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OPERATIONALLY EFFICIENT PROPULSION SYSTEM STUDY(OEPSS) DATA BOOK

Volume VIII Integrated Booster Propulsion Module (BPM) Engine Start Dynamics

30 October 1992

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Kennedy Space Center
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FOREWORD

This document is part of the final report for the Operationally Efficient Propulsion System Study (OEPSS) conducted by the Rocketdyne Division of Rockwell International. The study was conducted under NASA contract NAS10-11568, and the NASA Study Manager was Mr. R. E. Rhodes. The Rocketdyne Program Manager was R. P. Pauckert, the Deputy Program Manager was G. Waldrop, and the Project Engineer was T. J. Harmon. The period of study was from April 1989 to October 1992.

ABSTRACT

A fluid-dynamic, digital-transient computer model of an integrated, parallel propulsion system was developed for the CDC mainframe and the SUN workstation computers. Since all STME component designs were used for the integrated system, computer subroutines were written characterizing the performance and geometry of all the components used in the system, including the manifolds. Three transient analysis reports were completed. The first report evaluated the feasibility of integrated engine systems in regards to the start and cutoff transient behavior. The second report evaluated turbopump out and combined thrust chamber/turbopump out conditions. The third report presented sensitivity study results in staggered gas generator spin start and in pump performance characteristics. These reports are presented in sections one through three of this data book as follows:

Section 1:	Internal Letter 1128-0014, "Operationally Efficient Propulsion System Transient Analysis Study, Task 1.0," Victoria Kemp, 28 January 1991.
Section 2:	Internal Letter 2128-0037, "Operationally Efficient Propulsion System Study, Option 2, Transient Analysis Study: Turbopump Out and Combined Thrust Chamber/Turbopump Out Conditions," Victoria Kemp, dated March 5, 1992.
Section 3:	Internal Letter 2128-0041, "Operationally Efficient Propulsion System Study, Option 2, Transient Analysis Study: Sensitivity Studies in Staggered Gas Generator Spin Start and in Pump Performance Characteristics," Victoria Kemp, dated April 6, 1992.

Section 1

Internal Letter 1128-0014, "Operationally Efficient Propulsion System Transient Analysis Study, Task 1.0," Victoria Kemp, 28 January 1991.

Internal Letter

Rockwell International

Date: 28 January 1991

No: IL 1128-0014

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Subject: Operationally Efficient Propulsion System Transient Analysis Study, Task 1.0

References:

[1] Internal Letter EA90-011, "Operationally Efficient Propulsion System Study", W. Geniec, P. Chen, W. Bissell, C. Erickson to G.S. Wong, 22 March 1990.

[2} Notes: Additional steady state engine balance data, P. Chen, W. Bissell, 2 February 1990.

[3] Work Authorization, "IR&D Advanced Booster Module Design Analysis", W. Ingle to M.H. Taniguchi, 13 November 1989.

[4] Internal Letter 9128-0252, "IR&D Funded ALS Configuration Study", R. Nelson to W. Ingle, 28 August 1989.

[5] Internal Letter 0128-0070, "System Dynamics Support to STEP GG Cycle (Helium Start) November 1989 Base Line Analysis", K. Danny Woo to Vernon Gregoire, 14 June 1990.

[6] NBS Technical Note 617 - Thermophysical Properties of Parahydrogen, U.S. Department of Commerce, National Bureau of Standards, Issued April 1972.

[7] NBS Technical Note 384 - Thermophysical Properties of Oxygen, U.S. Department of Commerce, National Bureau of Standards, Issued July 1971.

Summary

In support of the Advanced Launch System (ALS), NASA/LeRC program, Operationally Efficient Propulsion System Study (OEPSS) Task 1.0, a fluid dynamic digital transient model was developed for the 8/4 integrated booster propulsion module (Figure 1). The model was used to study the transient behavior and to define a valve sequence for a satisfactory nominal start and cutoff simulation. The model was originally written for a CDC mainframe computer (NOS

operating system), and subsequently transferred to a SUN workstation, where the simulations were carried out.

