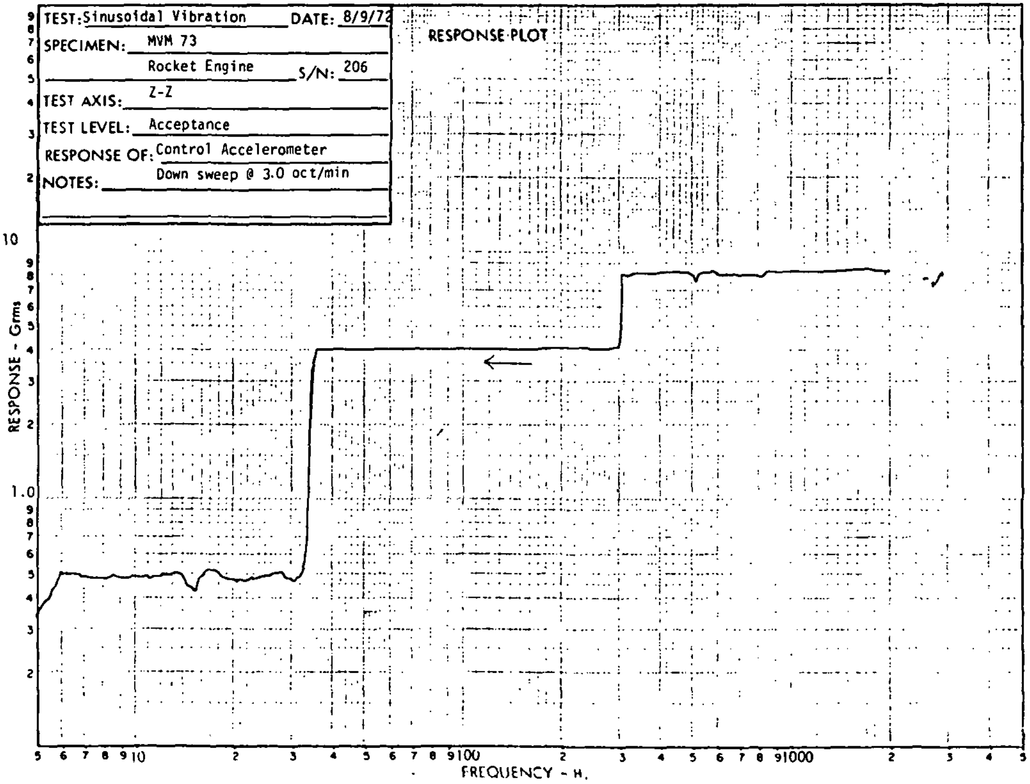
TEST AXIS: Z-Z

TEST LEVEL: Acceptance

RESPONSE OF: Control Accelerometer

NOTES: Up sweep @ 3.0 oct/min

Figure 5-93



TEST: Sinusoidal Vibration DATE: 8/9/72

SPECIMEN: MVM 73

Rocket Engine S/N: 206

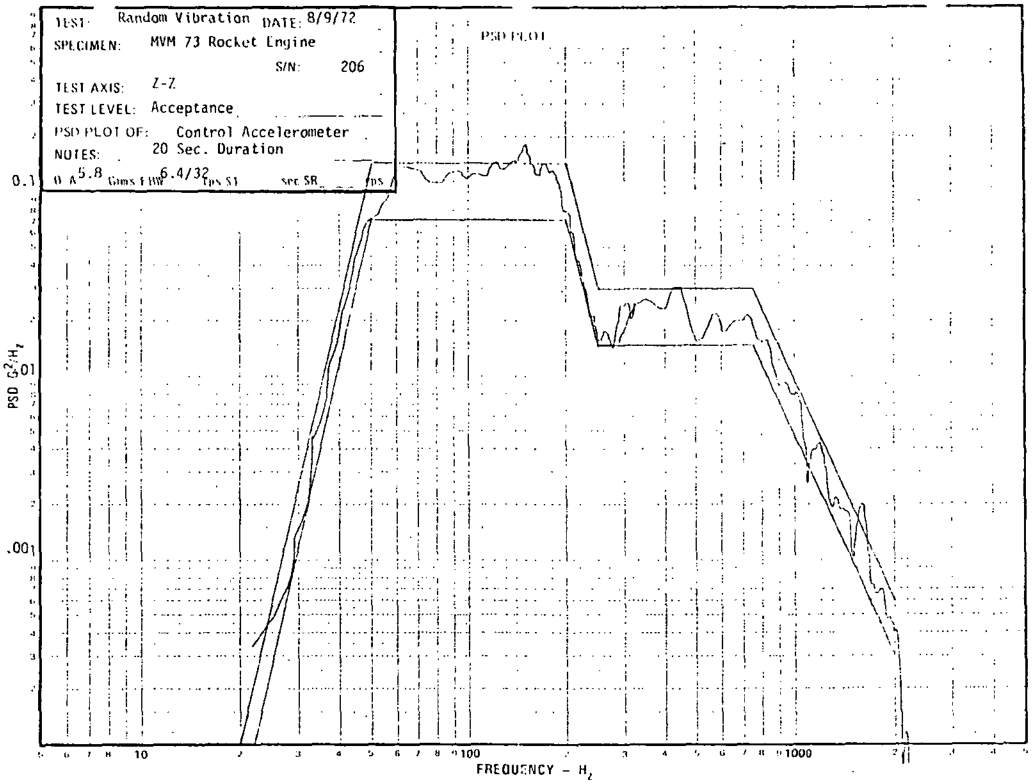
TEST AXIS: Z-Z

TEST LEVEL: Acceptance

RESPONSE OF: Control Accelerometer

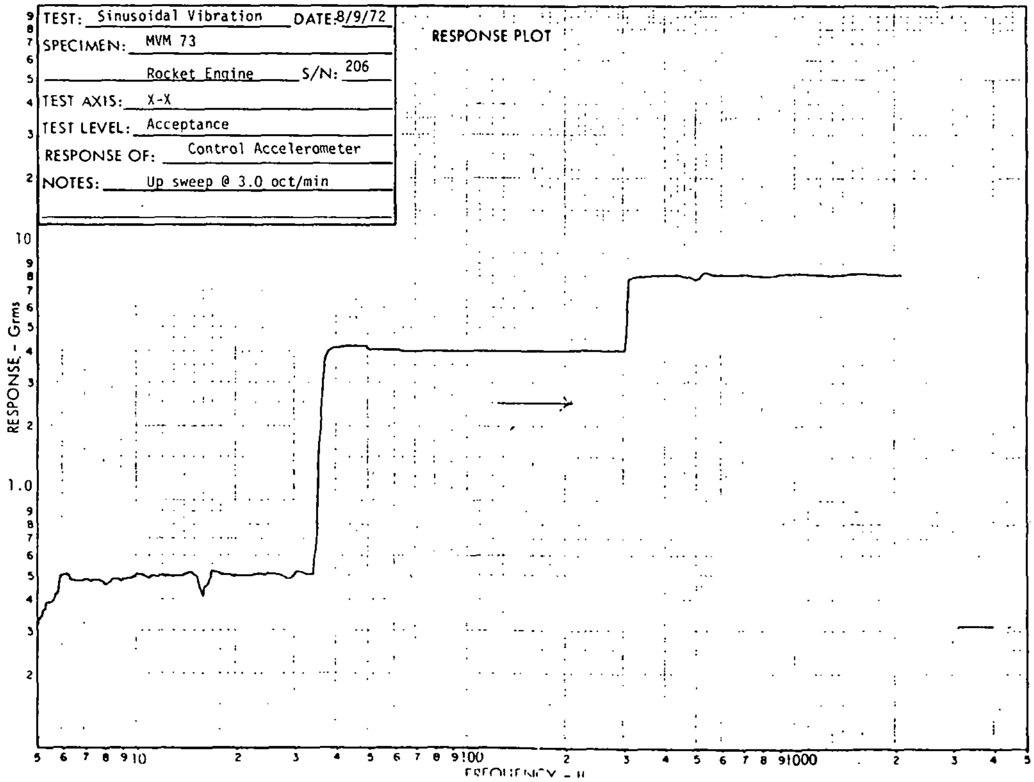
NOTES: Down sweep @ 3.0 oct/min

Figure 5-94



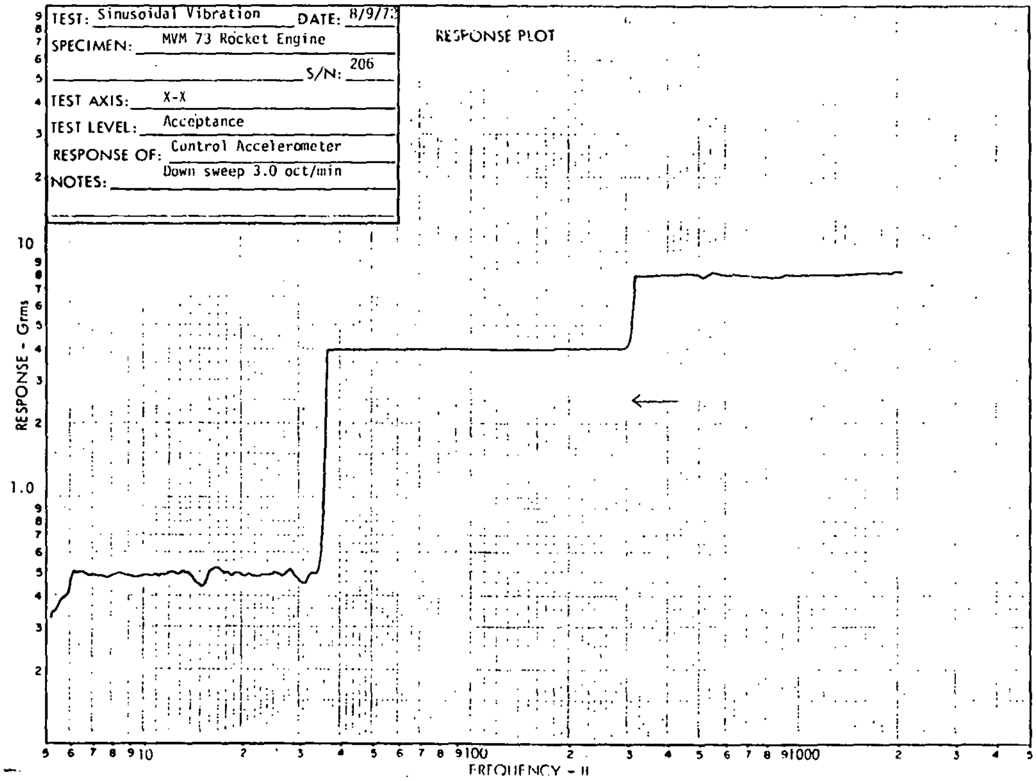
TEST: Random Vibration DATE: 8/9/72
SPECIMEN: MVM 73 Rocket Engine
S/N: 206
TEST AXIS: Z-Z
TEST LEVEL: Acceptance
PSD PLOT OF: Control Accelerometer
NOTES: 20 Sec. Duration
O A 5.8 Grms FBW 6.4/32 cps ST sec SR cps

Figure 5-95



TEST: Sinusoidal Vibration DATE: 8/9/72
SPECIMEN: MVM 73
Rocket Engine S/N: 206
TEST AXIS: X-X
TEST LEVEL: Acceptance
RESPONSE OF: Control Accelerometer
NOTES: Up sweep @ 3.0 oct/min

Figure 5-96



TEST: Sinusoidal Vibration DATE: 8/9/72

SPECIMEN: MVM 73 Rocket Engine

S/N: 206

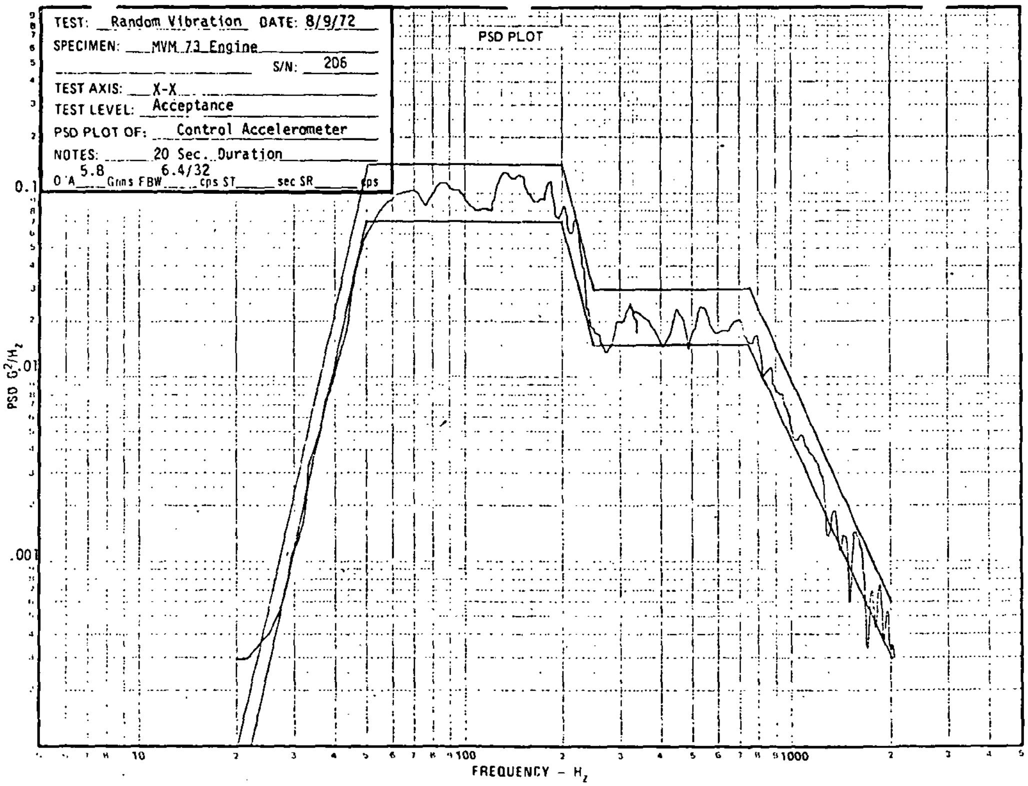
TEST AXIS: X-X

TEST LEVEL: Acceptance

RESPONSE OF: Control Accelerometer

NOTES: Down sweep 3.0 oct/min

Figure 5-97



TEST: Random Vibration DATE: 8/9/72

SPECIMEN: MVM 73 Engine

S/N: 206

TEST AXIS: X-X

TEST LEVEL: Acceptance

PSD PLOT OF: Control Accelerometer

NOTES: 20 Sec. Duration

O'A 5.8 Grms FBW 6.4/32 cps ST sec SR cps

Figure 5-98

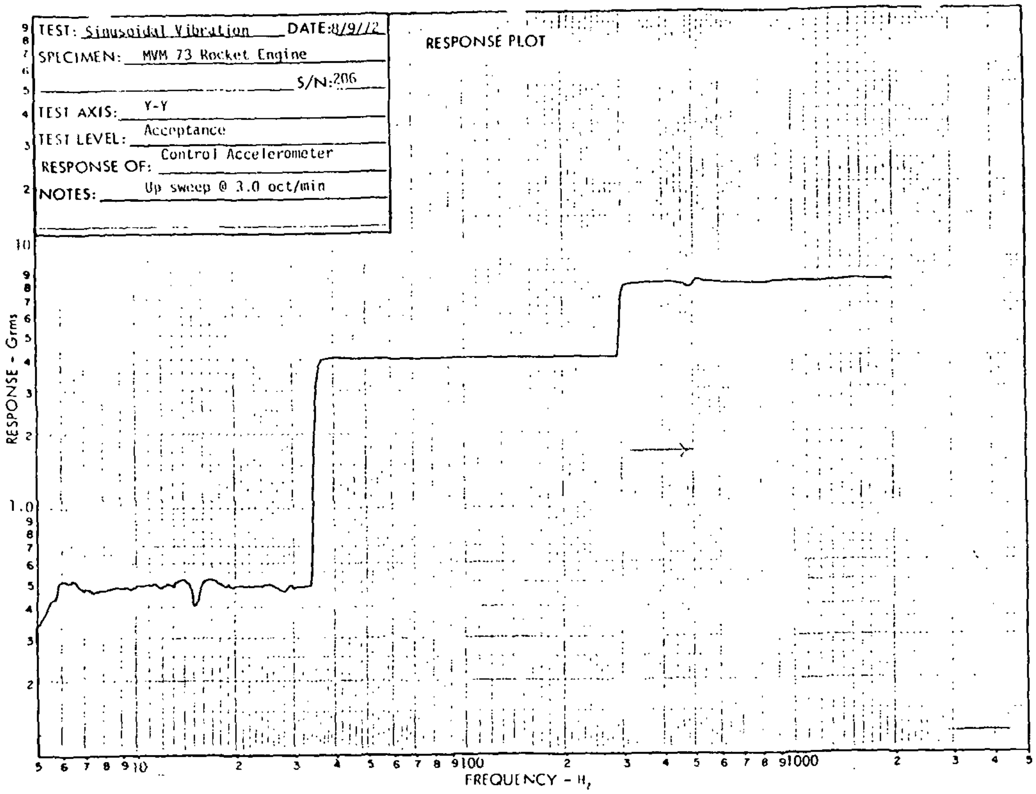

TEST: Sinusoidal Vibration DATE: 8/9/72
SPECIMEN: MVM 73 Rocket Engine
S/N: 206
TEST AXIS: Y-Y
TEST LEVEL: Acceptance
RESPONSE OF: Control Accelerometer
NOTES: Up sweep @ 3.0 oct/min

Figure 5-99

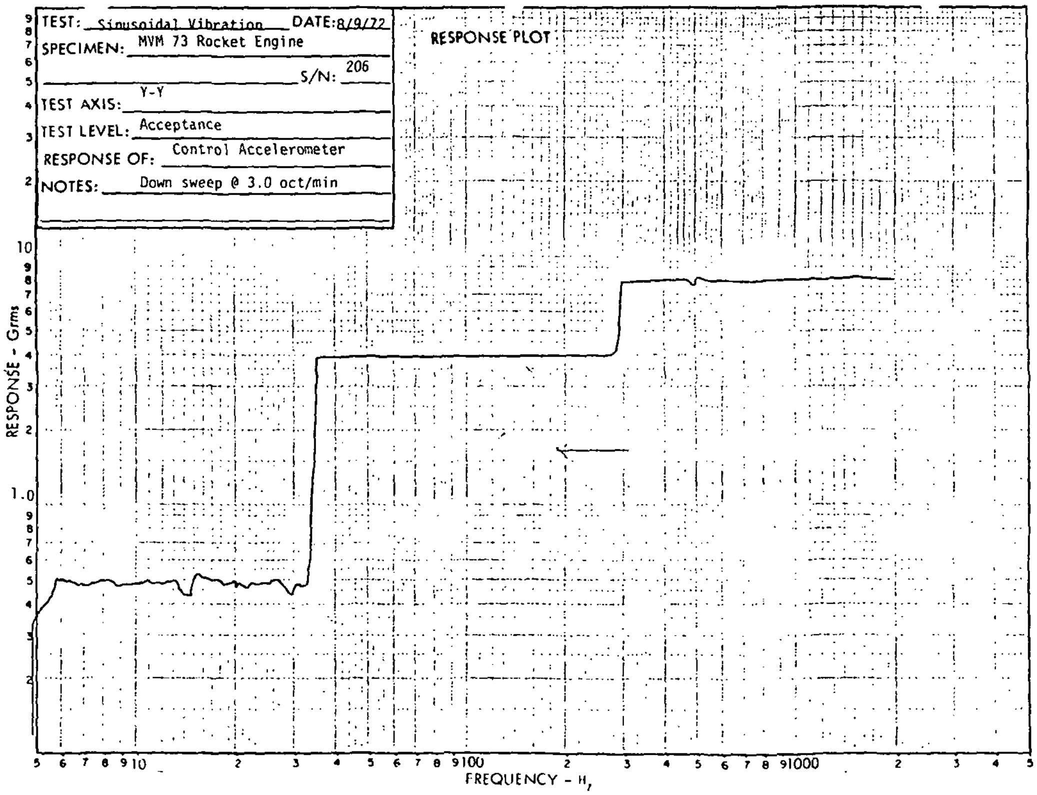

TEST: Sinusoidal Vibration DATE: 8/9/72
SPECIMEN: MVM 73 Rocket Engine
S/N: 206
TEST AXIS: Y-Y
TEST LEVEL: Acceptance
RESPONSE OF: Control Accelerometer
NOTES: Down sweep @ 3.0 oct/min

Figure 5-100

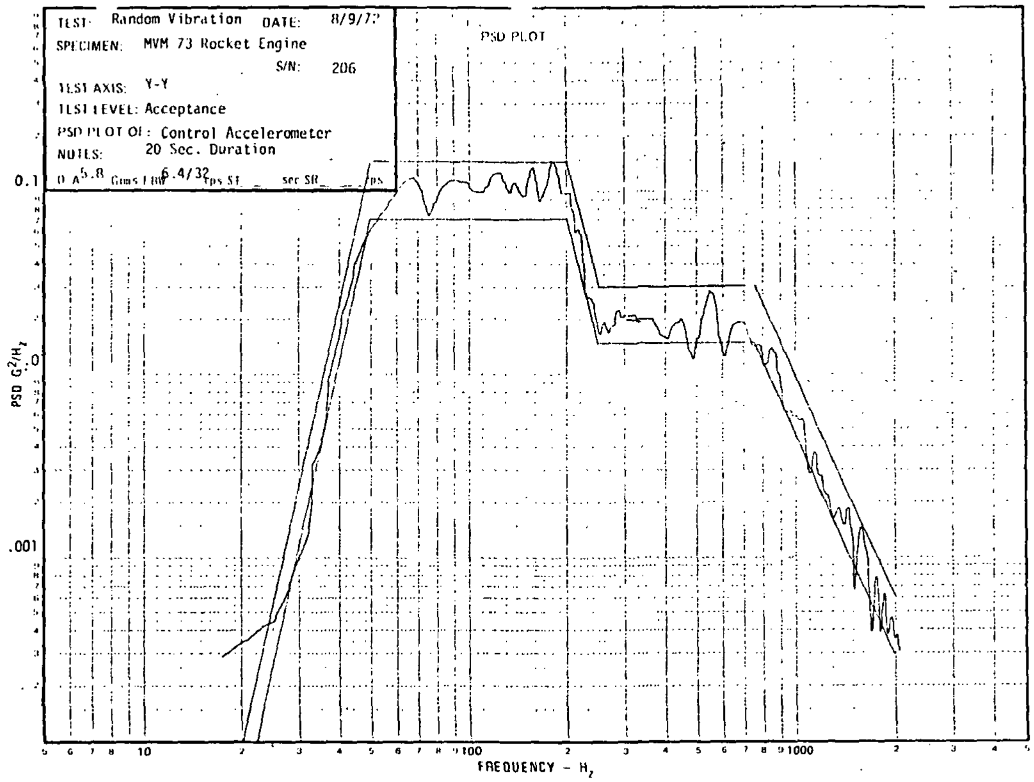

TEST: Random Vibration DATE: 8/9/72
SPECIMEN: MVM 73 Rocket Engine
S/N: 206
TEST AXIS: Y-Y
TEST LEVEL: Acceptance
PSD PLOT OF: Control Accelerometer
NOTES: 20 Sec. Duration
0 A 5.8 Grms EBW 6.4/32 cps ST _ sec SR _ cps

Figure 5-101

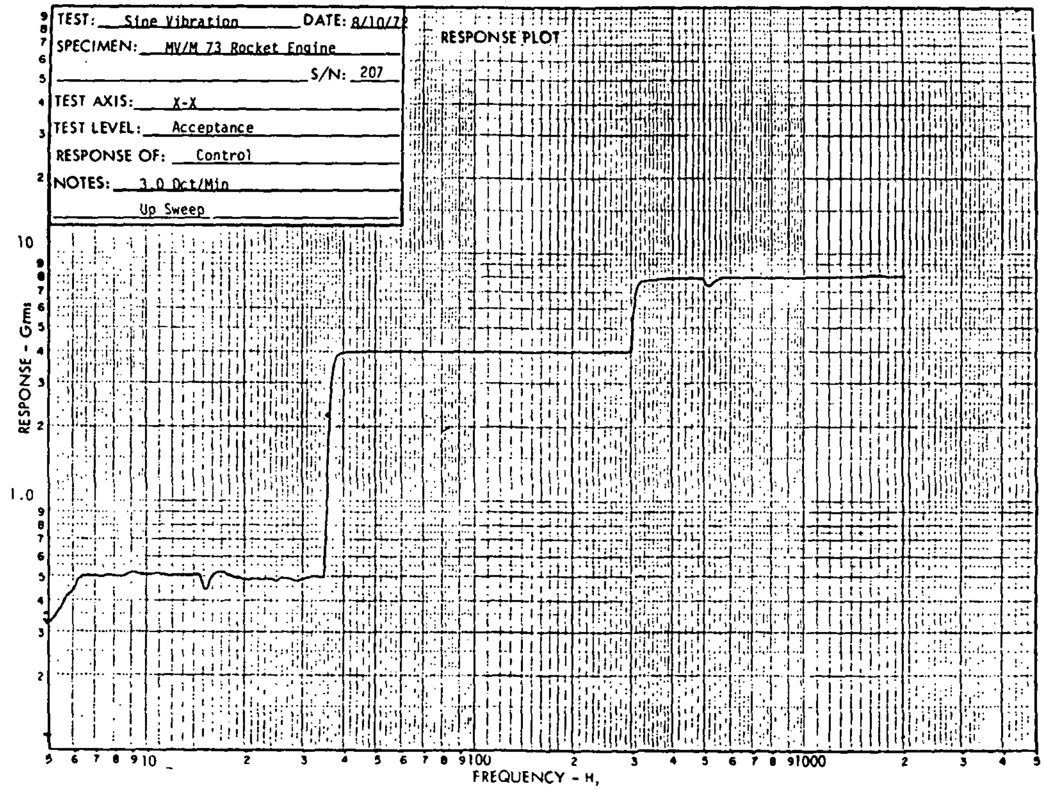
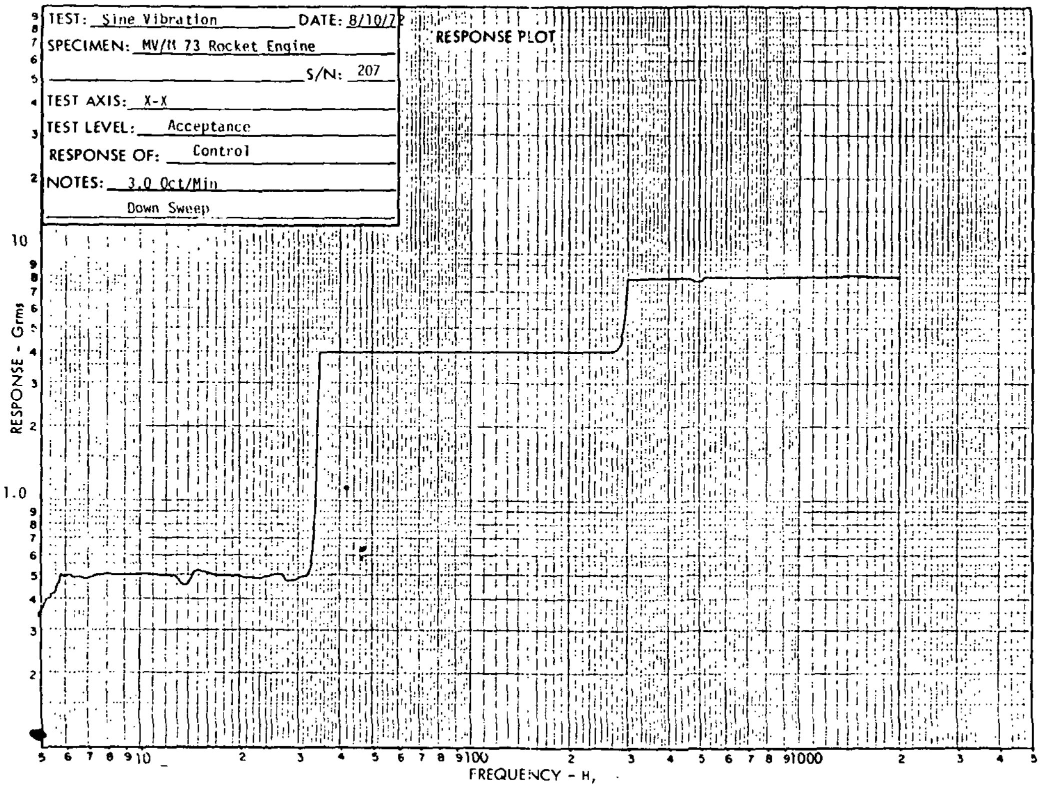

TEST: Sine Vibration DATE: 8/10/7
SPECIMEN: MV/M 73 Rocket Engine
S/N: 207
TEST AXIS: X-X
TEST LEVEL: Acceptance
RESPONSE OF: Control
NOTES: 3.0 Oct/Min
Up Sweep

Figure 5-102



TEST: Sine Vibration DATE: 8/10/72

SPECIMEN: MV/M 73 Rocket Engine

S/N: 207

TEST AXIS: X-X

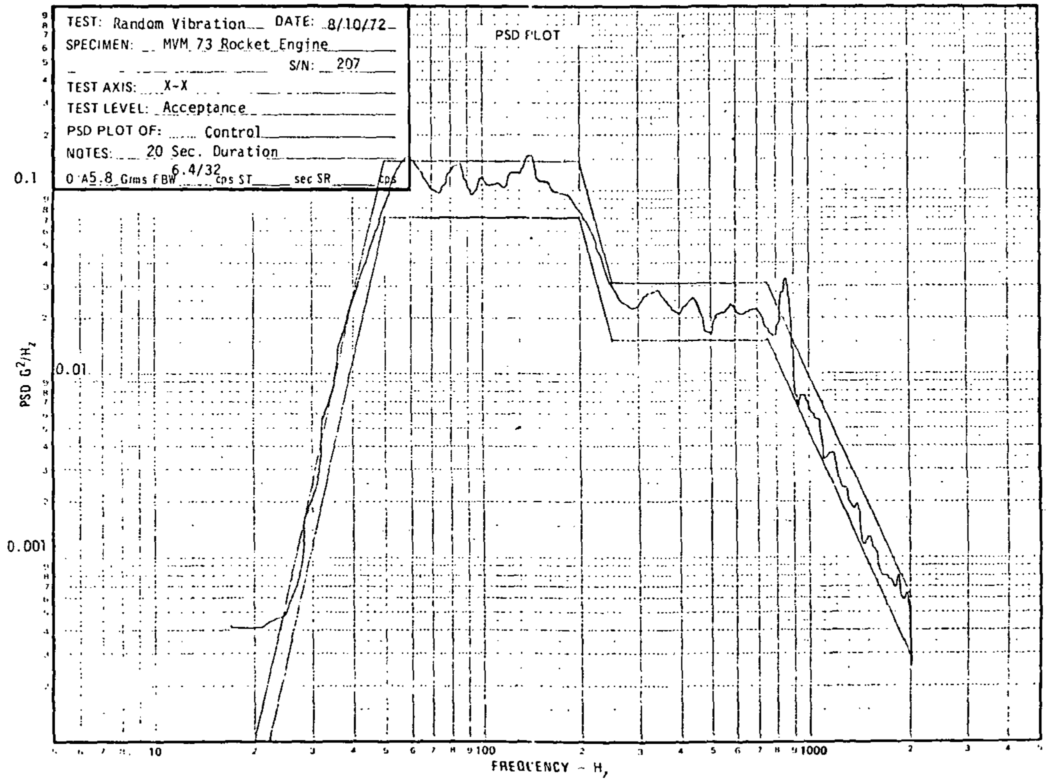
TEST LEVEL: Acceptance

RESPONSE OF: Control

NOTES: 3.0 Oct/Min

Down Sweep

Figure 5-103



TEST: Random Vibration DATE: 8/10/72

SPECIMEN: MVM 73 Rocket Engine

S/N: 207

TEST AXIS: X-X

TEST LEVEL: Acceptance

PSD PLOT OF: Control

NOTES: 20 Sec. Duration

0 A5.8 Grms FBW 6.4/32 cps ST sec SR cps

Figure 5-104

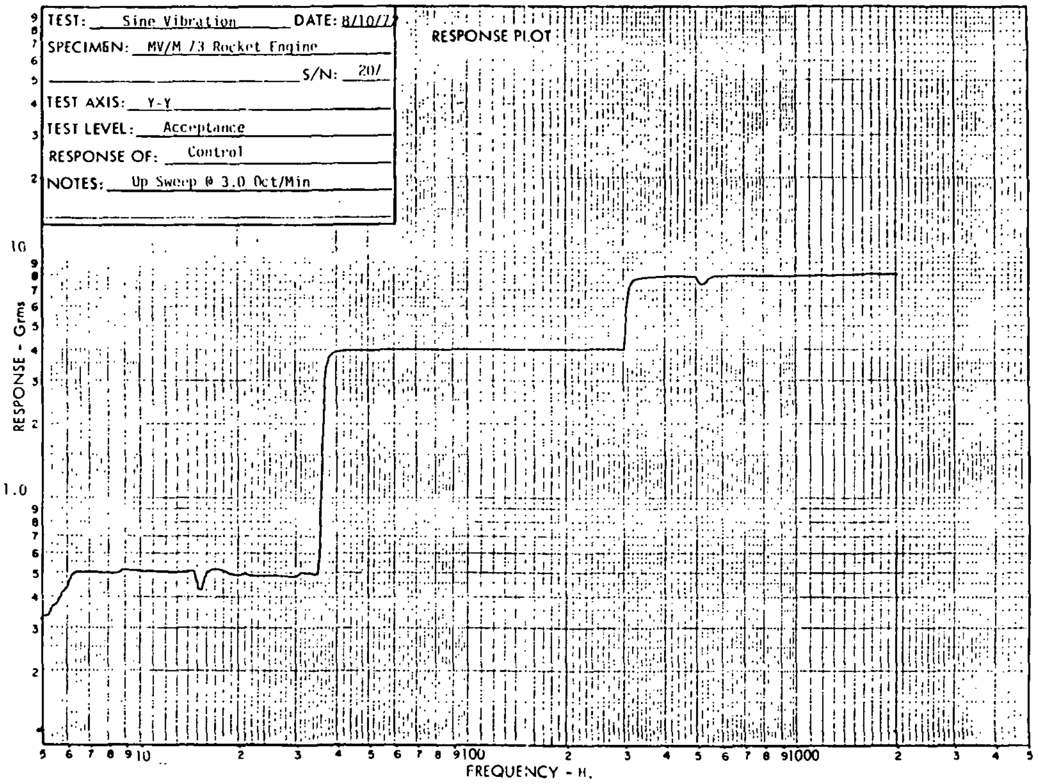

TEST: Sine Vibration DATE: 8/10/72
SPECIMEN: MV/M 73 Rocket Engine
S/N: 207
TEST AXIS: Y-Y
TEST LEVEL: Acceptance
RESPONSE OF: Control
NOTES: Up Sweep @ 3.0 Oct/Min

Figure 5-105

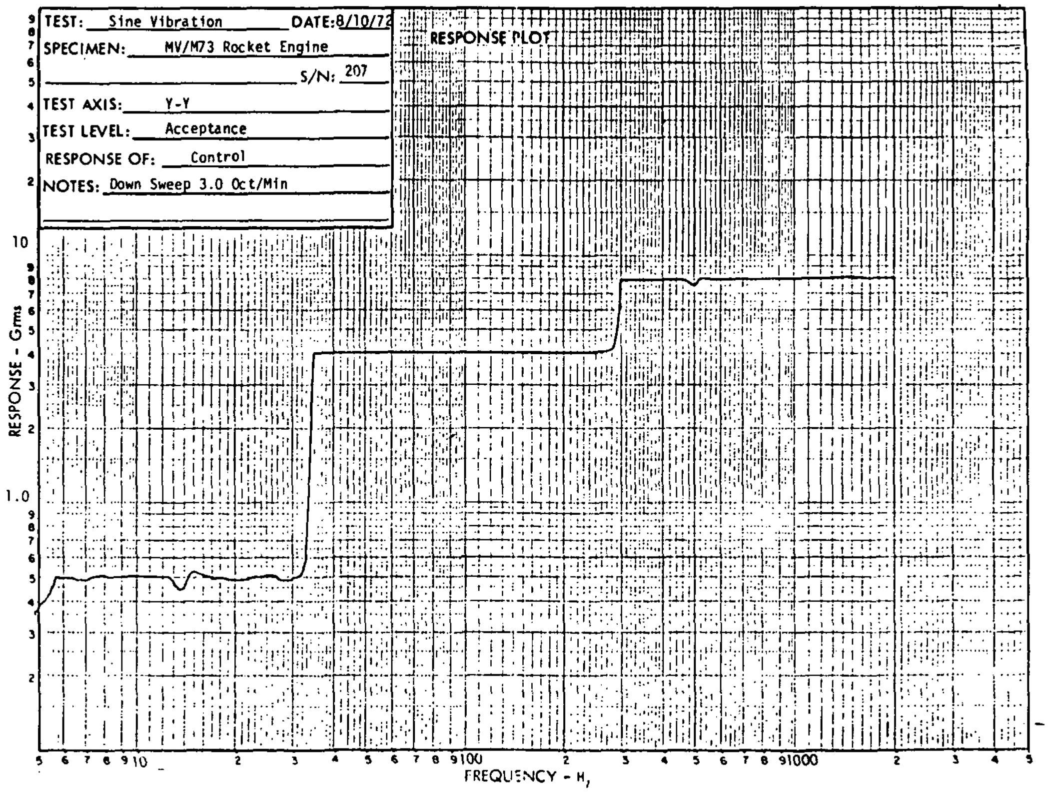

TEST: Sine Vibration DATE: 8/10/72
SPECIMEN: MV/M73 Rocket Engine
S/N: 207
TEST AXIS: Y-Y
TEST LEVEL: Acceptance
RESPONSE OF: Control
NOTES: Down Sweep 3.0 Oct/Min

Figure 5-106

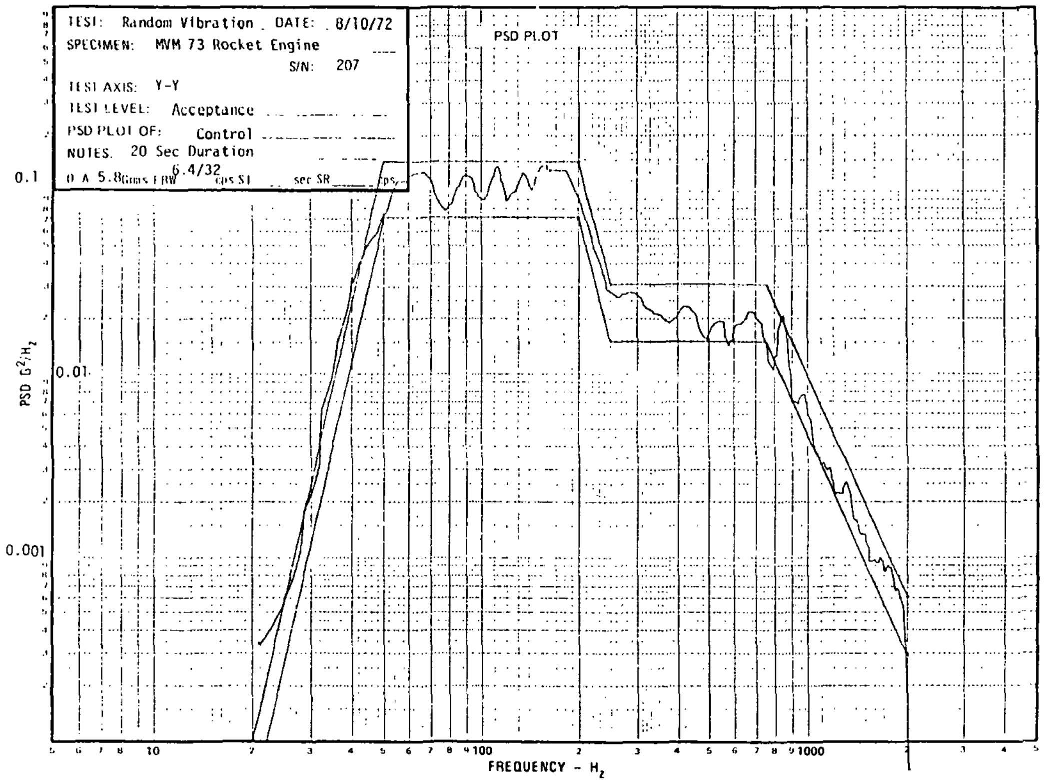

TEST: Random Vibration DATE: 8/10/72
SPECIMEN: MVM 73 Rocket Engine
S/N: 207
TEST AXIS: Y-Y
TEST LEVEL: Acceptance
PSD PLOT OF: Control
NOTES. 20 Sec Duration
O A 5.8Grms FBW 6.4/32 cps SI sec SR cps

Figure 5-107

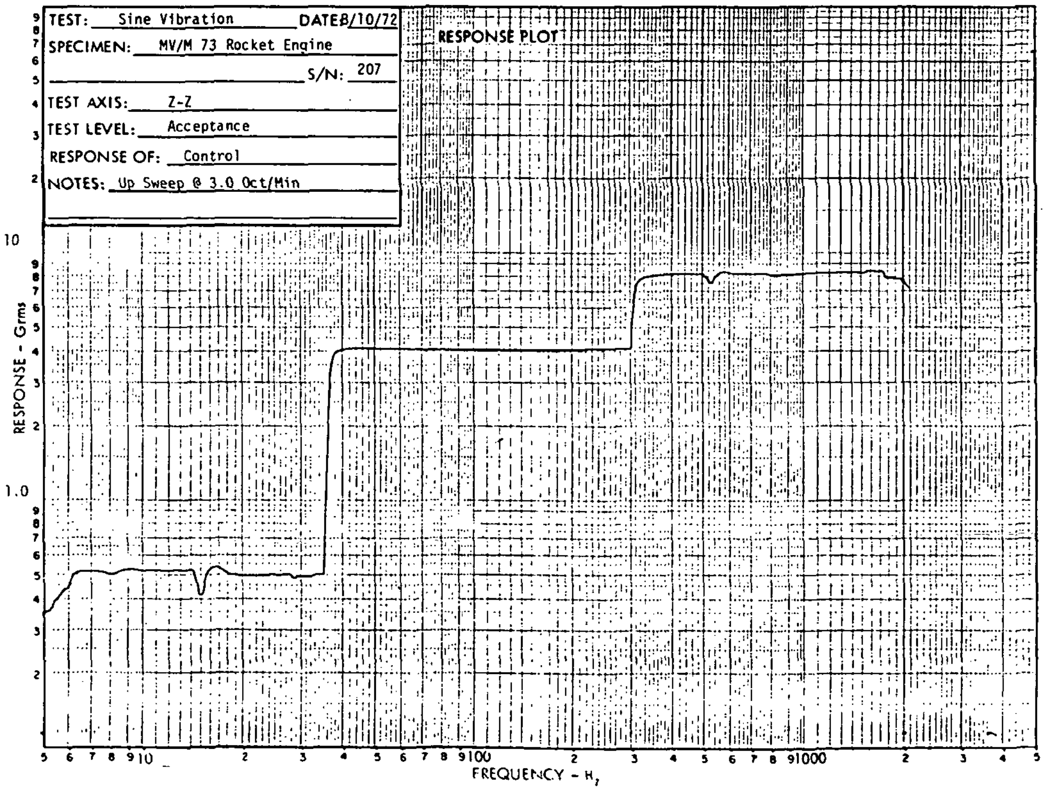
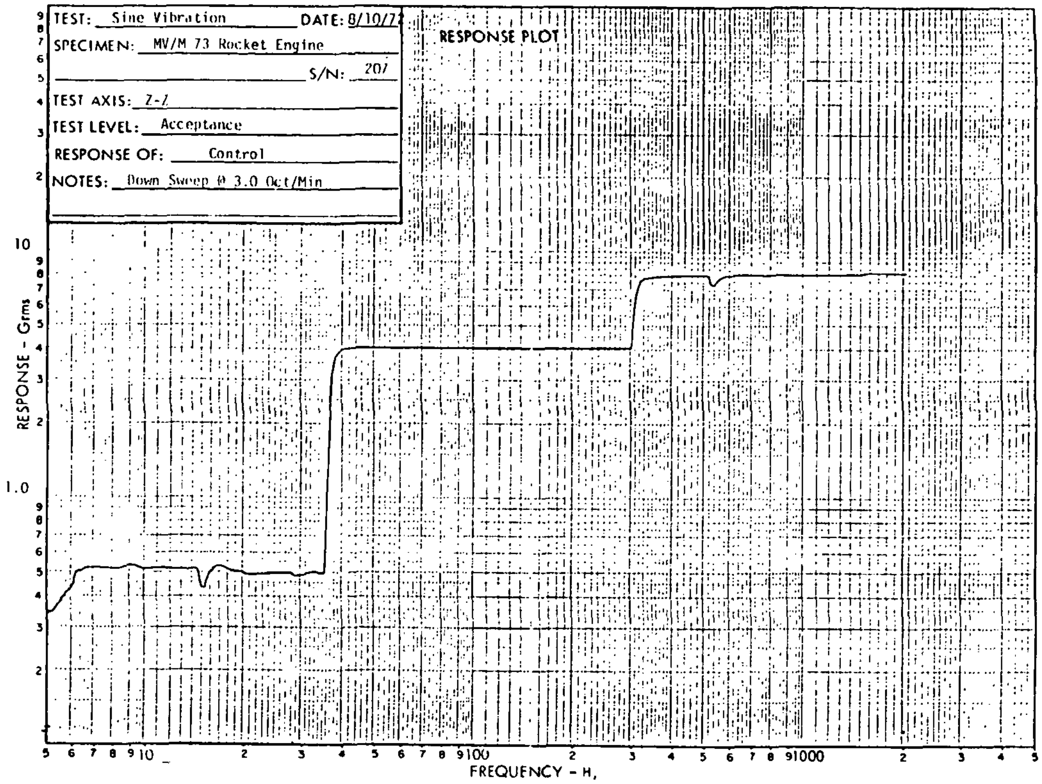

TEST: Sine Vibration DATE 8/10/72
SPECIMEN: MV/M 73 Rocket Engine
S/N: 207
TEST AXIS: Z-Z
TEST LEVEL: Acceptance
RESPONSE OF: Control
NOTES: Up Sweep @ 3.0 Oct/Min

Figure 5-108


TEST: Sine Vibration DATE: 8/10/72

SPECIMEN: MV/M 73 Rocket Engine

S/N: 207

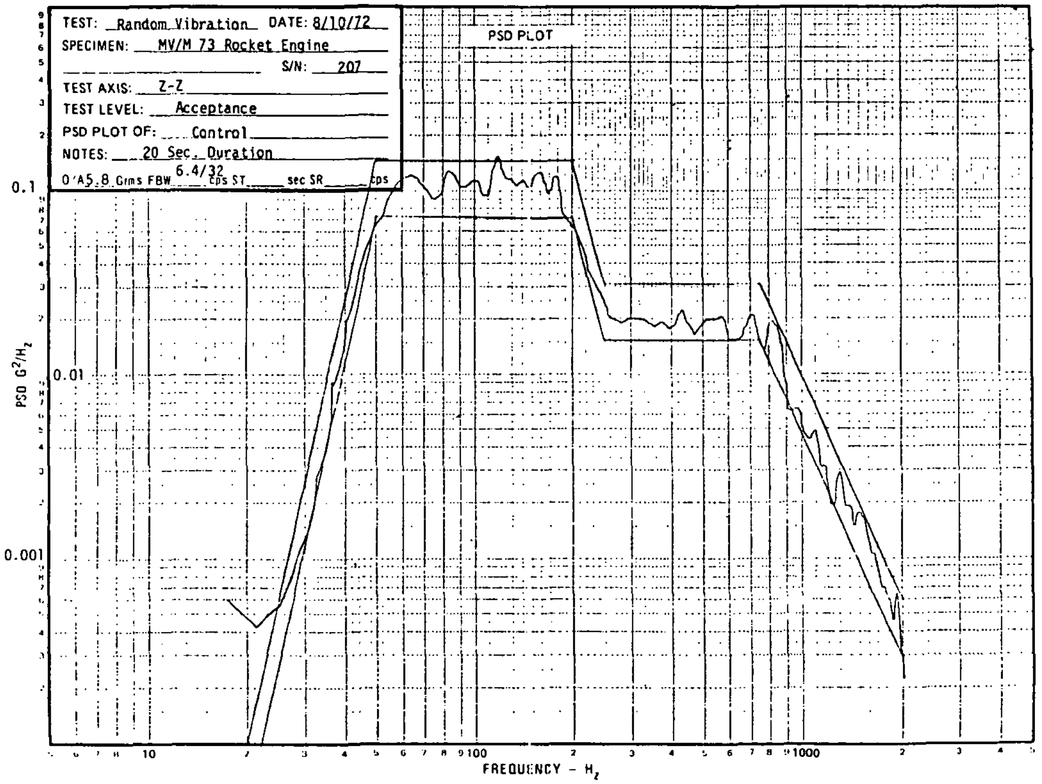
TEST AXIS: Z-Z

TEST LEVEL: Acceptance

RESPONSE OF: Control

NOTES: Down Sweep @ 3.0 Oct/Min

Figure 5-109


TEST: Random Vibration DATE: 8/10/72

SPECIMEN: MV/M 73 Rocket Engine

S/N: 207

TEST AXIS: Z-Z

TEST LEVEL: Acceptance

PSD PLOT OF: Control

NOTES: 20 Sec. Duration

O'A5.8 Grms FBW 6.4/32 cps ST____ sec SR____ cps

Figure 5-110

6. FLIGHT ACCEPTANCE HOT FIRE TESTS

6.1 TEST REQUIREMENT

The engine flight acceptance test requirement is as follows with the transition period from one thrust level to the next not greater than 5 seconds and with the engine at ambient temperature for start-ups:

	Test Duration (sec)	Chamber Pressure (psia)
	10	200 ± 5
Continuous Test	40	200 ± 5
	20	150 ± 5
	20	100 ± 5
	20	50 ± 5
	40	50 ± 5
Continuous Test	20	100 ± 5
	20	150 ± 5
	20	200 ± 5

To be accepted, in addition to structural survival of the tests, the engine must demonstrate characteristics of performance as specified as follows:

a) Specific impulse (F/W: Shall not be less than 228 lb_f - s/lb_m at 55 lb_f and 218.5_f - s/lb_m at 10 lb_f thrust, minimum specific impulse shall vary linearly between these limits.

b) Characteristic velocity (P_c. AT. G/W): Not less than 4100 ft/sec at any thrust level.

c) Engine roughness: Engine roughness shall not be greater than 10 percent of chamber pressure for chamber pressure oscillations of less than 50 Hz at any thrust level; and shall not be greater than 5 percent of chamber pressure for chamber pressure oscillations of 50 Hz or greater at any thrust level.