The booster propulsion module incorporates eight STME (Space Transportation Main Engine) thrust chambers and four turbopumps, where each turbopump nominally feeds two thrust chambers (Figure 2). Each of the pumps and gas generators accommodates twice the flow of the STME pumps and gas generator. Under nominal operation, the eight (8) thrust chambers operate at 85% of their rated thrust capacity and the four (4) turbopumps operate at 90% of their rated speed. Use of torroidal propellant feed manifolds, common to the four turbopumps and eight thrust chambers, permits a failure out condition of either one chamber, one turbopump, or both a chamber and a turbopump. In the case of a component failure, the remaining components can be powered up to their design operating levels to compensate for the losses.

The focus of this analysis was to study the feasibility of the cluster engine system concept in regards to the start and cutoff transient behavior. A valve sequence for both a nominal start and cutoff as well as for a single thrust chamber shutdown was defined, see Appendix A through D and E through H, respectively. The valve definition for start was based on an assisted hydrogen spin. Mainstage was reached in about 3.5 seconds, following a satisfactory transient interim. The shutdown transient behavior was also acceptable. In selecting a start/cutoff sequence, the following criteria were of primary concern: (1) Maintaining a fuel-rich environment in the gas generators and main chambers during start and shutdown to avoid damage to both the turbine blades and combustion chambers; (2) Avoiding a stall condition in the fuel pumps during start; and (3) Avoiding propellant boil-out in the fuel pumps during cutoff which could damage pump bearings.

The following is a list of scenarios which should be focused on for subsequent transient analysis studies:

- Single turbopump shutdown
- Combined thrust chamber/turbopump shutdown
- Staggered gas spin start of the gas generators
- Tank head start
- Sensitivity studies due to variations in pump performance, valve characteristics, etc.
- Sensitivity studies due to variations in inlet conditions

In addition, the gas generator engine configuration of the 8/4 cluster transient model may be modified for the evaluation of other engine power cycles (e.g. an expander cycle). The model can also be easily modified to evaluate cluster systems having component combinations other than four turbopumps and eight main chambers.

Method Of Analysis

In order to study the transient behavior of the integrated propulsion module comprised of eight STME thrust chambers and four turbopumps, a fluid dynamic digital transient model was developed. A partial system model fluid flow schematic, showing the basic flow configuration of one turbopump set, one gas generator, and one thrust chamber, is shown in Figure 3. The system may be envisioned as four sub-systems where each sub-system is comprised of a fuel and an oxidizer turbopump powered by a gas generator, eight valves, and two thrust chambers, interconnected by ducts and fuel/oxidizer torroidal manifolds. The eight valves consist of a pump discharge valve, a gas generator valve, and two thrust chamber inlet valves on each of the fuel and oxidizer sides. Reference will be made to each of these sub-systems as Systems 1, 2 , 3, and 4 where System 1 is comprised of gas generator (GG) 1 and thrust chambers (T/C) 1 and 2, System 2 is comprised of GG 2 and T/Cs 3 and 4, and so on. Each engine sub-system is configured as a gas generator cycle. A hydrogen spin is used on each of the four gas generators to assist in start.

Various information was required as input data for the model. The model was balanced to the engine design balance (ref. 1,2) at a thrust level of 497 Klb. A comparison between the engine design balance and the model steady state conditions is shown in Table 1. The configuration geometry is shown in Table 2. The valve effective flow areas are given in Table 3. These flow areas are slightly different between System 1 and Systems 2, 3, and 4 due to the model configuration. In System 1, the GG inlet lines originate at the pump discharge lines whereas in Systems 2, 3, and 4, the GG inlet lines originate at the torroidal manifolds. This configuration would permit a gas spin-assisted start of the System 1 GG and start of the System 2, 3, and 4 GGs off of the ring manifolds once adequate pressures were obtained there. For the model simulation presented herein, however, a hydrogen spin was used on each of the four gas generators to obtain a simultaneous start of all GGs. The valve characteristics depicting flow area versus position are shown in Figure 4 and are the same as those used in modelling the single STME GG engine design (ref. 5). The same valve characteristics were used for the pump discharge valves, the GG valves, and the thrust chamber inlet valves. The LOX and fuel pump performance maps, shown in Figures 5 through 8, were also obtained from the STME GG model.