6.2 TEST INSTALLATION

The FA hot firing tests were conducted at the TRW Systems Capistrano Test Site in the High Energy Propellant Test Stand (HEPTS). The HA3A test cell was used and the testing was conducted in accordance with Procedure JPL EP-507026.

Each engine was assembled with insulation (Part No. 10000908-1 and 10000908-2), thrust vector control support (Part No. 10000936-2), propulsion subsystem thrust plate (Part No. 10040182) and mounted in the altitude test cell. The pressure in the test cell was maintained continuously at less than 0.16 lb/in^2 one hour before, during, and at least 10 hours after each test. The test setup schematic for the acceptance test is shown in Figure 6-1. The instrumentation used for the test is shown in Figure 6-2.

A pictorial view of the thrust stand used for the engine tests is shown in Figure 6-3. Photos of the thrust stand with an engine installed is shown in Figure 6-4.

Three JPL furnished drums of hydrazine were used throughout the entire TA and FA test program. The hydrazine analysis for each of these drums is shown in Figure 6-5. Prior to each engine start fuel samples were taken and filed for future analysis if required.

6.3 FLIGHT ACCEPTANCE TEST DATA

Presented in Figures 6-6 through 6-11 is a summary of the steady state hot fire acceptance test data obtained from each flight engine. The parameters included in the summary are: inlet pressure, vacuum thrust, chamber pressure, fuel flow rate, propellant temperature, characteristic exhaust velocity (C-star) vacuum specific impulse and vacuum thrust coefficient. In addition, engine roughness (peak-to-peak high range chamber pressure) and catalyst bed resistance are also presented as a measure of overall engine operation during each test. The parameters presented, with the exception of roughness, for each data slice were averaged over a five second span with the midpoint at the indicated slice time.

A number of adjustments were made to the "as measured" data. These include: correction of thrust and chamber pressure for transducer zero shift, correction of measured throat area for thermal expansion, correction of valve and injector water flow calibration data for differences between water and hydrazine density, differences between calibration and hot fire test propellant temperature conditions, and an adjustment for an apparent bias in the water flow calibration data indicated by the re-water flowing of injector S/N 208. The adjustments were made to the "as measured" data by the following procedures:

- Zero shift — The zero levels for thrust (uncorrected) and chamber pressure were determined by averaging the post-test levels over a five second span beginning 10 seconds after the end of each test. These values were then subtracted from the thrust (vacuum) and chamber pressure to correct for zero shift.

- Throat area correction — The as measured throat area was corrected for thermal expansion by a JPL supplied equation as a function of measured throat temperature.

$$A_T = 0.9925\ A_{TC} + 2\ [(0.9925\ A_{TC})(B + CT_T + DT_T^{\ 2})(T_T - 70)]$$

where:

A_T = throat area

A_{TC} = throat area calculated with temperature of 70°F

$B = 6.67 \times 10^{-6}$

$C = 1.19 \times 10^{-9}$

$D = 1.75 \times 10^{-13}$

T_T = throat temperature, °F

- Water flow calibration correction — The water flow bench pressure drop data were corrected to the actual hot fire test conditions by multiplying the water flow pressure drop by the ratio of the density of water at 70°F to the density of hydrazine at the hot fire test conditions.

- Water flow measurement bias correction — The "as measured" water flow pressure drop data for all valve injector combinations were adjusted by an equation developed from the two series of calibrations conducted with injector S/N 208. The pressure drop correction equation is:

$$\Delta P_{corr} = -0.10898\ \dot{w} + 1.0324$$

ΔP_{corr} = ratio of corrected to original valve/injector pressure drop

$\dot{w}$ = water flow rate, lbm/sec

This factor represents the change observed for S/N 208 valve/injector combination and was used as a multiplier to adjust all the valve/injector pressure drops.

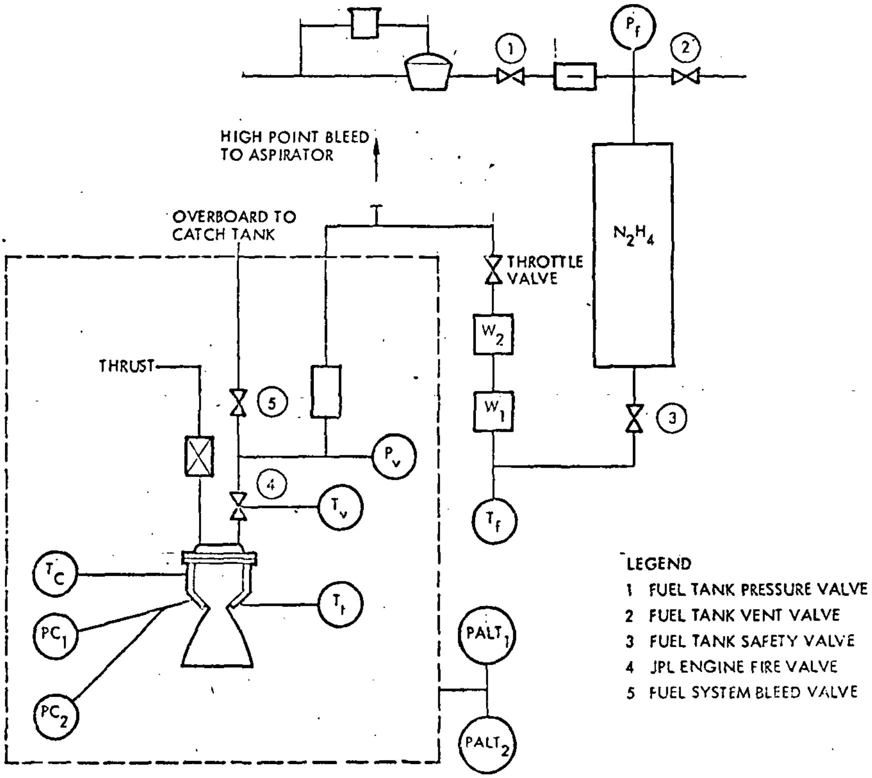


Figure 6-1. Test Setup for Engine Hot Fire Tests

Parameter	Range	Recorder
Pressure Fuel Tank (P_f)	0-750 psig	Speedomax/Oscillograph/Digital
Pressure Fuel Valve Inlet (P_v)	0-750 psig	Speedomax/Oscillograph/Digital
Chamber Pressure (P_{c-1})	0-300 psig	Speedomax/Oscillograph/Digital
Chamber Pressure (P_{c-2})	0-20 psig	Speedomax/Oscillograph/Digital
Thrust (F_1)	0-75 lb	Speedomax/Oscillograph/Digital
Thrust (F_2)	0-75 lb	Speedomax/Oscillograph/Digital
Fuel Flow Rate ($\dot{w}$-1)	0-0.4 lb/sec	Speedomax/Oscillograph/Digital
Fuel Flow Rate ($\dot{w}$-2)	0-0.4 lb/sec	Speedomax/Oscillograph/Digital
Cell Pressure (P_{alt-1})	0-1 psia	Speedomax/Oscillograph/Digital
Cell Pressure (P_{alt-2})	0-5 psia	Speedomax/Oscillograph/Digital
Throat Temperature (T_t)	32-2000°F	Speedomax/Digital
Chamber Temperature (T_c)	32-2000°F	Speedomax/Digital
Fuel Temperature (T_f)	32-150°F	Speedomax/Digital
Valve Temperature (T_v)	32-150°F	Speedomax/Digital
Thrust Plate Temperature (T_p)	32-500°F	Speedomax/Digital
Injector Temperature (T_1)	32-1800°F	Speedomax/Digital
Injector Temperature (T_2)	32-1000°F	Speedomax/Digital
Injector Temperature (T_3)	32-1000°F	Speedomax/Digital
Injector Temperature (T_4)	32-1000°F	Speedomax/Digital

Figure 6-2. Instrumentation Used for MV/M 73 REA FA Tests

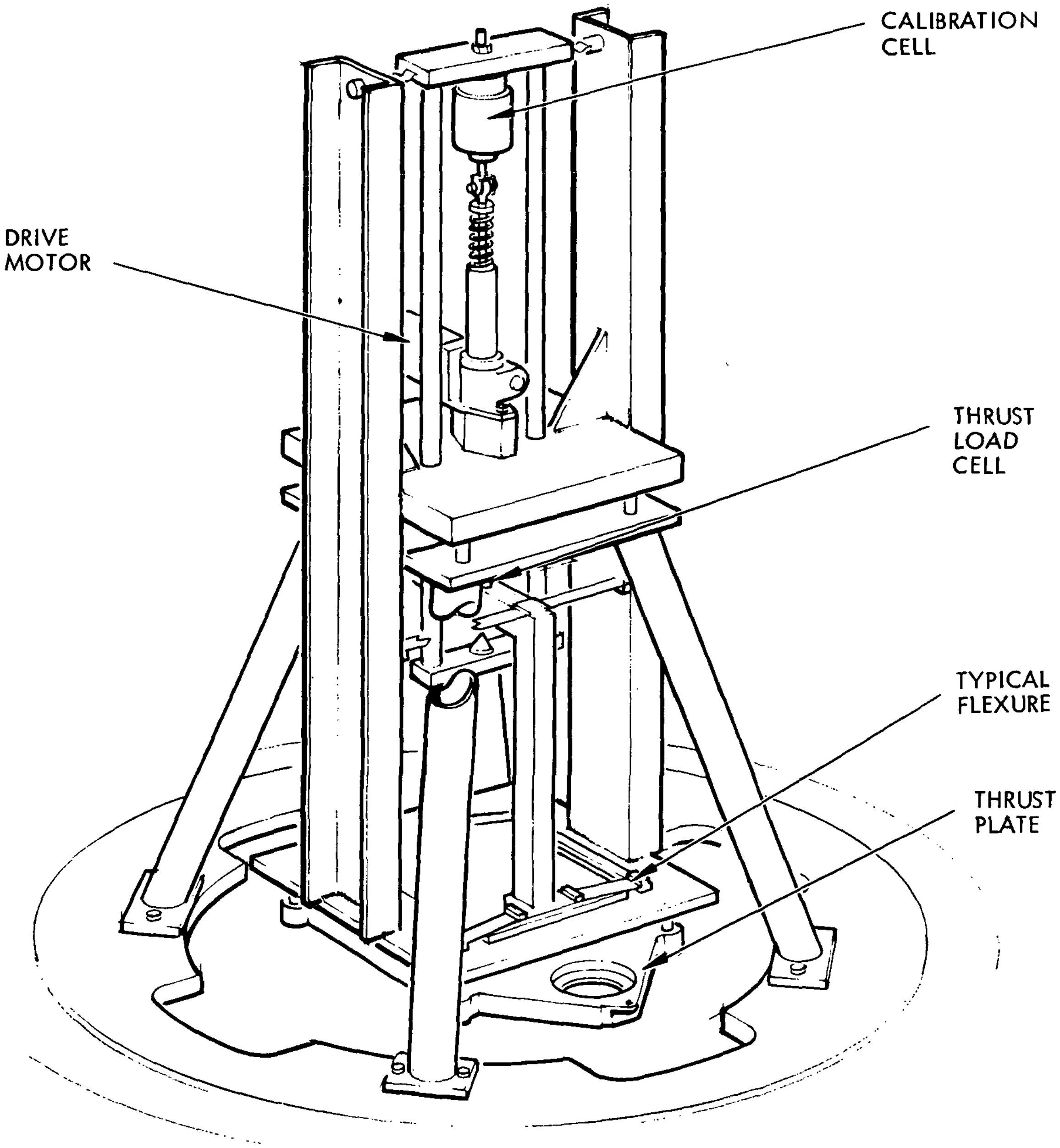


Figure 6-3. MV/M 73 Thrust Stand

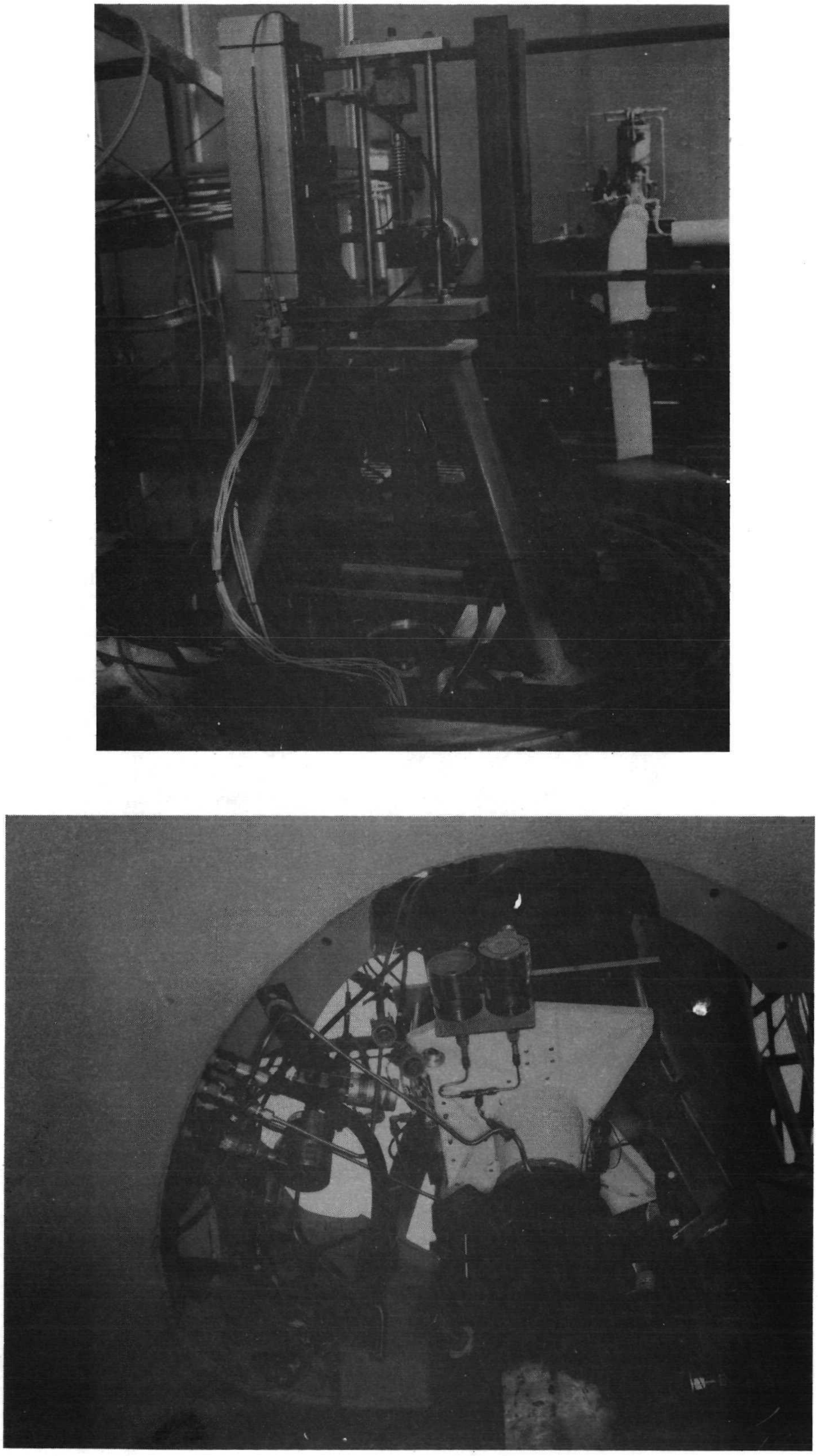


Figure 6-4. MV/M 73 REA Thrust Stand in HA3A Test Cell

Sample Source		DRUM NO. H. 3077	DRUM NO. H. 2581	DRUM NO. H. 2011
Sample Code No.		10-852	10-858	None
Sampling Date		4-18-72	5-11-72	7-31-72
Date Received		4-18-72	5-11-72	7-31-72
<u>Results</u>	Spec. Limits			
Density at 77°F, g/ml	NR	1.0042	1.0044	1.0047
Water, % by G.L.P.C.	1.5 max	Trace	Trace	0.51
Hydrazine Assay, %	98 min	100.0	100.0	99.25
Particulate, mg/l	10 max	<0.5	<0.5	<0.5
Particle Size Distribution per 100 ml	NR*			
6 - 10 micron		210	418	420
11 - 25 micron		85	290	280
26 - 50 micron		20	140	115
51 - 100 micron		5	15	27
101 - 250 micron		0	1	1
Fibers		0	0	0

NR* = Not Required

Figure 6-5. MV/M REA Hydrazine Analysis

ENGINE S/N 201

TEST NO./ SLICE NO.	DURATION sec	SLICE TIME sec	INLET PRESS. psia	THRUST lb_f	CHAMBER PRESSURE psia	FUEL FLOW RATE lbm/sec	ROUGHNESS % pc*	PROP. TEMP. deg. F	THROAT AREA in	CATALYST BED RESISTANCE	C-STAR ft/sec	I_{SP} $\frac{lbf/sec}{lbm}$	C_F
80	10			CHECK OUT TEST - NO PERFORMANCE DATA									
81-1	40	37.4	410	52.79	202.26	0.2294	6/4	71.8	0.1523	0.0515	4320	230.1	1.714
81-2	20	56.9	270	38.62	148.39	0.1687	7/4	71.7	0.1522	0.0519	4307	228.9	1.710
81-3	20	75.3	166	26.24	101.63	0.1160	8/4	71.8	0.1521	0.0529	4287	226.2	1.698
81-4	20	97.9	78	13.59	53.42	0.0617	10/5	72.0	0.1519	0.0575	4231	220.3	1.675
82-1	55	37.8	83	14.20	55.68	0.0642	10/5	69.9	0.1518	0.0600	4236	221.2	1.680
83-1	40	36.4	173	26.86	104.67	0.1194	9/4	69.5	0.1521	0.0537	4290	225.0	1.687
83-2	20	56.9	272	38.66	149.43	0.1698	8/4	69.4	0.1522	0.0520	4309	227.7	1.700
83-3	20	76.35	409	52.63	202.09	0.2295	5/4	69.5	0.1524	0.0508	4318	229.3	1.709

*FIRST VALUE IS FOR FREQUENCIES LESS THAN 50 CPS, SECOND VALUE IS FOR FREQUENCIES GREATER THAN 50 CPS.

Figure 6-6. MVM'73 Flight Acceptance Test Data Summary

ENGINE S/N 203

TEST NO./ SLICE NO.	RUN DURATION sec	SLICE TIME sec	INLET PRESS. psia	THRUST lb_f	CHAMBER PRESSURE psia	FUEL FLOW RATE lbm/sec	ROUGHNESS % pc	PROP. TEMP. deg. F	THROAT AREA in	CATALYST BED RESISTANCE	C-STAR ft/sec	I_{SP} $\frac{lbf/sec}{lbm}$	C_F
73	10			CHECK OUT TEST - NO PERFORMANCE DATA									
74-1	40	35.7	401	52.91	203.42	0.2299	3.0	70.6	0.1525	0.0382	4341	230.1	1.706
74-2	20	57.2	277	39.90	154.39	0.1746	4.0	70.6	0.1524	0.0423	4336	228.5	1.696
74-3	20	75.7	168	26.74	104.48	0.1186	5.6	70.7	0.1523	0.0446	4316	225.6	1.680
74-4	20	97.2	72	12.77	50.46	0.0579	9.5	70.4	0.1521	0.0525	4264	220.6	1.664
75	10			TEST ABORTED - NO PERFORMANCE DATA									
76-1	40	37.8	77	13.64	53.56	0.0617	8.9	69.1	0.1520	0.0513	4245	221.1	1.675
76-2	20	57.2	166	26.54	103.00	0.1172	4.9	70.2	0.1522	0.0445	4304	226.5	1.693
76-3	20	77.7	276	39.92	153.87	0.1743	4.5	70.6	0.1524	0.0413	4329	229.0	1.702
76-4	20	97.2	407	53.78	206.06	0.2330	3.2	71.0	0.1526	0.0359	4342	230.8	1.710

Figure 6-7. MVM'73 Flight Acceptance Test Data Summary

ENGINE S/N 204

TEST NO./ SLICE NO.	DURATION sec	SLICE TIME sec	INLET PRESS. psia	THRUST lbf	CHAMBER PRESSURE psia	FUEL FLOW RATE lbm/sec	ROUGHNESS % pc*/cps	PROP. TEMP. deg. F	THROAT AREA in	CATALYST BED RESISTANCE	C-STAR ft/sec	I_{SP} $\frac{\text{lbf/sec}}{\text{lbm}}$	C_F
106	10			CHECK OUT TEST - NO PERFORMANCE DATA									
107-1	40	37.4	397	52.05	206.06	0.2284	3/20 3/120	68.6	0.1524	0.0386	4337	227.9	1.690
107-2	20	56.9	269	38.64	150.81	0.1707	7/30 3/130	68.7	0.1522	0.0439	4326	226.4	1.683
107-3	20	75.3	167	26.31	103.51	0.1175	9/20 3/140	68.7	0.1521	0.0484	4311	223.9	1.671
107-4	20	97.9	74	12.72	51.09	0.0586	12/15 5/130	68.9	0.1519	0.0596	4261	217.1	1.639
108-1	40	37.4	73	12.72	50.79	0.0584	10/15 5/120	68.7	0.1518	0.0584	4247	217.8	1.650
108-2	20	56.9	169	26.84	104.88	0.1190	8/20 4/130	68.7	0.1521	0.0461	4313	225.5	1.682
108-3	20	75.3	263	38.38	148.35	0.1682	9/25 3/140	68.7	0.1523	0.0421	4322	228.2	1.699
108-4	20	97.9	399	52.77	202.91	0.2291	6/30 3/130	68.8	0.1524	0.0381	4343	230.4	1.706

*FIRST VALUE IS FOR FREQUENCIES LESS THAN 50 CPS, SECOND VALUE IS FOR FREQUENCIES GREATER THAN 50 CPS.

Figure 6-8. MVM'73 Flight Acceptance Test Data Summary

ENGINE S/N 205

TEST NO./ SLICE NO.	DURATION SEC	SLICE TIME sec	INLET PRESS. psia	THRUST lbf	CHAMBER PRESSURE psia	FUEL FLOW RATE lbm/sec	ROUGHNESS % pc*/cps	PROP. TEMP. deg. F	THROAT AREA in	CATALYST BED RESISTANCE	C-STAR ft/sec	I_{SP} $\frac{lbf/sec}{lbm}$	C_F
109	10	CHECK OUT TEST - NO PERFORMANCE DATA											
110-1	40	37.4	396	53.72	205.44	0.2320	3/40 2/120	70.0	0.1521	0.0277	4334	231.6	1.719
110-2	20	56.9	270	39.98	153.74	0.1739	4/35 2/120	70.0	0.1520	0.0348	4323	229.9	1.711
110-3	20	75.3	165	26.79	103.87	0.1179	5/30 3/120	70.1	0.1519	0.0420	4305	227.2	1.699
110-4	20	97.9	70	12.50	49.53	0.0568	8/25 5/120	70.0	0.1517	0.0536	4256	220.2	1.664
111-1	40	37.4	73	12.85	51.07	0.0589	10/25 5/130	67.9	0.1515	0.0516	4226	218.1	1.661
111-2	20	56.9	164	26.72	103.92	0.1183	5/35 3/120	68.3	0.1519	0.0386	4293	225.9	1.692
111-3	20	75.3	266	39.60	152.58	0.1729	6/40 4/140	68.5	0.1521	0.0321	4318	229.1	1.707
111-4	20	97.9	394	53.65	205.13	0.2322	4/45 2/120	68.8	0.1522	0.0244	4324	231.1	1.720

*FIRST VALUE IS FOR FREQUENCIES LESS THAN 50 CPS, SECOND VALUE IS FOR FREQUENCIES GREATER THAN 50 CPS.

Figure 6-9. MVM'73 Flight Acceptance Test Data Summary

ENGINE S/N 206

TEST NO./ SLICE NO.	DURATION sec	SLICE TIME sec	INLET PRESS. psia	THRUST lb_f	CHAMBER PRESSURE psia	FUEL FLOW RATE lbm/sec	ROUGHNESS % pc*	PROP. TEMP. deg.F	THROAT AREA in	CATALYST BED RESISTANCE	C-STAR ft/sec	I_{SP} $\frac{lbf/sec}{lbm}$	C_F
100	10	CHECK OUT TEST - NO PERFORMANCE DATA											
100-1	40	37.4	404	52.98	203.56	0.2305	4/2	69.8	0.1517	0.0463	4310	229.9	1.716
101-2	20	56.9	267	38.81	148.96	0.1690	8/4	69.8	0.1516	0.0503	4299	229.6	1.718
101-3	20	75.3	165	26.26	101.68	0.1158	7/4	69.8	0.1515	0.0533	4280	226.8	1.705
101-4	20	97.9	74	12.79	50.53	0.0583	9/5	69.9	0.1513	0.0631	4219	219.4	1.673
102-1	40	37.4	69	12.11	47.94	0.0554	10/5	70.5	0.1512	0.0610	4209	218.6	1.670
102-2	20	56.9	163	26.06	101.30	0.1152	5/4	70.3	0.1515	0.0540	4286	226.2	1.698
102-3	20	75.3	267	38.96	149.96	0.1698	8/4	70.1	0.1517	0.0478	4310	229.4	1.712
102-4	20	97.9	377	50.73	194.43	0.2200	5/4	70.0	0.1518	0.0444	4310	230.6	1.719

*FIRST VALUE IS FOR FREQUENCIES LESS THAN 50 CPS, SECOND VALUE IS FOR FREQUENCIES GREATER THAN 50 CPS.

Figure 6-10. MVM'73 Flight Acceptance Test Data Summary

ENGINE S/N 207

TEST NO./ SLICE NO.	DURATION sec	SLICE TIME sec	INLET PRFSS. psia	THRUST lbf	CHAMBER PRESSURE psia	FUEL FLOW RATE lbm/sec	ROUGHNESS % pc*	PROP. TEMP. deg. F	THROAT AREA in	CATALYST BED RESISTANCE	C-STAR ft/sec	I_{SP} $\frac{\text{lbf/sec}}{\text{lbm}}$	C_F
103	10			CHECK OUT TEST - NO PERFORMANCE DATA									
104-1	40	37.4	400	53.28	203.75	0.2306	6/3	69.05	0.1515	0.0495	4307	231.0	1.726
104-2	20	56.9	262	38.50	148.08	0.1678	7/4	69.09	0.1514	0.0521	4299	229.4	1.717
104-3	20	75.3	161	25.83	100.16	0.1139	6/4	69.13	0.1512	0.0561	4278	226.8	1.706
104-4	20	97.9	72	12.60	49.69	0.0572	10/5	68.98	0.1510	0.0629	4220	220.3	1.679
105-1	40	37.4	68	11.81	47.01	0.0543	12/5	70.13	0.1509	0.0636	4203	217.4	1.664
105-2	20	56.9	162	25.96	101.10	0.1150	5/4	69.97	0.1512	0.0547	4277	225.8	1.698
105-3	20	75.3	261	38.29	147.66	0.1673	7/3	69.93	0.1514	0.0517	4299	228.9	1.713
105-4	20	97.9	400	53.25	203.75	0.2304	5/3	69.93	0.1516	0.0495	4313	231.1	1.724

*FIRST VALUE IS FOR FREQUENCIES LESS THAN 50 CPS, SECOND VALUE IS FOR FREQUENCIES GREATER THAN 50 CPS.

Figure 6-11. MVM'73 Flight Acceptance Test Data Summary

The final correction to the catalyst bed resistance was initiated by a concern over the results of the water flow calibrations conducted on both S/N 0003 and S/N 0004 propellant valves. The results from both tests indicated a change in slope at the lower propellant flow rates (0. 15 to 0. 04 lbm/sec). This change in slope also corresponded to a change in slope of the calibration of the pressure transducer used for the original water flow calibrations of both valves and the valve/injector combinations through Engine S/N 207. A change to the water flow bench instrumentation and calibration method was then incorporated to improve the accuracy of the lower range data. A lower range (0 to 50 psia) pressure transducer was installed and was recorded for the lower range flow rates.

Then, following the calibration and hot fire testing of the final two units, a special calibration series using both propellant valves and injector S/N 208 was conducted to resolve any biases in the determination of pressure drop in either the valve or valve/injector water flow calibrations. In addition to using a lower range pressure transducer, the sensitivity of both the flow rate measurement and pressure measurement were expanded to gain significant digits. The results of the special calibration series on valve S/N 0004 shown in Figures 5-14 and 5-15 indicated the same change in slope observed in the original data. It is concluded, on the basis of this calibration that the change in slope observed during the valve calibrations was not due to instrumentation errors but is apparently a characteristic of the valve. This conclusion is further supported by the results of the valve/injector combination calibration which did not show a change in slope over the full range of flow rate. The recalibration of injector S/N 208 with valve S/N 0004 shown in Figures 5-33 and 5-34 did, however, exhibit a different pressure drop characteristic from the original calibration series. The increase in pressure drop ranged from approximately 3 percent at the low flow rates (0. 05 lbm/sec) to 0. 8 percent at the high flow rate (0. 24 lbm/sec).

The final resistance correction, then, was achieved by recalculation of the original valve/injector combination pressure drop during the ing the hot fire tests and correcting it by the observed change in injector S/N 208. The correction factor was applied for all the hot fire test data including the last two units (S/N 204 and S/N 205) even though some improvement to data acquisition was made prior to these tests. This is justified by the assertion that the final improvements to the recording system, initiated for the special calibration series, were the primary cause for the differences observed between the original and final calibrations conducted on injector S/N 208.

A review of the engine performance data (C-star, specific impulse, and thrust coefficient) presented in Figures 6-12 through 6-14 revealed that at least one specific impulse value for engines 204, 205, 206, and 207 fell below the minimum specification limit for the lowest inlet pressure (80 psia). Both values of specific impulse for engine S/N 204, however, were observed to be below the minimum specification limit. All of the characteristic exhaust velocity (C-star) values exceeded the specification minimum of 4100 ft/sec. Two out of specification roughness values were also observed. The first occurred during test 105 (engine 207) at the lowest inlet pressure level and exceeded the low frequency roughness specification ($\pm$ 10 percent) by 2 percent. The second occurred during test 107 (engine 204) also at the lowest inlet pressure level and exceeded the specification by the same amount. On the basis of the above it is recommended that a review of the specific impulse minimum requirement be initiated to determine if a lower specific impulse can be tolerated within the expected mission duty cycle constraints. If not, then engines S/N 205, 206, and 207 can only marginally be recommended based on the average of the two low inlet pressure tests. For flight use Engine S/N 204, which exhibited below average specific impulse throughout, can not be recommended for flight use.

A statistical summary of the steady state performance is shown in Figure 6-15. Included are the mean values and 3 sigma engine to engine scatter demonstrated by the six flight engines. Comparison of the engine-to-engine variations in specific impulse, thrust, C-star, chamber pressure and thrust coefficient demonstrated by the Mariner '69 flight engines to the MV/M '73 flight engines indicated, in general, a reduction in scatter from the Mariner '69 engines. The only exception being the scatter in vacuum thrust, which increased from 3.1 percent to 3.8 percent. The vacuum specific impulse scatter, however decreased from 1.7 to 1.1 percent.

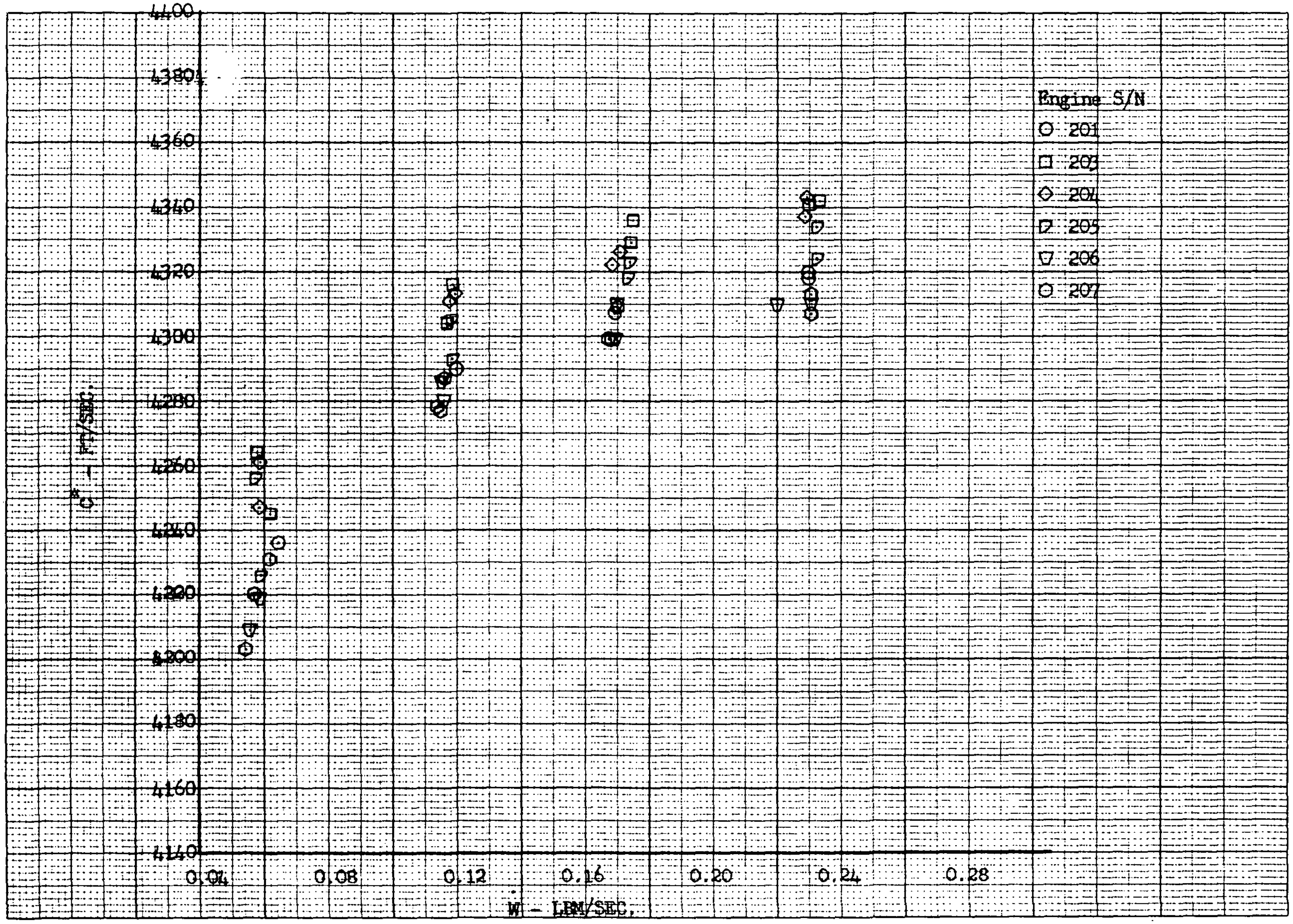


Figure 6-12. Flight Acceptance Engine Data

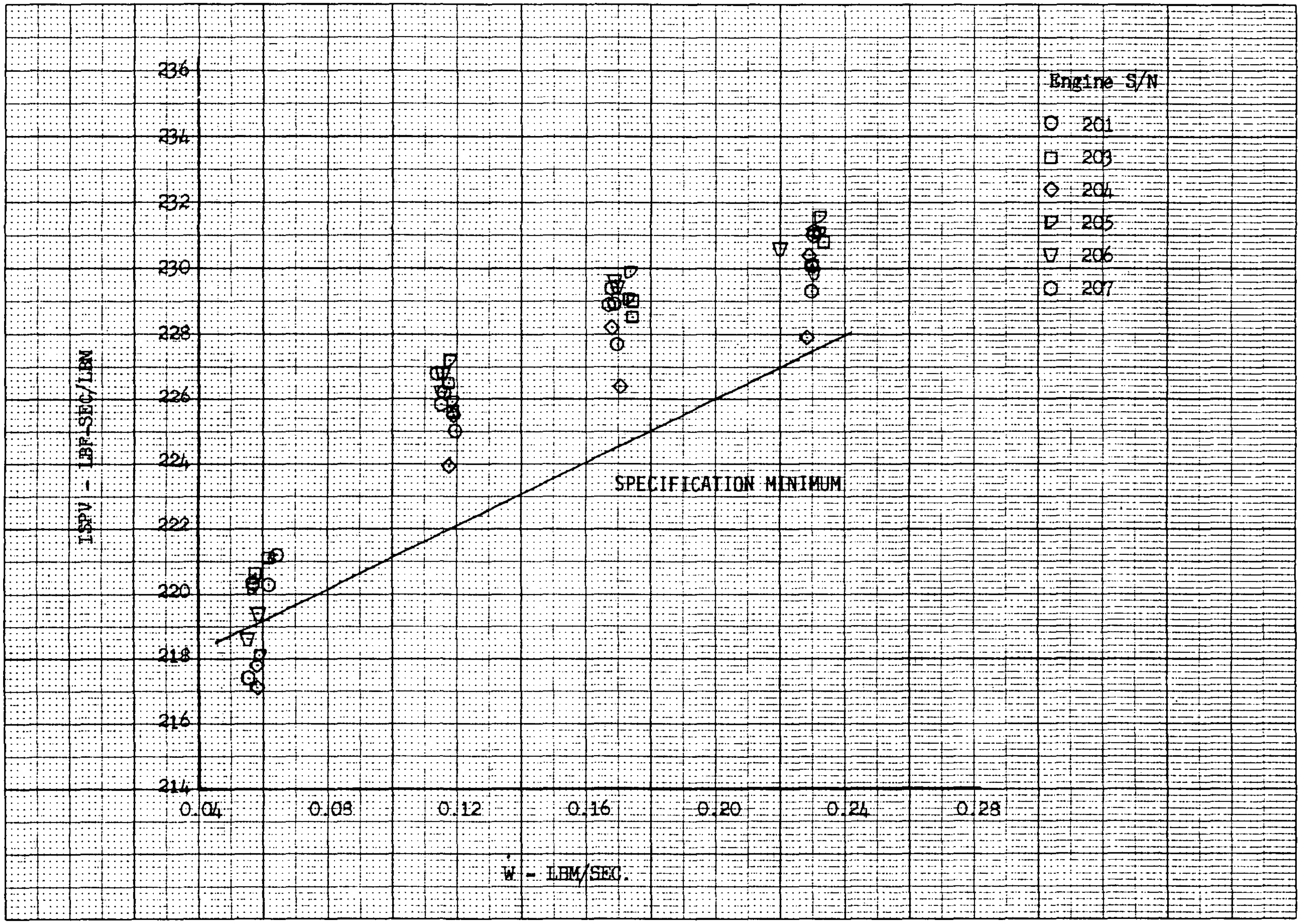


Figure 6-13. Flight Acceptance Engine Data

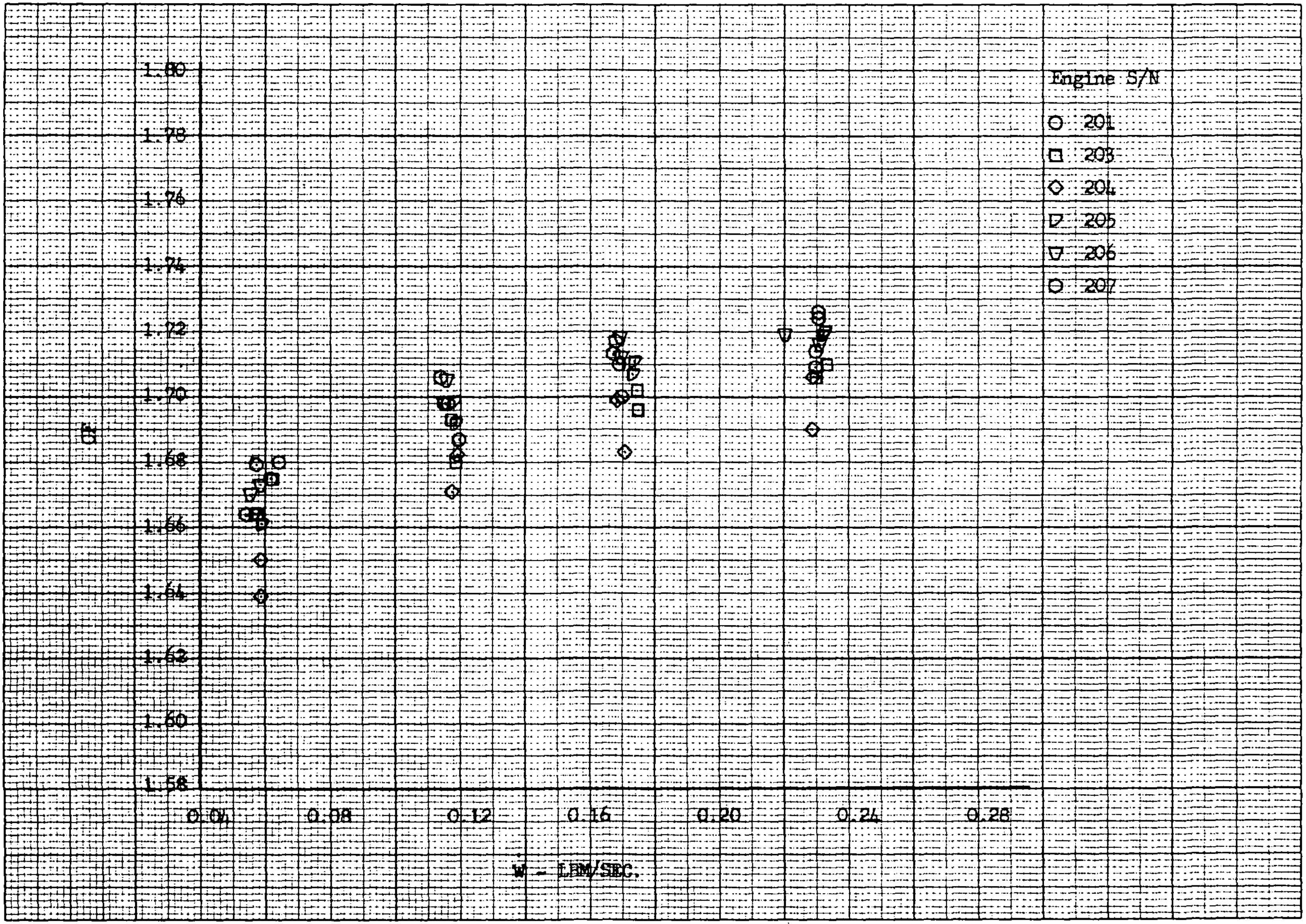


Figure 6-14. Flight Acceptance Engine Data

THRUST LEVEL	SPECIFIC IMPULSE		D.F.**	THRUST		D.F.	C-STAR		D.F.	CHAMBER PRESSURE		D.F.	THRUST COEFF.		D.F.**
	MEAN $\frac{\text{lbf-sec}}{\text{lbm}}$	3σ* %		MEAN lbf	3σ* %		MEAN ft/sec	3σ* %		MEAN psia	3σ* %		MEAN	3σ* %	
50	230.3	1.06	5	52.88	3.85	5	4325	0.99	5	203.28	3.32	5	1.714	1.68	5
40	228.8	1.12	5	39.02	5.10	5	4314	0.89	5	150.60	4.90	5	1.706	1.65	5
25	225.9	0.90	5	26.43	3.75	5	4295	0.99	5	102.85	4.23	5	1.692	1.76	5
12	219.3	1.78	5	12.86	14.2	5	4235	1.32	5	50.90	13.0	5	1.666	2.16	5

*Engine to engine variability
**Degrees of freedom

Figure 6-15. Statistical Summary of MVM'73 Engine Performance

A summary of the corrected catalyst bed resistance as a function of flow rate for all the flight engines is shown in Figure 6-16. Review of the data indicates a fairly wide range of resistances across the engine set especially at the high flow rate. Closer inspection reveals that the engines can be partitioned on the basis of catalyst bed resistance into like sets (e.g., S/N 203 and S/N 204). The only exception being S/N 205 which exhibited a grossly lower catalyst bed resistance especially at the middle to high flow rate range.

6.4 START-UP/SHUTDOWN ANALYSIS

Presented in Figures 6-17 to 6-22 are the results of the integration of the start-up thrust and chamber pressure and shutdown chamber pressure for all the Flight Acceptance engines. The integration was obtained digitally at a maximum sample rate of 2500 samples per second over the first 5 seconds and from shutdown to shutdown plus 10 seconds for each test. In addition, the shutdown integration of chamber pressure was obtained from both the high range pressure transducer and the low range transducer. The high range transducer was used from full steady state operation to the point where chamber pressure had decayed to 19 psia. The low range transducer was then used for integration until either chamber pressure decayed to less than capsule pressure or the time interval of approximately 40 seconds was reached. This technique was used to provide the maximum accuracy available for shutdown integration. The only corrections that were applied to these results were to adjust for thrust or chamber pressure zero shift and to correct the integration data to the true shutdown time recorded to the nearest millisecond by a digital voltmeter.