Figure 1
8 - Engine Booster Propulsion Module

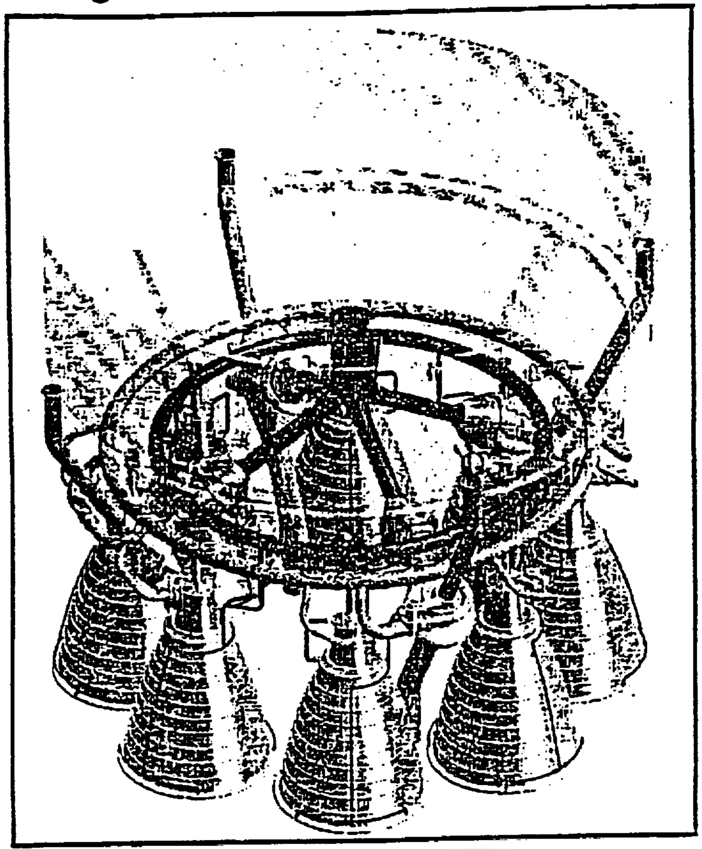

Figure 2
Integrated System Fluid Flow Schematic

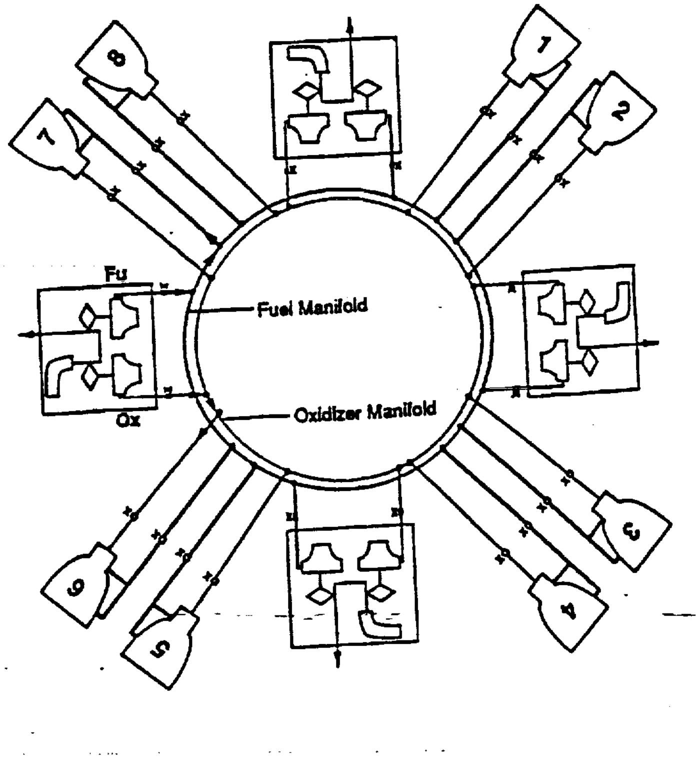

FIGURE 3 : STME THRUST CHAMBER FOR CLUSTER DESIGN
4 T/P + 8 T/C