The oscillographs for each start-up and shutdown of every flight engine is shown in appendix B.

A statistical summary of the start-up and shutdown integration for all six flight engines is shown in Figure 6-23. A direct comparison of the start-up mean value and scatter at 50 pounds thrust to those demonstrated by the Mariner '69 engines is not possible due to the difference in defining the interval for start-up integration. The Mariner '69 start-up interval was defined as the time from valve signal to steady state chamber pressure minus 10 percent which averaged approximately one second. An

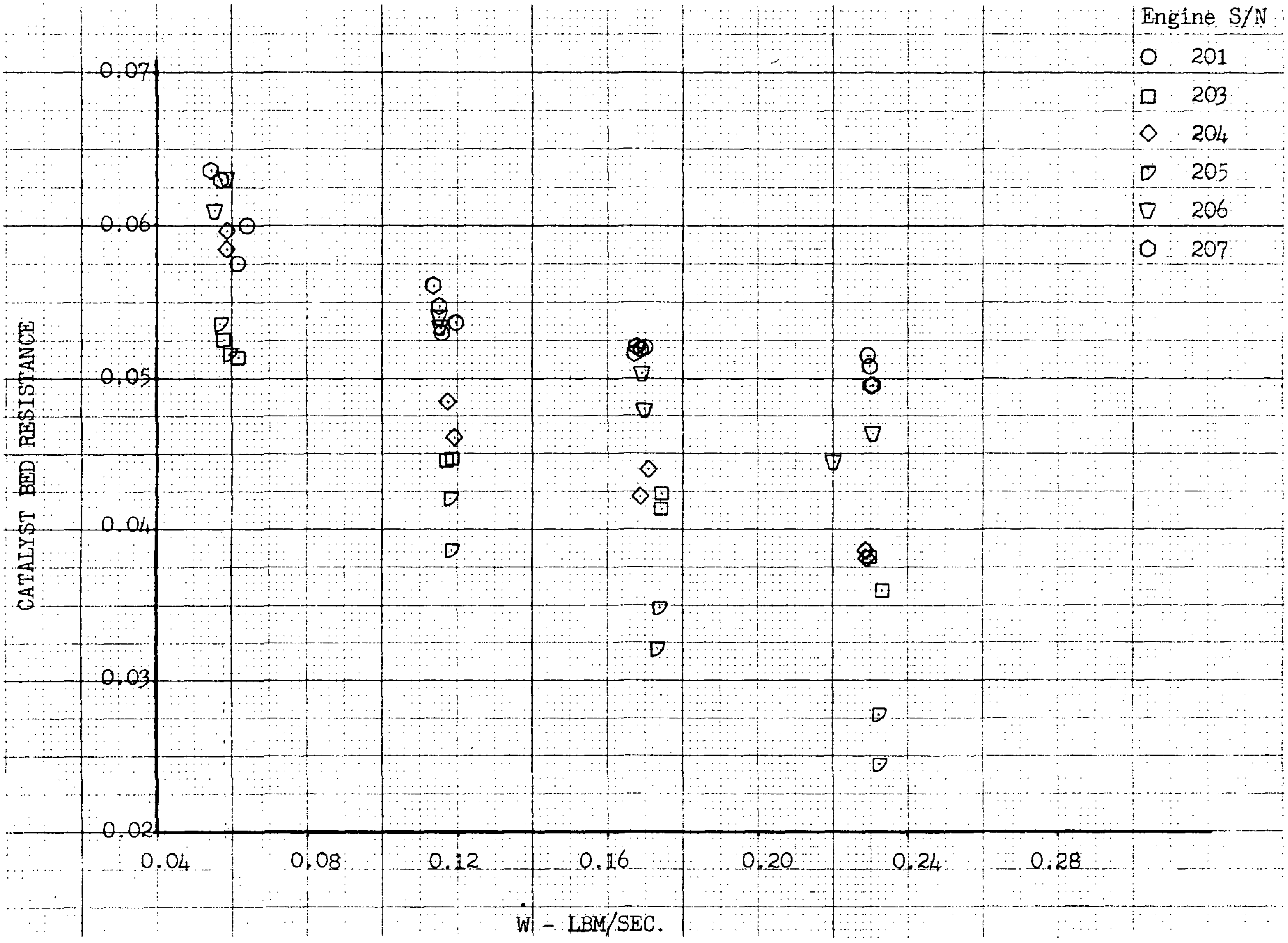


Figure 6-16. Flight Acceptance Engine Data

ENGINE S/N 201

TEST NO.	STARTUP					SHUTDOWN			
	LEVEL lbf	PTF* psia	INT. PC psia sec	INT. F lbf-sec	DUR. sec	TIME sec	LEVEL lbf	INT. PC psia sec	DUR. sec
080	50	494	967.9	252.0	5.082	9.992	50	16.38	42.975
081	50	494	967.7	249.0	5.082	99.979	12	9.17	37.864
082	12	92	248.3	63.3	5.082	-	-	-	-
083	26	495	456.8	117.5	5.069	80.004	50	15.73	35.797

*LOCKUP PRESSURE

Figure 6-17. MVM'73 Summary of Start-Up/Shutdown Integration

Engine S/N 203

START UP						SHUT DOWN			
TEST NO.	LEVEL lbf	PTF* psia	INT. PC psia sec	INT. F lbf-sec	DUR. sec	TIME sec	LEVEL lbf	INT. PC psia sec	DUR. sec
073	50	500	973.8	251.4	5.005	9.997	50	17.50	37.683
074	50	490	947.3	243.2	5.005	99.904	12	10.14	49.037
076	12	85	234.8	60.22	5.005	99.968	50	14.73	47.849

* Lock-up pressure

Figure 6-18. MVM'73 Summary of Start-Up/Shutdown Integration

ENGINE S/N 204

TEST NO.	START UP					SHUTDOWN			
	LEVEL lbf	PTF* psia	INT. PC psia sec	INT. F lbf-sec	DUR. sec	TIME sec	LEVEL lbf	INT. PC psia sec	DUR. sec
106	BAD DIGITAL TAPE - NO INTEGRATION DATA AVAILABLE								
107	50	495	972.4	246.9	5.082	100.001	12	11.40	40.914
108	12	80	226.4	57.3	5.082	100.001	50	15.93	40.914

*Lock-up pressure

Figure 6-19. MVM'73 Summary of Start-Up/Shutdown Integration

ENGINE S/N 205

TEST NO.	START UP					SHUTDOWN			
	LEVEL lbf	PTF* psia	INT. PC psia sec	INT. F lbf-sec	DUR. sec	TIME sec	LEVEL lbf	INT. PC psia sec	DUR. sec
109	50	485	974.8	252.2	5.082	9.989	50	16.68	39.906
110	50	485	985.7	254.3	5.082	99.976	12	9.10	40.939
111	12	80	228.0	57.6	5.-82	100.001	50	13.76	38.866

* Lock-up pressure

Figure 6-20. MVM'73 Summary of Start-Up/Shutdown Integration

ENGINE S/N 206

	START UP					SHUTDOWN			
TEST NO.	LEVEL lbf	PTF* psia	INT. PC psia sec	INT. F lbf-sec	DUR. sec	TIME sec	LEVEL lbf	INT. PC psia sec	DUR. sec
100	50	495	985.7	255.1	5.082	9.990	50	13.61	28.628
101	50	494	981.3	253.0	5.082	99.977	12	7.49	35.793
102	12	76	211.1	53.6	5.982	100.015	50	17.77	28.646

*LOCK UP PRESSURE

Figure 6-21. MVM'73 Summary of Start-Up/Shutdown Integration

ENGINE S/N 207

START-UP						SHUTDOWN			
TEST NO.	LEVEL lbf	PTF* psia	INT. PC psia sec	INT. F lbf-sec	DUR. sec	TIME sec	LEVEL lbf	INT. PC psia sec	DUR. sec
103	50	495	981.6	253.6	5.082	10.002	50	18.35	28.639
104	50	492	975.3	251.6	5.082	99.990	12	8.95	28.629
105	12	75	207.2	52.2	5.082	99.990	50	12.50	28.629

*LOCKUP PRESSURE

Figure 6-22. MVM'73 Summary of Start-Up/Shutdown Integration

THRUST LEVEL lbf	START-UP						SHUTDOWN		
	Integral of Chamber Press			Impulse			Integral of Pc		
	Mean, $\overline{x}$ psia-sec	3σ %	d.f.	Mean, $\overline{x}$ ldf-sec	3σ %	d.f.	Mean, $\overline{x}$ psia-sec	3σ %	d.f.
50	973.8	2.6	5	250.8	3.7	5	15.74	6.9	5
12	226.0	20.2	5	57.4	21.5	5	9.38	41.8	5

Figure 6-23. MVM '73 Statistical Summary of Start-up/Shutdown Integration

integration interval defined in this manner will produce a larger amount of scatter in startup impulse and chamber pressure integral. The close agreement of the percentage scatter of the startup impulse to the chamber pressure integral, for the MV/M '73 testing does, however, indicate a very precise determination of the mean values especially for the 50 pound thrust starts.

A direct comparison of the 50 pound thrust shutdown integration to that measured during the Mariner '69 testing is possible because the integration intervals are defined the same and the results indicate a very close agreement. The shutdown integration mean for the Mariner '69 engines was 14.6 psia-sec, this compares to a value of 15.7 psia-sec for the MV/M '73 engines. The variability from engine to engine, however, was approximately one tenth of that demonstrated by the Mariner '69 engines.

Presented in Figure 6-24 is a summary of valve and engine startup response times for all six flight engines. The valve opening time is measured from the receipt of valve signal to the first indication of poppet travel. The chamber pressure response times are measured from the receipt of valve opening signal to the first indication of chamber pressure rise. The valve opening times are not available for tests 101 and 102 because an apparent electrical saturation of both current and voltage signals.

6.5 HOT FIRE TEST INSTRUMENTATION UNCERTAINTIES

Presented in Figure 6-25 is an overall summary of the assessment of instrumentation and performance calculation uncertainties for the hot fire testing conducted on the MV/M '73 Flight Acceptance engines. Also included is a summary of the affects of these uncertainties on the key performance parameters (i.e., specific impulse, C-star, and thrust coefficient). As is clearly evident from a review of the results a satisfactory compliance to the specification requirement was achieved for nearly every measurement type. The slightly higher than specification value for chamber pressure at the low thrust level is compensated by the lower than required uncertainty in thrust and flow rate. As a result the uncertainties in the key performance parameters are within desired goals.

The analysis of the thrust uncertainty was based on data acquired from a special calibration and hot fire test series conducted prior to the

ENGINE NO.	TEST NUMBER	VALVE VOLTAGE VOLTS	PROPELLANT TEMPERATURE °F	INLET PRESSURE psia	VALVE OPENING TIME sec	CHAMBER PRESSURE RISE LOW RANGE sec	HIGH RANGE sec
201	080	23.5	75.3	408	.0271	.0468	.0552
201	981	23.7	71.8	410	.0334	.0611	.0654
201	082	24.7	69.9	83	.0074	.0627	.0705
201	083	24.7	69.5	173	.0378	.0581	.0659
203	73	24.5	69.5	412	.0256	0.0456	.0536
203	74	23.9	70.6	401	.0300	0.0569	.0628
203	75	N.A.	N.A.	N.A.	.0074	0.0577	.0669
203	76	23.5	69.1	77	.0077	0.0592	.0674
204	106	31.3	70.3	404	.0101	.0255	.0392
204	107	31.2	68.6	397	.0102	.0329	.0372
204	108	31.4	68.7	73	.0058	.0527	.0612
205	109	31.3	69.3	396	.0110	.0276	.0401
205	110	31.4	70.0	396	.0107	.0333	.0391
205	111	31.2	67.9	73	.0059	.0554	.0610
206	101	N.A.*	69.8	404	-	.0359	.0396
206	102	N.A.*	70.5	69	-	.0650	.0738
207	103	29.7	70.6	403	.0120	.0310	.0383
207	104	30.0	69.1	400	.0110	.0360	.0400
207	105	30.0	70.1	68	.0053	.0601	.0674

*Valve opening time cannot be determined due to amplifier saturation.

Figure 6-24. Summary of MVM 73 Start-up Response Characteristics

PARAMETER	ACTUAL 3σ%	SPECIFICATION 3σ%
THRUST	(0.6 - 1.17)*	1.75
PRESSURES	(0.33 - 1.1)*	1.0
FLOW RATE	0.7	1.0
TEMPERATURES (0-150°F)	0.5 - 0.8	1.0
TEMPERATURES (150-2000°F)	1.9	2.0
ISP	0.9 - 1.4*	2.0**
C*	0.8 - 1.3*	1.4**
CF	0.7 - 1.6*	2.0**

*First value applies to high thrust operation (50 pounds thrust) second value applies to low thrust operation (12 pounds thrust).

**These values are desired goals not specification requirements.

Figure 6-25. MVM '73 Instrumentation and Performance Uncertainties start of Flight Acceptance testing and is presented in detail in this report. The analysis of the low range temperature measurements was based on a previous error analysis conducted at the CTS facility by TRW and is summarized in this report. The high range temperature measurement analysis was based on actual hot fire test data (i.e., throat temperature measurement) from MV/M '73 Flight Acceptance testing and is also presented in this report. The assessment of the remaining two measurement types pressure and flowrate was based on the results documented from the Mariner '69 Flight Acceptance Test Program (see appendix).

6.5.1 Thrust Measurement Uncertainties

This section presents the results of an error analysis conducted as part of the MV/M '73 program to assure that the instrumentation uncertainty associated with the measurement of thrust satisfies the specification requirement of ± 1.75 percent at all thrust levels. In addition to satisfying the requirement, it was also the intent of the plan to reduce the individual sources of uncertainty where possible by modifying the test stand or changing the methods of thrust reduction toward a goal of ± 0.5 percent (3 sigma). The approach taken for the development of each uncertainty is in accordance with the procedures developed in References 1 through 3 and is formally documented in Reference 4. (See appendix C). The development and presentation of each uncertainty estimate, therefore, is both consistent with previous TRW error analyses and with generally accepted standardized statistical techniques.

6.5.1.1 Summary

A summary of the thrust measurement uncertainties at 10 pound increments from 10 to 50 pounds thrust is presented in Figure 6-26. The precision estimates (3 times the sample standard deviation) and bias estimates are stated as percentages of each thrust level. Each precision and bias estimate was developed by combining the appropriate components of static and dynamic uncertainties. The degrees of freedom associated with each precision estimate was developed from the Welch-Satterthwaite formula (Reference 1) and is a weighted average of the degrees of freedom of each uncertainty component based on the magnitude of each precision estimate.

Thrust Level (lbf)	Precision 3S, % of Level	Bias % of Level	Total % of Level	Degrees* of Freedom	Spec. % of Level
10	1.17	0.11	1.28	30	1.75
20	0.70	0.10	0.80	38	1.75
30	0.71	0.11	0.82	33	1.75
40	0.57	0.10	0.67	29	1.75
50	0.56	0.10	0.66	29	1.75

*Calculated from the Welch-Satterthwaite formula.

Figure 6-26. Overall Thrust Measurement Uncertainty

A review of the overall estimates of uncertainty indicates that the specification requirement was met at every thrust level. In addition, the uncertainty estimate at the 40 and 50 pound thrust level are very close to the desired goal of ± 0.5 percent as a result of the changes made to both the stand and the reduction procedures. The continued review of the thrust data during the testing program maintained the measurement of thrust within the limits stated in this report.

6.5.1.2 Approach

The approach taken to develop the thrust uncertainty at each thrust level has been documented in detail in Reference 4 and is attached as an appendix. Briefly, however, the approach was to partition the components of uncertainty into static and dynamic modes. The static components are those associated with the end to end calibrations of the test load cell and reference load cell. The dynamic components are those associated with the difference (channel deviation) between the redundant thrust measurement channels and the difference (shift) between the pre and post test thrust zero level obtained from actual hot fire test data.

6.5.1.3 Statistical Model

The general statistical model which applies for the development of total thrust uncertainty is a combination of bias estimates and precision indices and can be expressed by the following equation:

$$U = (B + nS)$$

where:

B = bias estimate, non-random component of uncertainty

S = total precision index, random component of uncertainty

n = multiplying factor to establish desired confidence level, in this case n = 3.

The bias estimate (B) is identified as the sum of the non-random components that relate the measured value to the true value and are obtained from the mean statistic. The precision index (S) is identified as the sum of the random components of uncertainty and is developed from the standard deviation statistic.

The statistical model developed for the analysis of thrust measurement uncertainty can be expressed by the following equation:

$$S_F = \sqrt{S_{CAL}^2 + S_{STD}^2 + S_{CD}^2 + S_{ZS}^2}$$

$$B_F = \sqrt{\Delta_{CAL}^2 + \Delta_{STD}^2}$$

$$df = \frac{S_F^4}{\frac{S_{CAL}^4}{df_{CAL}} + \frac{S_{STD}^4}{df_{STD}} + \frac{S_{CD}^4}{df_{CD}} + \frac{S_{ZS}^4}{df_{ZS}}} \quad \left(\text{Welch-Satterthwaite equation}\right)$$

where:

S_{CAL} = Calibration to calibration precision index of test load cell (% level)

S_{STD} = Precision index of standard load cell (% level)

S_{CD} = Run to run precision index of the thrust channel deviation (% level)

S_{ZS} = Run to run precision index of the thrust measurement zero shift (% level)

Δ_{CAL} = Calibration to calibration bias estimate of the test load cell (% level)

Δ_{STD} = Bias estimate of the standard load cell

df_{CAL}, df_{CD}, df_{ZS} = degrees of freedom associated with each corresponding precision index

6.5.1.4 Development of Estimates

The static mode calibration to calibration precision index and bias of the test load cell were developed from a series of end to end calibrations. The precision and bias estimates for each thrust level were obtained from the differences (residuals) between the applied load and the least squares line through the data. A summary of the calibration data and resulting precision and bias estimates for each load cell are shown in Figures 6-27 and 6-28. Included are the thrust calibrations conducted

(LOAD CELL A)

	← ASCENDING									DESCENDING →								
	10		20		30		40		50		40		30		20		10	
TEST NO.	ACTUAL LOAD lbf	DIFF. LOAD lbf	ACTUAL LOAD lbf	DIFF. LOAD lbf	ACTUAL LOAD lbf	DIFF. LOAD lbf	ACTUAL LOAD lbf	DIFF. LOAD lbf	ACTUAL LOAD lbf	DIFF. LOAD lbf	ACTUAL LOAD lbf	DIFF. LOAD lbf	ACTUAL LOAD lbf	DIFF. LOAD lbf	ACTUAL LOAD lbf	DIFF. LOAD lbf	ACTUAL LOAD lbf	DIFF. LOAD lbf
057	11.575	-.02775	21.142	-.03695	29.840	-.02986	42.491	-.01217	51.700	.00327	41.322	.02113	31.806	.01471	21.013	.03015	9.631	.03748
058	10.239	-.05306	20.575	-.05123	29.651	-.05403	41.531	-.00074	50.703	.00426	41.965	.02139	31.162	.01085	21.690	.05186	9.016	.07072
059	10.982	-.02215	21.179	-.01826	30.008	-.02647	40.086	-.00853	51.742	.00287	41.134	.01105	31.241	.01437	21.722	.02188	9.384	.02524
060	10.317	-.01251	20.927	-.02814	29.888	-.04918	40.654	-.00758	51.047	.01278	40.856	.02094	31.140	.00466	21.089	.02137	10.248	.03764
061	11.238	-.02035	22.338	-.01328	29.992	-.03683	39.637	-.00152	50.219	.00374	40.023	.01249	29.827	.00941	20.710	.02350	10.156	.02285
062	0.530	-.06505	20.878	-.04299	29.651	-.06966	39.736	-.00399	49.584	-.00718	39.869	.03408	30.308	.02565	20.475	.05914	10.417	.06999
063-67	10.331	-.06310	21.113	-.02305	29.643	-.04327	39.074	-.01628	50.206	-.00199	40.194	.02853	30.469	.01187	20.497	.05178	10.338	.05550
068-070	10.591	-.00604	21.031	-.03727	31.266	.00205	41.680	-.00665	52.044	-.01644	42.077	.01918	31.588	.01422	21.472	.03027	10.918	.00069
071	10.318	-.04004	20.677	-.00129	30.912	-.01440	41.393	-.05712	51.980	.02738	39.001	.03964	30.991	-.00057	20.830	-.01667	10.043	.06307
072	9.949	-.02155	20.686	-.03275	29.695	-.00199	39.969	-.00648	51.238	.00069	40.515	.01818	30.714	-.00200	19.958	.00665	9.258	.03925
073	10.315	-.03528	20.311	-.03163	29.351	-.03022	39.642	-.00516	50.502	-.00947	41.165	.03153	31.278	.00725	21.113	.02816	10.034	.04481
074	10.296	.01102	20.644	.01945	30.026	-.03058	40.162	-.00138	50.619	.00502	40.622	.01731	30.573	-.01277	20.245	-.00261	10.163	-.00545
MEAN	10.473	-.02966	20.958	-.02478	29.990	-.03238	40.505	-.01063	50.943	.00208	40.729	.02295	30.925	.00814	20.901	.02546	9.957	.03848
STD. DEV.		.02292		.01941		.02021		.01532		.01109		.00872		.00990		.02241		.02477
MEAN %		-0.283		-0.118		-0.108		-0.026		0.004		0.056		0.026		0.122		0.386
3X STD. DEV. %		0.656		0.278		0.202		0.113		0.065		0.063		0.096		0.322		0.746

Figure 6-27. Summary of End-to-End Calibrations

(LOAD CELL B)

TEST NO.	← ASCENDING DESCENDING →																	
	10		20		30		40		50		40		30.		20		10	
	ACTUAL LOAD lbf	DIFF. LOAD lbf	ACTUAL LOAD lbf	DIFF. LOAD lbf	ACTUAL LOAD lbf	DIFF. LOAD lbf	ACTUAL LOAD lbf	DIFF. LOAD lbf	ACTUAL LOAD lbf	DIFF. LOAD lbf	ACTUAL LOAD lbf	DIFF. LOAD lbf	ACTUAL LOAD lbf	DIFF. LOAD lbf	ACTUAL LOAD lbf	DIFF. LOAD lbf	ACTUAL LOAD lbf	DIFF. LOAD lbf
057	11.575	-.02796	21.142	-.04194	29.840	-.03099	42.491	-.01202	51.700	.00366	41.322	.01860	31.806	.01942	21.013	.03318	9.631	.03895
058	10.239	-.04209	20.575	-.04271	29.651	-.05017	41.531	.00068	50.703	.00585	41.965	.01718	31.162	.00627	21.690	.04713	9.016	.05735
059	10.982	-.02259	21.179	-.01866	30.008	-.02627	40.086	-.00821	51.472	.00357	41.134	.00993	31.241	.01237	21.722	.02520	9.384	.02466
060	10.317	-.01723	20.927	-.03041	29.888	-.03949	40.654	-.01023	51.047	.01134	40.856	.01793	31.140	.00626	21.089	.02440	10.248	.03742
061	11.238	-.02408	22.338	-.01314	29.992	-.05234	39.637	-.00121	50.219	.00746	40.023	.01366	29.827	.01182	20.710	.02984	10.156	.02799
062	9.530	-.06864	20.878	-.04123	29.651	-.07066	39.736	-.00406	49.584	-.00699	39.869	.03357	30.308	.02451	20.475	.06202	10.417	.07147
063-067	10.331	-.04797	21.113	-.01434	29.643	-.03559	39.074	-.01750	50.206	-.00115	40.194	.02738	30.469	.00839	20.497	.03890	10.338	.04187
068-070	10.591	-.02435	21.031	-.04749	31.226	-.01890	41.680	.00588	52.044	-.01999	42.077	.02078	31.588	.01772	21.472	.04516	10.918	.02119
071	10.318	-.04493	20.677	-.00571	30.912	-.01892	41.393	-.02676	51.980	.01561	39.001	.03209	30.991	-.01323	20.830	-.00075	10.043	.06262
072	9.949	-.02642	20.686	-.03077	29.695	-.01116	39.969	-.01830	51.238	.01193	40.515	.01110	30.714	.00303	19.958	.02271	9.258	.03788
074	10.296	-.00249	20.644	.01234	30.026	-.03452	40.162	-.00354	50.619	.00292	40.622	.02030	30.573	-.00503	20.245	.00283	10.163	.00718
076	10.891	-.02606	21.294	-.02850	30.528	-.04054	41.516	-.00815	51.811	.01886	42.240	.00525	31.672	-.00151	21.497	.04005	11.027	.04151
MEAN	10.521	-.03131	21.040	-.02521	30.088	-.03580	40.661	-.00862	51.052	.00442	40.818	.01898	30.958	.00750	20.933	.03089	10.050	.03914
STD. DEV.		.01714		.01785		.01658		.00912		.01049		.00866		.01074		.01789		.01820
MEAN %		-0.298		-0.120		-0.119		-0.021		0.008		0.046		0.024		0.143		0.389
3X STD. DEV. %		0.489		0.254		0.165		0.067		0.062		0.064		0.104		0.256		0.543
d.f.		11		11		11		11		11		11		11		11		11

Figure 6-28. Summary of End-to-End Calibrations

during the thrust uncertainty development testing and those conducted during the acceptance testing of the First Flight Acceptance (FA) engine. A summary of the overall thrust calibration uncertainty associated with the test load cell calibration is shown in Figure 6-29. The overall estimates (S_{CAL} and Δ_{CAL}) were obtained by first statistically combining the corresponding ascending and descending thrust level values for each load cell bridge and then pooling across the two independent load cell bridges.

A metrology calibration of the reference load cell was conducted prior to the start of the thrust uncertainty development testing. As with the test cell the bias estimate was developed from the residuals from the least squares line through the data and in order to be conservative the largest residual (0.1%) was selected to be applied over the full thrust range. An estimate of calibration to calibration precision was not available from this single calibration and, therefore, a conservatively large value of 0.2 percent was assumed. This estimate is approximately 5 times that indicated by the manufacturer's specification and is considered to be reasonable based on previous analyses.

A summary of the dynamic mode zero shift precision index (S_{ZS}) developed from actual hot firing of a JPL supplied test engine and the FA engines is shown in Figure 6-30. During the initial phases of the hot fire testing, however, modifications of the stand to reduce the pre to post test zero shift were incorporated and therefore only the data starting with Test 068 is applicable to the precision index and bias estimate. Later testing of the Flight Acceptance Engines resulted in a still further change in zero shift and therefore only the Flight Acceptance data was used to develop the final zero shift precision index. The overall zero shift bias estimate of 0.028 pounds is accounted for in the reduction of test data by applying a linearly varying zero adjustment with time to the individual thrust data slice averages and therefore this bias is reduced to zero.

A summary of the dynamic mode precision index (S_{CD}) associated with the differences (channel deviation) between the two load cell bridges is shown in Figure 6-31. Again, as with the development of the other dynamic components of uncertainty, the data from both the thrust uncertainty hot fire tests and the FA tests are included.

THRUST LEVEL (lbs)	LOAD CELL A		LOAD CELL B		POOLED	
	BIAS Δ, %	PRECISION 3S, %	BIAS Δ, %	PRECISION 3S, %	BIAS Δ, %	PRECISION 3S, %
10	0.052	0.702	0.046	0.517	0.049	0.616
20	0.002	0.301	0.014	0.255	0.008	0.279
30	-0.041	0.158	-0.048	0.138	-0.046	0.148
40	0.015	0.091	0.012	0.066	0.013	0.079
50	0.004	0.065	0.008	0.062	0.006	0.064

Figure 6-29. Summary of End-to-End Calibration Statistics

TEST NO.	DURATION sec	LOAD CELL A PRE TEST lbf	LOAD CELL A POST TEST lbf	LOAD CELL A DIFFERENCE lbf	LOAD CELL B PRE TEST lbf	LOAD CELL B POST TEST lbf	LOAD CELL B DIFFERENCE lbf
057	30	0.104	-0.287	0.391	0.111	0.237	0.398
058	30	-0.354	-0.849	0.495	-0.262	-0.732	0.470
059	60	0.126	-0.411	0.537	0.189	-0.380	0.569
060	60	-0.216	-0.704	0.488	-0.272	-0.798	0.526
061	100	-0.244	-0.611	0.367	-0.271	-0.624	0.353
062	100	-0.578	-0.768	0.190	-0.675	-0.873	0.198
063	10	-	-	-	-	-	-
064	*60	-0.332	-	-	-0.312	-	-
065	*50	-0.323	-	-	0.263	-	-
066	*50	-0.335	-	-	-0.262	-	-
067	10	-	-	-	-	-	-
068	30	-0.044	-0.270	0.226	-0.148	-0.271	0.123
069	30	-0.108	-0.240	0.132	-0.082	-0.230	0.148
070	30	0.018	-0.086	0.104	-0.043	-0.184	0.141
071	30	-0.200	-0.374	0.174	-0.151	-0.285	0.134
072	30	-0.064	-0.219	0.155	-0.061	-0.207	0.146
073	10	-	-	-	-	-	-
074	100	-0.175	-0.309	0.134	-0.148	-0.309	0.161
075	ABORT	-	-	-	-	-	-
076	100	-	-	-	-	-	-
080	10	-	-	-	-	-	-
081	100	-0.870	-0.940	0.070	-0.830	-0.910	0.080
082	55	-0.720	-0.740	0.020	-0.660	-0.700	0.040
083	80	-0.830	-0.780	-0.050	-0.690	-0.780	0.090
100	10	-	-	-	-	-	-
101	100	-0.180	-0.140	-0.040	-0.150	-0.100	-0.050
102	100	-0.210	-0.190	-0.020	-0.190	-0.150	-0.040
103	10	-	-	-	-	-	-
104	100	-0.110	-0.150	0.040	-0.040	-0.070	0.030
105	100	-0.150	-0.160	0.010	-0.200	-0.180	-0.020
106	10	-	-	-	-	-	-
107	100	-0.140	-0.060	-0.080	-0.210	-0.120	-0.090
108	100	0.010	0.180	-0.070	0.070	0.250	-0.180
109	10	-	-	-	-	-	-
110	100	0.060	0.004	0.054	0.050	0.003	0.047
111	100	0.0	-0.020	0.020	0.020	0.0	0.020
MEAN (Δ), lbf				0.007		0.048	
STANDARD DEVIATION (S), lbf				0.060		0.083	
DEGREES OF FREEDOM (d.f.)				12		13	
POOLED MEAN					0.028		
POOLED STANDARD DEV(S_p), lbf					0.073		
DEGREES OF FREEDOM,lbf					25		

*These tests did not have sufficient post test data to obtain a compatible post test zero level.

Figure 6-30. Summary of Pre/Post Test Zero Shift Data

LEVEL lbf	TEST NO.	DURATION sec.	CHANNEL DEV (E), %
50	057	30	-0.004
	058	30	-0.240
	059	60	-0.079
	060	60	0.150
	061	100	0.013
	062	100	0.183
	066	50	-0.170
	068	30	-0.077
	069	30	-0.151
	070	30	0.021
	071	30	-0.242
	072	30	-0.077
	074	100	-0.077
	081	100	-0.106
	101	100	-0.096
	102	100	0.027
	104	100	-0.165
	105	100	0.013
	107	100	0.095
	108	100	-0.041
	110	100	-0.049
	111	100	-0.079
	STANDARD DEVIATION, %		0.084
	DEGREES OF FREEDOM		22
40	064	60	-0.101
	065	50	-0.169
	066	50	-0.204
	074	100	-0.099
	081	100	-0.108
	101	100	-0.131
	102	100	-0.028
	104	100	-0.213
	105	100	0.045
	107	100	0.150
	108	100	-0.075
	110	100	-0.047
	111	100	-0.107
	STANDARD DEVIATION, %		0.089
	DEGREES OF FREEDOM		13

Figure 6-31. Summary of Channel Deviation Data

LEVEL lbf	TEST NO.	DURATION sec.	CHANNEL DEV (E), %
25	064	60	-0.176
	065	50	-0.244
	066	50	-0.299
	074	100	-0.160
	081	100	-0.148
	101	100	-0.231
	102	100	-0.098
	104	100	-0.352
	105	100	0.057
	107	100	0.250
	108	100	-0.180
	110	100	-0.081
	111	100	-0.191
	STANDARD DEVIATION, %		0.141
	DEGREES OF FREEDOM		13
12	064	60	-0.313
	066	50	-0.611
	074	100	-0.422
	081	100	-0.309
	101	100	-0.401
	102	100	-0.412
	104	100	-0.624
	105	100	0.268
	107	100	0.500
	108	100	-0.440
	110	100	-0.142
	111	100	-0.334
	STANDARD DEVIATION, %		0.285
	DEGREES OF FREEDOM		13

Figure 6-31. Summary of Channel Deviation Data (Continued)

A summary of the individual static and dynamic sources of uncertainty for each thrust level are shown in Figure 6-32. Note that for the reference load cell the precision and bias estimates are assumed to be constant with respect to thrust level. This is justified by the fact that the estimates for the reference cell were inflated from those quoted by the manufacturer. Additional inflation to account for lower thrust levels was not considered necessary. In addition, the precision estimate of the thrust zero shift data were available only for tests conducted over the full thrust range. For the thrust levels other than 50 pounds, it was assumed that the precision was constant. This assumption is based primarily on previous analyses and is considered to be reasonable for this measurement system.

REFERENCES

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3. C.H. Oki and G.E. Urner, "LEMDE Instrumentation Error Analysis," TRW Report 01827-6002-R0-00, 31 August 1966.
4. R.S. Williams to D. Snoke, "MVM '73 Thrust Measurement Uncertainty Plan," TRW Report 4783.4.72-13, 29 March 1972.

NOMINAL THRUST LEVEL (lbf)	STATIC UNCERTAINTIES (% LEVEL)					DYNAMIC UNCERTAINTIES (% LEVEL)			
	END TO END CALIBRATION			STANDARD LOAD CELL		CHANNEL DEVIATIONS		ZERO SHIFT	
	PRECISION (3S %)	BIAS (%)	d.f.	PRECISION (3S %)	BIAS (%)	PRECISION (3S %)	d.f.	PRECISION (3S %)	d.f.
10	0.616	0.049	11	0.2*	0.1	0.86	12	0.45	25
20	0.279	0.008	11	0.2*	0.1	0.423	13	0.45	25
30	0.148	-0.046	11	0.2*	0.1	0.49	13	0.45	25
40	0.079	0.013	11	0.2*	0.1	0.27	13	0.45	25
50	0.064	0.006	11	0.2*	0.1	0.25	22	0.45	25

*Precision is assumed to be a constant percentage over the thrust range.

Figure 6-32. Summary of Thrust Measurement Uncertainties

6.5.2 Low Temperature Measurement Uncertainties

The type of transducers, platinum resistance emersion probes, used to measure propellant temperatures in the range of 40 to 150 degrees Farenheit have been analyzed by TRW during previous testing programs. The previous analysis which involved special calibration tests conducted at each of the three separate testing facilities at CTS is documented in detail in Appendix "D". For convenience a short summary of the approach, statistical model and results are presented in this section.

6.5.2.1 Approach

The development of the data for an overall uncertainty estimate for resistance emersion probes was carried out by a series of special calibration tests. A known resistance was placed in the temperature lines at the test stand and the output recorded at a digital voltmeter located in the control room. The resistance was varied from a minimum value corresponding to a temperature of $30^{\circ}F$ to a value corresponding to $130^{\circ}F$. The tests were conducted with nine triple bridge unit-sensor. Sets utilizing four lines at each stand and a variety of amplifiers.

6.5.2.2 Statistical Model

Based upon the method by which the platinum resistance transducers are used, the instrumentation uncertainties were conveniently partitioned into three components of error. These are the uncertainties of the digital acquisition system, the uncertainties of the calibration data, and the uncertainty due to installation and systems effects. Based upon this consideration, the following statistical models were established to facilitate the error analysis.

FIXED UNCERTAINTY

$$\epsilon_T = \epsilon_{DS} + \epsilon_{CAL} + \epsilon_{\text{installation and system}} \qquad (1)$$

Where,

ϵ_{DS} = the fixed uncertainty of the digital system, % FS

ϵ_{CAL} = fixed uncertainty of the sensor calibration, % FS

$\epsilon_{\text{instal. \& system}}$ = fixed uncertainty due to installation and system effects, % FS

RANDOM UNCERTAINTY

$$\sigma^2_T = \sigma^2_{DS} + \sigma^2_{CAL} + \sigma^2_{\text{installation and system}} \qquad (2)$$

Where,

σ_{DS} = the fixed uncertainty of the digital system, % FS

σ_{CAL} = fixed uncertainty of the sensor calibration, % FS

$\sigma_{\text{instal. \& system}}$ = fixed uncertainty due to installation and system effects, % FS

TOTAL UNCERTAINTY

$$E_T = \epsilon_T + k\,\sigma_T \qquad (3)$$

Where,

k = tolerance factor

6.5.2.3 Results

The uncertainties associated with the sensor calibration and installation/system effects defined by equations 1 and 2 were developed from examining the differences between a true input load and the output of the measurement device. The method and resulting statistics are described in detail in the appendix. The digital system was assigned a value of 0.1

percent fixed uncertainty based on the digital acquisition rate. The overall results of the analysis are presented in Figure 6-33. The values for total uncertainty were converted to percent of reading by multiplying by the ratio of the output voltage corresponding to 130°F to the voltage corresponding to each temperature level. The values of uncertainty, then were averaged to produce an estimate over the range of 30 to 110°F of 0.55 percent. The value for the range between 110 and 150°F was taken to be the estimate of 130°F.

Since no changes have occurred to degrade the measurement system at CTS from the date of the original analysis no further testing to develop additional data was conducted. The results from this original analysis, then are asserted to be valid for the MV/M '73 testing conducted at the CTS Hepts facility.

6.5.3 High Temperature Measurement Uncertainties

As part of the overall instrumentation error analysis, an evaluation of the thermocouple data acquired from the Flight Acceptance Tests was conducted to develop the estimates of uncertainty for temperatures in the range of 150 to 2000°F. The data, specifically the two throat temperatures, from each hot fire acceptance tests were utilized for the analysis

Temperature Level	Fixed Uncertainty % FS	Random Uncertainty (3σ) % FS	Total Uncertainty (3σ) % Reading
30	0.167	0.249	0.50
50	0.146	0.324	0.54
70	0.244	0.270	0.50
90	0.205	0.357	0.60
110	0.156	0.354	0.53
130	0.394	0.438	0.83

Figure 6-33. Summary of Instrumentation Uncertainties of the Platinum Resistance Transducers

because the use of actual data from testing conducted during this program was preferred over estimating the uncertainty from manufacturer's specifications.

6.5.3.1 Approach

The approach taken to develop the thermocouple temperature uncertainty was based primarily on the assumption that the distribution of the difference between the two thermocouples located in the throat section is an indicator of the precision of thermocouple measurement. For this specific test series, however, and additional assumption was necessary because the order of the injection pressure levels was reversed after the first acceptance test. It was assumed that this had no effect on the differences between the two throat temperatures. This approach is similar to the approach used to evaluate truly redundant measurements. It differs by the fact that for redundant measurements the bias or difference between the two outputs is assumed to be zero whereas for this case the bias is assumed to be not zero but constant from test to test on the same engine. The procedure then was to first calculate the standard deviation of the average of differences between the outputs of the two throat temperature measurements for consecutive tests with the same engine. The standard deviation for each pair of tests was then pooled across all the acceptance engines to develop the overall statistic.

6.5.3.2 Analysis

A summary of the throat temperature measurements from all of the 100 second flight acceptance tests as well as the differences in percent for each pair of measurements is shown in Figure 6-34. A review of the temperature differences indicated that tests 107 and 108 were significantly different from the rest of the data set. Closer inspection revealed that the data from thermocouple TTH-2 was non repeatible and therefore the data from this series was not used for statistical analysis. The estimates of uncertainty based on the remainder of the data set are shown in Figure 6-35. The three sigma uncertainty of approximately 2 percent may or may not be conservative because of the assumptions involved in the development of this statistic. Because of the absence of dual temperature data at other locations on the engine this estimate is asserted to be valid over the range of 150 to 2000°F.

TEST NO.	THRUST LEVEL LBS.	TTH-1 °F	TTH-2 °F	DIFF. °F	DIFF. %
74-1	50	1582.3	1579.9	2.4	0.152
-2	40	1554.9	1563.7	-8.8	-.563
-3	25	1516.6	1529.4	-12.8	-0.837
-4	12	1456.3	1473.5	-17.2	-1.17
76-1	12	1416.6	1406.6	10.0	0.711
-2	25	1494.1	1489.7	4.4	0.295
-3	40	1550.4	1553.3	-2.9	-0.187
-4	50	1593.1	1600.5	-7.4	-0.462
81-1	50	1573.6	1517.6	56	3.69
-2	40	1537.7	1485.7	52	3.50
-3	25	1498.3	1447.9	50.4	3.48
-4	12	1442.3	1396.5	45.8	3.28
82-1	12	1419.2	1370.8	48.4	3.53
83-1	25	1486.1	1438.2	47.9	3.33
-2	40	1533.4	1486.0	47.4	3.19
-3	50	1576.3	1528.9	47.4	3.10
101-1	50	1442.4	1480.0	-37.6	-2.54
-2	40	1411.3	1461.4	-50.1	-3.43
-3	25	1373.7	1426.3	-52.6	-3.69
-4	12	1306.9	1350.1	-43.2	-3.20
102-1	12	1260.7	1296.0	-35.3	-2.72
-2	25	1357.7	1404.0	-46.3	-3.30
-3	40	1419.8	1470.5	-50.7	-3.45
-4	50	1468.6	1516.7	-48.1	-3.17
104-1	50	1548.4	1512.1	36.3	2.40
-2	40	1509.8	1481.3	28.5	1.92
-3	25	1466.1	1440.8	25.3	1.76
-4	12	1402.7	1378.3	24.4	1.77
105-1	12	1366.6	1325.5	41.1	3.10
-2	25	1462.3	1423.3	39.0	2.74
-3	40	1517.5	1483.8	33.7	2.27
-4	50	1567.9	1536.1	31.8	2.07
107-1	50	1523.4	1435.5	87.9	6.12
-2	40	1488.9	1424.8	64.1	4.50
-3	25	1448.8	1393.7	55.1	3.95
-4	12	1381.0	1342.4	38.6	2.88
108-1	12	1360.8	1235.0	125.8	10.19
-2	25	1449.2	1352.7	96.5	7.14
-3	40	1497.1	1421.4	75.7	5.32
-4	50	1545.5	1480.6	64.9	4.38
110-1	50	1517.3	1516.9	0.4	0.026
-2	40	1492.6	1492.8	-0.2	-0.013
-3	25	1453.6	1453.4	0.2	0.014
-4	12	1388.2	1387.6	0.6	0.043
111-1	12	1336.7	1319.6	17.1	1.29
-2	25	1436.7	1419.4	17.3	1.22
-3	40	1496.0	1485.2	10.8	0.73
-4	50	1546.5	1542.5	4.0	0.26

Figure 6-34. Summary of Throat Temperature Measurements

Engine S/N	Precision σ (%)	Degrees of Freedom
201	0.177	1
203	0.615	1
205	0.760	1
206	0.049	1
207	0.516	1

Pooled Estimate (3σ)	1.50 (%)
Degrees of Freedom	5
Average bias	0.42 (%)
Total	1.92 (%)

Figure 6-35. Thermocouple Uncertainty-Summary-Range 150-2000°F

6.6 DATA ACQUISITION/REDUCTION PROCEDURES

The digital data acquired during the hot fire acceptance testing conducted during the MV/M '73 program was processed by means of the Capistrano Test Site Program one (CTSP1) data reduction program. The program has the capability to process 50 input channels at sample rate ranging from 39.2 to 2500 samples per second at the maximum system sampling rate. The minimum sampling rate channel utilized for MV/M '73 testing, however, was 78 samples per second thereby allowing for printout of all channels every 0.0128 seconds during startup and shutdown. A summary of the channel assignments (i.e., sampling rate) for each key performance parameter recorded during MV/M '73 hot fire testing is shown in Figure 6-36.

In addition, the program has the capability to calculate 40 higher order "Performance Parameters," (e.g. resistances, corrected throat area, specific impulse). The only restriction is that a maximum of 70 parameters can be printed out for a single pass through the tape. The program is arranged to printout the first 10 requested channels plus time for the first 30 time slices, and then print the remaining parameters in groups of 10 until all requested parameters have been printed. The program will then return to the first requested group of parameters and continue this scheme until all requested data has been printed.

The processing of the hot fire data is conducted in the following manner. The zero and calibration files are processed first and a summary is printed out of the channel assignments, parameter equivalents and the zero and calibration count levels. From the calibration and zero files a table of engineering unit conversion constants are established for all the input parameters. The actual hot fire data file is then processed using these constants to completion.

The integration of the thrust and chamber pressure is achieved by summing the average times the interval of each data slice both at the start and shutdown of each test. The cutoff criteria for startup integration is defined at 5 seconds and is input as a constant. The shutdown integration is initiated at a time input prior to the test and is cutoff either at the point

Parameter	Program Mnemonic	Sample Rate (Samples/Sec)
Inlet Pressure	PVIN	1250.0
Chamber Pressure	PC HR	1250.0
Chamber Pressure	PC LR	1250.0
Flowrate	WF1	156.8
Flowrate	WF2	156.8
Thrust	F1	2500.0
Thrust	F2	2500.0

Figure 6-36. MVM 73 Key Instrumentation Channel Assignments

at which low range chamber pressure has decayed to less than capsule pressure or at the end of the data file (approximately 40 seconds after the end of the test).

There is no capability for adjusting for zero drift during the reduction of the data. The printout of the zero levels prior to and after the engine firing are used for an adjustment of the data for zero shift after processing.

7. PROBLEM AREAS

The major problem uncovered during fabrication and assembly of the flight engines was the pressure transducer tube on JPL Drawing 10013190C.

The original pressure transducer tubes were fabricated of L-605 material by machining the outside of the tube, eloxing the 0.064 inch I.D. and then forming the tube. The tube was welded on to the shell and a leak check of the weld was not made until the engine was completed.

Engine S/N 203 had the pressure transducer tube eloxed and the engine passed all leak checks and completed FA testing at CTS. However, on engine S/N 202 (TA Engine see TA Summary Report) the tube to shell weld indicated a leak. The tube was welded on engine S/N 201 and a fixture was constructed to leak check the weld prior to catalyst loading. After checking the tube to shell weld a leak was found on engine S/N 201.

A thorough investigation was conducted which resulted in the following:

a) Eloxing the 0.064 I.D. of the L605 0.125 inch O.D. tube embrittles the inside of the tube. During welding there is a high possibility of the tube cracking with a resultant weld crack.

b) Hastelloy W filler rod is recommended for welding the tube onto the shell rather than the L605 filler as called out on JPL Drawing 10013191.

The eloxed tube was removed on engine S/N 203 after FA tests by maintaining the engine nozzle in the downward position and maintaining a suction on the nozzle to remove all chips.

The eloxed tube was also removed on engine S/N 201, however since this engine was not catalyst loaded the same precautions used on S/N 203 were not used.

New pressure transducer tubes were then fabricated by drilling the I.D. of the tube and welding with a Hastelloy W filler rod. All engines fabricated for MV/M73 program have the drilled pressure transducer tube and Hastelloy W filler weld.

During vibration and FA testing at CTS several test facility anomalies occurred. The vibration response was out of tolerance due to the amplification of the JPL furnished vibration fixture. As more experience was gained with the fixture the response was maintained in tolerance.

The FA testing anomalies were due to unforeseen minor failures of supporting or controlling test components. These failures caused extra starts and longer FA test times on several engines.

All the above vibration and testing anomalies are called out in Section 8 under the Problem/Failure Reports.

8. PROBLEM/FAILURE REPORTS

PFR #5651 — Engine S/N 203

During random FA vibration response shows engine was subjected to levels below and above tolerance limits due to amplification of vibration fixture.

PFR #5652 — Vibration Fixture

This PFR written against vibration fixture (See PFR #5652).

PFR #5653 — Engine S/N 203

During second 100 sec acceptance test facility throttle valve timer anomaly caused engine to be subjected to 200 psi chamber pressure versus a required start pressure of 50 psi. Test was terminated after 10 seconds.

PFR #5654 — Engine S/N 203

Engine roughness exceeded 5% of chamber pressure as required by JPL Spec TS 506207A at the following data points

Test 74-3	5.6% of Pc	Pc=104.48 psi
Test 74-4	9.5% of Pc	Pc=50.46 psi
Test 76-1	8.9% of Pc	Pc=53.56 psi

PFR #5658 — Engine S/N 201

During random vibration FA vibration response plots indicate engine was subjected to levels below and above 1.5 db tolerance limits due to fixture amplification and sensitivity of equipment controls.

PFR #5659 — Engine S/N 201

During second throttle point on the pressure increase acceptance test the facility tank pressure regulator failed. Test was aborted and repeated successfully. Engine S/N 201 had thirty five (35) seconds of additional run time.

PFR #5663 — Engine S/N 204

During random vibration of 22-axis the response was out of specification at 1400 to 1800 Hz. Maximum deviation is 10 db.

PFR #5665	Engine S/N 205 During random vibration of 22-axis the response was out of tolerance at 1300 to 1800 Hz.
PFR #5673	Engine S/N 206 During firing run HA3A-102 equipment failed to maintain Pc at 200 ±5 psia. Pc degraded in final 10 seconds to 193.5 psia.
PFR #5674	Engine S/N 206 Run HA3A-101, Specific Impulse was 218.6 at Pc of 50 psi. JPL spec indicated specific impulse should be 218.9.
PFR #5675	Engine S/N 207 Run HA3A-105 Specific Impulse was 217.4 at Pc of 50 psi. JPL spec indicated specific impulse should be 218.9.
PFR #5676	Engine S/N 207 Run HA3A-105-1. Engine roughness was 12% of Pc for frequencies less than 50 CPS. JPL spec indicated roughness should not be over 10% of Pc.
PFR #5677	Engine S/N 204 Firing Runs HA3A-107 and HA3A-108 Specific Impulse below JPL specification Run HA3A-107 Impulse was 217.1 @ 50 Pc, should be 219.1 Run HA3A-108 Impulse was 217.8 @ 50 Pc, should be 219.1.
PFR #5678	Engine S/N 204 On firing run HA3A-107 engine roughness was 12%. JPL spec indicated roughness should not exceed 10%.
PFR #5679	Engine S/N 205 During firing run HA3A-111 Specific Impulse was 218.1 at 50 Pc. JPL spec indicated Specific Impulse should be 219.1.

TRW SYSTEMS

INTEROFFICE CORRESPONDENCE

MV/M 73-021
4780.12-44

TO: H. S. Dobbie

CC: See Below

DATE: 7 November 1972

SUBJECT: New Technology Reporting on JPL Contract 953361 Fabrication and Test of Rocket Engine Assemblies for Mariner Venus/Mercury 1973.

FROM: D. R. Snoke

BLDG.	ROOM	EXT.
01	2281	61530

As TRW Project Manager on Contract 953361, I certify that a complete search has been made with all project people working on the contract and no reportable items of New Technology have become apparent during the length of this contract. This is not unusual since this contract covered the fabrication and test of Rocket Engine Assemblies to JPL furnished drawings and specifications.

D. R. Snoke
MV/M 73 REA
Project Manager

cc: Herbert H. Rosen
Section 9.0 Final Report

APPENDIX A

WATER FLOW BENCH UNCERTAINTY ANALYSES

TRW
SYSTEMS GROUP

INTEROFFICE CORRESPONDENCE

72.4702.38-009

TO: G. J. Geier
CC: See Distribution
DATE: 18 May 1972

SUBJECT: Pressure Measurement System Uncertainty on MVM'73 Program (water flow test)

J. D. Dorman
FROM: J. D. Dorman
BLDG. M2 MAIL STA. 2115C EXT. 61690

Reference: JPL Specification TS506207 Rev. A. Detail Specification for MVM 73 Equipment Flight Acceptance Tests

A study of the subject measurement uncertainty has been made in accordance with your request. Uncertainty was determined using data from five system level calibrations. A summary of all data is given in Figure 1. It is concluded that these data demonstrate conformance to the System Uncertainty requirements of Section 4.3.7 of the referenced document.

The procedures used in obtaining these calibrations simulate those which would occur in worst-case test conditions. Transducer zero and full-scale output were initially adjusted. Some sixteen hours later the data of Figure 3 were taken. Transducer output was balanced to zero (full-scale output was not adjusted) prior to the calibration of Figure 4. Data of Figures 5 and 6 were subsequently taken without adjustment. Figure 6 data occured 20 hours after the last zero adjustment and 40 hours after full scale had been set. Transducer zero and full scale were then reset and Figure 7 data taken. Close correlation between Figures 3 and 7 is evident.

Some comment regarding interpretation of the data is warranted. First, the effect of errors in the standard calibration gauge is evident in two ways. These are:

a) The non-linearity of the curves is not characteristic for a strain-gauge type transducer. Such transducers always exhibit smooth output curves between zero and full scale. The discontinuity found between 15 and 20 psi points is therefore due entirely to differences in the calibration gauges.

b) The hysteresis exhibited is also atypical of strain-gauge transducers which always yield lower output at increasing pressure than at decreasing pressure. The polarity of the indicated hysteresis is that of the gauge and is associated with frictional forces. The general inconsistency of the hysteresis, at pressures which are low with respect to the range of each of the two gauges, also indicates that the hysteresis is that of the calibration standards.

Significant improvement in the uncertainty at low pressures could be effected through use of a Bridge Balance Unit having a finer potentiometer than is contained in the balance unit used currently. It is now virtually impossible to achieve initial zero balance to better than ± 20 microvolts. At one psi this offset represents an uncertainty ± 2 percent of the reading. The measured zero offsets were not used to correct calibration data since this practice is not part of the normal operating procedure.

Recent MVM-73 pressure data did not range below 3.4 psi. Inspection of Figure 1 indicates a high probability that all pressure data is within the required ± 1 percent uncertainity limit. An improved Bridge Balance Unit will be utilized in fiture testing on this program.

J. D. Dorman
J. D. Dorman

JDD:se

Distribution

E. Bouckaert
P. Brown
J. Ethington
E. Kacian
L. Kent
D. Snoke

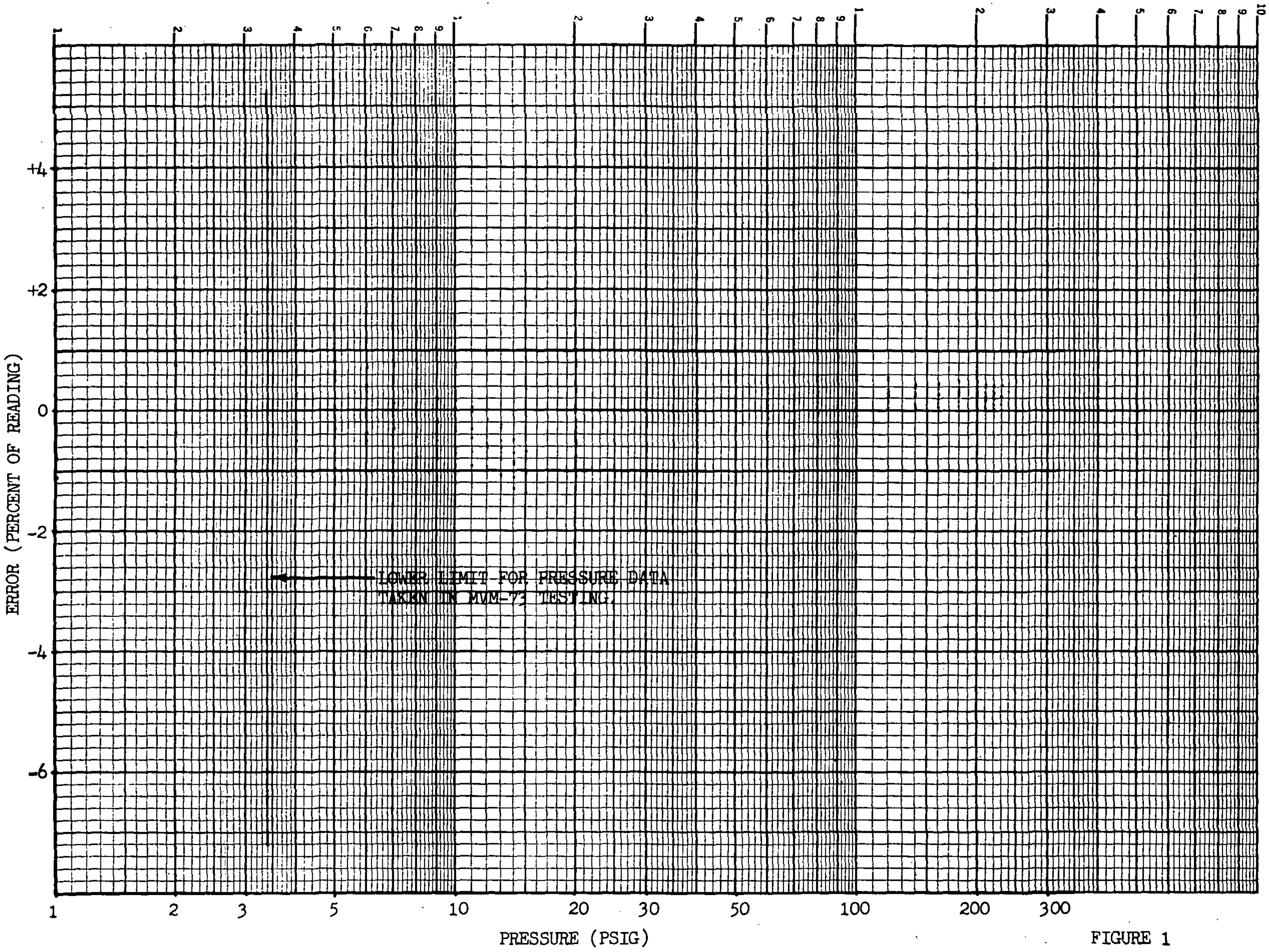
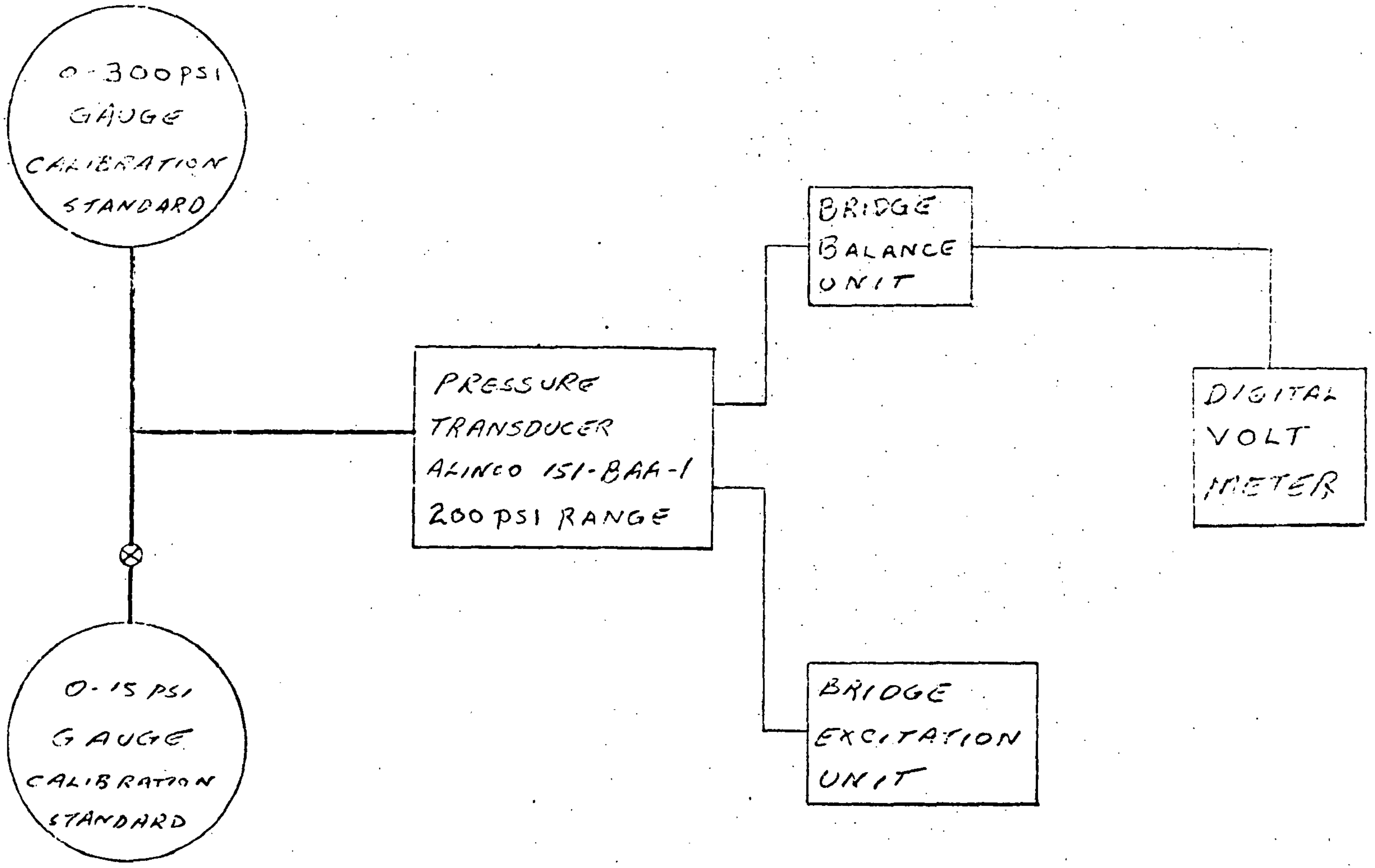

ERROR (PERCENT OF READING)
+4
+2
0
-2
-4
-6
1
2
3
5
10
20
30
50
100
200
300
PRESSURE (PSIG)
LOWER LIMIT FOR PRESSURE DATA TAKEN IN MVM-73 TESTING.

FIGURE 1



PRESSURE MEASUREMENT SYSTEM
INCLUDING CALIBRATION GAUGES

FIGURE 2

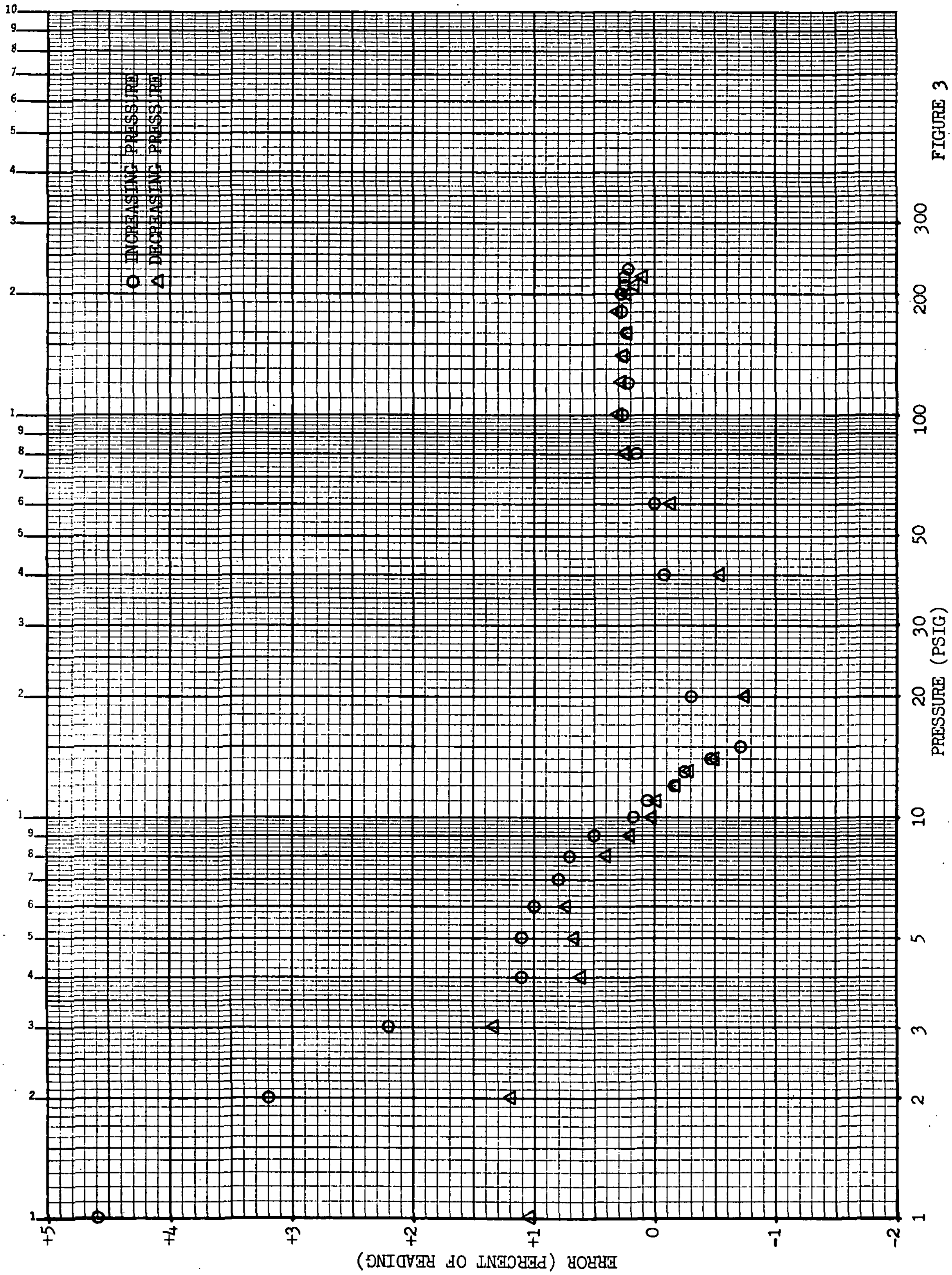

○ INCREASING PRESSURE
△ DECREASING PRESSURE
PRESSURE (PSIG)
1
2
3
5
10
20
30
50
100
200
300
ERROR (PERCENT OF READING)
+5
+4
+3
+2
+1
0
-1
-2

FIGURE 3

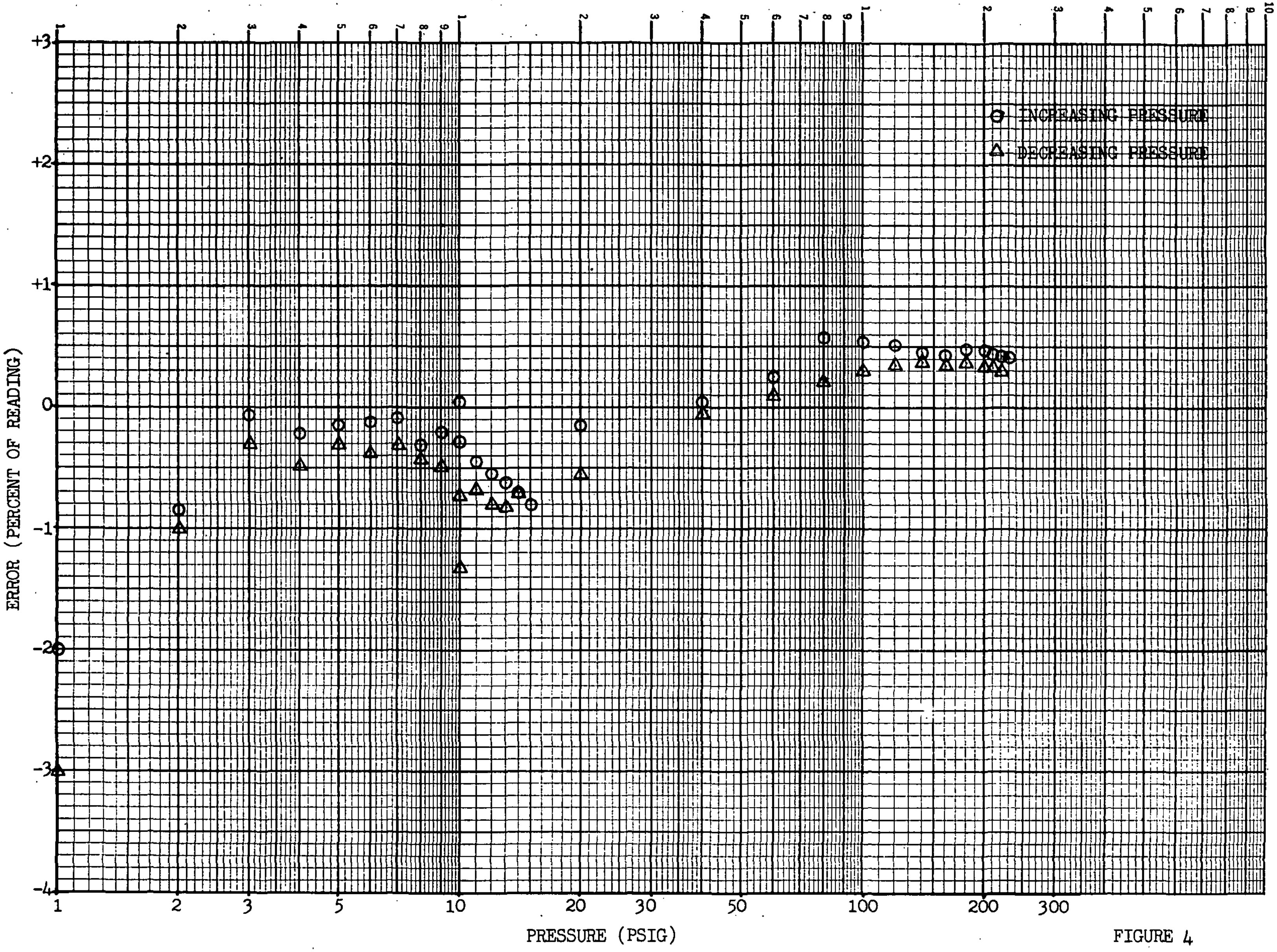

○ INCREASING PRESSURE
△ DECREASING PRESSURE
ERROR (PERCENT OF READING)
+3
+2
+1
0
-1
-2
-3
-4
PRESSURE (PSIG)
1
2
3
5
10
20
30
50
100
200
300

FIGURE 4

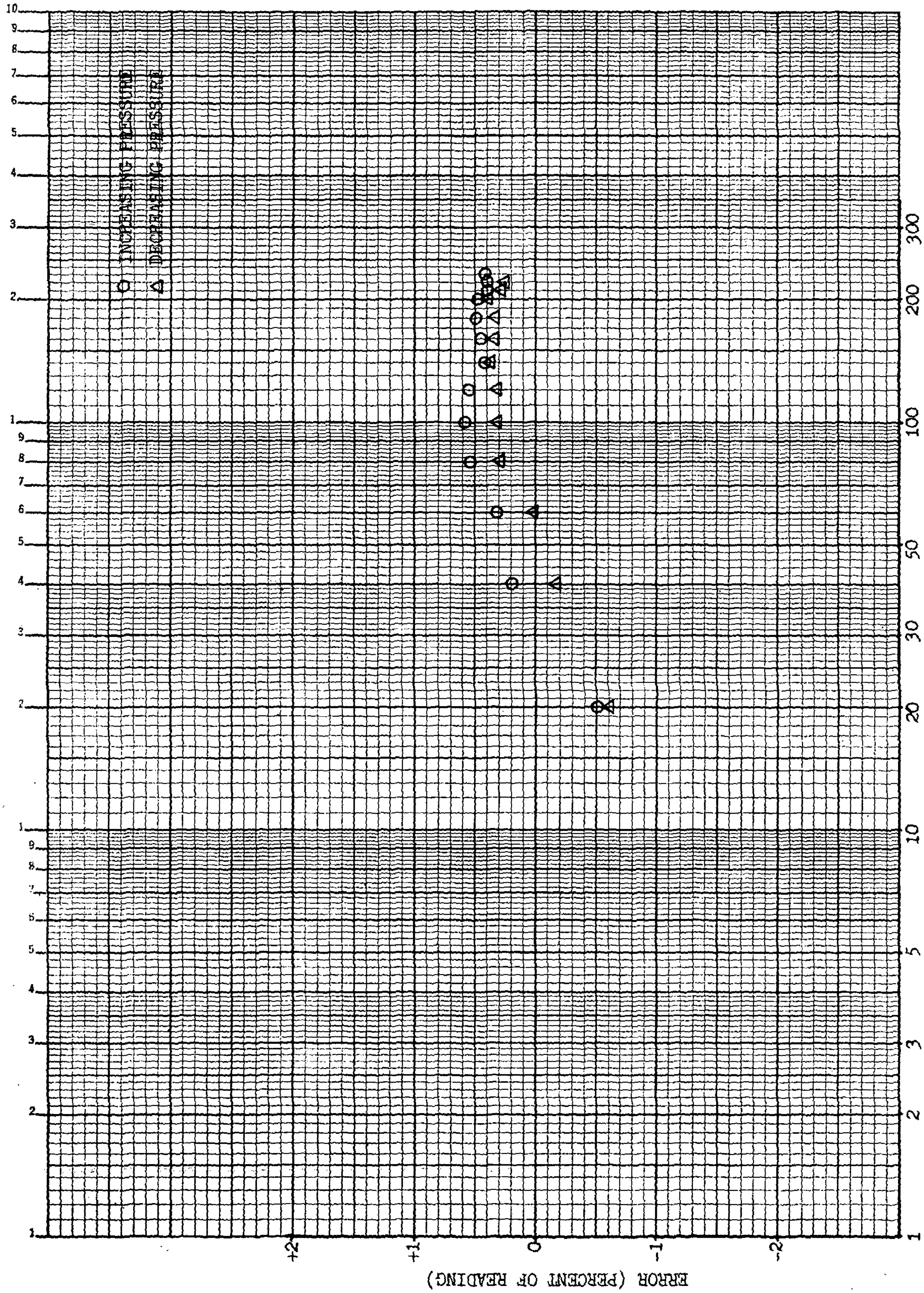

○ INCREASING PRESSURE
△ DECREASING PRESSURE
PRESSURE (PSIG)
1
2
3
5
10
20
30
50
100
200
300
ERROR (PERCENT OF READING)
+2
+1
0
-1
-2

FIGURE 5

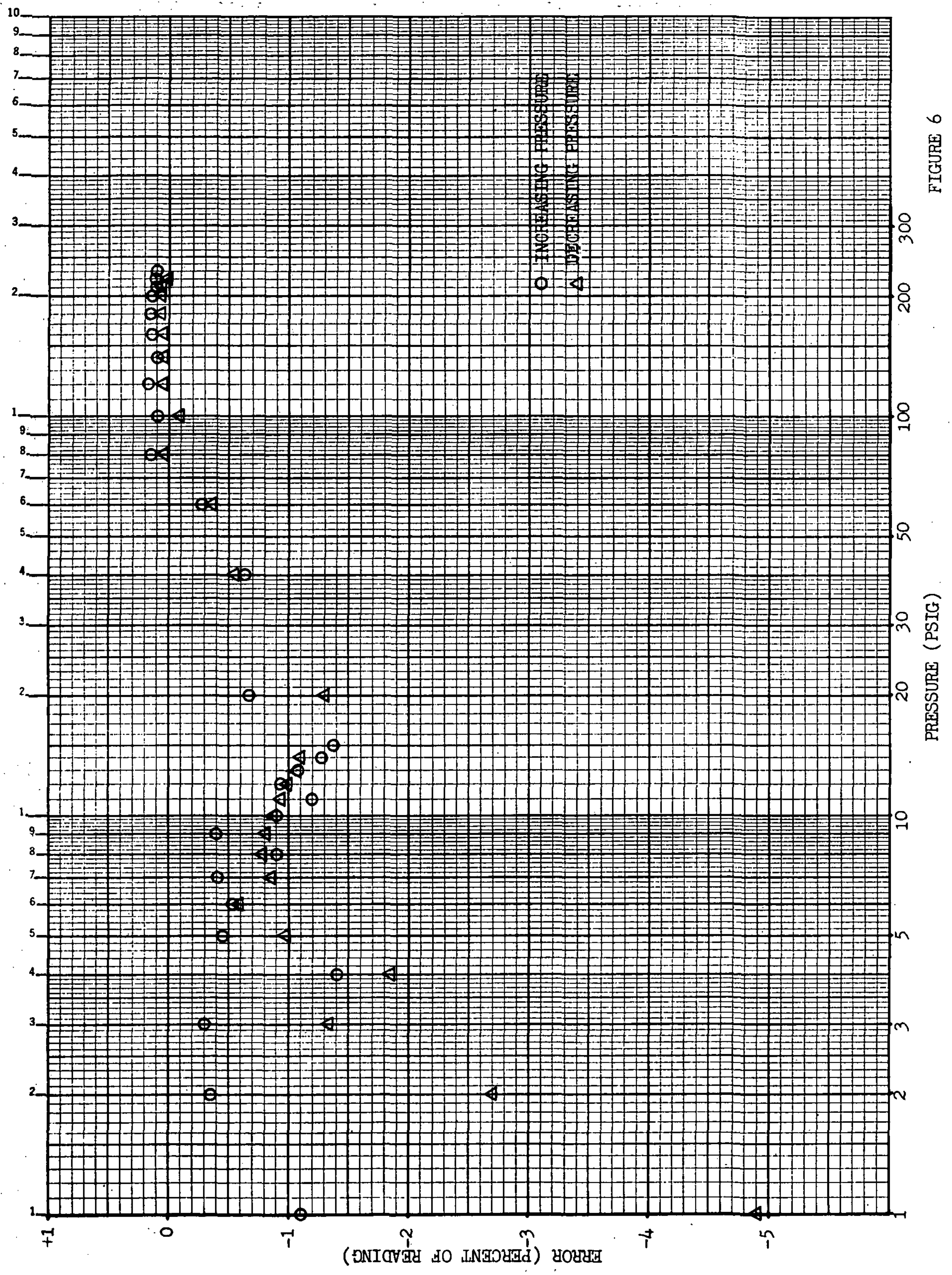

INCREASING PRESSURE
DECREASING PRESSURE
PRESSURE (PSIG)
1
2
3
5
10
20
30
50
100
200
300
ERROR (PERCENT OF READING)
+1
0
-1
-2
-3
-4
-5

FIGURE 6

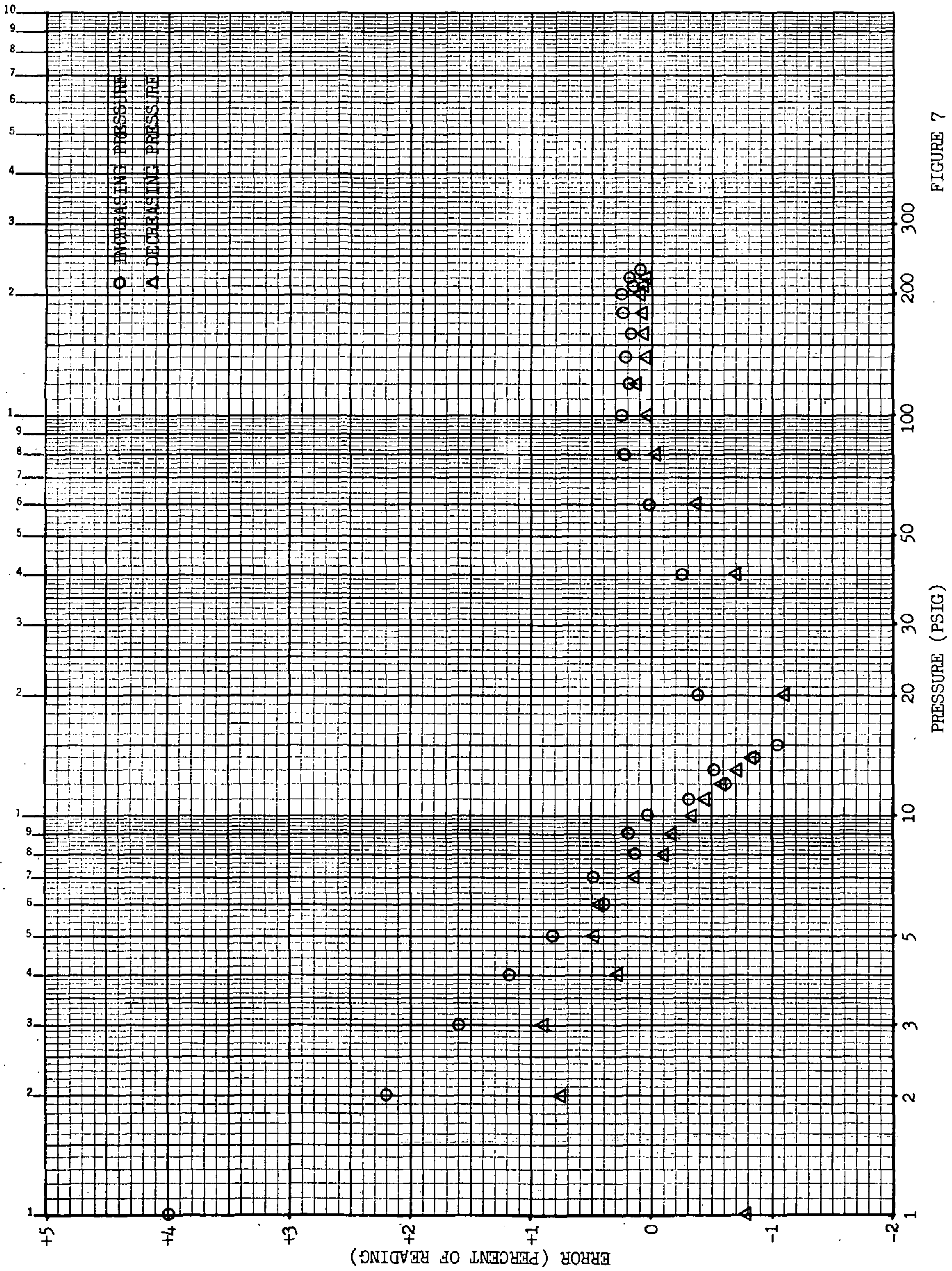

○ INCREASING PRESSURE
△ DECREASING PRESSURE
PRESSURE (PSIG)
1
2
3
5
10
20
30
50
100
200
300
ERROR (PERCENT OF READING)
+5
+4
+3
+2
+1
0
-1
-2

FIGURE 7

TRW
SYSTEMS GROUP

INTEROFFICE CORRESPONDENCE

TO: G. Geier
CC: Distribution
DATE: June 21, 1972

SUBJECT: FLOW MEASUREMENT SYSTEM UNCERTAINTY ON MV/M '73 PROGRAM WATER FLOW TEST

FROM: J. D. Dorman
BLDG. M2 MAIL STA. 2115 EXT. 6

Reference: JPL Specification TS506207 Revision A,
Detail Specification for MV/M '73
Equipment Flight Acceptance Tests

A study of the subject flow measurement uncertainty has been made in response to your request. A worst case analysis demonstrates that the system uncertainty is less than ± 0.6 percent of reading at 0.04 pounds per second flowrate (the MVM '73 minimum) and diminishes with increasing flowrate. This is well within the ± 1.0 percent required by Section 4.3.7 of the referenced document.

Components of the flowmeter uncertainty are:

Flowmeter Calibration	± 0.5 %
Electronic Counter Accuracy	± 0.027%
Temperature Effect on Water Density	± 0.064%
Total	± 0.591%

Deriviation of these values is described below:

Flowmeter Calibration - Flowmeters are calibrated at maximum three month intervals or more frequently when in continuous use. Calibration is performed by an independent firm using NBS certified or traceable equipment and Mil Standard procedures. The ± 0.5% value assigned is actually greater than twice the maximum shift in any point occurring in consecutive three month calibrations.

In comparing points from these consecutive calibrations, variations in calibration factor in excess of ± 0.25% (but generally less than ± 0.5%) occur frequently at flowrates below 35 percent of full range. This results from the fact that, at low flowrates, the frictional forces in the meters turbine mechanism are not completely cancelled by the viscous forces of the fluid. TRW is currently using two flowmeters of different ranges in this program. Neither meter is used below its 35% FS point thus further assuring conservatism in the ± 0.5% estimated uncertainty value for the flowmeter performance.

Electronic Counter Accuracy - The uncertainty value for the Electronic Counter has two components. These are, according to the Hewlett-Packard specification;

- o Time Base Stability of ± 0.0002% per week. Over TRW 12 week calibration cycle for this equipment this error would amount to 0.0024% maximum.

Continued -

- o A ± 1 count error in the display. Using five digits in the display, this would constitute an error of ± 0.025% at the minimum flowrate of 0.04 pounds per second.

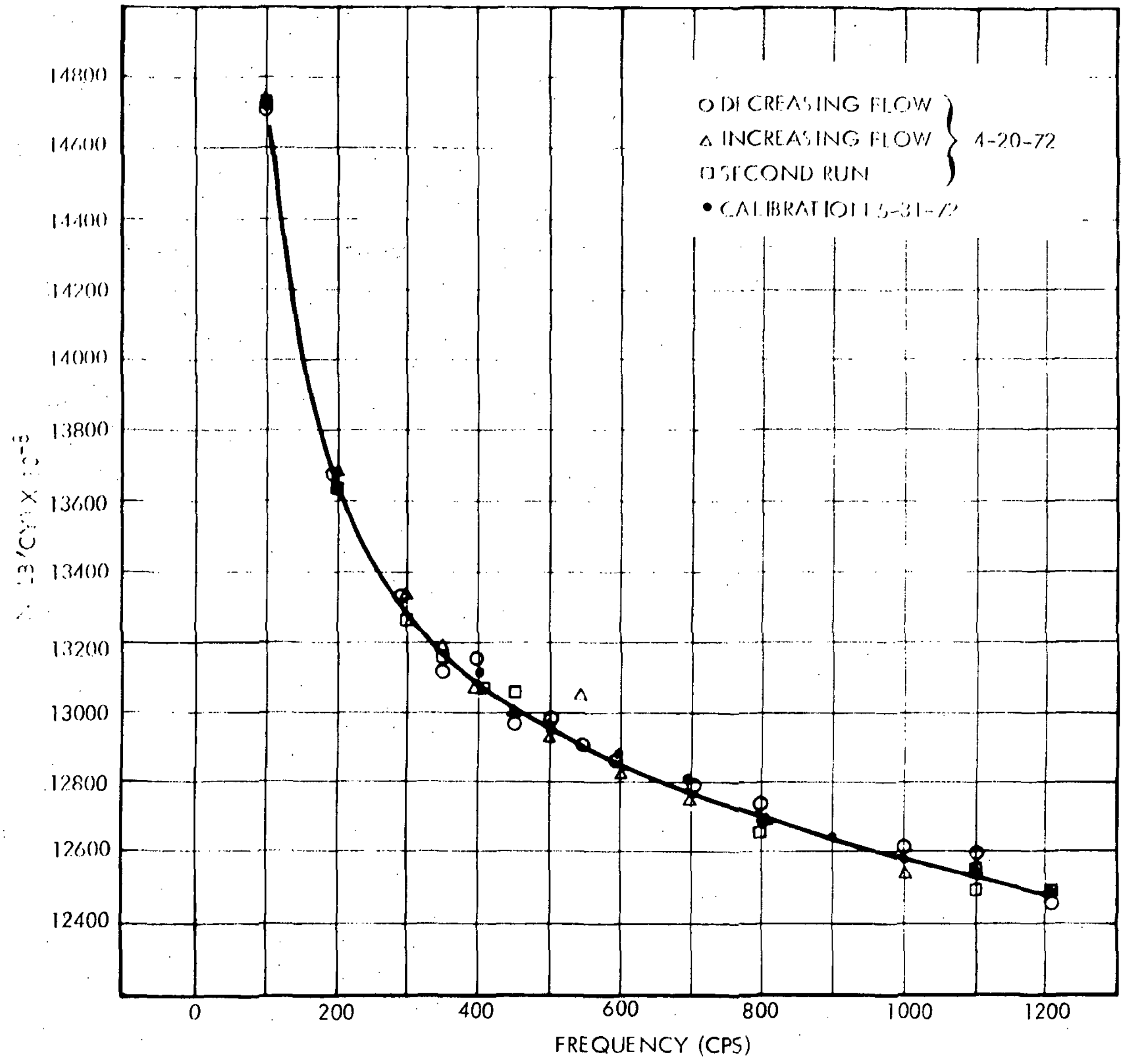
Water Density Variation - Turbine flowmeters are volumetric devices. Conversion of data from a volume to mass basis is effected during flowmeter calibration data reduction and is based on 70°F water temperature. If the temperature ranges between 65°F and 75°F, as allowed by section 3.7 of the referenced specification, the maximum reading uncertainty arising from density variation is ± 0.064%.

J. D. Dorman

J. D. Dorman

JDD:ddj

cc: E. Bouckaert
P. Brown
J. Ethington
E. Kacian
L. Kent
D. Snoke


14800
14600
14400
14200
14000
13800
13600
13400
13200
13000
12800
12600
12400
K 13'/CYL X 10-3
0
200
400
600
800
1000
1200
FREQUENCY (CPS)
○ DECREASING FLOW
△ INCREASING FLOW
□ SECOND RUN
4-20-72
● CALIBRATION 5-31-72

SYSTEMS GROUP

APPENDIX

INTEROFFICE CORRESPONDENCE

D. R. Snoke

CC: W. M. King
C. H. Oki
A. W. Parnell

DATE: 29 March 1972

MVM '73 Thrust Measurement Uncertainty Plan

FROM: R. S. Williams

BLDG. 01 MAIL STA. 1053 EXT. 64[illegible]

As part of the MVM '73 contract a requirement exists to develop the instrumentation uncertainty associated with the measurement of vacuum thrust prior to the start of reactive testing. In addition, it is understood and agreed that all reasonable modifications to the thrust measurement system and methods for reduction of calibration data in order to reduce the instrumentation uncertainty towards a goal of ± 0.5 per cent (3 sigma) will be implemented. This report documents the general approach to be used to develop the thrust measurement uncertainty.

The development of the thrust measurement uncertainty can be separated into static components and dynamic components. The static components consist of the random (precision) and fixed (bias) uncertainty estimates associated with the test load cell calibrations and the random and fixed uncertainty estimates associated with the reference or standard load cell. The dynamic components consist of the random estimates associated with the difference (channel deviation) between the redundant thrust measurement channels and the random and fixed uncertainties associated with the pre to post test thrust zero level shift.

The random and fixed estimates associated with the test load cell will be obtained from a series (15 to 20) end to end calibrations using the load cell calibrator. The calibrations will be conducted with the engine and instrumentation installed, propellant lines attached and pressurized, and at altitude cell pressure to duplicate the actual pre test condition. Each calibration will consist of the application of loads from zero to 100 per cent full scale in increments of 25 per cent full scale and then decreasing back to zero in increments of 25 per cent full scale. The calibration data for each thrust channel will then be reduced by a straight line fit through all calibration levels in the same manner as that to be used for the reactive test calibrations.

Each measured calibration level will then be analyzed to develop the repeatability (random component) of the output load and the average bias (fixed component) between the applied load (reference cell) and the measured load (test cell). It is recognized that this does not represent a true end to end calibration of the thrust stand in that the alignment of the thrust stand is not verified. This approach, however, is preferred in view of the difficulties involved and questionable results derived from a true end to end calibration and has been found to be acceptable by JPL assigned instrumentation engineers. The alignment of thrust stand will be verified, however, by the normal test facility procedures. The development of the random and fixed uncertainties of the reference cell will be developed from existing laboratory calibration history for this reference load cell.

The dynamic uncertainty estimates (channel deviation and pre/post zero shift) will be developed from a series of ten thruster firings (approximately 100 seconds duration). Before these data are obtained, however, a series of thruster firings to investigate the reduction of the pre to post test zero shift due to temperature soak back will be conducted. The thrust data from each test will be reviewed to determine the magnitude of the zero shift and, depending upon the magnitude of the shift, modifications to the stand to reduce the shift will be incorporated. It is expected that the pre to post test zero shift random and fixed uncertainties can be reduced to approximately 0.2 per cent (3 sigma) based on MMBPS experience.

The overall thrust uncertainty will be developed by statistically combining the static and dynamic random and fixed uncertainties. In addition, the end to end load cell calibration data, pre to post zero shift data, and the channel deviation data will be used to establish control limits for continuous monitoring of the thrust measurement system throughout the reactive testing program.

RSW/hk

R. S. Williams, Member
Data Analysis Section

DISTRIBUTION:

D. L. Byrd	01/2281
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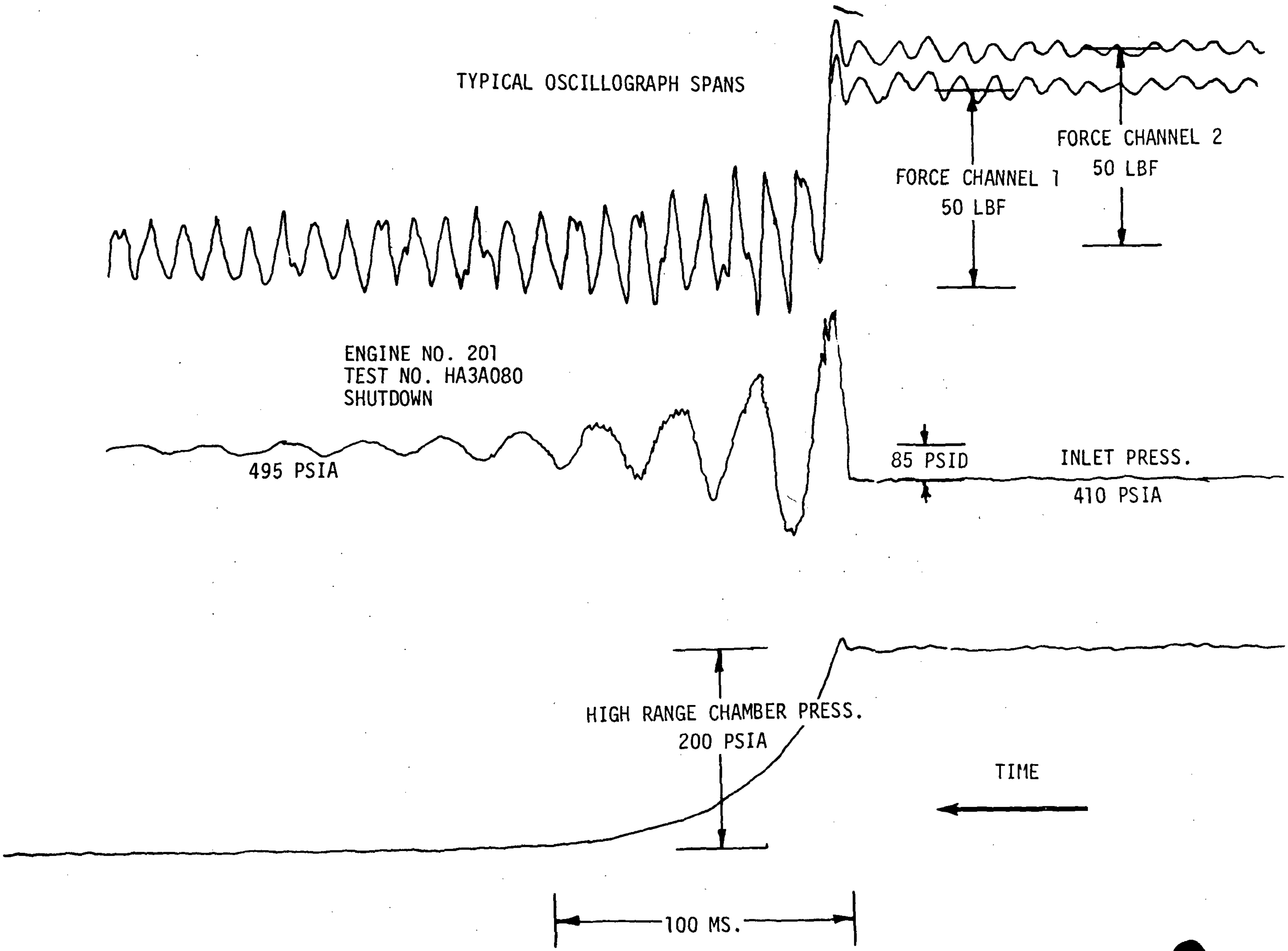
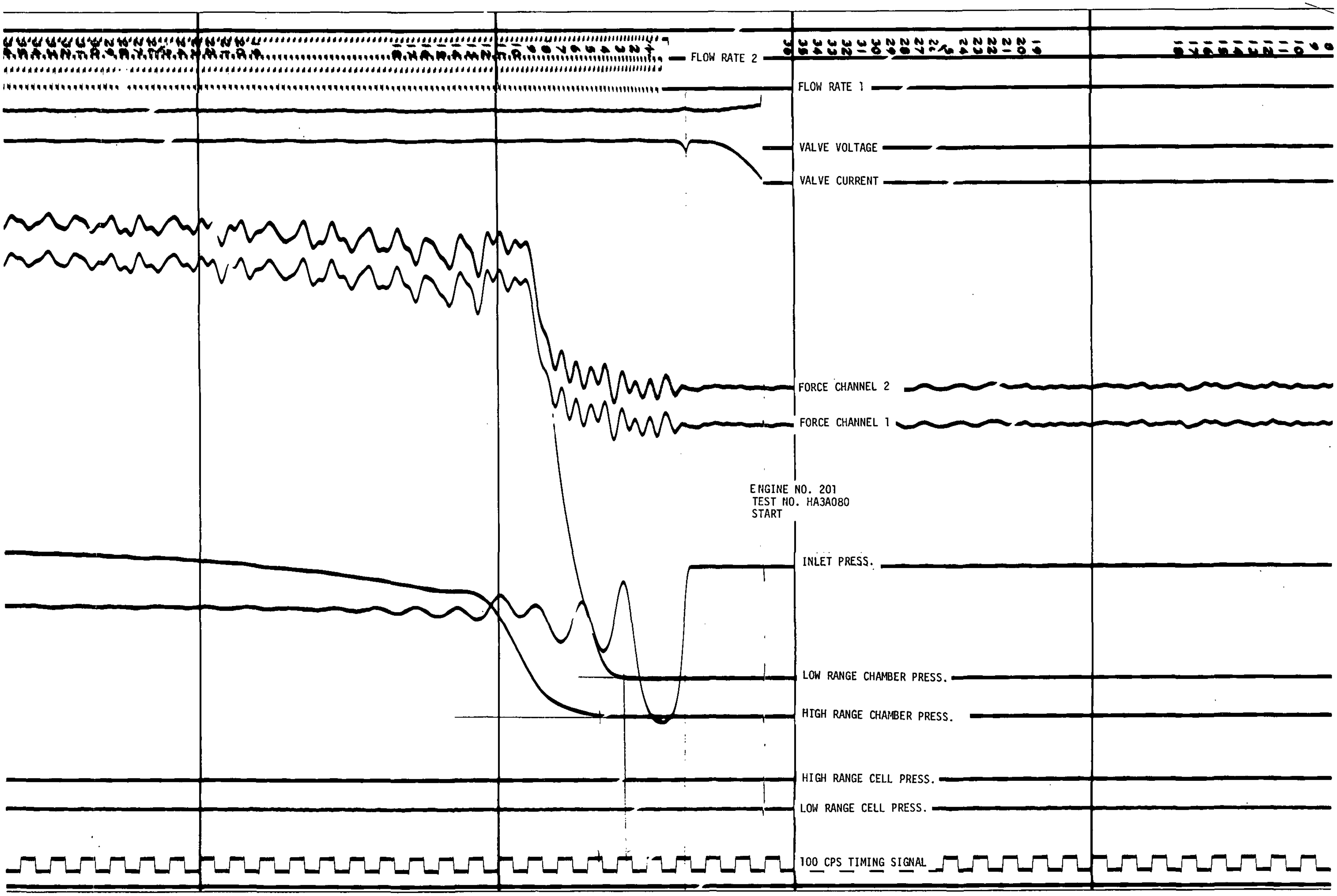
H. Jankowski	41A/1048
C. F. Vaughan	01/2261

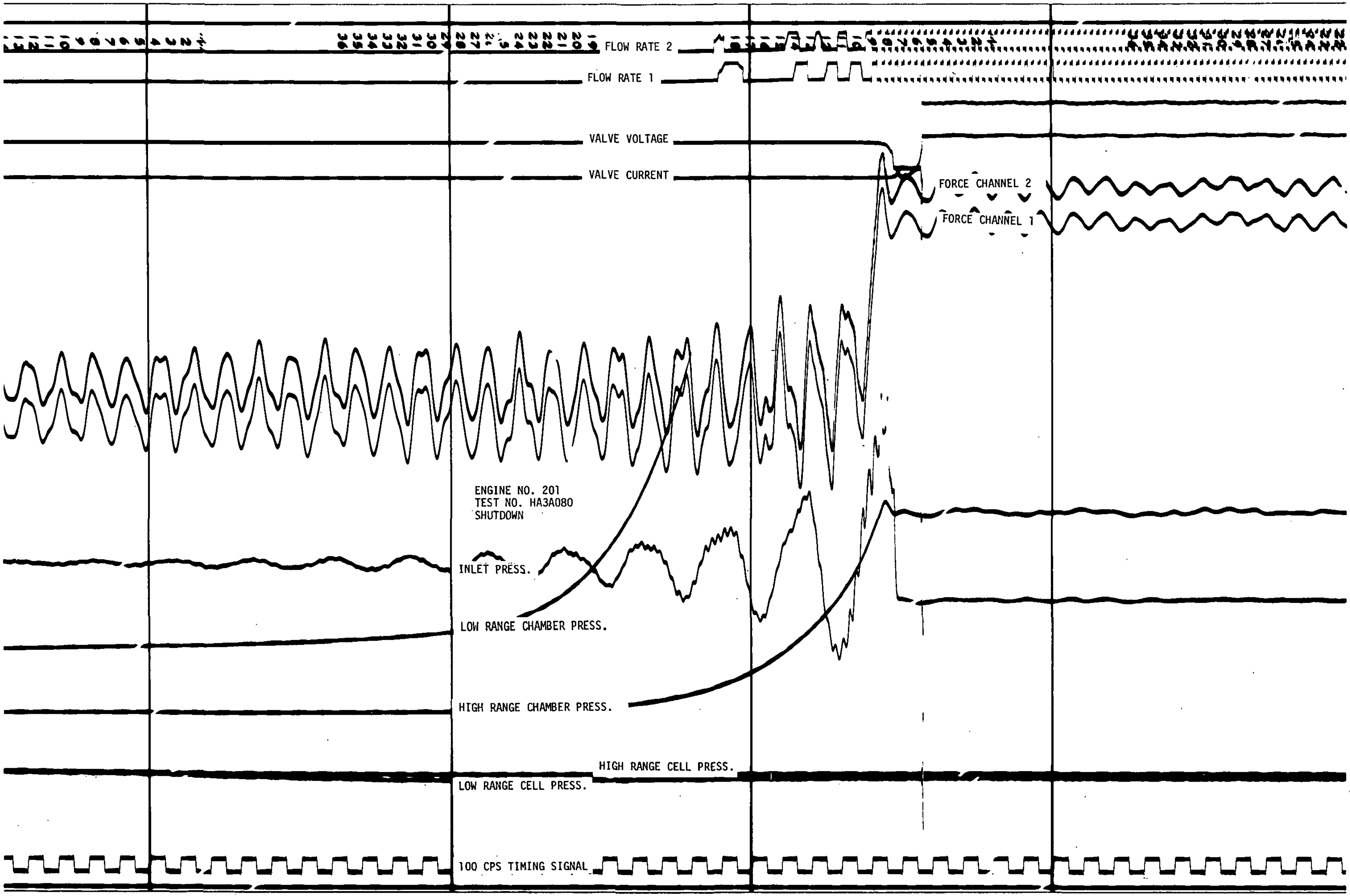
APPENDIX B

OSCILLOGRAPHS OF START-UP AND SHUTDOWN FOR EACH FLIGHT ENGINE

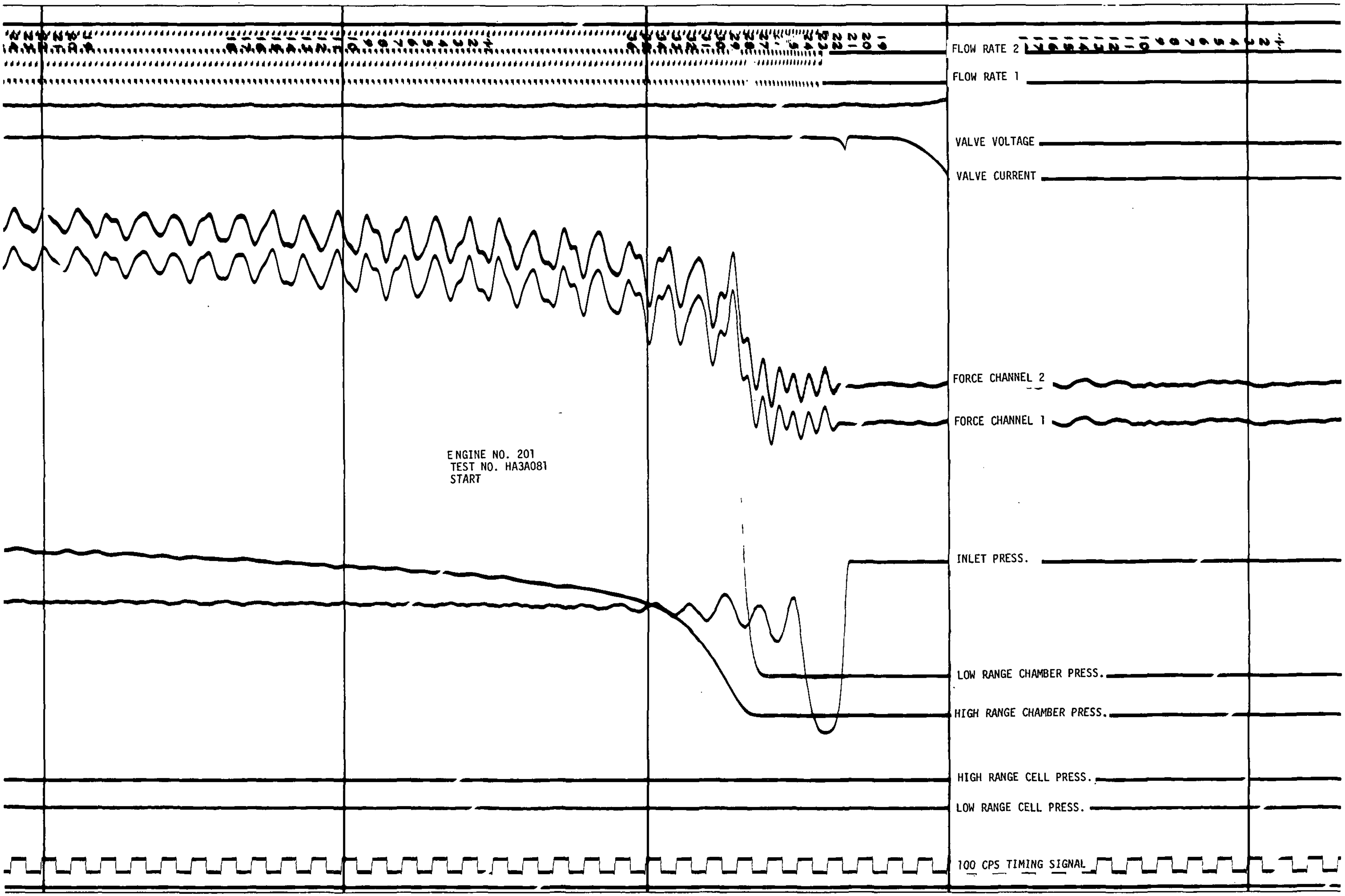


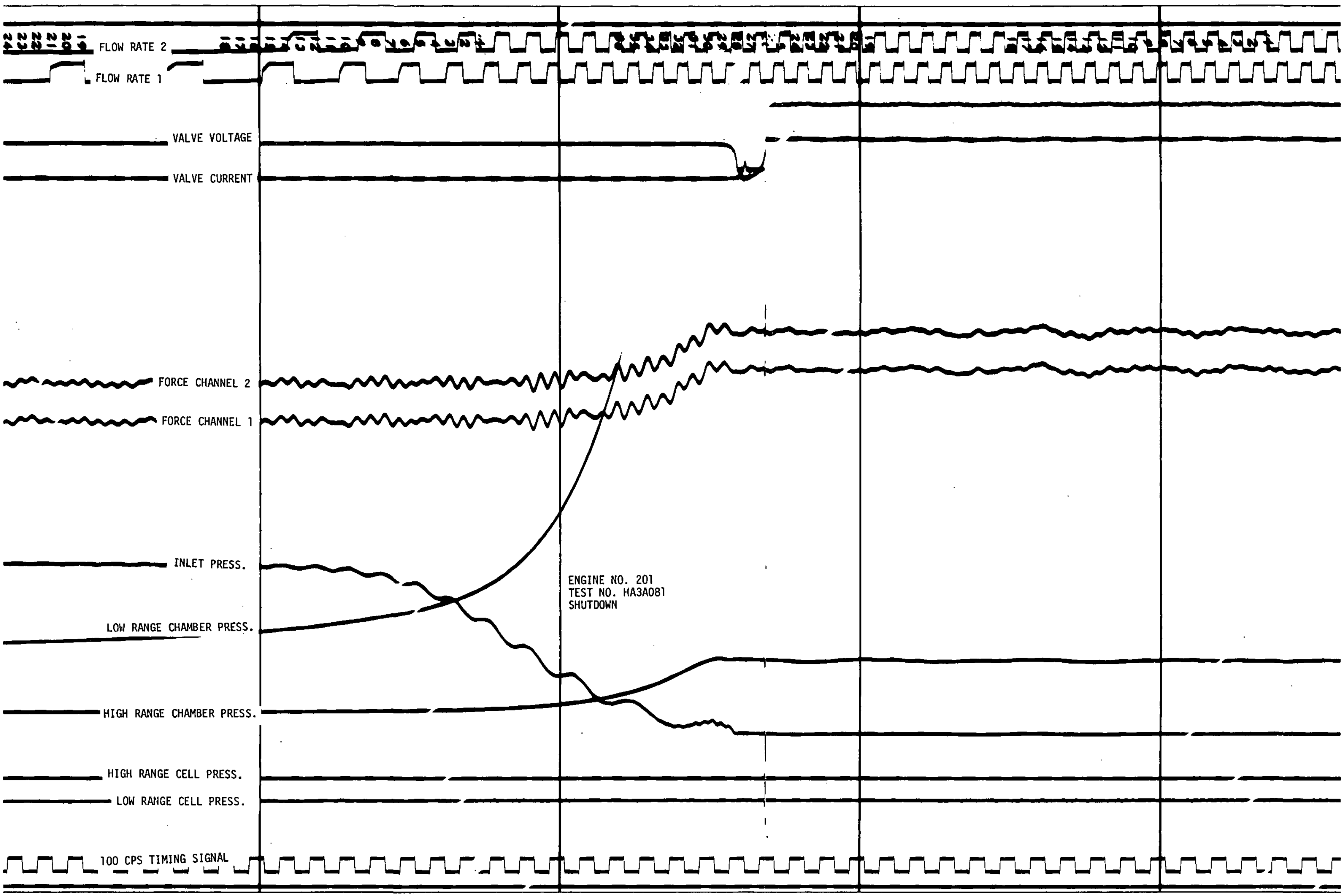
TYPICAL OSCILLOGRAPH SPANS


FLOW RATE 2
FLOW RATE 1
VALVE VOLTAGE
VALVE CURRENT
FORCE CHANNEL 2
FORCE CHANNEL 1
ENGINE NO. 201
TEST NO. HA3A080
START
INLET PRESS.
LOW RANGE CHAMBER PRESS.
HIGH RANGE CHAMBER PRESS.
HIGH RANGE CELL PRESS.
LOW RANGE CELL PRESS.
100 CPS TIMING SIGNAL

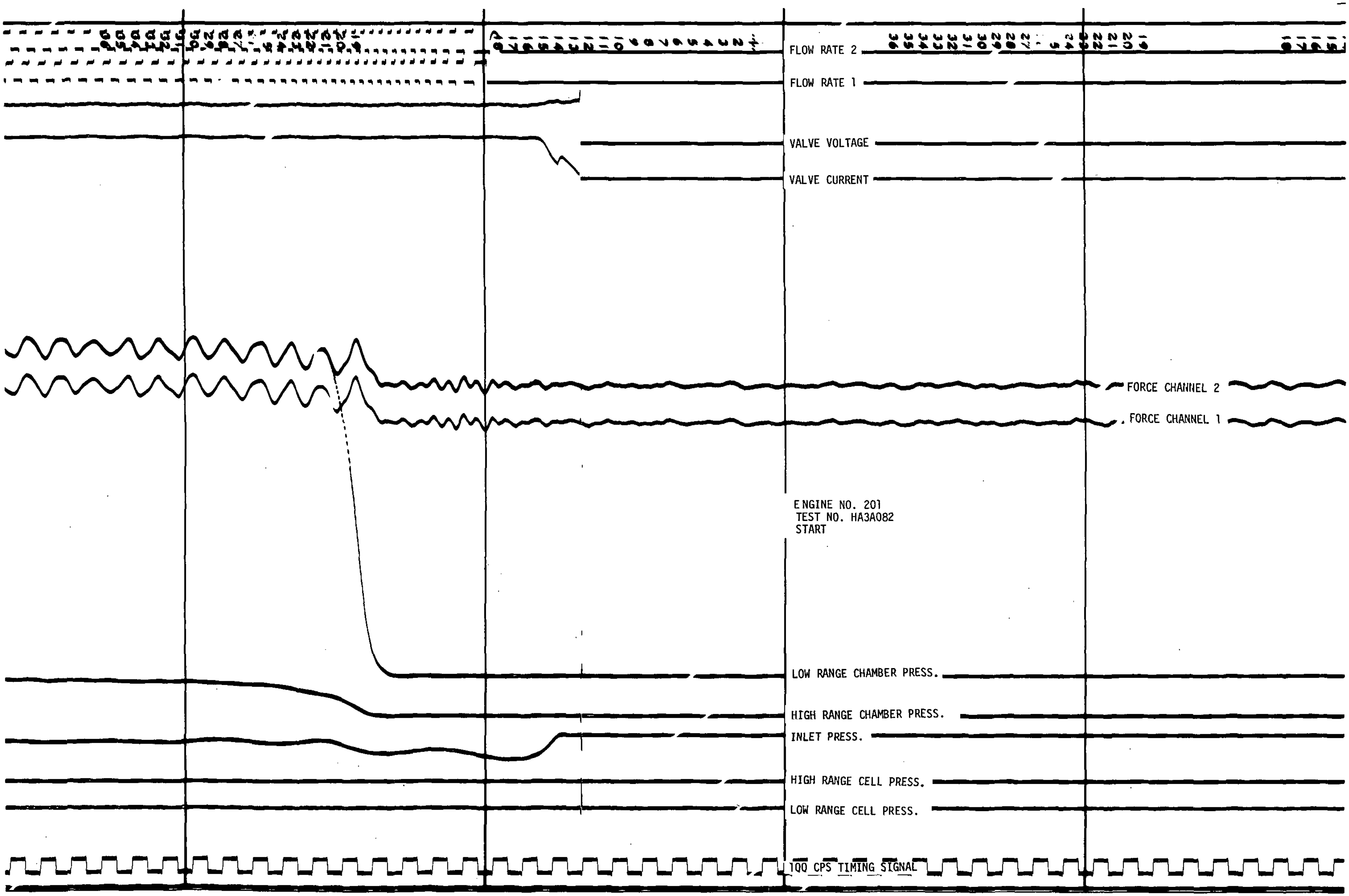


ENGINE NO. 201
TEST NO. HA3A080
SHUTDOWN

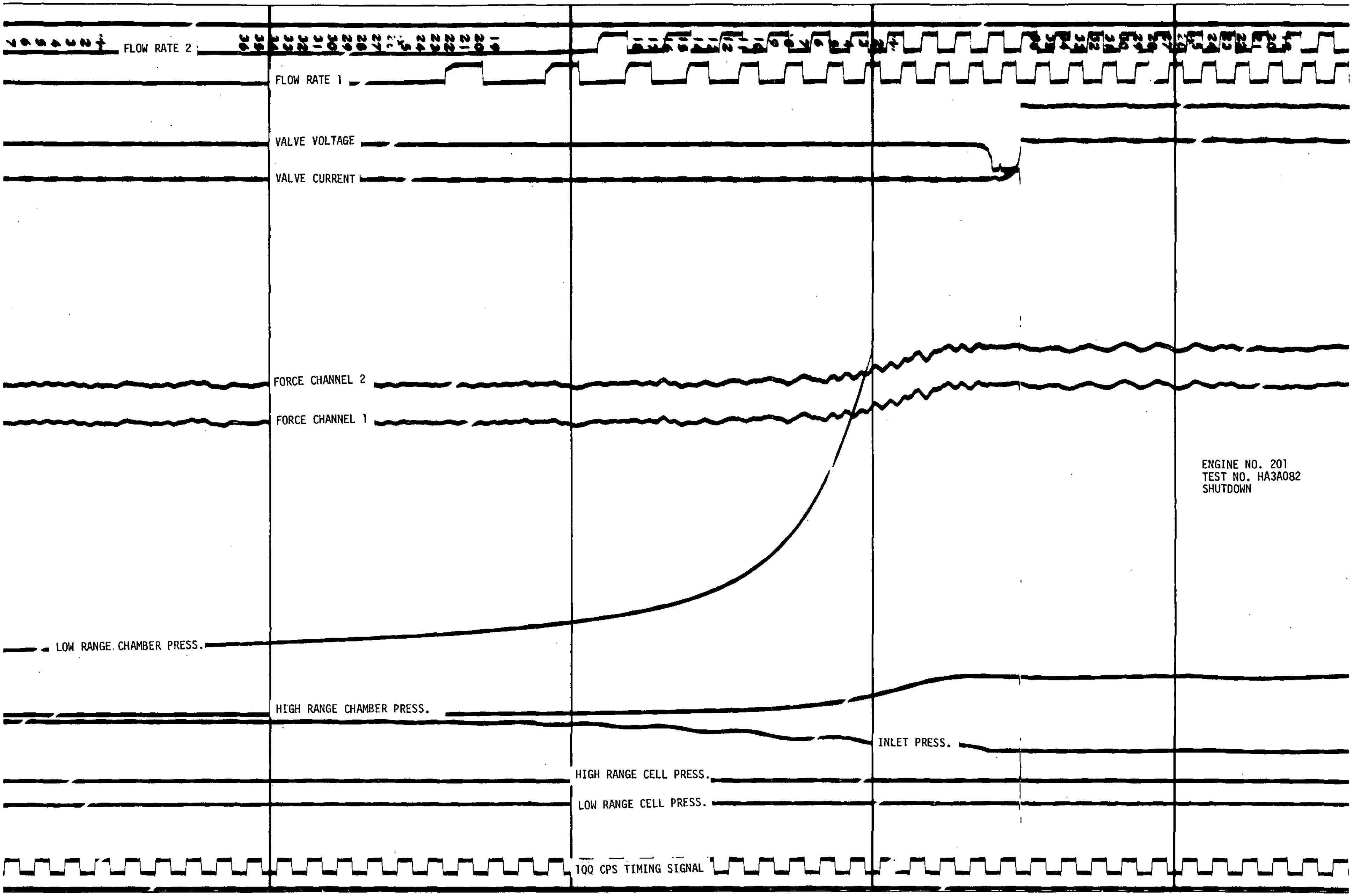

ENGINE NO. 201
TEST NO. HA3A081
START
FLOW RATE 2
FLOW RATE 1
VALVE VOLTAGE
VALVE CURRENT
FORCE CHANNEL 2
FORCE CHANNEL 1
INLET PRESS.
LOW RANGE CHAMBER PRESS.
HIGH RANGE CHAMBER PRESS.
HIGH RANGE CELL PRESS.
LOW RANGE CELL PRESS.
100 CPS TIMING SIGNAL



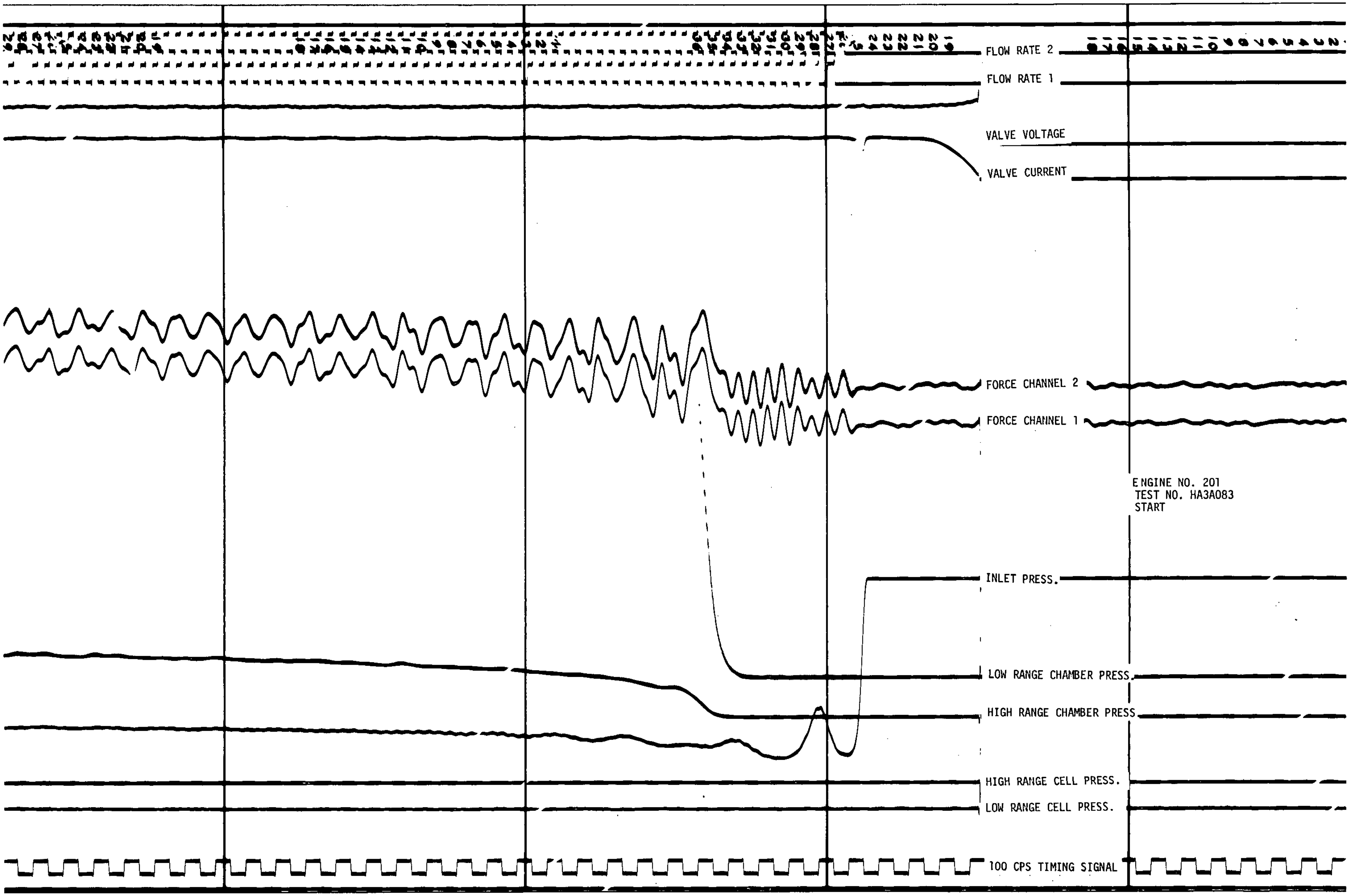
FLOW RATE 2
FLOW RATE 1
VALVE VOLTAGE
VALVE CURRENT
FORCE CHANNEL 2
FORCE CHANNEL 1
INLET PRESS.
LOW RANGE CHAMBER PRESS.
HIGH RANGE CHAMBER PRESS.
HIGH RANGE CELL PRESS.
LOW RANGE CELL PRESS.
100 CPS TIMING SIGNAL
ENGINE NO. 201
TEST NO. HA3A081
SHUTDOWN



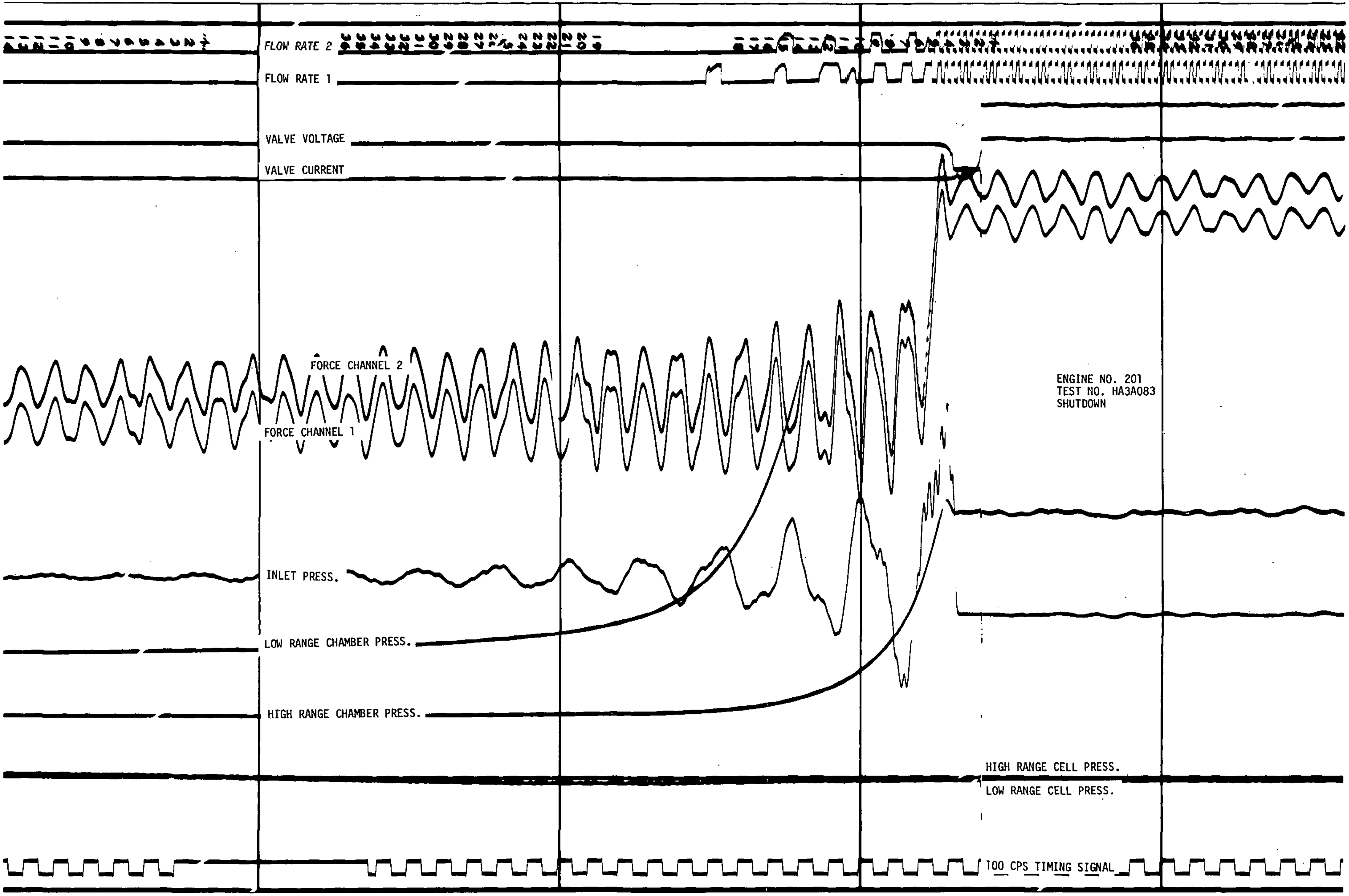
ENGINE NO. 201
TEST NO. HA3A082
START



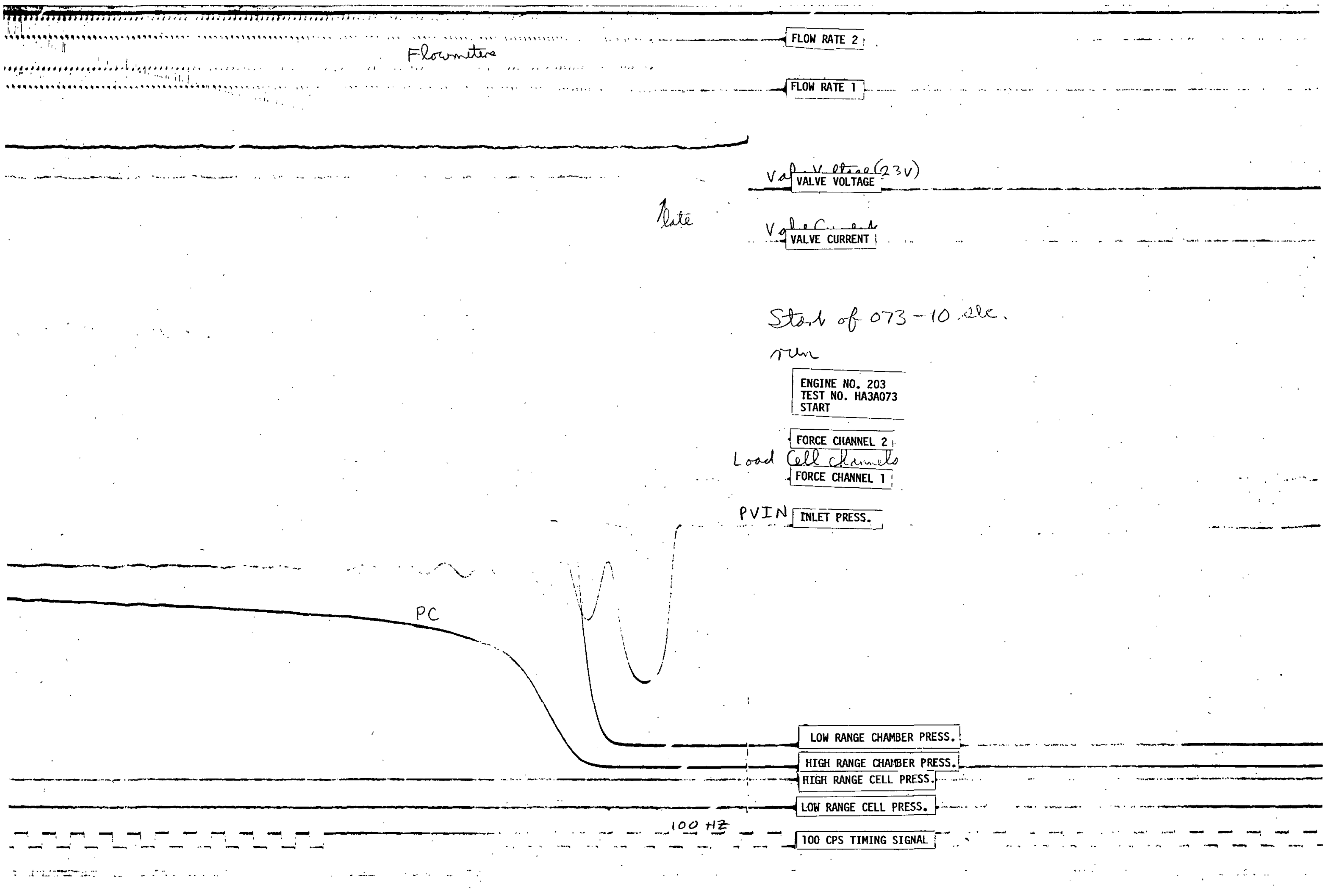
ENGINE NO. 201
TEST NO. HA3A082
SHUTDOWN

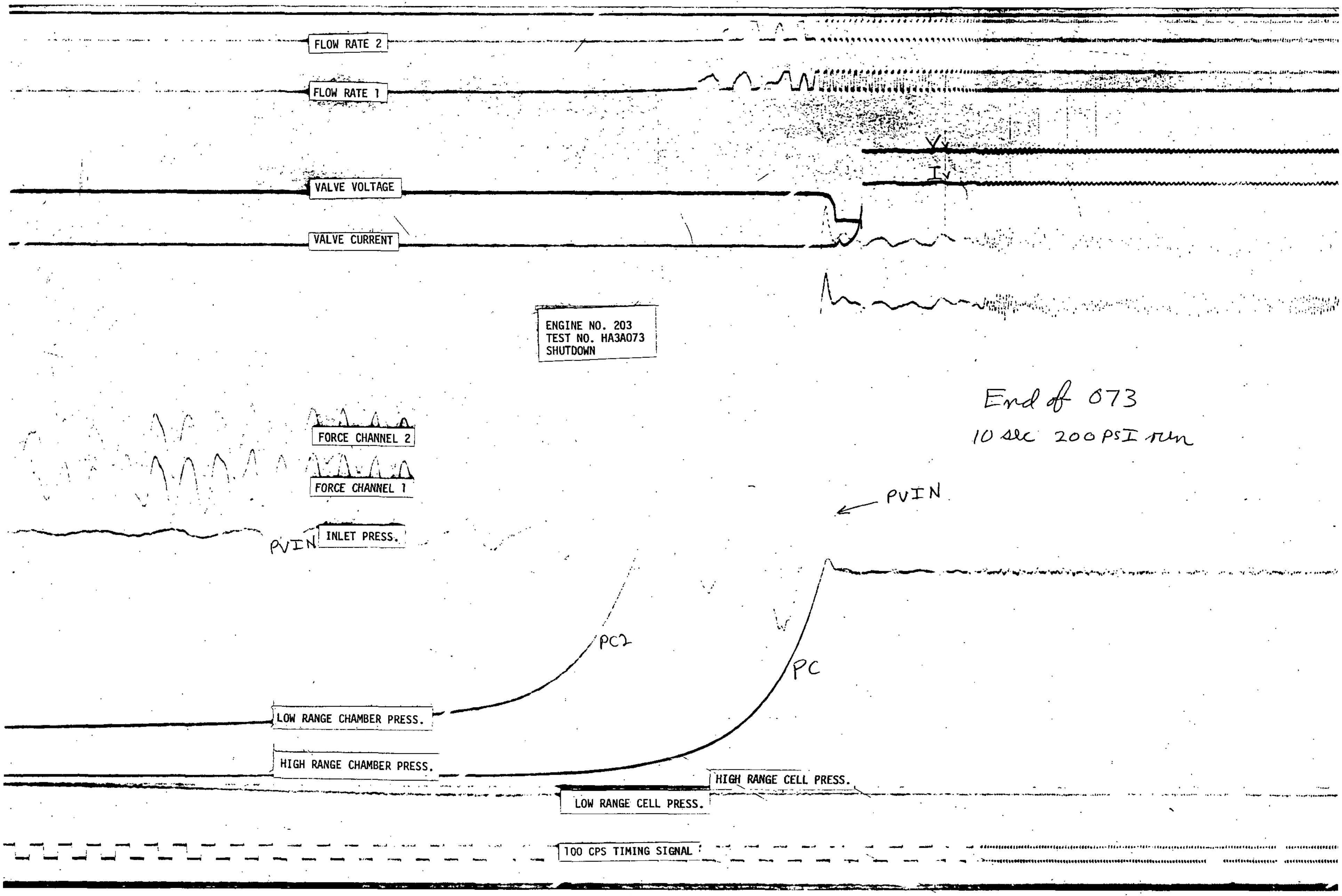


ENGINE NO. 201
TEST NO. HA3A083
START



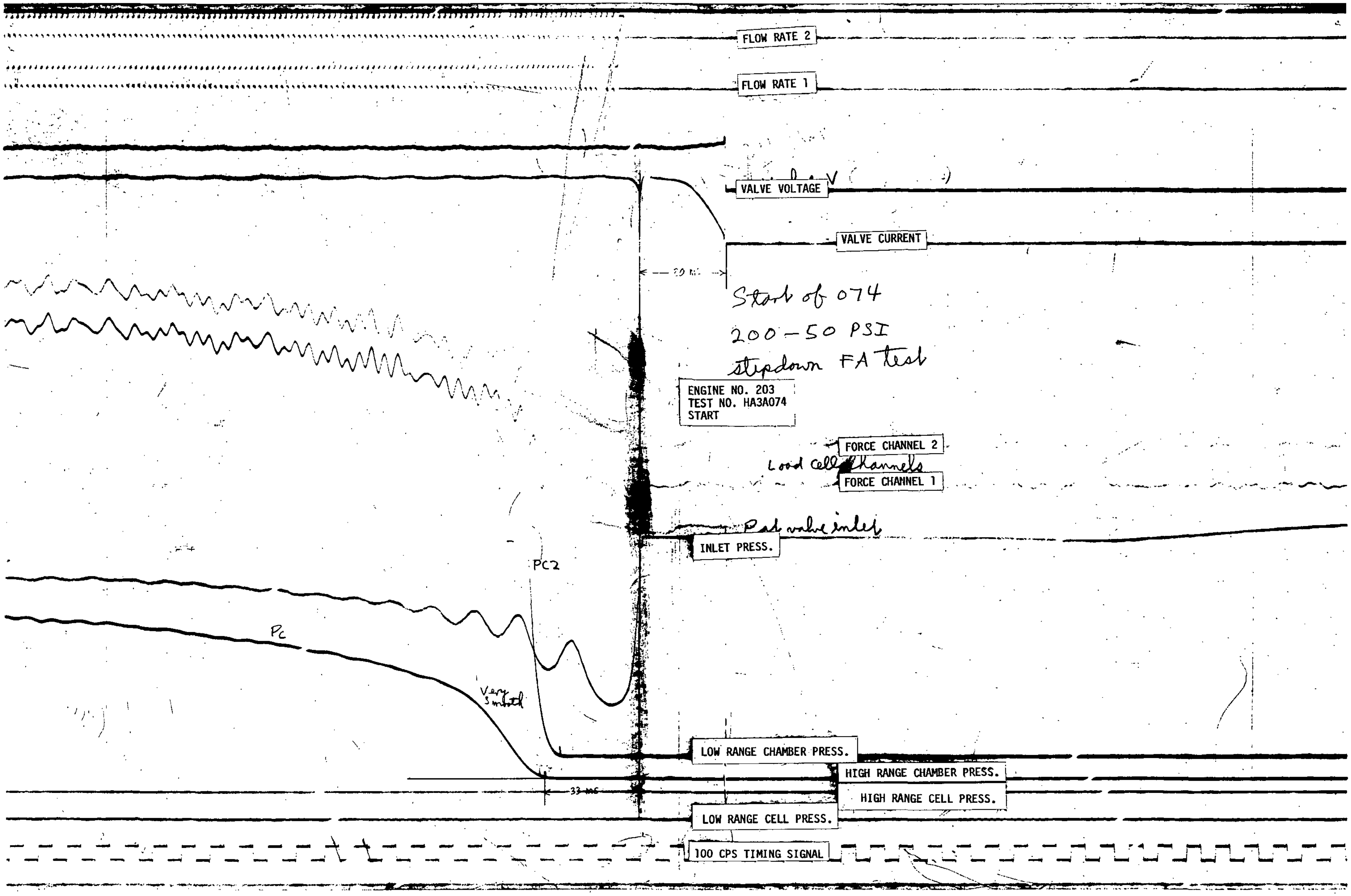
ENGINE NO. 201
TEST NO. HA3A083
SHUTDOWN


FLOW RATE 2
Flowmeters
FLOW RATE 1
Valve Voltage (23V)
VALVE VOLTAGE
Rate
Valve Current
VALVE CURRENT
Start of 073-10 sec. run
ENGINE NO. 203
TEST NO. HA3A073
START
FORCE CHANNEL 2
Load Cell Channels
FORCE CHANNEL 1
PVIN
INLET PRESS.
PC
LOW RANGE CHAMBER PRESS.
HIGH RANGE CHAMBER PRESS.
HIGH RANGE CELL PRESS.
LOW RANGE CELL PRESS.
100 HZ
100 CPS TIMING SIGNAL



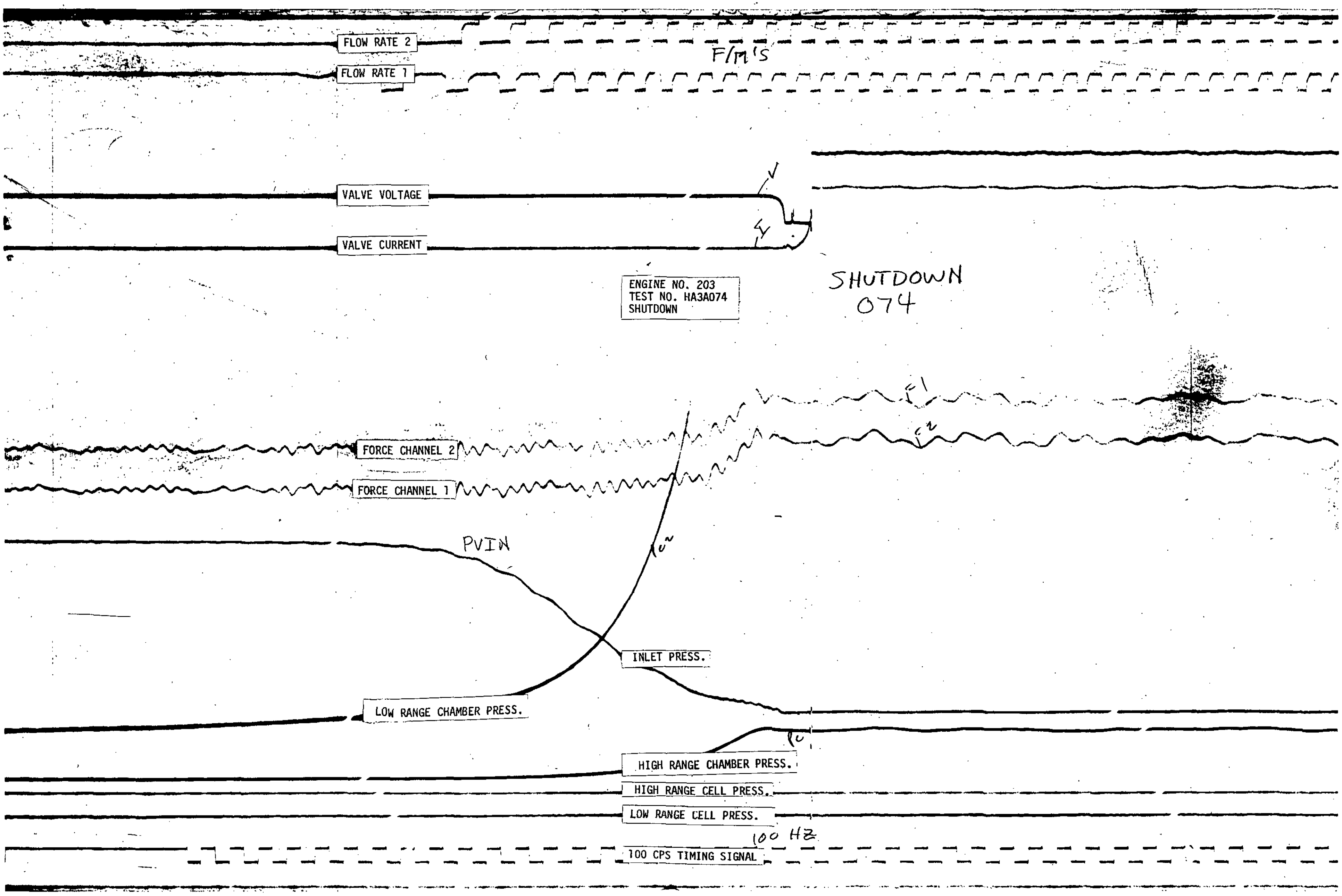
ENGINE NO. 203
TEST NO. HA3A073
SHUTDOWN

End of 073
10 sec 200 PSI run



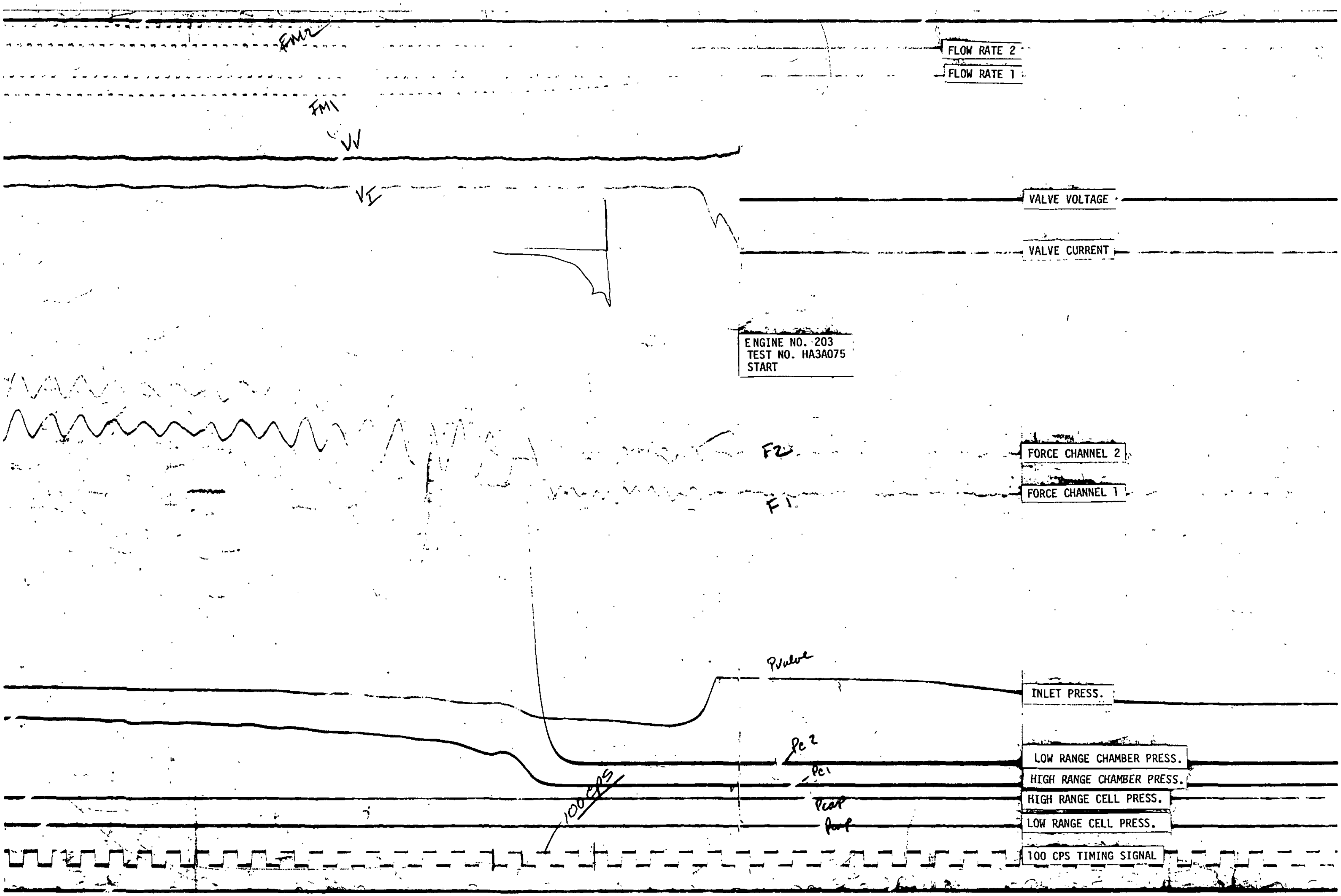
ENGINE NO. 203
TEST NO. HA3A074
START

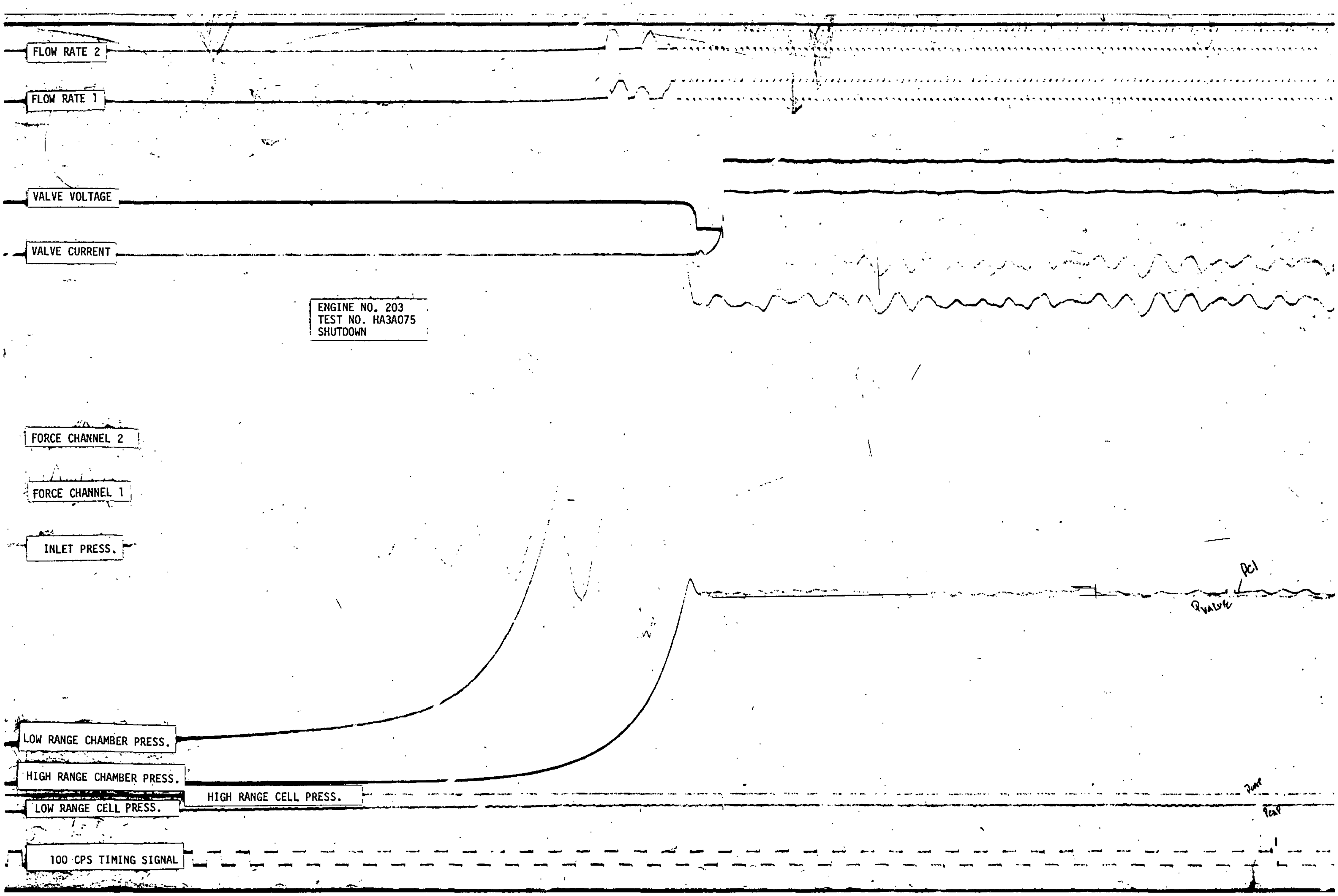
Start of 074
200-50 PSI
stepdown FA test



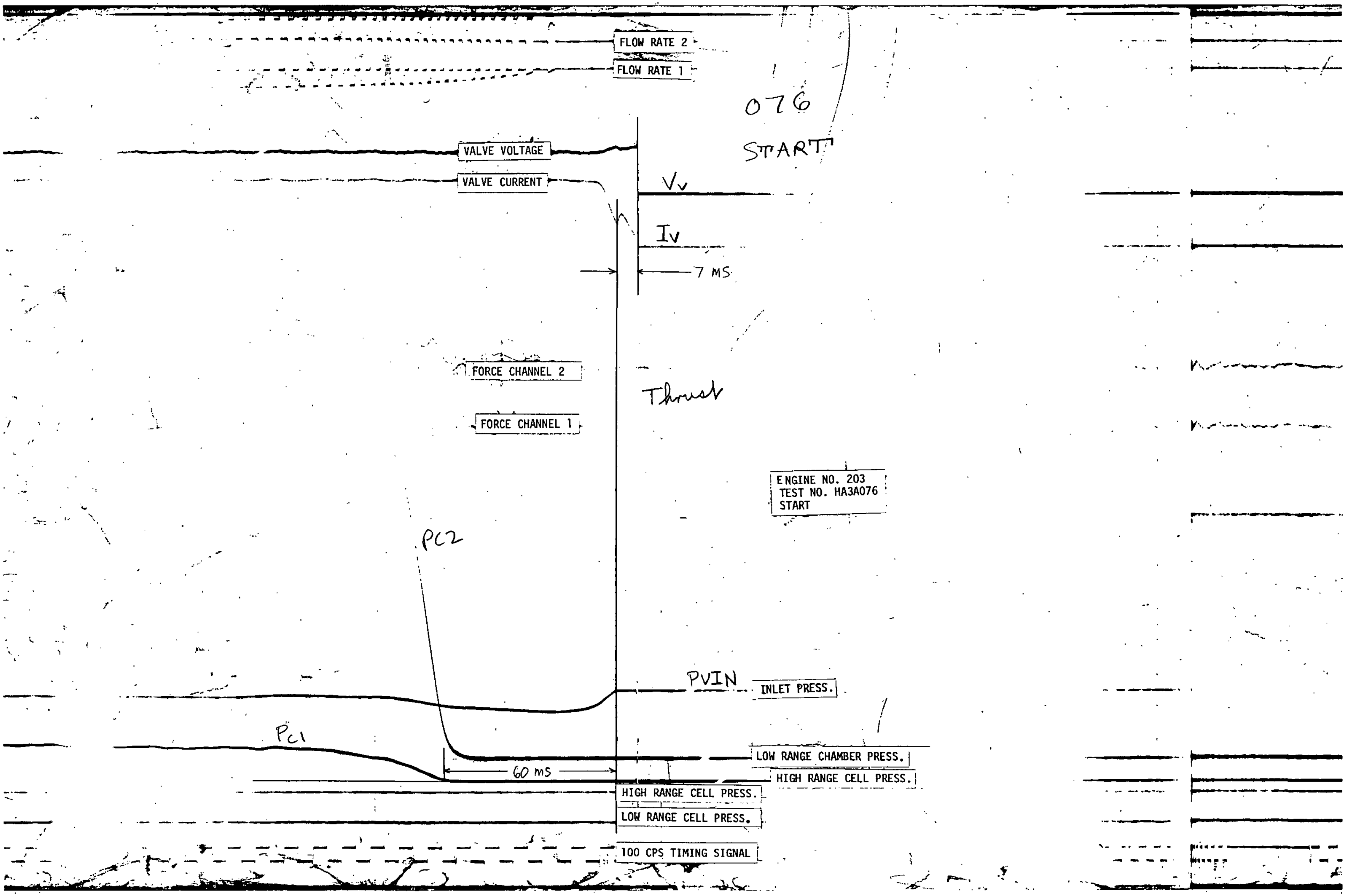
ENGINE NO. 203
TEST NO. HA3A074
SHUTDOWN

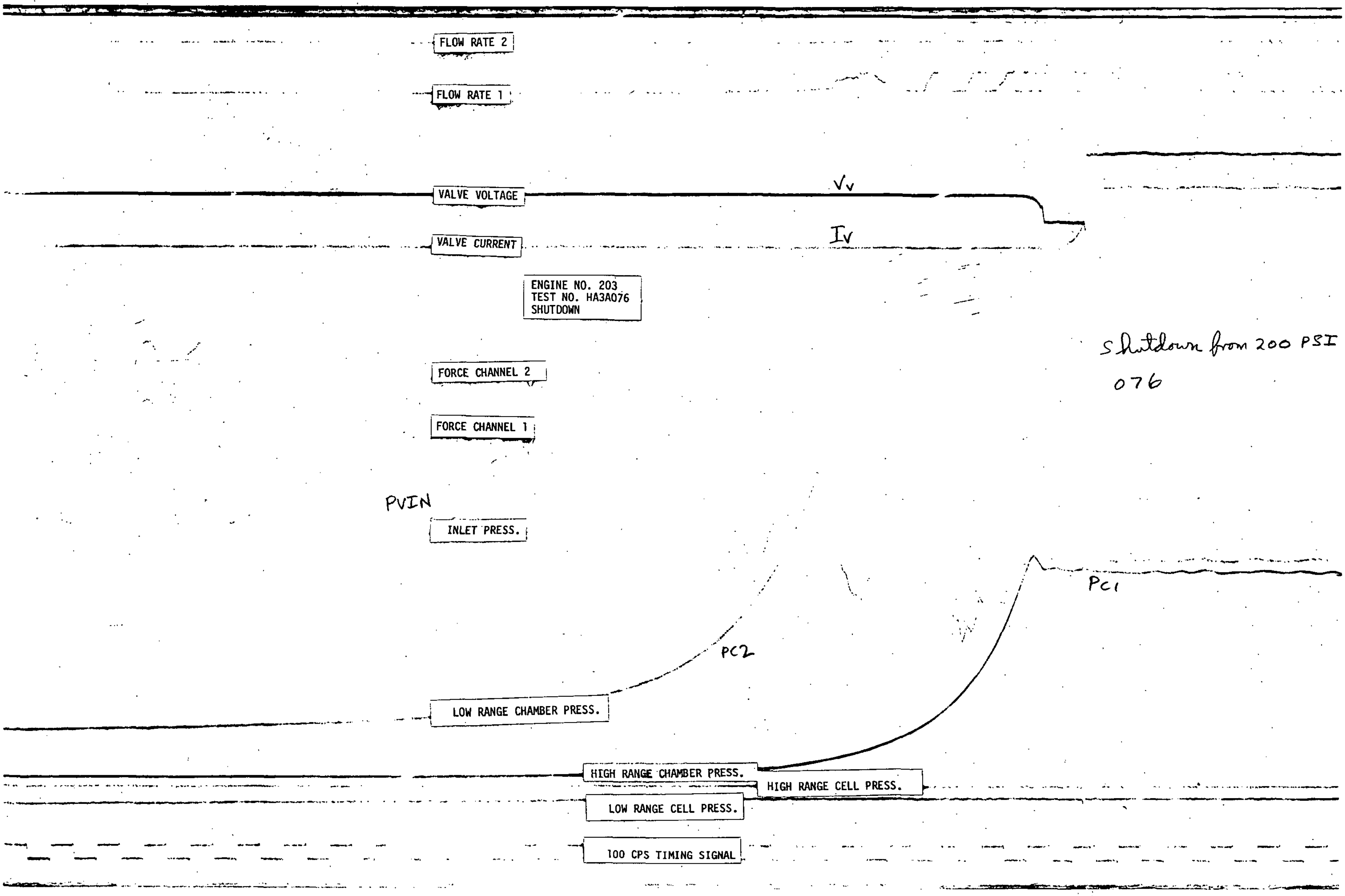
SHUTDOWN
074


FM2
FLOW RATE 2
FLOW RATE 1
FM1
VV
VI
VALVE VOLTAGE
VALVE CURRENT
ENGINE NO. 203
TEST NO. HA3A075
START
F2
F1
FORCE CHANNEL 2
FORCE CHANNEL 1
Pvalve
INLET PRESS.
Pc2
Pc1
LOW RANGE CHAMBER PRESS.
HIGH RANGE CHAMBER PRESS.
Pcap
Pcel
HIGH RANGE CELL PRESS.
LOW RANGE CELL PRESS.
100 CPS
100 CPS TIMING SIGNAL



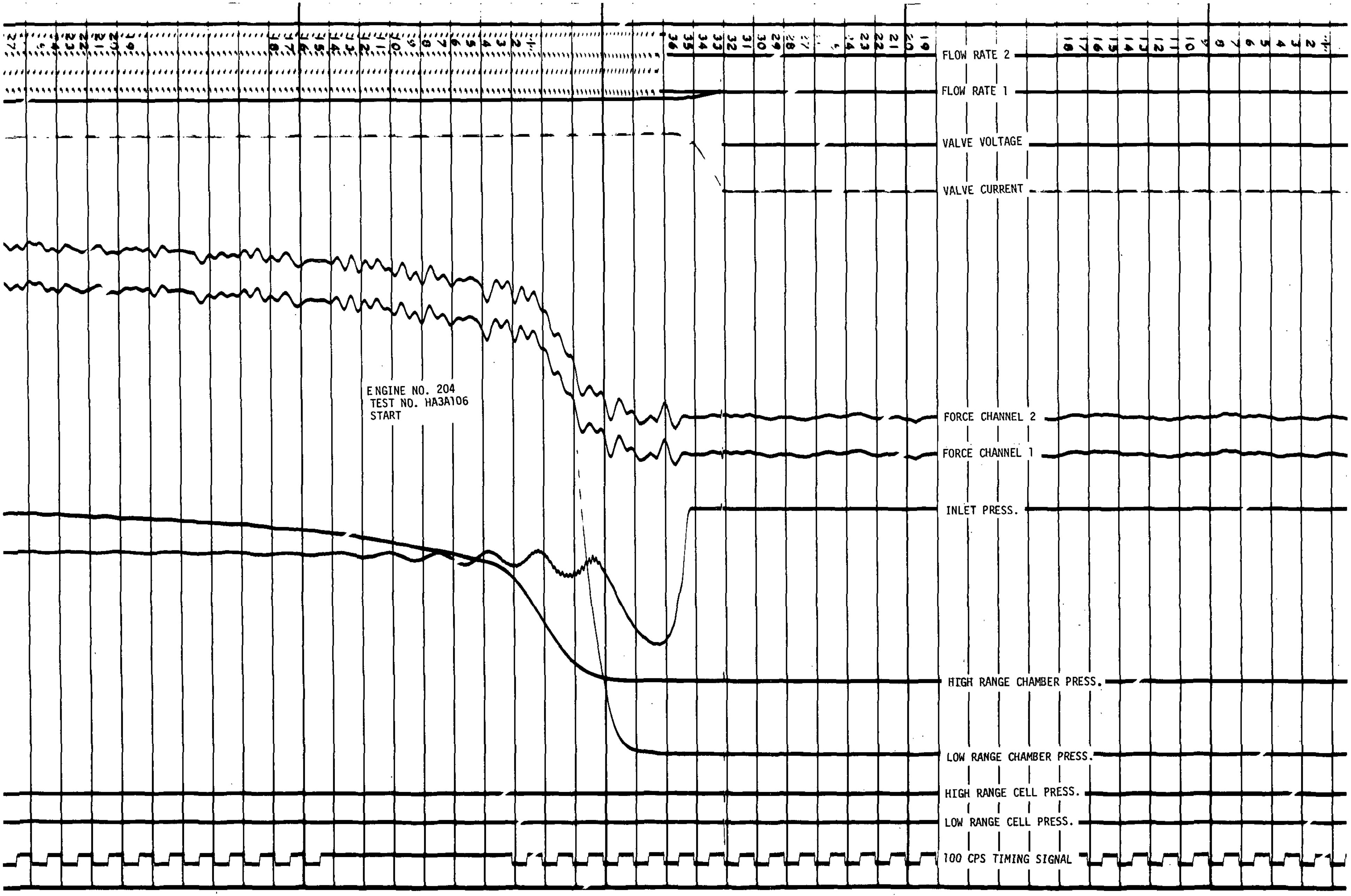
ENGINE NO. 203
TEST NO. HA3A075
SHUTDOWN


FLOW RATE 2
FLOW RATE 1
076
START
VALVE VOLTAGE
VALVE CURRENT
V_v
I_v
7 MS
FORCE CHANNEL 2
FORCE CHANNEL 1
Thrust
ENGINE NO. 203
TEST NO. HA3A076
START
PC2
PVIN
INLET PRESS.
Pc1
LOW RANGE CHAMBER PRESS.
60 MS
HIGH RANGE CELL PRESS.
HIGH RANGE CELL PRESS.
LOW RANGE CELL PRESS.
100 CPS TIMING SIGNAL

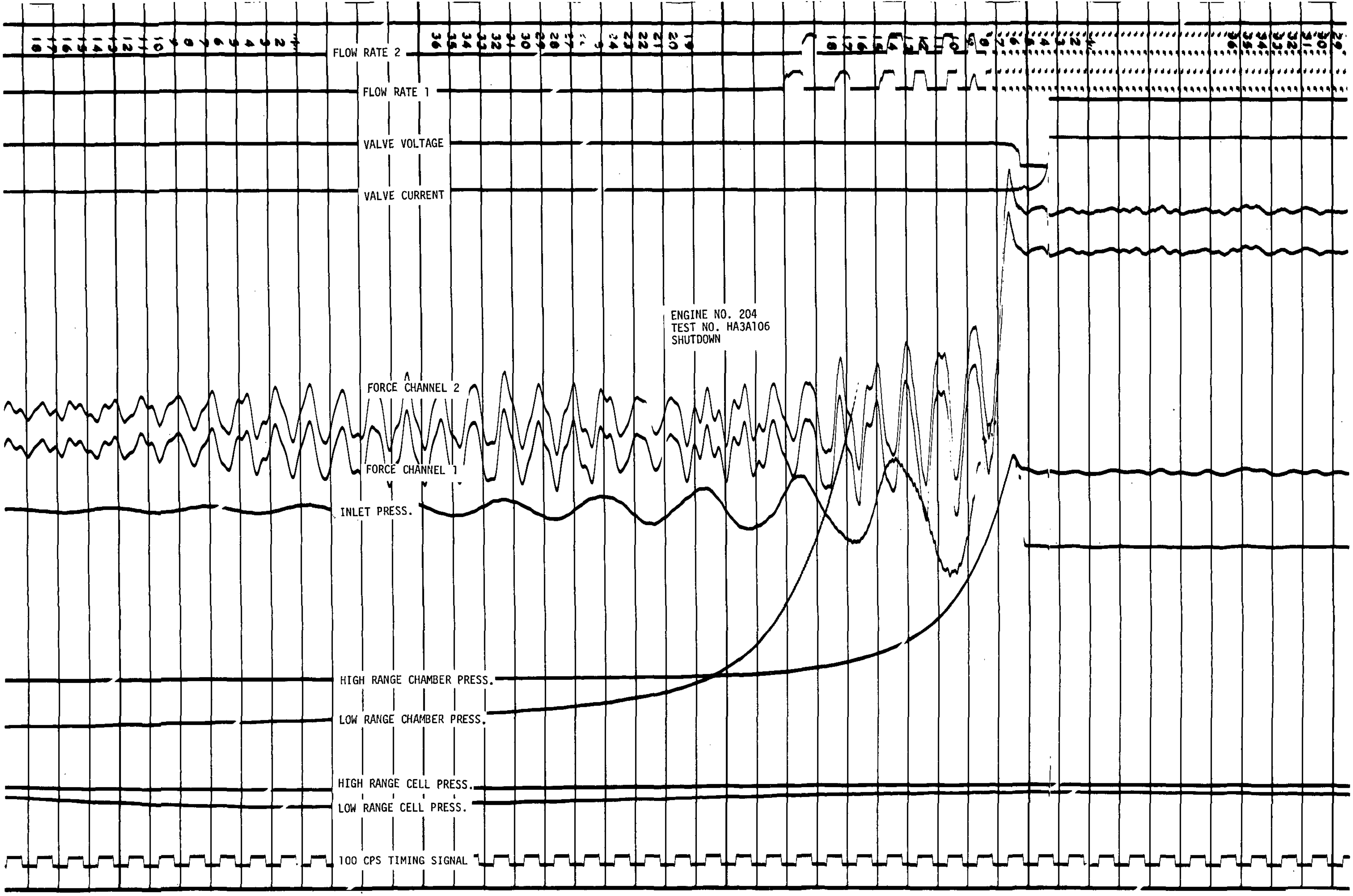


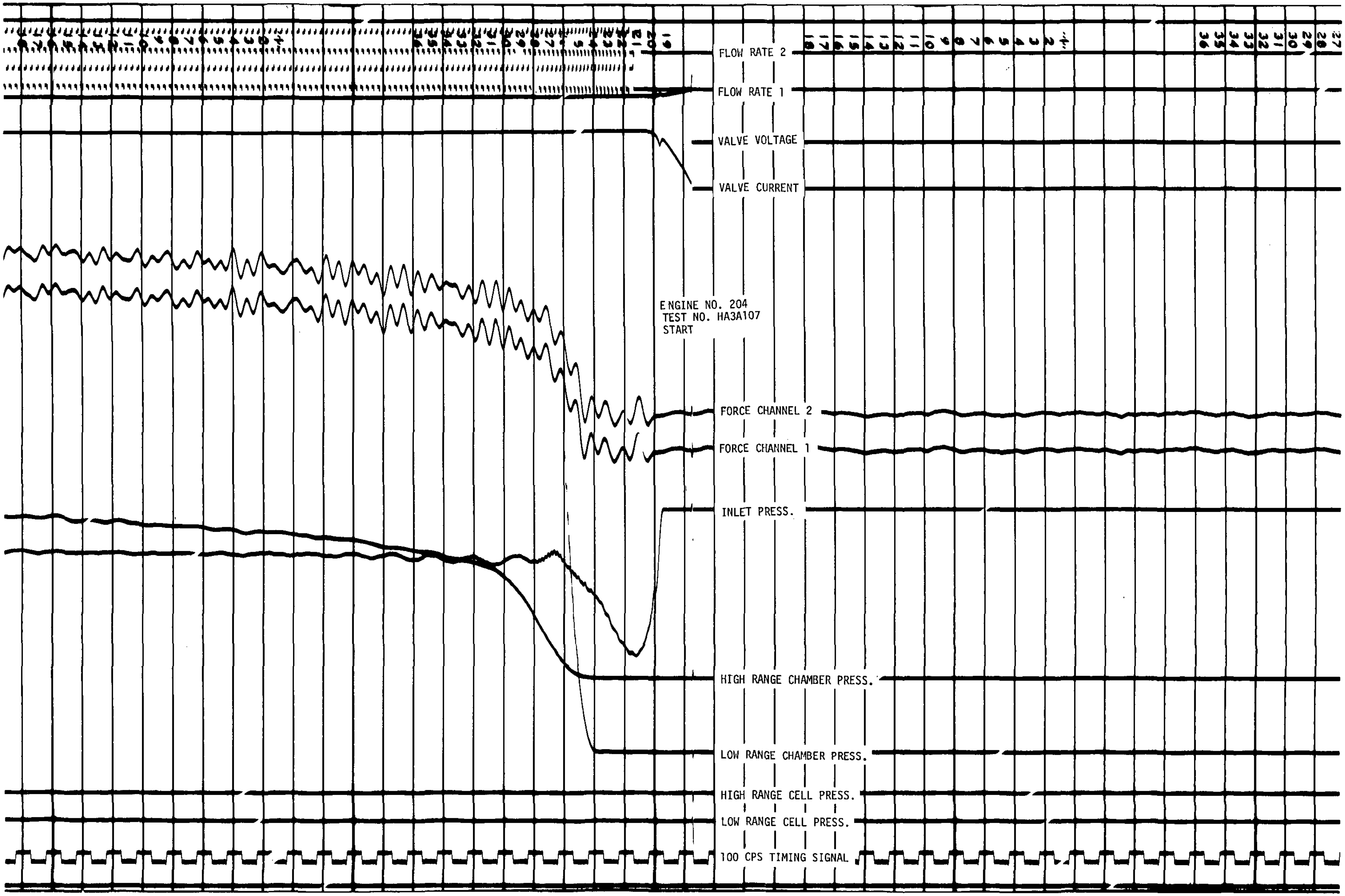
Shutdown from 200 PSI

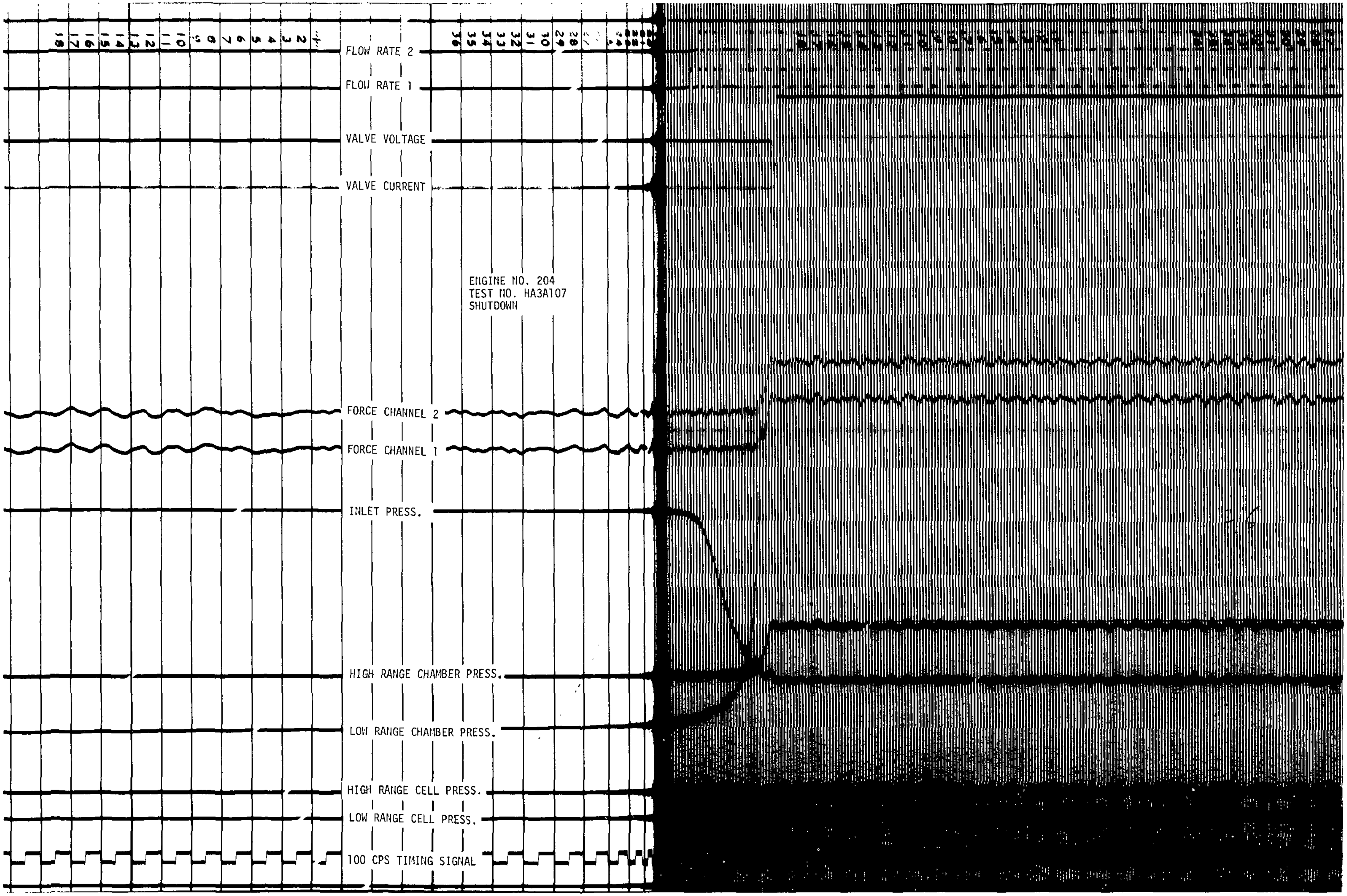
076



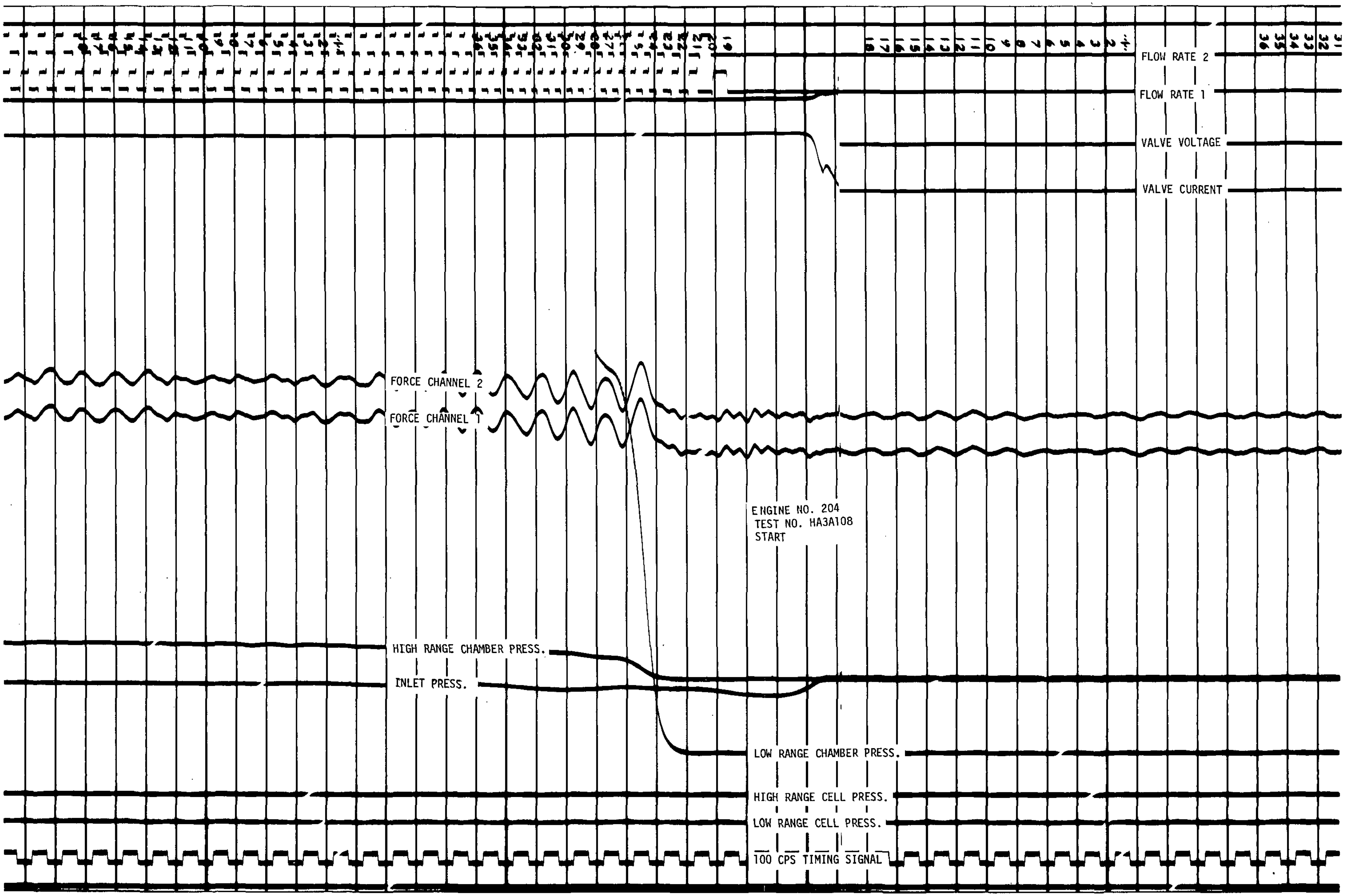
ENGINE NO. 204
TEST NO. HA3A106
START

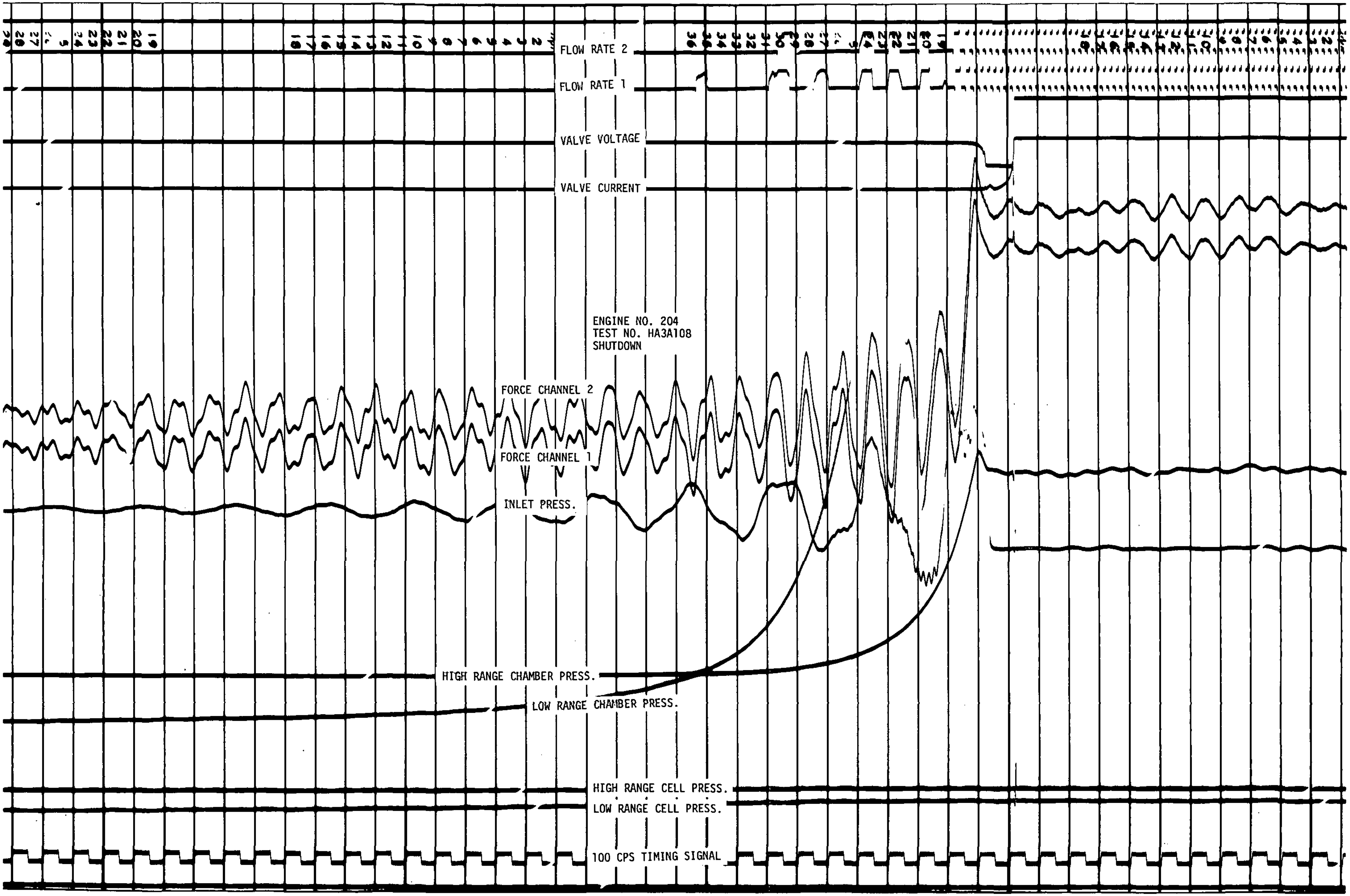

FLOW RATE 2
FLOW RATE 1
VALVE VOLTAGE
VALVE CURRENT
ENGINE NO. 204
TEST NO. HA3A106
SHUTDOWN
FORCE CHANNEL 2
FORCE CHANNEL 1
INLET PRESS.
HIGH RANGE CHAMBER PRESS.
LOW RANGE CHAMBER PRESS.
HIGH RANGE CELL PRESS.
LOW RANGE CELL PRESS.
100 CPS TIMING SIGNAL


FLOW RATE 2
FLOW RATE 1
VALVE VOLTAGE
VALVE CURRENT
ENGINE NO. 204
TEST NO. HA3A107
START
FORCE CHANNEL 2
FORCE CHANNEL 1
INLET PRESS.
HIGH RANGE CHAMBER PRESS.
LOW RANGE CHAMBER PRESS.
HIGH RANGE CELL PRESS.
LOW RANGE CELL PRESS.
100 CPS TIMING SIGNAL

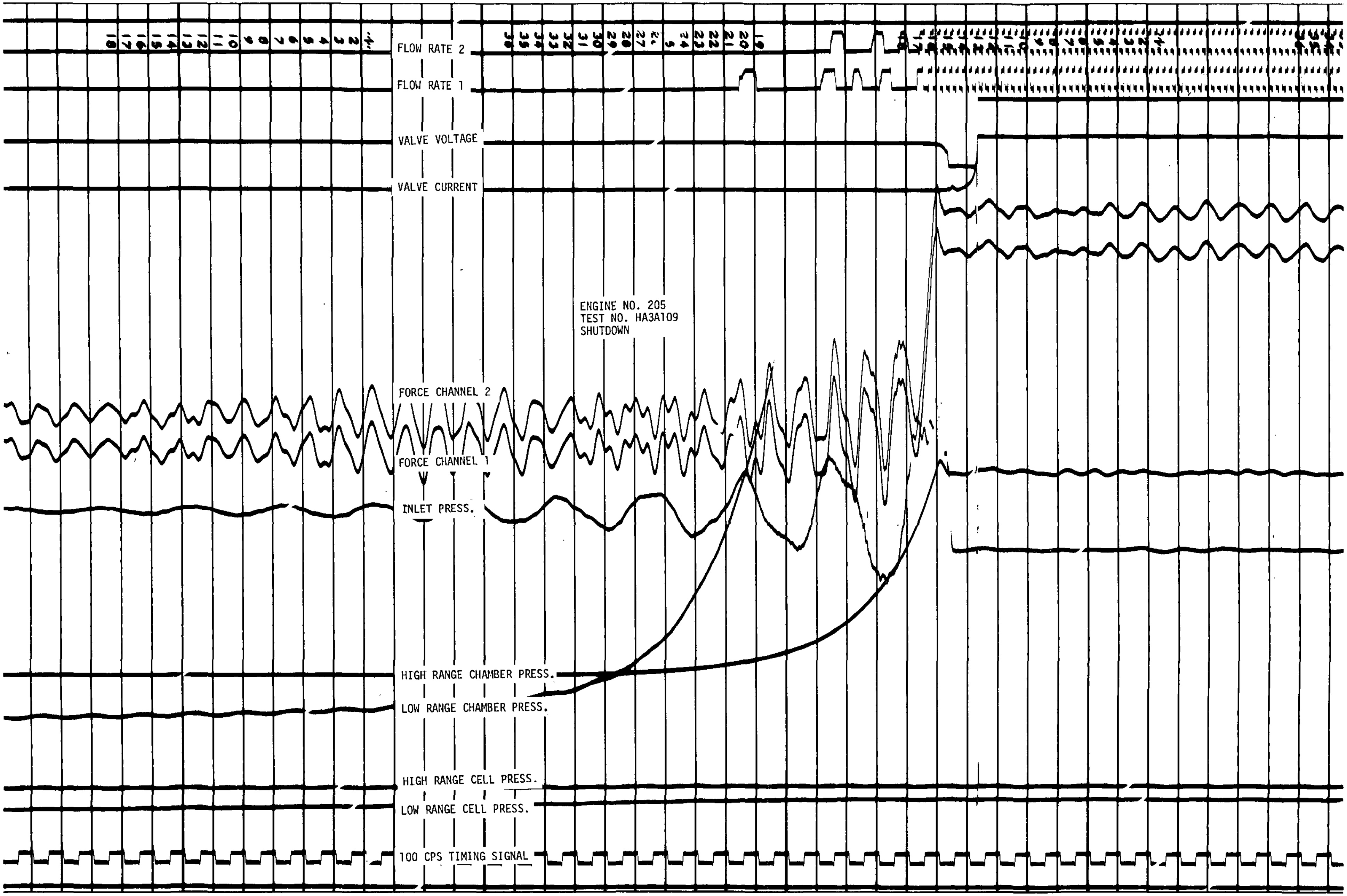


ENGINE NO. 204
TEST NO. HA3A107
SHUTDOWN

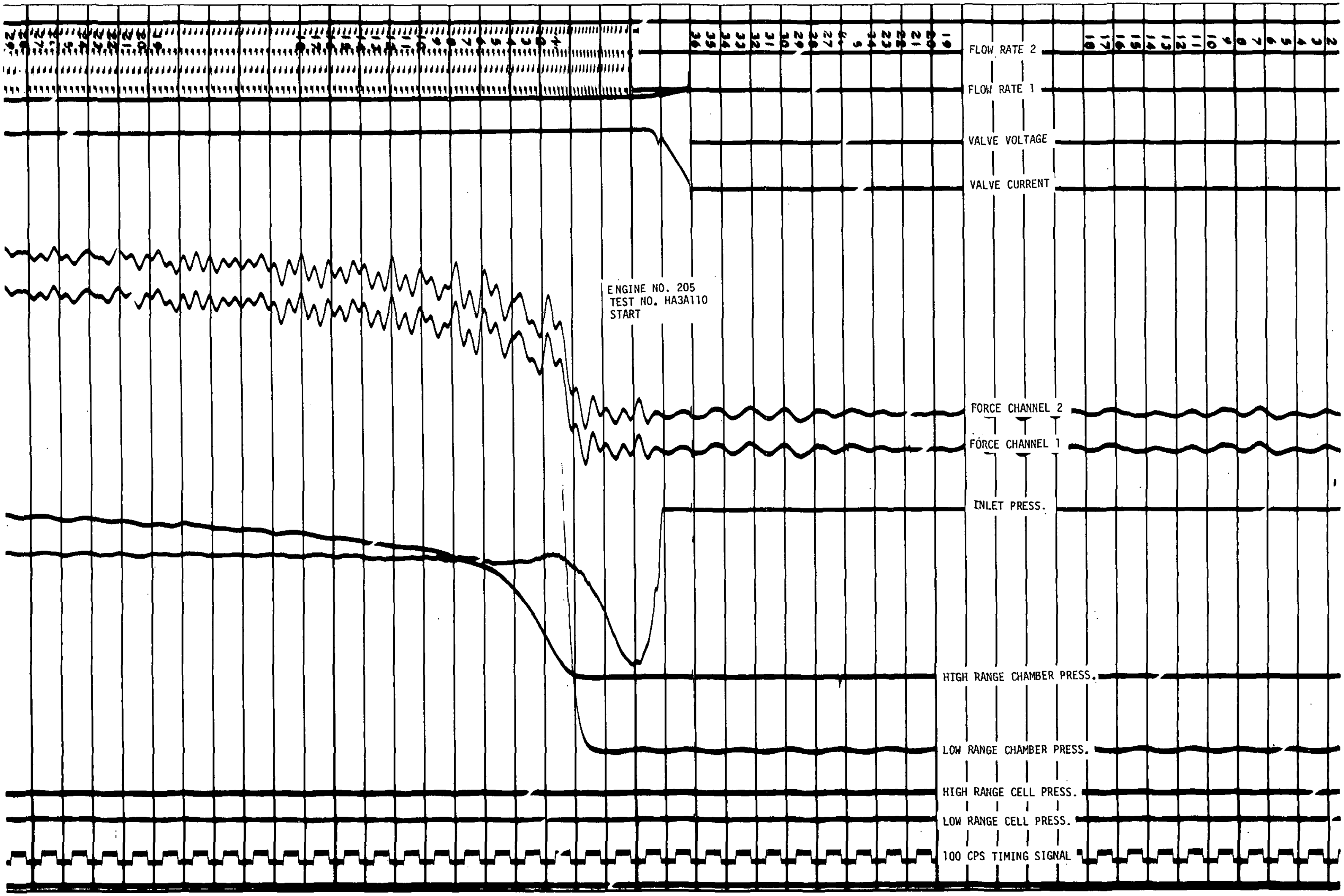

FLOW RATE 2
FLOW RATE 1
VALVE VOLTAGE
VALVE CURRENT
FORCE CHANNEL 2
FORCE CHANNEL 1
ENGINE NO. 204
TEST NO. HA3A108
START
HIGH RANGE CHAMBER PRESS.
INLET PRESS.
LOW RANGE CHAMBER PRESS.
HIGH RANGE CELL PRESS.
LOW RANGE CELL PRESS.
100 CPS TIMING SIGNAL

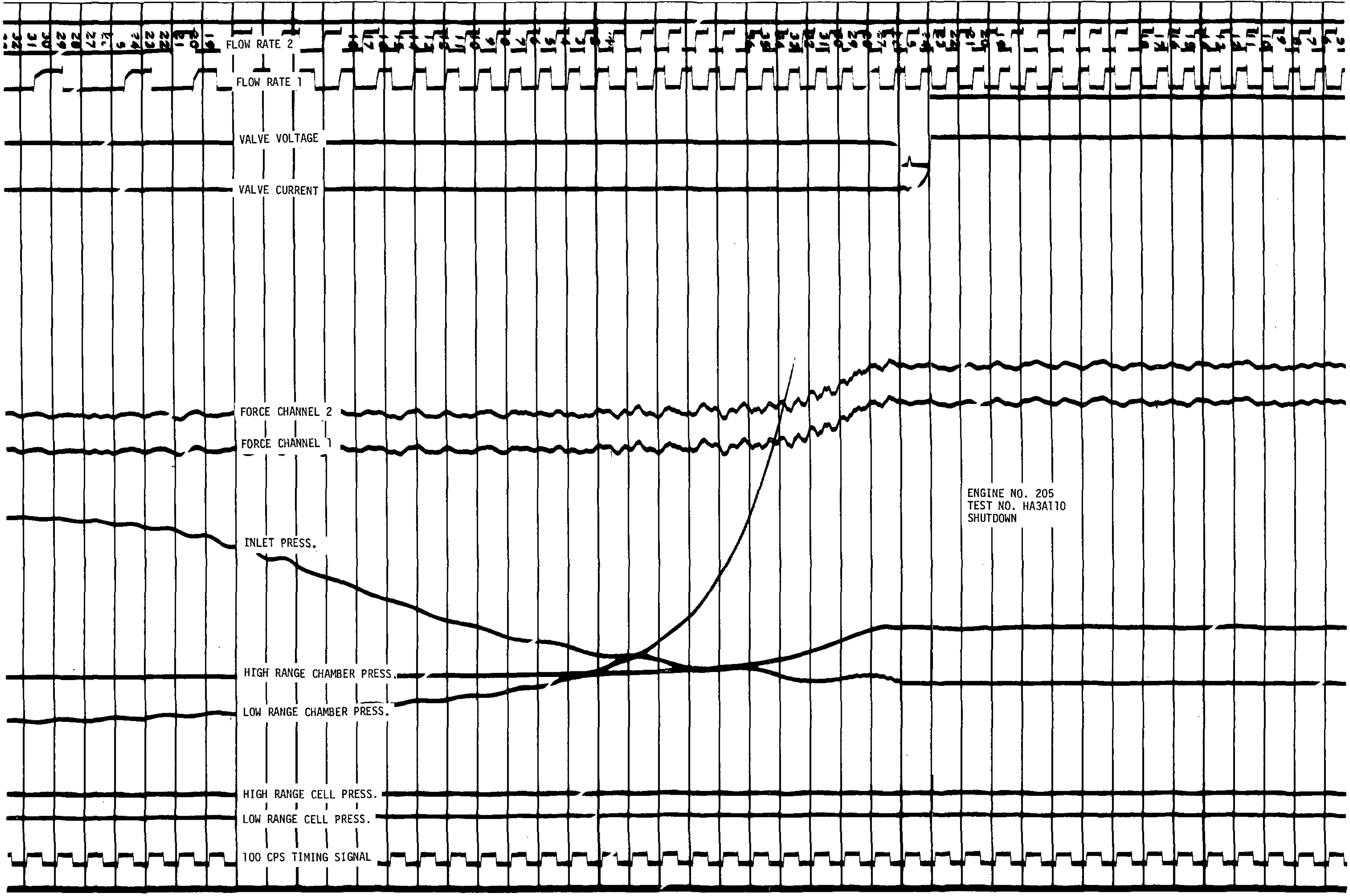

FLOW RATE 2
FLOW RATE 1
VALVE VOLTAGE
VALVE CURRENT
ENGINE NO. 204
TEST NO. HA3A108
SHUTDOWN
FORCE CHANNEL 2
FORCE CHANNEL 1
INLET PRESS.
HIGH RANGE CHAMBER PRESS.
LOW RANGE CHAMBER PRESS.
HIGH RANGE CELL PRESS.
LOW RANGE CELL PRESS.
100 CPS TIMING SIGNAL

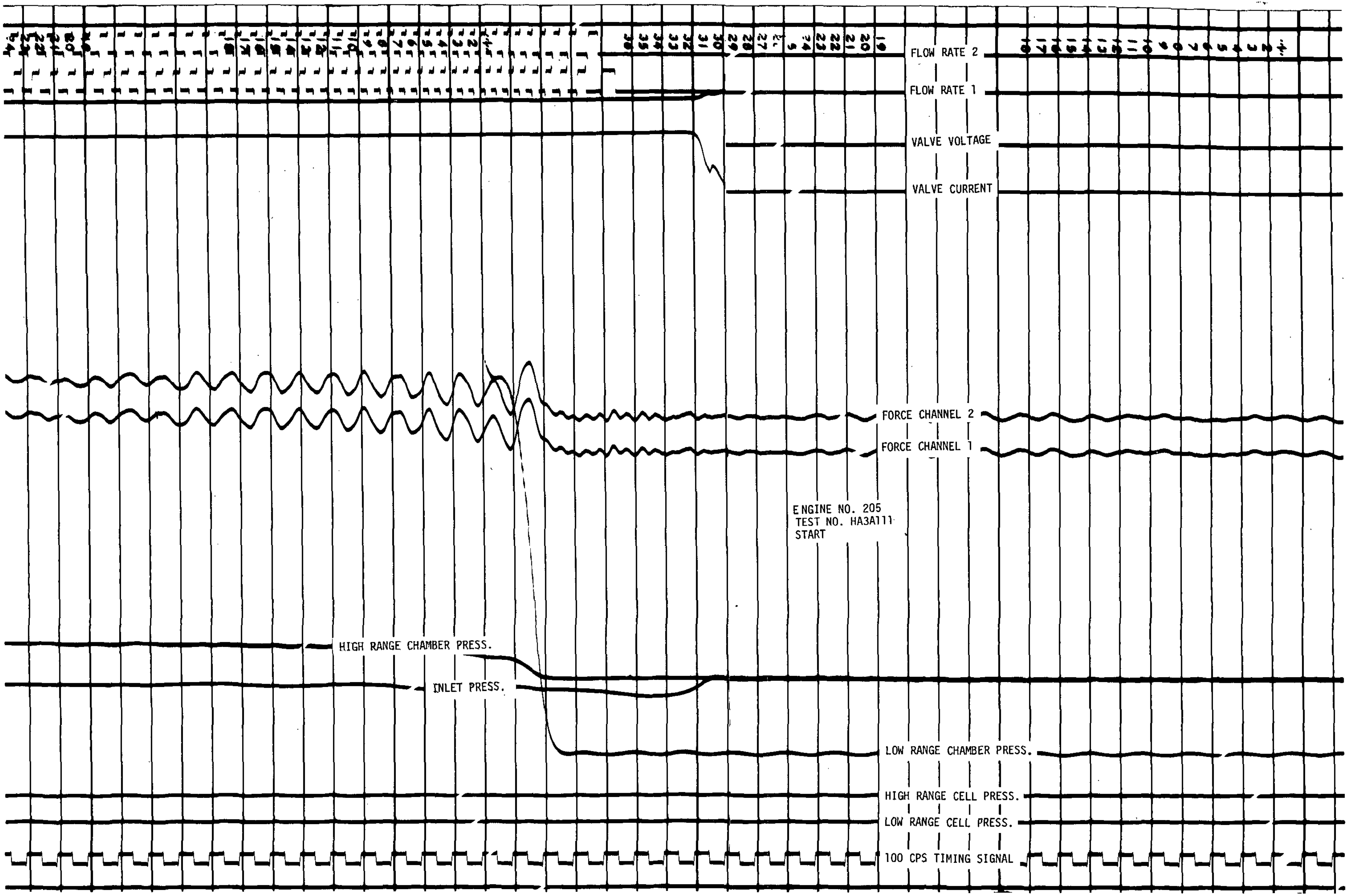
ENGINE NO. 205
TEST NO. HA3A-109
START

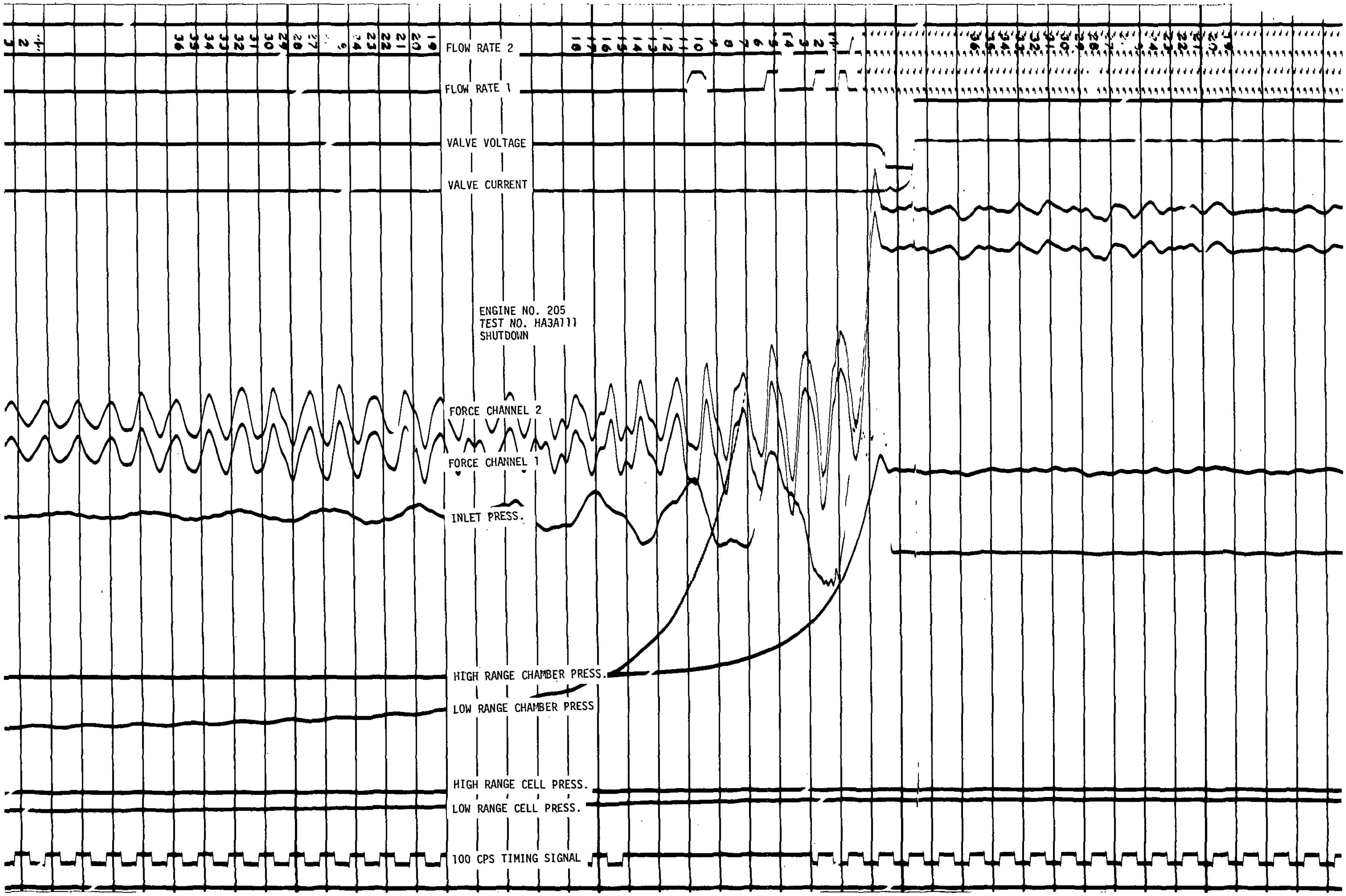


ENGINE NO. 205
TEST NO. HA3A109
SHUTDOWN

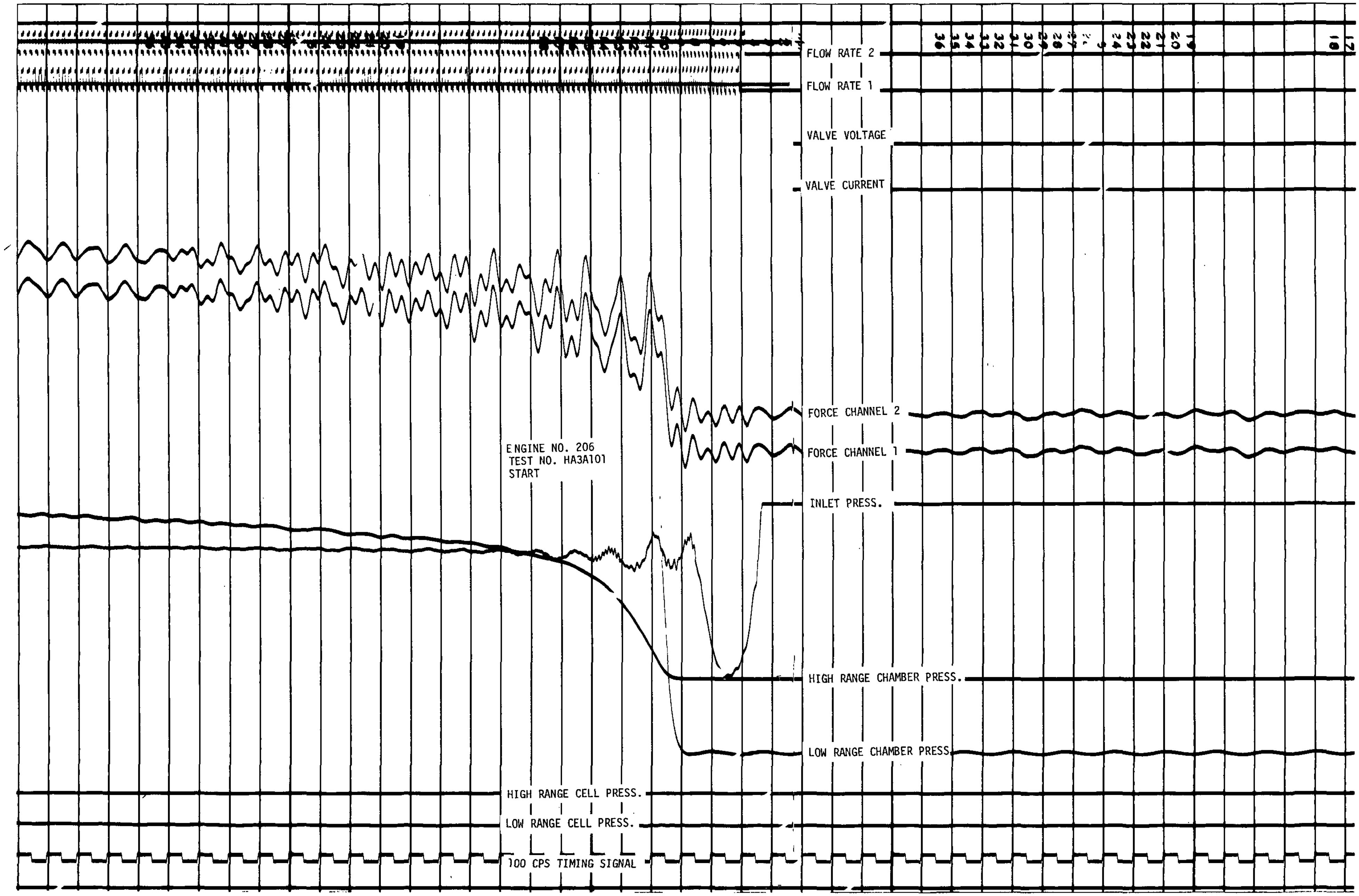

FLOW RATE 2
FLOW RATE 1
VALVE VOLTAGE
VALVE CURRENT
ENGINE NO. 205
TEST NO. HA3A110
START
FORCE CHANNEL 2
FORCE CHANNEL 1
INLET PRESS.
HIGH RANGE CHAMBER PRESS.
LOW RANGE CHAMBER PRESS.
HIGH RANGE CELL PRESS.
LOW RANGE CELL PRESS.
100 CPS TIMING SIGNAL


FLOW RATE 2
FLOW RATE 1
VALVE VOLTAGE
VALVE CURRENT
FORCE CHANNEL 2
FORCE CHANNEL 1
INLET PRESS.
HIGH RANGE CHAMBER PRESS.
LOW RANGE CHAMBER PRESS.
HIGH RANGE CELL PRESS.
LOW RANGE CELL PRESS.
100 CPS TIMING SIGNAL
ENGINE NO. 205
TEST NO. HA3A110
SHUTDOWN

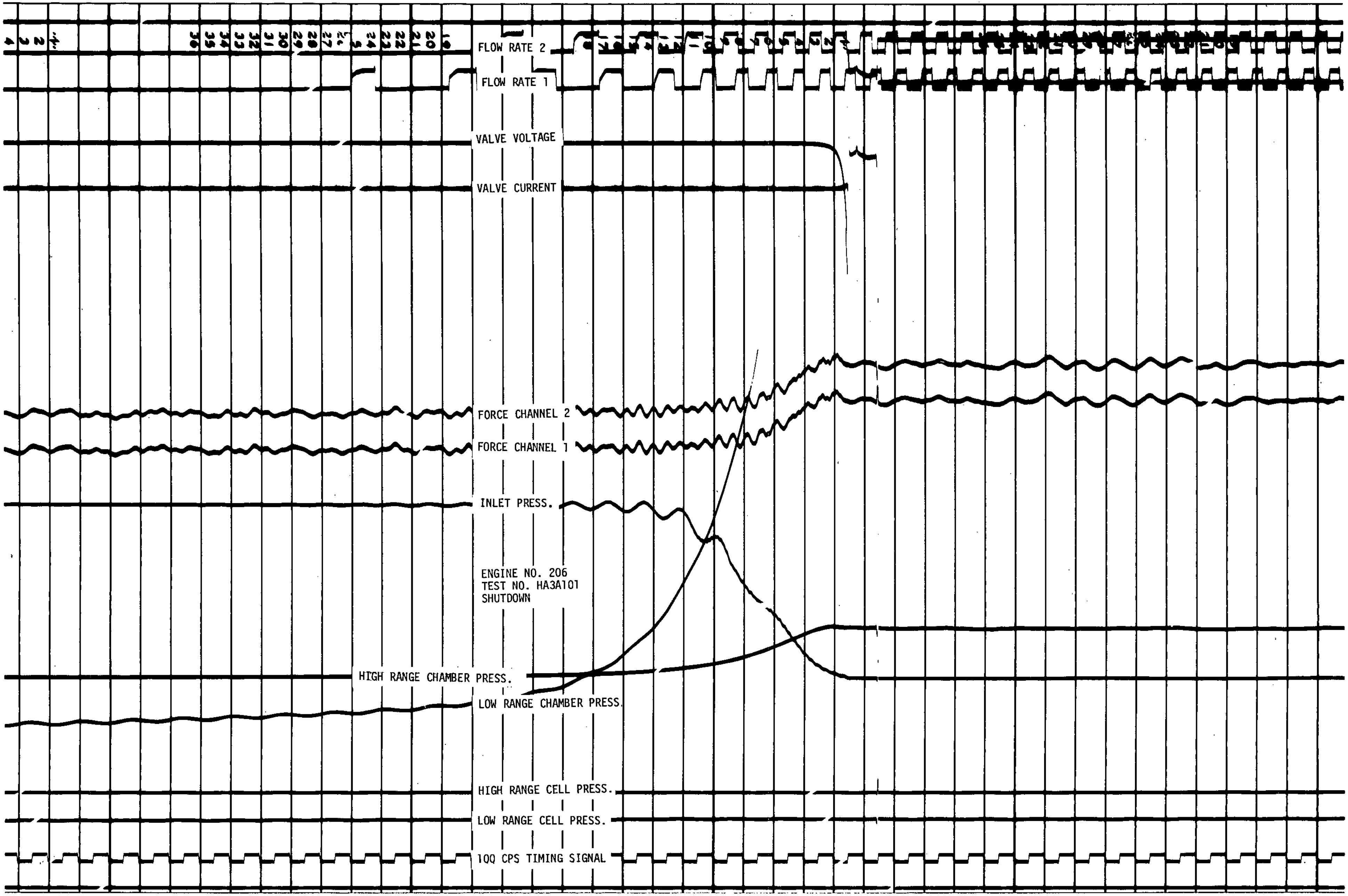

FLOW RATE 2
FLOW RATE 1
VALVE VOLTAGE
VALVE CURRENT
FORCE CHANNEL 2
FORCE CHANNEL 1
ENGINE NO. 205
TEST NO. HA3A111
START
HIGH RANGE CHAMBER PRESS.
INLET PRESS.
LOW RANGE CHAMBER PRESS.
HIGH RANGE CELL PRESS.
LOW RANGE CELL PRESS.
100 CPS TIMING SIGNAL

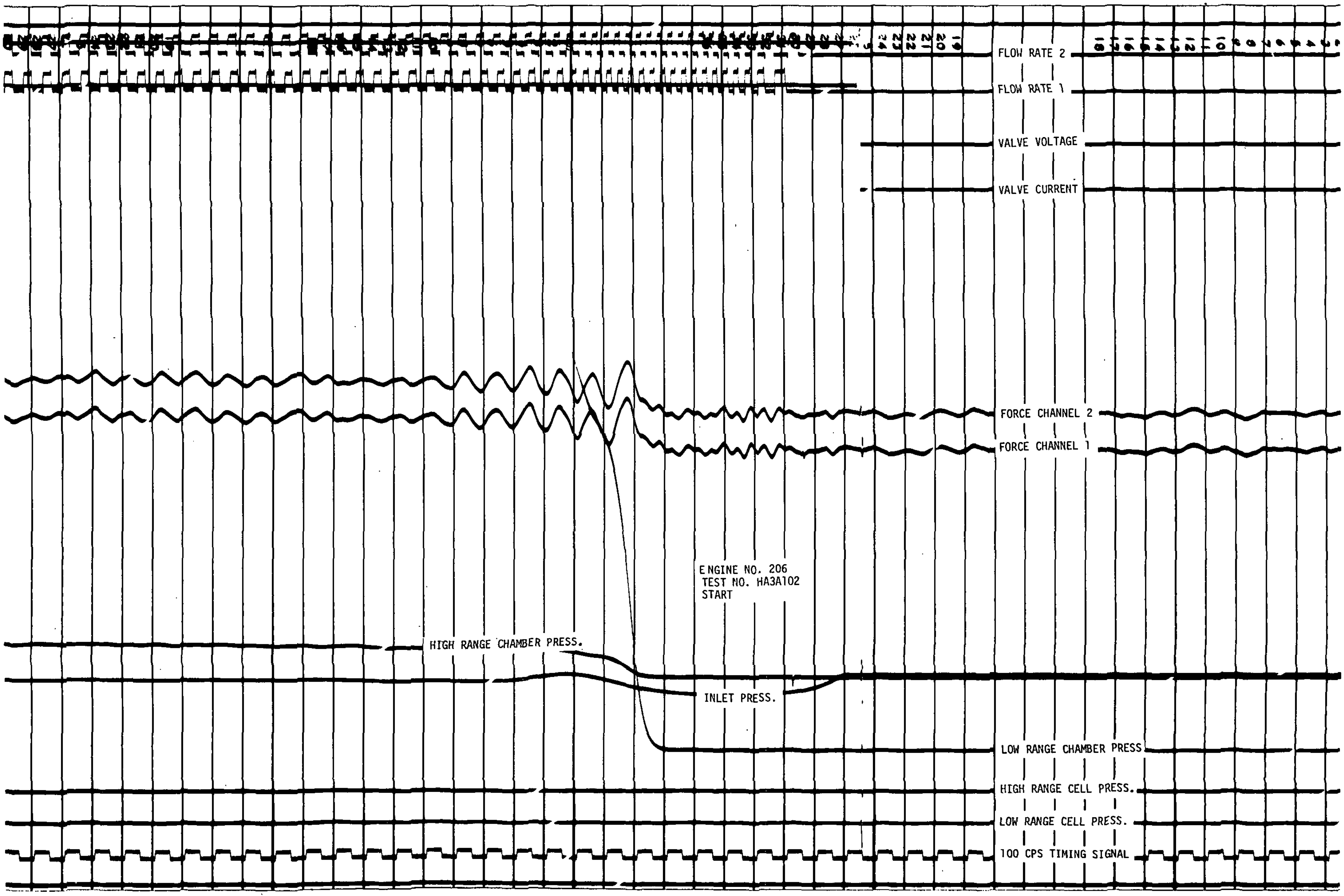


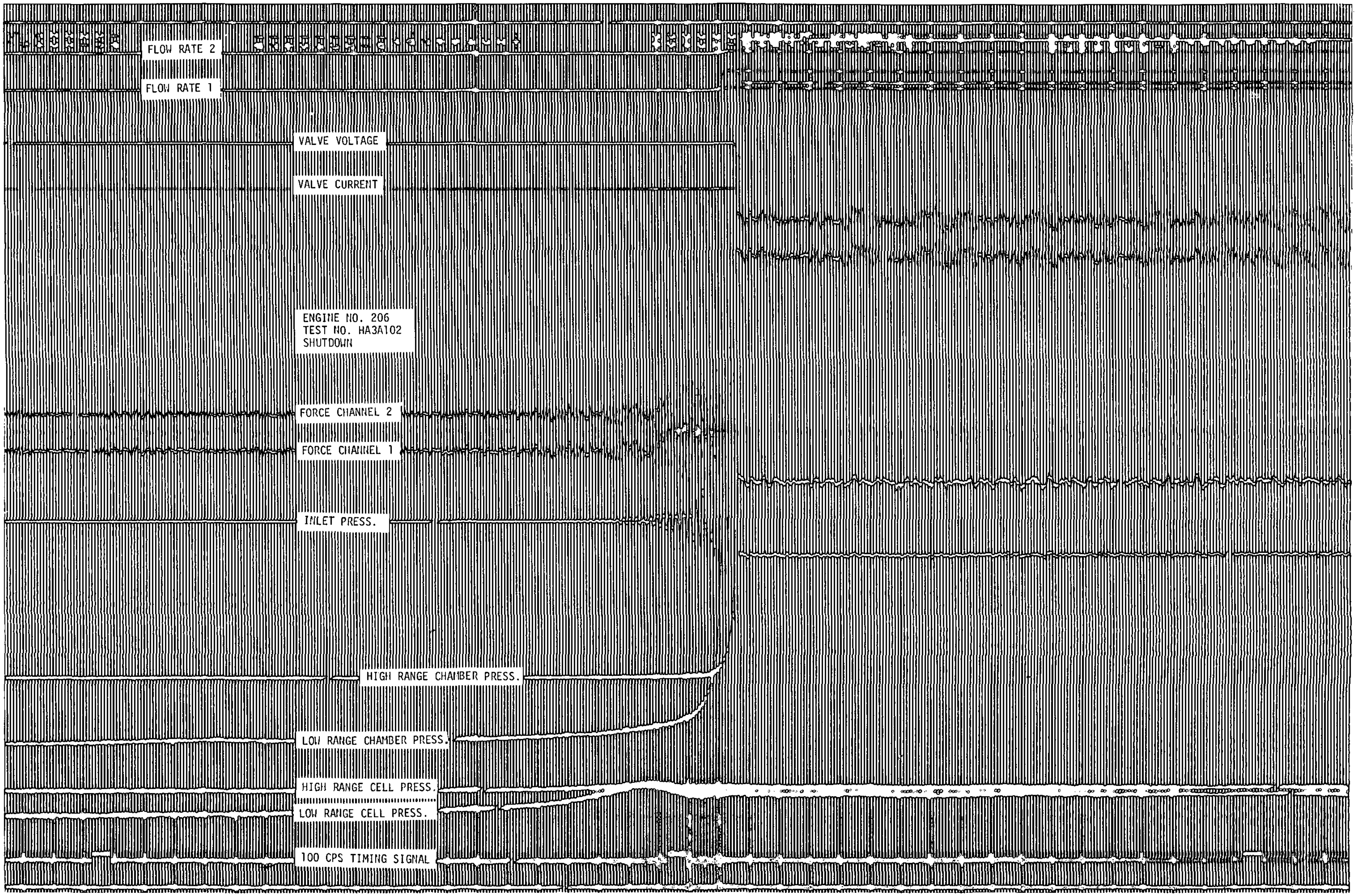
ENGINE NO. 205
TEST NO. HA3A111
SHUTDOWN

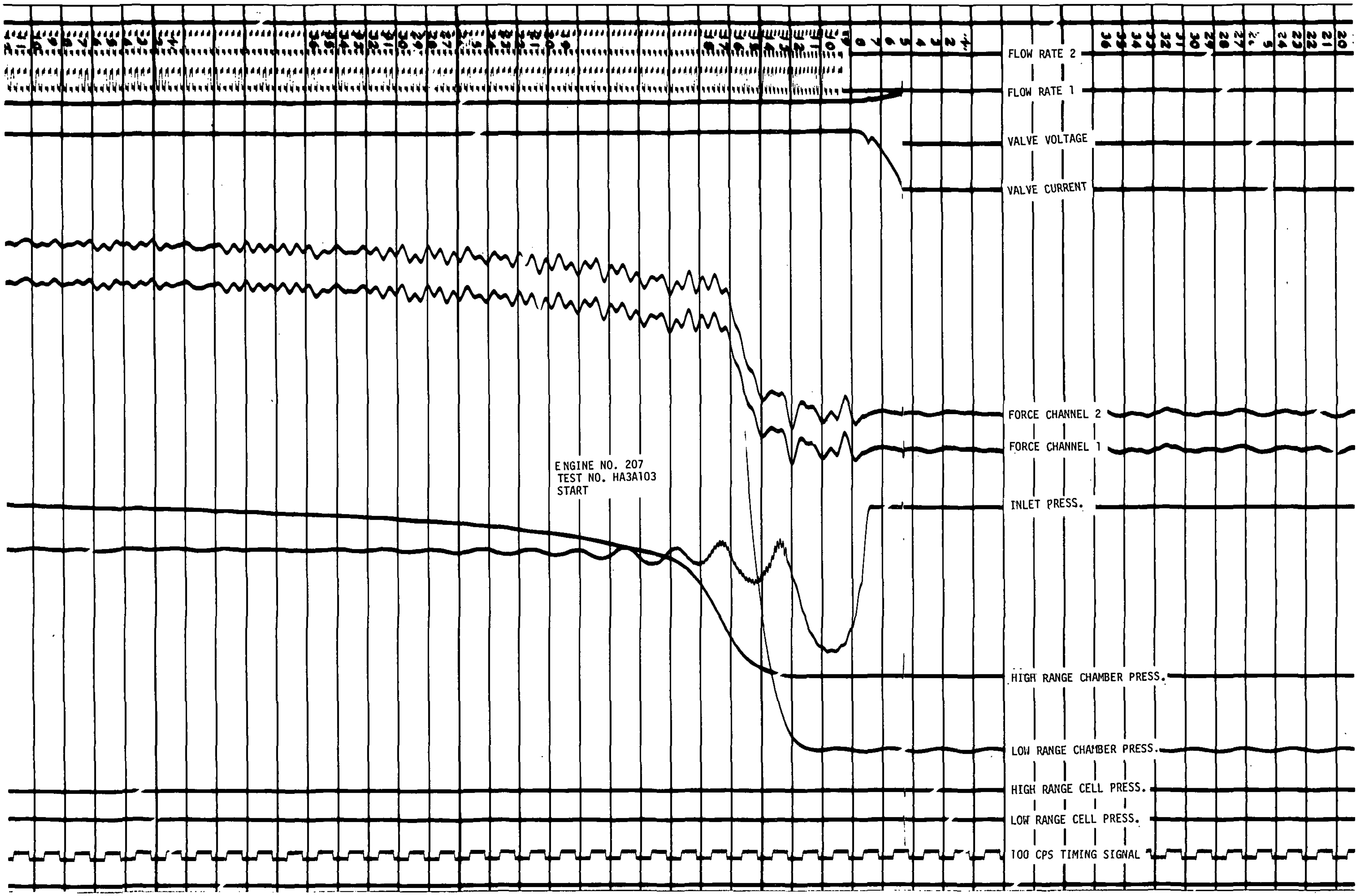


ENGINE NO. 206
TEST NO. HA3A101
START

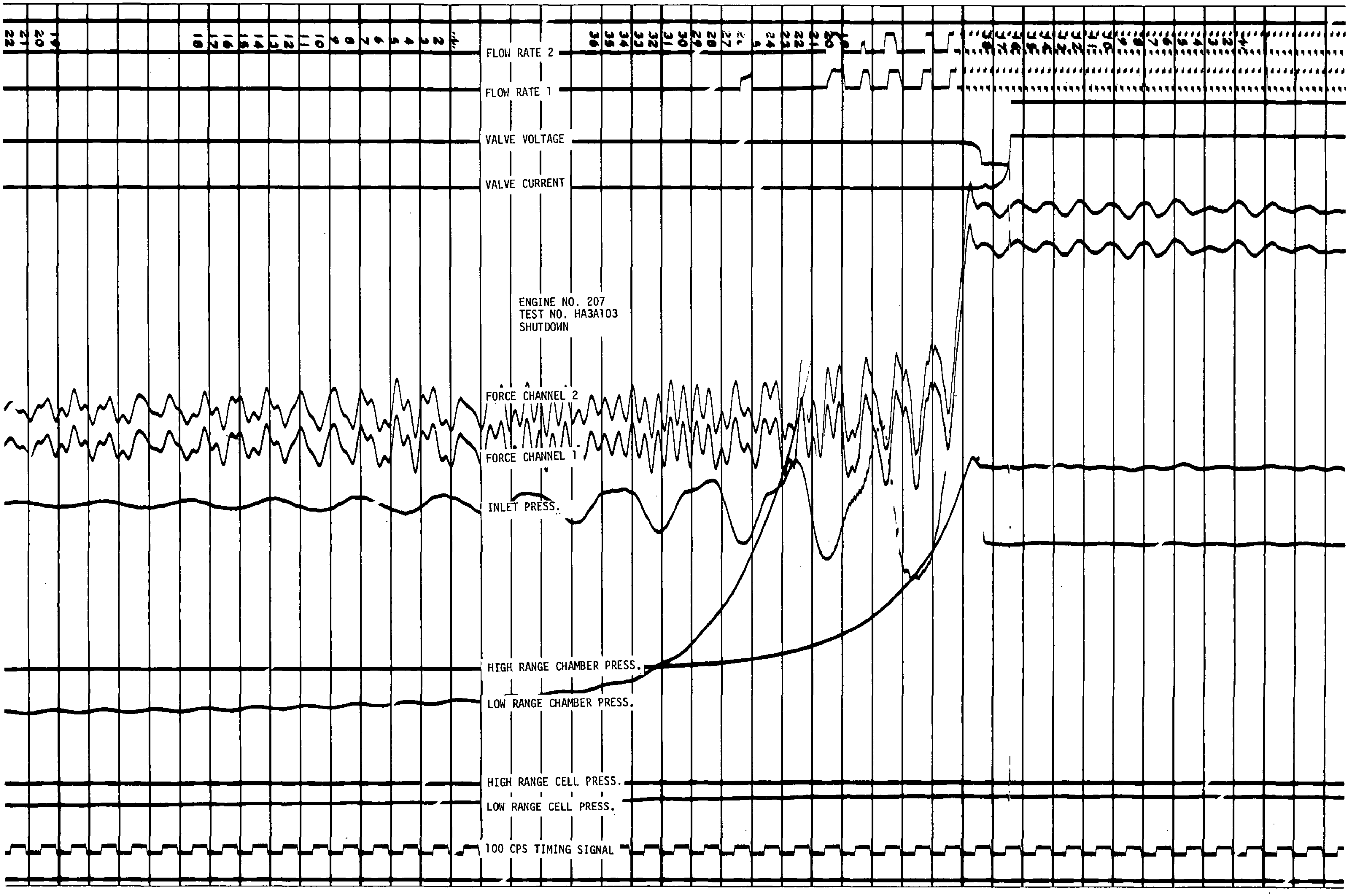

FLOW RATE 2
FLOW RATE 1
VALVE VOLTAGE
VALVE CURRENT
FORCE CHANNEL 2
FORCE CHANNEL 1
INLET PRESS.
ENGINE NO. 206
TEST NO. HA3A101
SHUTDOWN
HIGH RANGE CHAMBER PRESS.
LOW RANGE CHAMBER PRESS.
HIGH RANGE CELL PRESS.
LOW RANGE CELL PRESS.
100 CPS TIMING SIGNAL

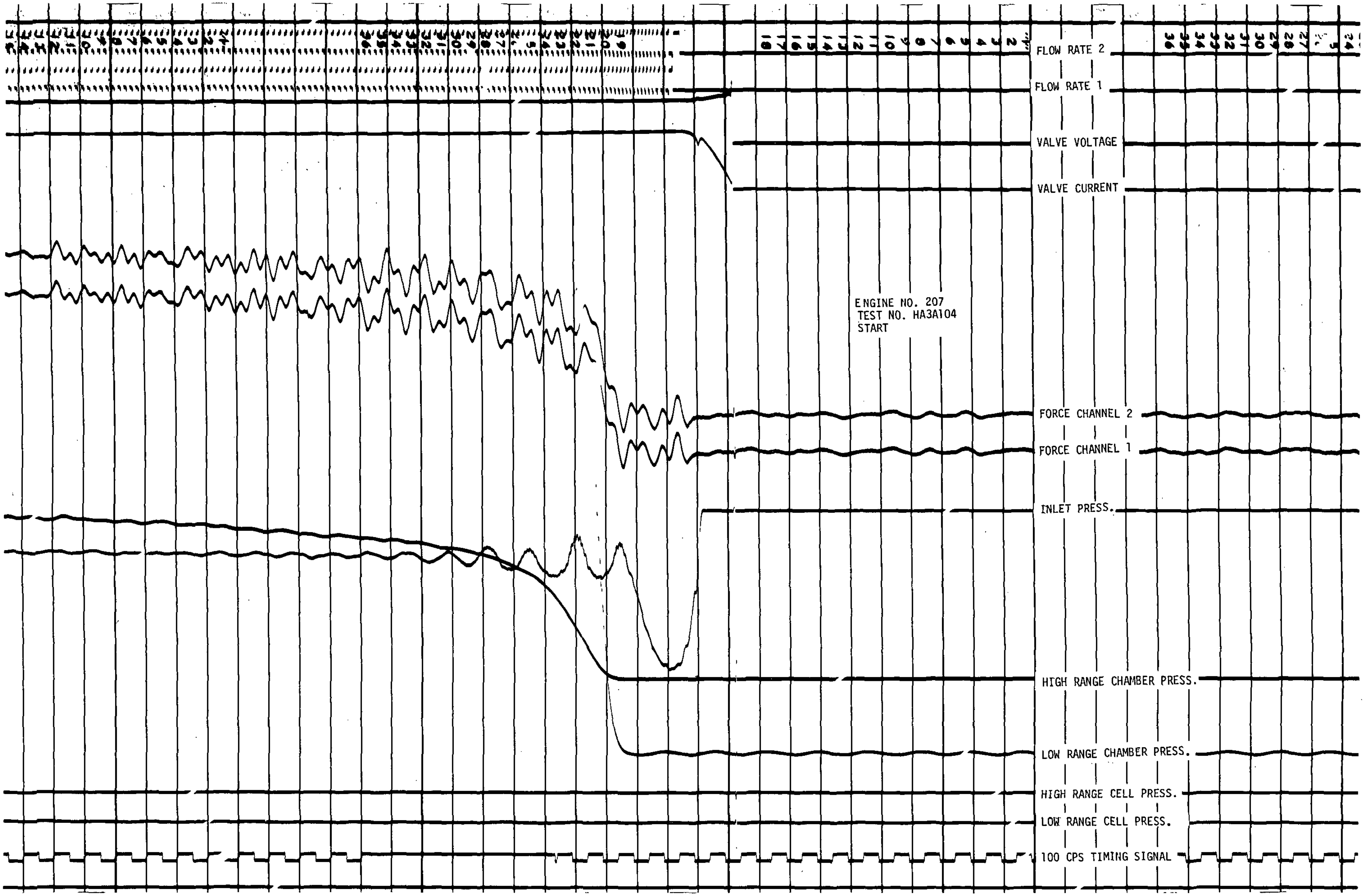

FLOW RATE 2
FLOW RATE 1
VALVE VOLTAGE
VALVE CURRENT
FORCE CHANNEL 2
FORCE CHANNEL 1
ENGINE NO. 206
TEST NO. HA3A102
START
HIGH RANGE CHAMBER PRESS.
INLET PRESS.
LOW RANGE CHAMBER PRESS
HIGH RANGE CELL PRESS.
LOW RANGE CELL PRESS.
100 CPS TIMING SIGNAL

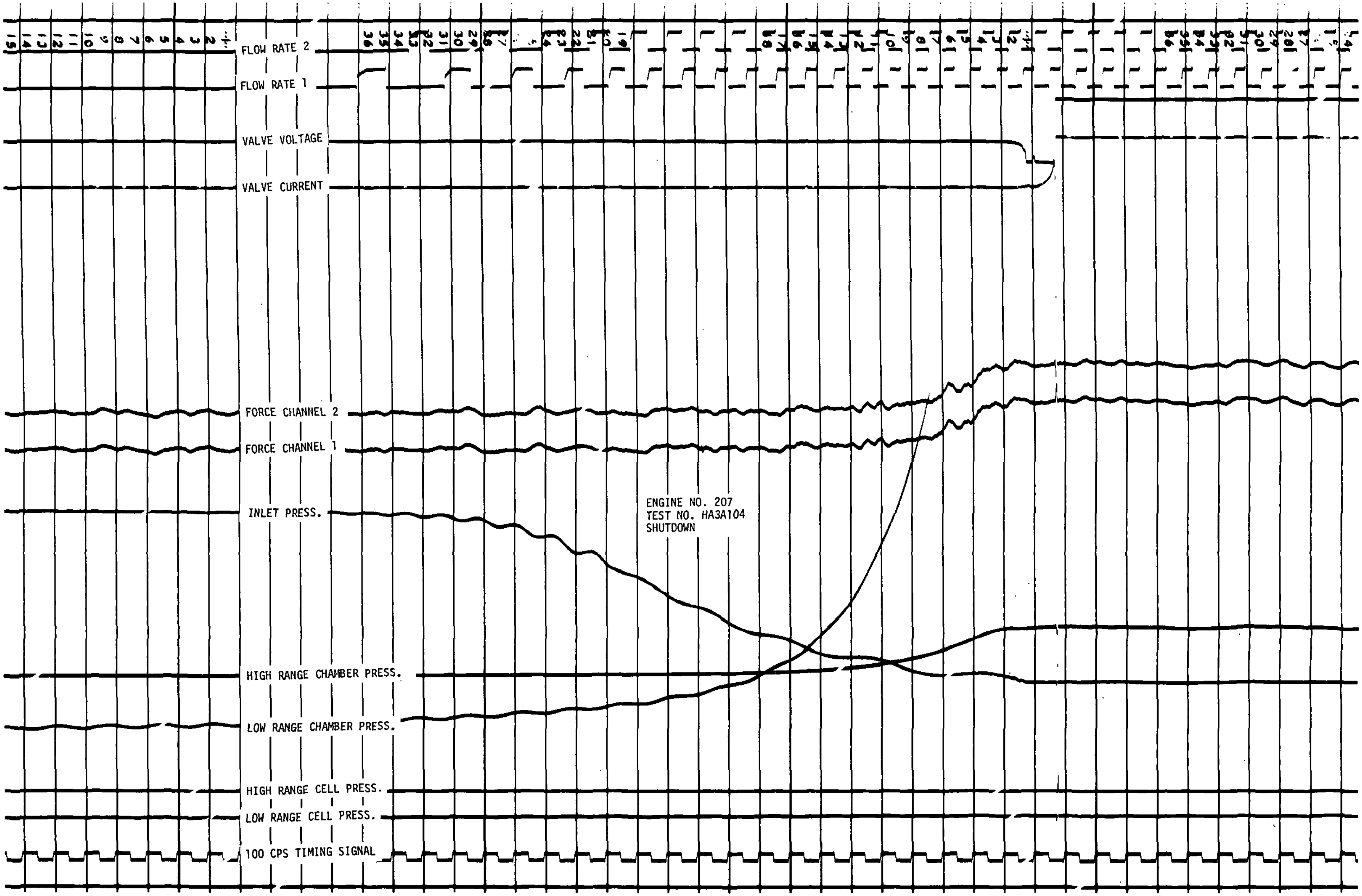

FLOW RATE 2
FLOW RATE 1
VALVE VOLTAGE
VALVE CURRENT
ENGINE NO. 206
TEST NO. HA3A102
SHUTDOWN
FORCE CHANNEL 2
FORCE CHANNEL 1
INLET PRESS.
HIGH RANGE CHAMBER PRESS.
LOW RANGE CHAMBER PRESS.
HIGH RANGE CELL PRESS.
LOW RANGE CELL PRESS.
100 CPS TIMING SIGNAL



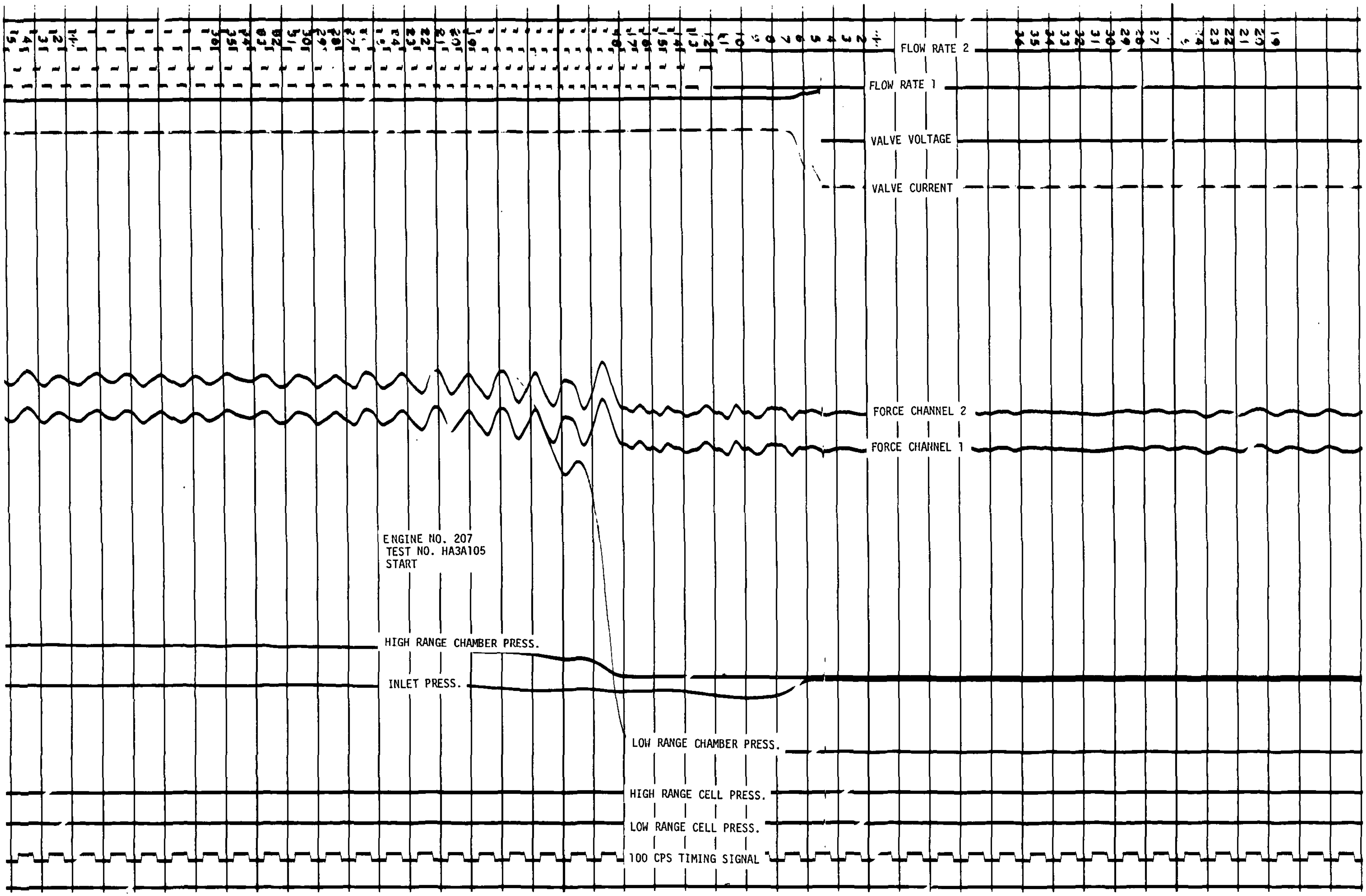
ENGINE NO. 207
TEST NO. HA3A103
START

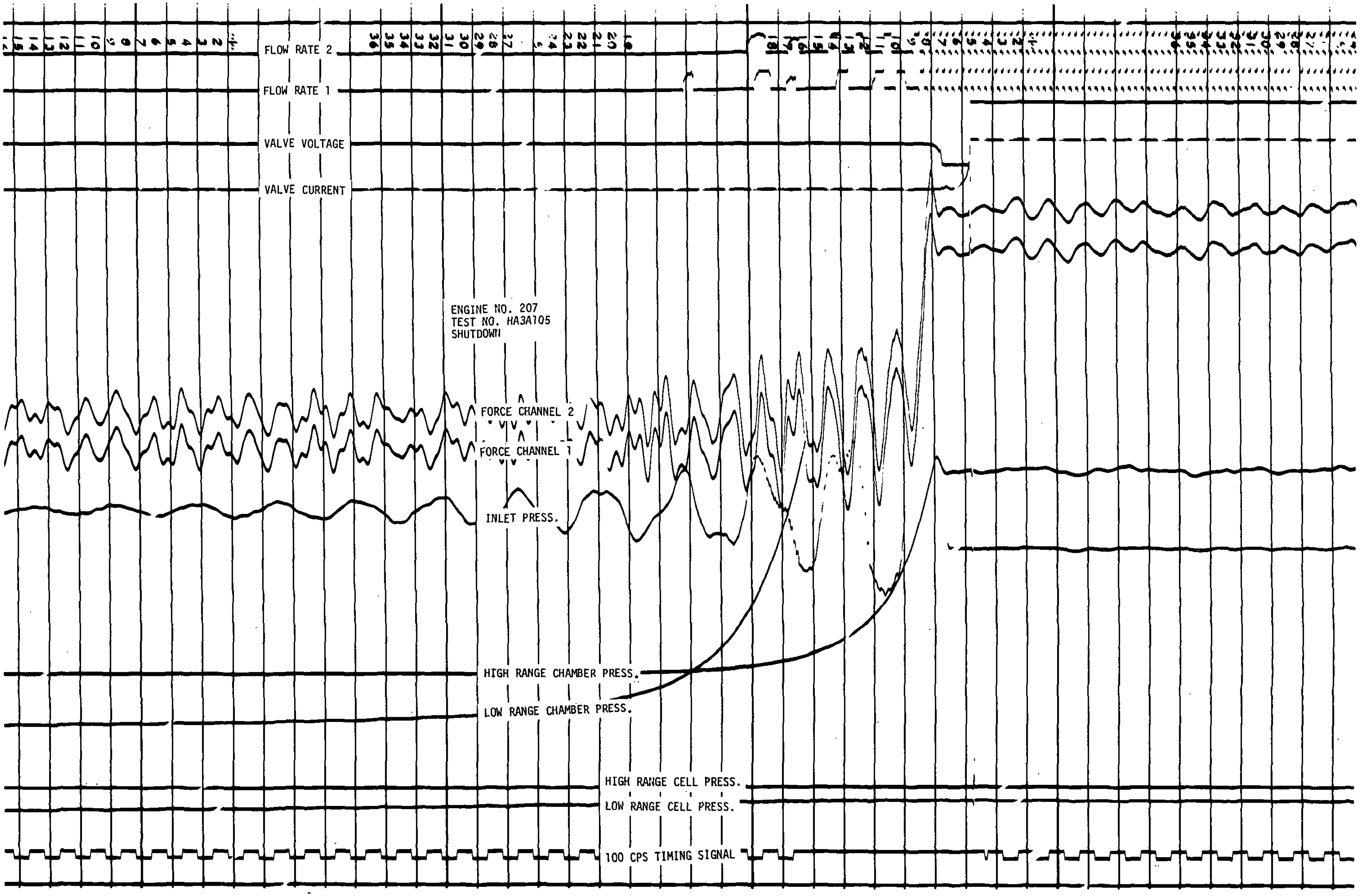

FLOW RATE 2
FLOW RATE 1
VALVE VOLTAGE
VALVE CURRENT
ENGINE NO. 207
TEST NO. HA3A103
SHUTDOWN
FORCE CHANNEL 2
FORCE CHANNEL 1
INLET PRESS.
HIGH RANGE CHAMBER PRESS.
LOW RANGE CHAMBER PRESS.
HIGH RANGE CELL PRESS.
LOW RANGE CELL PRESS.
100 CPS TIMING SIGNAL


ENGINE NO. 207
TEST NO. HA3A104
START



ENGINE NO. 207
TEST NO. HA3A104
SHUTDOWN


ENGINE NO. 207
TEST NO. HA3A105
START


ENGINE NO. 207
TEST NO. HA3A105
SHUTDOWN

APPENDIX C

THRUST MEASUREMENT UNCERTAINTY PLAN

TRW
SYSTEMS GROUP

INTEROFFICE CORRESPONDENCE

TO: D. R. Snoke

CC: W. M. King
C. H. Oki
A. W. Parnell

DATE: 29 March 1972

SUBJECT: MVM '73 Thrust Measurement Uncertainty Plan

FROM: R. S. Williams

BLDG. 01 MAIL STA. 1051 EXT. 64083

As part of the MVM '73 contract a requirement exists to develop the instrumentation uncertainty associated with the measurement of vacuum thrust prior to the start of reactive testing. In addition, it is understood and agreed that all reasonable modifications to the thrust measurement system and methods for reduction of calibration data in order to reduce the instrumentation uncertainty towards a goal of ± 0.5 per cent (3 sigma) will be implemented. This report documents the general approach to be used to develop the thrust measurement uncertainty.

The development of the thrust measurement uncertainty can be separated into static components and dynamic components. The static components consist of the random (precision) and fixed (bias) uncertainty estimates associated with the test load cell calibrations and the random and fixed uncertainty estimates associated with the reference or standard load cell. The dynamic components consist of the random estimates associated with the difference (channel deviation) between the redundant thrust measurement channels and the random and fixed uncertainties associated with the pre to post test thrust zero level shift.

The random and fixed estimates associated with the test load cell will be obtained from a series (15 to 20) end to end calibrations using the load cell calibrator. The calibrations will be conducted with the engine and instrumentation installed, propellant lines attached and pressurized, and at altitude cell pressure to duplicate the actual pre test condition. Each calibration will consist of the application of loads from zero to 100 per cent full scale in increments of 25 per cent full scale and then decreasing back to zero in increments of 25 per cent full scale. The calibration data for each thrust channel will then be reduced by a straight line fit through all calibration levels in the same manner as that to be used for the reactive test calibrations.

Each measured calibration level will then be analyzed to develop the repeatability (random component) of the output load and the average bias (fixed component) between the applied load (reference cell) and the measured load (test cell). It is recognized that this does not represent a true end to end calibration of the thrust stand in that the alignment of the thrust stand is not verified. This approach, however, is preferred in view of the difficulties involved and questionable results derived from a true end to end calibration and has been found to be acceptable by JPL assigned instrumentation engineers. The alignment of thrust stand will be verified, however, by the normal test facility procedures. The development of the random and fixed uncertainties of the reference cell will be developed from existing laboratory calibration history for this reference load cell.

The dynamic uncertainty estimates (channel deviation and pre/post zero shift) will be developed from a series of ten thruster firings (approximately 100 seconds duration). Before these data are obtained, however, a series of thruster firings to investigate the reduction of the pre to post test zero shift due to temperature soak back will be conducted. The thrust data from each test will be reviewed to determine the magnitude of the zero shift and, depending upon the magnitude of the shift, modifications to the stand to reduce the shift will be incorporated. It is expected that the pre to post test zero shift random and fixed uncertainties can be reduced to approximately 0.2 per cent (3 sigma) based on MMBPS experience.

The overall thrust uncertainty will be developed by statistically combining the static and dynamic random and fixed uncertainties. In addition, the end to end load cell calibration data, pre to post zero shift data, and the channel deviation data will be used to establish control limits for continuous monitoring of the thrust measurement system throughout the reactive testing program.

RSW/hk

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APPENDIX D

LOW TEMPERATURE MEASUREMENT UNCERTAINTY ANALYSIS

TRW
SYSTEMS GROUP
INTEROFFICE CORRESPONDENCE

TO: J. Miller/J. Champion
CC: Distribution
DATE: 27 November 1967

SUBJECT: Instrumentation Uncertainty of the Platinum Resistance Transducers Used to Measure Propellant Temperatures
FROM: C. H. Oki cHo
BLDG O-1 MAIL STA. 2180 EXT. 64361

Reference: LMDE Instrumentation Error Analysis dated 31 August 1966, 01827-6002-R000 by C. H. Oki/G. E. Urner

SUMMARY

A re-evaluation of the instrumentation uncertainties of the platinum resistance transducers used to measure propellant temperatures was made because the previous analysis (reference) was considered to be incomplete. The previous study was based upon a small sample size (degrees of freedom of 8) and did not include the increase in uncertainty due to installation effects. However, the results of this current study indicate good agreement.

The total instrumentation uncertainty of the propellant temperature measurements using platinum resistance transducers were computed to vary between 0.416% FS to 0.562% FS for the range of temperature between 30 and 110 degrees Farenheit. As was determined in the previous study, there was a marked increase in the uncertainty at a temperature of 130 degrees (0.832% FS).

DISCUSSION

A re-evaluation of the instrumentation uncertainties associated with the platinum resistance transducer used to measure the propellant temperature was made because there was a possibility that all of the uncertainties were not properly accounted for in the previous study presented in the reference. Therefore, additional effort which included special tests as well as additional analysis was conducted.

It was proposed that a significant amount of error might be induced into the system due to the installation of the sensors and the triple bridge units. Therefore, special tests were conducted to determine the installation effects by making total system tests. A known resistance was placed in the temperature lines at the test stand and the output was recorded on a digital voltmeter which was located in the control room. The resistance was varied from a minimum value which corresponds to a nominal temperature of 30°F to a value which corresponds to 130°F. These tests were conducted at the HATS, VETS and HEPTS facilities. These tests were conducted with 9 triple bridge unit-sensor sets utilizing four lines at each stand and a variety of amplifiers to transmit and amplify signals. In addition to this test data, calibration data that is determined routinely in the laboratory was analyzed to provide additional statistical data to facilitate the error analysis.

Method of Acquisition

The propellant temperatures during static engine fire tests are presently monitored with a platinum resistance transducer. These transducers consist of a sensor and a triple bridge unit (TBU). The units are calibrated separately, but are calibrated in such a manner that they must be used as a unit. The sensors are calibrated by experimentally determining the variation of the resistance with temperature. Based upon these resistances the TBU's are adjusted to provide zero milivolt output for an input temperature of 30° and 4 milivolt output at 70°F. For further detail of the calibration method the reader is referred to the reference.

Prior to a given static engine firing test the calibration signals for the temperature measurements are developed independently of the temperature measurement system. For example, in the VETS and HATS test area, a standard input of 5 milivolts (50°F) is used to establish the sensitivity of the temperature system. An open circuit is used for the 30° level and a linear relationship is used to obtain the temperature in degrees farenheit. For acquisition of data at HEPTS the standard signal of 10 milivolts is used.

Statistical Model

Based upon the method by which the platinum resistance transducers are used, it is apparent that the instrumentation uncertainties can be conveniently partitioned into three components of error. These are the uncertainties of the digital acquisition system, the uncertainties of the calibration data, and the uncertainty due to installation and systems effects. Based upon this consideration, the following statistical models were established to facilitate the error analysis. As was done in previous cases the model was broken into fixed and random uncertainties.

- FIXED UNCERTAINTY

$$\epsilon_T = \epsilon_{DS} + \epsilon_{CAL} + \epsilon_{\text{instal. \& system}} \qquad (1)$$

Where,

ϵ_{DS} = the fixed uncertainty of the digital system, % FS

ϵ_{CAL} = fixed uncertainty of the sensor calibration, % FS

$\epsilon_{\text{instal. \& system}}$ = fixed uncertainty due to installation and system effects, % FS

RANDOM UNCERTAINTY

$$\sigma^2_T = \sigma^2_{DS} + \sigma^2_{CAL} + \sigma^2_{\text{instal. \& system}} \qquad (2)$$

Where,

σ_{DS} = random uncertainty of the digital system, % FS

σ_{CAL} = random fixed uncertainty of the sensor calibration, % FS

$\sigma_{instal.\ \&\ system}$ = random uncertainty due to installation and system effects, % FS

TOTAL UNCERTAINTY

$$E_T = \epsilon_T + k\,\sigma_T \tag{3}$$

Where,

k = tolerance factor

Analysis and Results

In the analysis discussed in the reference it was reported that the fixed and random uncertainties of the digital system were respectively 0.1% FS and 0.168% FS. These uncertainties included all of the system uncertainties which included the non-linearity of the amplifiers. The approach taken for this most recent analysis was that of including the instrumentation uncertainties due to electronic errors as part of the uncertainty associated with the installation and system effects. Therefore, for the purpose of this study the fixed uncertainty was taken to be .1% FS (due to the least count of the system) and the random uncertainty of the digital system was taken to be zero.

In order to determine the uncertainty due to the installation and variability of the system, special calibration tests were conducted. The statistics of these calibrations are presented in Tables 1 and 2. The basic data that was determined from the calibration tests are presented in Table 3.

The uncertainty due to the installation and total system effects was developed by analyzing the deviation between the measured output and the expected standard output which would correspond to the known resistance input. Due to the variations in the resistances of the sensors, the standard outputs were developed from the calibration data of the individual sensors. These values along with the measured output are recorded in Table 3. Based upon the deviations that were determined between the standard output and the measured output, a mean and estimate of standard deviation was computed. The resulting statistics are presented in Table 1. Review of the data presented in Table 1 indicate no significant differences between the mean or the estimates of standard deviations for the increasing and decreasing cases. The values were therefore pooled to obtain the statistics presented in Table 2.

Based upon the degrees of freedom the unbiased estimate of standard deviation (sigma) were developed. The fixed uncertainty is given by the grand mean of the data and one sigma random uncertainty is given by the unbiased estimate of standard deviation.

The uncertainty of the sensor resistance was developed by examining consecutive calibrations of 13 sensors. In a manner similar to the installation and systems uncertainties, the deviations in the resistance determined in consecutive calibrations were examined. The calibration data that were used for the analysis are presented in Table 4. The statistics developed from the deviations observed from consecutive calibrations are presented in Table 5. The mean deviation together with the estimate of standard deviation were computed and are summarized in Table 5. The unbiased estimate was developed based upon the associated degrees of freedom. The fixed and random uncertainties of the sensor calibration is given by the mean deviation and the unbiased estimate of the deviations.

In order to compute the fixed and random uncertainties of the temperature measurements, the individual contribution in accordance with the statistical model defined by equations 1, 2 and 3 were developed and are summarized in Tables 6 and 7.

The total three sigma uncertainty is summarized in Table 8. As indicated in this table, the total uncertainties varied randomly between 0.416 to 0.562% FS in the range of temperature measurements from 30° to 110° F. For temperatures greater than 110° F (the uncertainty is increased markedly) to 0.832% FS at a temperature of 130° F.

A.W. Parnell
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AWP:sc

TABLE 1

INSTALLATION AND SYSTEM CALIBRATION STATISTICS

LEVEL				
Resistance ohms	Temperature °F	$\bar{d}$ % FS	s % FS	d.f.
200	32	0.059	0.073	20
208	50	0.040	0.097	20
216	68	0.139	0.078	20
224	86	0.100	0.109	20
232	104	-0.058	0.105	20
240	122	-0.285	0.137	20
232	104	-0.055	0.106	20
224	86	0.103	0.110	20
216	68	0.136	0.081	20
208	50	0.041	0.100	20
200	32	0.058	0.070	20

TABLE 2

INSTRUMENTATION UNCERTAINTY OF TRANSDUCER AND ACQUISITION SYSTEM

LEVEL					
Resistance Ohms	Temperature °F	$\bar{\bar{d}}$ % FS	s_p % FS	d.f.	σ % FS
200	32	0.058	0.072	40	0.072
208	50	0.040	0.098	40	0.099
216	68	0.138	0.080	40	0.080
224	86	0.102	0.110	40	0.111
232	104	-0.056	0.106	40	0.107
240	122	0.285	0.137	20	0.139

TABLE 3

INSTALLATION AND ACQUISITION SYSTEM CALIBRATION DATA

TBU SERIAL NO. 145								
Test Stand Line Designation Amplifier No.			HATS RTT3 AMP 52		HEPTS RTT3 AMP 59			
Test No.	Resistance Ω	Standard Output mv	Measured Output mv	Deviation %	Measured Output mv	Deviation %	Measured Output mv	Deviation %
1	200	0.1993	0.204	0.047	0.202	0.027		
2	208	2.0113	2.014	0.027	2.019	0.077		
3	216	3.8272	3.838	0.108	3.844	0.168		
4	224	5.6484	5.662	0.136	5.668	0.196		
5	232	7.4777	7.477	-0.007	7.481	0.033		
6	240	9.3119	9.291	-0.209	9.294	-0.179		
7	232	7.4777	7.478	0.003	7.481	0.033		
8	224	5.6484	5.663	0.146	5.668	0.196		
9	216	3.8272	3.838	0.108	3.844	0.168		
10	208	2.0113	2.015	0.037	2.019	0.077		
11	200	0.1993	0.204	0.047	0.202	0.027		

TABLE 3 (Continued)

TBU SERIAL NO. 156								
Test Stand Line Designation Amplifier No.			HETS RTT2 AMP 56		HATS RTT3 AMP 52		HEPTS RTT3 AMP 59	
Test No.	Resistance Ω	Standard Output mv	Measured Output mv	Deviation %	Measured Output mv	Deviation %	Measured Output mv	Deviation %
1	200	0.2054	0.210	0.046	0.208	0.026	0.210	0.046
2	208	2.0113	2.022	0.107	2.014	0.027	2.023	0.117
3	216	3.8269	3.844	0.171	3.834	0.071	3.845	0.131
4	224	5.6548	5.664	0.092	5.655	0.002	5.666	0.112
5	232	7.4819	7.474	-0.079	7.465	-0.169	7.474	-0.079
6	240	9.3195	9.285	-0.345	9.275	-0.445	9.234	-0.355
7	232	7.4819	7.474	-0.079	7.466	-0.159	7.474	-0.079
8	224	5.6548	5.664	0.092	5.656	0.012	5.665	0.102
9	216	3.8269	3.844	0.171	3.834	0.071	3.846	0.101
10	208	2.0113	2.022	0.107	2.015	0.037	2.025	0.137
11	200	0.2054	0.211	0.056	0.208	0.026	0.212	0.066
Test Stand Line Designation Amplifier No.			HATS RTT1 AMP 50		HEPTS RTT1 AMP 55		HATS RTT2 AMP 51	
1	200	0.2054	0.207	0.016	0.210	0.046	0.203	-0.024
2	208	2.0113	2.016	0.047	2.024	0.127	2.009	-0.023
3	216	3.8269	3.838	0.111	3.846	0.191	3.828	0.011
4	224	5.6548	5.658	0.032	5.668	0.132	5.648	-0.068
5	232	7.4819	7.470	-0.119	7.478	-0.039	7.458	-0.239
6	240	9.3195	9.282	-0.375	8.286	-0.335	9.269	-0.505
7	232	7.4819	7.470	-0.119	7.478	-0.039	7.460	-0.219
8	224	5.6548	5.659	0.042	5.668	0.132	5.649	-0.058
9	216	3.8269	3.837	0.101	3.846	0.191	3.829	0.021
10	208	2.0113	2.015	0.037	2.024	0.127	2.010	-0.013
11	200	0.2054	0.209	0.036	0.210	0.046	0.204	-0.014

TABLE 3 (Continued)

TBU SERIAL NO. 156									
Test Stand Line Designation Amplifier No.		HATS RTT4 AMP 53					VETS RTT2 AMP 34		
Test No.	Resistance Ω	Standard Output mv	Measured Output mv	Deviation %	Test No.	Resistance Ω	Standard Output mv	Measured Output mv	Deviation %
1	200	0.2054	0.212	0.066	1	200	0.1674	0.169	0.016
2	208	2.0113	2.019	0.077	2	208	1.9773	1.987	0.097
3	216	3.8269	3.838	0.111	3	216	3.7929	3.808	0.151
4	224	5.6548	5.658	0.032	4	224	5.6164	5.627	0.106
5	232	7.4819	7.469	-0.129	5	232	7.4433	7.438	0.053
6	240	9.3195	9.281	-0.385	6	240	9.2790	9.247	-0.320
7	232	7.4819	7.469	-0.129	7	232	7.4433	7.439	0.043
8	224	5.6548	5.658	0.032	8	224	5.6164	5.628	0.116
9	216	3.8269	3.838	0.111	9	216	3.7929	3.808	0.151
10	208	2.0113	2.018	0.067	10	208	1.9773	1.987	0.097
11	200	0.2054	0.211	0.056	11	200	0.1674	0.169	0.016

TABLE 3 (Continued)

TBU SERIAL NO. 5130					SENSOR SERIAL NO. 1210			
Test Stand Line Designation Amplifier No.			HATS RTT4 AMP 53		HEPTS RTT4 AMP 58			
Test No.	Resistance Ω	Standard Output mv	Measured Output mv	Deviation %	Measured Output mv	Deviation %	Measured Output mv	Deviation %
1	200	0.1561	0.147	-0.091	0.154	-0.021		
2	208	1.9661	1.949	-0.171	1.962	-0.041		
3	216	3.7686	3.764	-0.046	3.780	0.114		
4	224	5.5945	5.579	-0.155	5.595	0.005		
5	232	7.4123	7.384	-0.233	7.403	-0.093		
6	240	9.2374	9.191	-0.464	9.208	-0.294		
7	232	7.4123	7.382	-0.303	7.402	-0.103		
8	224	5.5945	5.578	-0.165	5.595	0.005		
9	216	3.7686	3.763	-0.056	3.779	0.104		
10	208	1.9661	1.949	-0.171	1.962	-0.041		
11	200	0.1561	0.147	-0.091	0.154	-0.021		

TABLE 3 (Continued)

TBU SERIAL NO. 5133 SENSOR SERIAL NO. 1213					TBU SERIAL NO. 5134 SENSOR SERIAL NO. 1214				
Test Stand Line Designation Amplifier No.		HATS RTT3 AMP 52					VETS RTT3 AMP 35		
Test No.	Resistance Ω	Standard Output mv	Measured Output mv	Deviation %	Test No.	Resistance Ω	Standard Output mv	Measured Output mv	Deviation %
1	200	0.2297	0.223	-0.067	1	200	0.1625	0.185	0.225
2	208	2.0316	2.026	-0.056	2	208	1.9684	1.983	0.146
3	216	3.8433	3.843	-0.003	3	216	3.7775	3.798	0.204
4	224	5.6650	5.659	-0.060	4	224	5.5970	5.610	0.130
5	232	7.4880	7.466	-0.220	5	232	7.4181	7.416	-0.021
6	240	9.3196	9.273	-0.466	6	240	9.2457	9.217	-0.287
7	232	7.4880	7.467	-0.210	7	232	7.4181	7.418	-0.001
8	224	5.6650	5.660	-0.050	8	224	5.5970	5.609	0.120
9	216	3.8433	3.844	-0.007	9	216	3.7776	3.796	0.184
10	208	2.0316	2.026	-0.056	10	208	1.9684	1.982	0.136
11	200	0.2297	0.224	-0.057	11	200	0.1625	0.178	0.155

TABLE 3 (Continued)

TBU SERIAL NO. 5136						SENSOR SERIAL NO. 1218		
Test Stand Line Designation Amplifier No.			HATS RTT2 AMP 51		HEPTS RTT2 AMP 56		HEPTS RTT4 AMP 53	
Test No.	Resistance Ω	Standard Output mv	Measured Output mv	Deviation %	Measured Output mv	Deviation %	Measured Output mv	Deviation %
1	200	0.2207	0.232	0.113	0.230	0.093	0.230	0.093
2	208	2.0226	2.036	0.134	2.038	0.154	2.039	0.164
3	216	3.8365	3.851	0.145	3.856	0.195	3.857	0.205
4	224	5.6538	5.667	0.132	5.673	0.192	5.675	0.212
5	232	7.4792	7.474	-0.052	7.478	-0.012	7.482	0.028
6	240	9.3074	9.279	-0.284	9.285	-0.224	9.288	-0.194
7	232	7.4792	7.474	-0.052	7.478	-0.012	7.482	0.028
8	224	5.6538	5.669	0.152	5.672	0.182	5.674	0.202
9	216	3.8365	3.853	0.165	3.856	0.195	3.858	0.215
10	208	2.0226	2.037	0.144	2.038	0.154	2.040	0.174
11	200	0.2207	0.234	0.133	0.230	0.098	0.231	0.103

TABLE 3 (Continued)

TBU SERIAL NO. 5140					SENSOR SERIAL NO 1220			
Test Stand Line Designation Amplifier No.			VETS RTT1 AMP 33		VETS RTT2 AMP 34		VETS RTT4 AMP 36	
Test No.	Resistance Ω	Standard Output mv	Measured Output mv	Deviation %	Measured Output mv	Deviation %	Measured Output mv	Deviation %
1	200	0.1826	0.199	0.164	0.193	0.104	0.200	0.174
2	208	2.0136	2.004	-0.096	2.004	-0.096	2.006	-0.076
3	216	3.7981	3.820	0.219	3.821	0.229	3.822	0.239
4	224	5.6150	5.640	0.250	5.635	0.200	5.639	0.240
5	232	7.4406	7.450	0.094	7.441	0.004	7.447	0.064
6	240	9.2671	9.264	-0.031	9.264	-0.031	9.254	-0.131
7	232	7.4406	7.450	0.094	7.443	0.024	7.447	0.064
8	224	5.6150	5.640	0.250	5.637	0.220	5.640	0.250
9	216	3.7981	3.821	0.229	3.822	0.239	3.823	0.249
10	208	2.0136	2.004	-0.096	2.006	-0.096	2.006	-0.096
11	200	0.1826	0.199	0.164	0.194	0.114	0.200	0.174

TABLE 3 (Continued)

TBU SERIAL NO. 5142 SENSOR SERIAL NO. 1340

Test Stand VETS
Line Designation RTT4
Amplifier No. AMP 36

Test No.	Resistance Ω	Standard Output mv	Measured Output mv	Deviation %	Measured Output mv	Deviation %	Measured Output mv	Deviation %
1	200	0.2169	0.225	0.081				
2	208	2.0249	2.034	0.091				
3	216	3.8388	3.853	0.142				
4	224	5.6562	5.674	0.178				
5	232	7.4794	7.484	0.046				
6	240	9.3074	9.294	-0.134				
7	232	7.4794	7.485	0.056				
8	224	5.6562	5.674	0.178				
9	216	3.8388	3.854	0.152				
10	208	2.0249	2.034	0.091				
11	200	0.2169	0.226	0.091				

TABLE 4

LABORATORY CALIBRATION DATA OF SENSOR

Sensor No.	145			156			170		
Calibration Date	Resistance 5/23/67 ohms	8/26/67 ohms	Deviation ohms	Resistance 2/2/67 ohms	7/29/67 ohms	Deviation ohms	Resistance 5/23/67 ohms	8/26/67 ohms	Deviation ohms
Level									
30	199.11	199.12	0.01	199.07	199.09	0.02	199.12	199.10	0.02
50	207.95	207.95	0.00	207.92	207.95	0.03	207.93	207.93	0.00
70	216.76	216.76	0.00	216.75	216.76	0.01	216.73	216.72	-0.01
90	225.57	225.54	-0.03	225.58	225.51	0.03	225.46	225.49	0.03
110	234.22	234.28	0.06	234.25	234.26	0.01	234.43	234.22	-0.21
130	242.93	243.00	0.07	242.97	242.96	-0.01	243.38	242.94	-0.44

Sensor No.	177			204			1210		
Calibration Date	Resistance 5/8/67 ohms	8/28/67 ohms	Deviation ohms	Resistance 5/8/67 ohms	8/26/67 ohms	Deviation ohms	Resistance 6/17/67 ohms	9/26/67 ohms	Deviation ohms
Level									
30	199.23	199.26	0.03	199.26	199.29	0.03	199.27	199.31	0.04
50	208.11	208.10	-0.01	208.12	208.18	0.06	208.16	208.15	-0.01
70	216.90	216.91	0.01	216.95	216.95	0.00	216.98	217.02	0.04
90	225.72	225.68	-0.04	225.77	225.74	-0.03	225.78	225.78	0.00
110	234.46	234.43	-0.03	234.52	234.47	-0.05	234.54	234.58	0.04
130	243.15	243.14	-0.01	243.23	243.21	-0.02	243.27	243.34	0.07

TABLE 4 (Continued)

Sensor No.	1211			1213			1214		
Calibration Date	Resistance 5/8/67 ohms	Resistance 8/26/67 ohms	Deviation ohms	Resistance 2/9/67 ohms	Resistance 7/29/67 ohms	Deviation ohms	Resistance 3/29/67 ohms	Resistance 8/29/67 ohms	Deviation ohms
Level									
30	199.42	199.44	0.02	198.98	198.98	0.00	199.27	199.28	0.01
50	208.32	208.31	-0.01	207.87	207.86	-0.01	208.13	208.14	0.01
70	217.16	217.16	0.00	216.66	216.69	0.03	216.94	216.98	0.04
90	225.98	225.98	0.00	225.42	225.47	0.05	225.75	225.77	0.02
110	234.77	234.75	-0.02	234.19	234.24	0.05	234.52	234.55	0.03
130	243.53	243.52	-0.01	242.88	242.97	0.09	243.29	243.30	0.01

Sensor No.	1217			1218			1220		
Calibration Date	Resistance 5/8/67 ohms	Resistance 8/26/67 ohms	Deviation ohms	Resistance 6/7/67 ohms	Resistance 9/26/67 ohms	Deviation ohms	Resistance 5/3/67 ohms	Resistance 8/29/67 ohms	Deviation ohms
Level									
30	199.48	199.49	0.01	199.01	199.02	0.01	199.16	199.19	0.03
50	208.31	208.37	0.06	207.85	207.90	0.05	208.04	208.06	0.02
70	217.22	217.23	0.01	216.68	216.72	0.04	216.88	216.89	0.01
90	226.06	226.06	0.00	225.46	225.52	0.06	225.67	225.69	0.02
110	234.82	234.84	0.02	234.26	234.28	0.02	234.39	234.45	0.06
130	243.64	243.62	-0.02	243.97	243.03	0.06	243.17	243.21	0.04

TABLE 4 (Continued)

Sensor No.	1340						
Calibration Date	Resistance 5/8/67 ohms	 8/29/67 ohms	Deviation ohms	Resistance	Deviation	Resistance	Deviation
Level							
30	198.99	199.04	0.05				
50	207.90	207.89	-0.01				
70	216.71	216.71	0.00				
90	225.51	225.51	0.00				
110	234.26	234.26	0.02				
130	243.03	243.03	0.00				

TABLE 5

CALIBRATION UNCERTAINTY OF SENSOR RESISTANCE

Level	$\bar{d}$		S	Degrees of Freedom	σ	
	ohms	% FS	ohms		ohms	% FS
30	0.0215	0.009	0.014	12	0.014	0.006
50	0.0138	0.006	0.028	12	0.029	0.012
70	0.0138	0.006	0.018	12	0.018	0.007
90	0.0085	0.003	0.030	12	0.031	0.013
110	0.000	0.000	0.071	12	0.073	0.030
130	0.022	0.009	0.041	11	0.042	0.017

TABLE 6

SUMMARY OF FIXED UNCERTAINTIES

Level	Digital System ϵ_{DS} % FS	Sensor Calibration ϵ_{CAL} % FS	Installation And Electrical System ϵ [illegible] & SYS % FS	Total ϵ_T % FS
30	0.1	0.009	0.058	0.167
50	0.1	0.006	0.040	0.146
70	0.1	0.006	0.138	0.244
90	0.1	0.003	0.102	0.205
110	0.1	0.000	-0.056	0.156
130	0.1	0.009	0.285	0.394

TABLE 7

SUMMARY OF RANDOM UNCERTAINTIES

Level °F	Sensor Calibration σ_{CAL}	Transducer And Electrical System $\sigma_{INSTAL\ \&\ SYS}$	Calibration Instruments σ_{INST}	Total σ_T
30	0.006	0.072	0.041	0.083
50	0.012	0.099	0.041	0.108
70	0.007	0.080	0.041	0.090
90	0.013	0.111	0.041	0.119
110	0.030	0.107	0.041	0.118
130	0.017	0.139	0.041	0.146

TABLE 8

SUMMARY OF INSTRUMENTATION UNCERTAINTIES OF THE PLATINUM RESISTANCE TRANSDUCERS

Temperature Level	Fixed Uncertainty % FS	Random Uncertainty (3σ) % FS	Total Uncertainty (3σ) % FS
30	0.167	0.249	0.416
50	0.146	0.324	0.470
70	0.244	0.270	0.514
90	0.205	0.357	0.562
110	0.156	0.354	0.510
130	0.394	0.438	0.832

APPENDIX E

CALIBRATION DATA FOR PRESSURE TRANSDUCERS AND FLOWMETERS USED ON THE WATER FLOW TESTS ON MV/M '73 REA PROJECT

TRW SYSTEMS

Water Flow Bench.

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                    TRANSDUCER CALIBRATION REPORT          01/12/71

MFR.TABER          S/N 661433  RANGE   50.0PSIA   CAL DATE 720106   DUE DATE     -0
        TRANSDUCER      PRESSURE       COMPUTED      RESIDUAL       COMMENTS AND DIAGNOSTICS
        OUTPUT,MV       LOAD,PSI       LOAD,PSI      PCT FS         CALIBRATED AT    75 DEG. F TEMP

   UP      .00170       0.00000       -.02848        .057
   UP     6.00690      10.00000       10.01176      -.024
   UP    11.99500      20.00000       20.02341      -.047
   UP    17.97300      30.00000       30.01817      -.036
   UP    23.94500      40.00000       40.00290      -.006
   FS    29.90000      50.00000       49.95921       .082
   DN    23.94500      40.00000       40.00290      -.006
   DN    17.97000      30.00000       30.01315      -.026
   DN    11.98700      20.00000       20.01003      -.020
   DN     6.00450      10.00000       10.00775      -.015
   DN      .00630       0.00000       -.02079        .042

        R-CAL,MV      R-CAL EQUIV    ** LEAST   SQUARES CURVE DATA    **   RAW ZERO LEVELS      **
                                     **                               **                        **
   1      7.79320      12.99832      **  SLOPE A(1) =     1.67192     **   PRE-CAL   =    .0017 **
   2     15.57900      26.01558      **  INTER A(0) =    -.03132      **   POST-CAL  =    .0063 **
   3     24.91500      41.62467     **                               **                       **
   4     31.08800      51.94545      **  STD ERROR EST =    .0218     **   CAL TO SPEC          **
   5     -0.00000       0.00000      **  PCT FULL SCALE =   .0436     **          0203          **
                                     **                               **                        **
   UP = INCREASING LOAD    DN = DECREASING LOAD    FS = FULL SCALE LOAD
   OFFSET =       .05010

   ****** NO. 3 R-CAL IS CHECKED AGAINST PREVIOUS CAL VALUE =    41.631
```

TRW

PRODUCT ASSURANCE

Procedure No. ______

REPORT OF CALIBRATION

Transducer/Load cell

Item PRESSURE TRANSDUCER Mfg ALINCO Mod 151-BAA-1 S/N 34814

Combined Linearity and Hysterisis ±.08% FSO Range 250 PSIG Prop.No CL-031517

Excitation 10.000 V DC Pins D (+) B (-) Balance Wiper 100 kΩ

Output Pins E (+) A (-) Balance Pot 25 kΩ

Shunt Pins F K Zero Offset (+).171

Insulation Resistance 20,000 MEG Ω at 50 V DC Excitation Line Resistance 0 Ω

Balance Mode Pins D, E, B Shunt Line Resistance 0 Ω

Applied Load (in PSIG) (%)		Instrument Response (in MV) Increase	Decrease	Shunt Resistance (in Ω)
0	0	0.000	(+).004	
10	25	(+)2.967	2.974	
20	50	5.946	5.954	147,360
30	75	8.935	8.943	
40	100	11.926	11.936	73,373
50	125	14.921	14.930	
60	150	17.915	17.924	48,772
70	175	20.906	20.916	
80	200	23.894	23.900	36,513
90	225	26.878	26.880	
100	250	29.848	—	29,186

Fixed R-Cal		Output	Fixed R-Cal	Output
R1	112,200 Ω	(+)7.807	500kΩ	(+)1.754
R2	56,000 Ω	15.612	100kΩ	8.757
R3	34,940 Ω	24.961	50kΩ	17.477
R4	27,950 Ω	31.157	25kΩ	34.802
R5	Ω			

Comments ______

Date 09-05-72

Technician R. A 726

Approved G. V

Measurement Standards
Metrology

ICC 234
Rev. 4-17-71

HOMER R. DULIN CO.

CALIBRATION DATA SHEET

~~FOR:~~ TRW

DIVISION: REDONDO BEACH

FL. MTR. S/N: CL-016246

MFRS. S/N: FOXBORO 32997

MODEL NO.: 1/2-2-81-107

~~TUBE:~~ TURBINE

~~FLOAT:~~

FLUID: H2O

EQUIP. NO.: 11601A

TECHNICIAN: L.B.E.

DATE: 5-31-72

RECALL: 6 MOS

ACCURACY: ± 0.5%

PRICE: $80 00

P.O. NO.: 683-SF-2C

DEPT. NO.:

BENCH NO.:

FLUID TEMP. R.	CORR. FACTOR	P.S.I.G.	INDICATED FLOW	TIME SECONDS	TIME MINUTES	TOTAL VOL.			
			HZ			VOL	GAL	GPM	K
80°F			1098.6	28.97	0.4829	0.230.0	0.9957	2.061	31,982
81°F			909.7	34.88	0.5814	0.230.0	0.9957	1.712	31,882
82°F			806.0	39.74	0.6624	1.000	1.000	1.509	32,047
			707.0	45.40	0.7568	1-1.5	1.0065	1.329	31,918
83°F			604.6	53.12	0.8855	1-1.5	1.0065	1.136	31,933
			505.2	63.85	1.0643	1-2.0	1.0066	0.947	32,008
84°F			400.6	80.38	1.3399	1-1.5	1.0065	0.751	32,005
			302.4	27.71	0.4619	989	0.2612	0.565	32,113
85°F			202.0	41.48	0.6914	994	0.2626	0.379	31,978
			102.6	60.90	1.0152	760	0.2007	0.197	31,249
			101.0	47.31	0.7886	582	0.1537	0.194	31,237
			300.1	28.08	0.4680	1000	0.2642	0.564	31,925
88°F			504.3	63.80	1.0635	1-1.5	1.0065	0.946	31,985
			805.3	39.78	0.6631	1-1.0	1.0043	1.514	31,914
			1005.5	31.70	0.5284	1.000	1.000	1.892	31,887

Flowmeter Certified With Homer R. Dulin Co. Equip. No. 11601A Calibrated 8-71 Calib. Due 8-72 Accuracy 0.02%
Certified By County of Los Angeles Sealer of Weights and Measures
Division of Metrological Services MS 3129
Our Standards Are Certified By Or Are Traceable To The National Bureau
of Standards. Equipment and procedure 101L comply with MIL-C-45662-A

REMARKS: CALIB IN H2O @ INDICATED TEMP

HOMER R. DULIN CO.

CALIBRATION DATA SHEET

FOR: TRW

DIVISION: REDONDO BEACH

FL. MTR. S/N: CL-016246

MFRS. S/N: FOXBORO 32997

MODEL NO.: 1/2-2-81-107

~~TUBE~~: TURBINE

FLOAT: —

FLUID: H2O

EQUIP. NO.: 11601 A

TECHNICIAN: L.B & G.S.

DATE: 5-31-72

RECALL: 6 MOS

ACCURACY: ± 0.5%

PRICE: $80.00

P.O. NO.: 683-SF-2C

DEPT. NO.:

BENCH NO.:

FLUID TEMP. R.	CORR. FACTOR	P.S.I.G.	INDICATED FLOW	TIME SECONDS	TIME MINUTES	TOTAL VOL. VOL	TOTAL VOL. GAL	GPM	K
			Hz			VOL	GAL	GPM	K
88°F			202.4	41.12	0.6854	986	0.2605	0.380	31,958
			402.0	80.19	1.3367	1-1.0	1.0043	0.751	32,117
			605.5	52.92	0.8821	1-1.0	1.0043	1.138	31,929
			706.8	45.48	0.7581	1-2.0	1.0086	1.330	31,885
			906.9	35.63	0.5939	1-1.5	1.0065	1.694	32,121
88°F			1007.7	31.92	0.5321	1-1.0	1.0043	1.887	32,041

CALCULATIONS:

REMARKS: CALIB IN H2O @ INDICATED TEMP

HOMER R. DULIN CO.

CALIBRATION DATA SHEET

FOR: TRW
DIVISION: REDONDO BEACH
FL. MTR. S/N: CL-032156
MFRS. S/N: POTTER
SPACET-MF-1
MODEL NO.: MF-90-4135
~~TUBE~~: TURBINE
FLOAT: —
FLUID: H2O
EQUIP. NO.: 11601A
TECHNICIAN: LB & GS
DATE: 5-31-72
RECALL: 6 MOS
ACCURACY: ± 0.5%
PRICE: $80.00
P.O. NO.: 683-SF-2
DEPT. NO.:
BENCH NO.:

FLUID TEMP R.	CORR. FACTOR	P.S.I.G.	INDICATED FLOW	TIME SECONDS	TIME MINUTES	TOTAL VOL. VOL	TOTAL VOL. GAL	GPM	K
			Hz						
91°F			1202.3	55.81	0.9303	1-1.0	1.0043	1.079	66,856
			1102.0	60.70	1.0118	1-2.0	1.0086	0.996	66385
92°F			1005.7	66.14	1.1025	1-1.5	1.0065	0.912	66164
			903.4	73.49	1.2250	1-1.5	1.0065	0.821	66,022
89°F			803.8	82.30	1.3719	1-1.0	1.0043	0.732	65,835
			697.6	24.44	0.4074	996	0.2631	0.645	64893
90°F			611.1	27.97	0.4662	998	0.2636	0.565	64895
			505.0	33.37	0.5562	996	0.2631	0.473	64,059
91°F			403.1	41.50	0.6918	996	0.2631	0.380	63,647
			302.8	54.18	0.9031	990	0.2615	0.289	62,865
[illegible]°F			202.8	59.62	0.9938	750	0.1981	0.199	61,145
			101.5	57.39	0.9566	388	0.1025	0.107	56,915

CALCULATIONS:

Flowmeter Certified With Homer R. Dulin Co. Equip. No. 11601A Calibrated 8-71 Calib. Due 8-72 Accuracy 0.02%
Certified By County of Los Angeles Sealer of Weights and Measures
Division of Metrological Services MS 3129
Our Standards Are Certified By Or Are Traceable To The National Bureau of Standards. Equipment and procedure 1011 comply with MIL-C-45662-A

REMARKS: CALIB IN H2O @ INDICATED TEMP

HOMER R. DULIN CO.

CALIBRATION DATA SHEET

TRW

DIVISION: REDONDO BEACH

FL. MTR. S/N: CL- 032156

MFRS. S/N: POTTER

SPACET - MF-1

MODEL NO.: MF-90-4135

TUBE: TURBINE

FLOAT:

FLUID: H2O

EQUIP. NO.: 11601 A

TECHNICIAN: LB & GS.

DATE: 5-31-72

RECALL: 6 MOS

ACCURACY: ± 0.5%

PRICE: $80.00

P.O. NO.: 683-SF- 2C

DEPT. NO.:

BENCH NO.:

FLUID TEMP. R.	CORR. FACTOR	P.S.I.G.	INDICATED FLOW	TIME SECONDS	TIME MINUTES	TOTAL VOL.	TOTAL VOL.		
			HZ			VOL	GAL	GPM	$\overline{K}$
85°F			100.8	59.38	0.9898	402	0.1062	0.107	56 523
			201.6	54.11	0.9020	679	0.1793	0.198	61,091 ✓
85°F			302.8	54.25	0.9043	992	0.2620	0.289	62,865 ✓
			404.2	41.31	0.6886	996	0.2631	0.382	63,487 ×
			502.6	33.45	0.5576	992	0.2620	0.469	64 298 ✓
86°F			604.6	27.84	0.4640	990	0.2615	0.563	64,433 ✓
			706.0	92.41	1.5404	1-0.5	1.0021	0.650	65,169 ✓
87°F			805.7	81.23	1.3541	1.00	1.0000	0.738	65 504 ✓
			902.1	73.12	1.2189	1-1.0	1.0043	0.823	65 766 ✓
88°F			1005.4	65.92	1.0988	1-1.0	1.0043	0.913	66 072 ✓
			1107.9	60.02	1.0005	1-1.0	1.0043	1.003	66,275 ✓
			1202.7	55.69	0.9283	1-1.5	1.0065	1.084	66 570 ✓

CALCULATIONS:

REMARKS: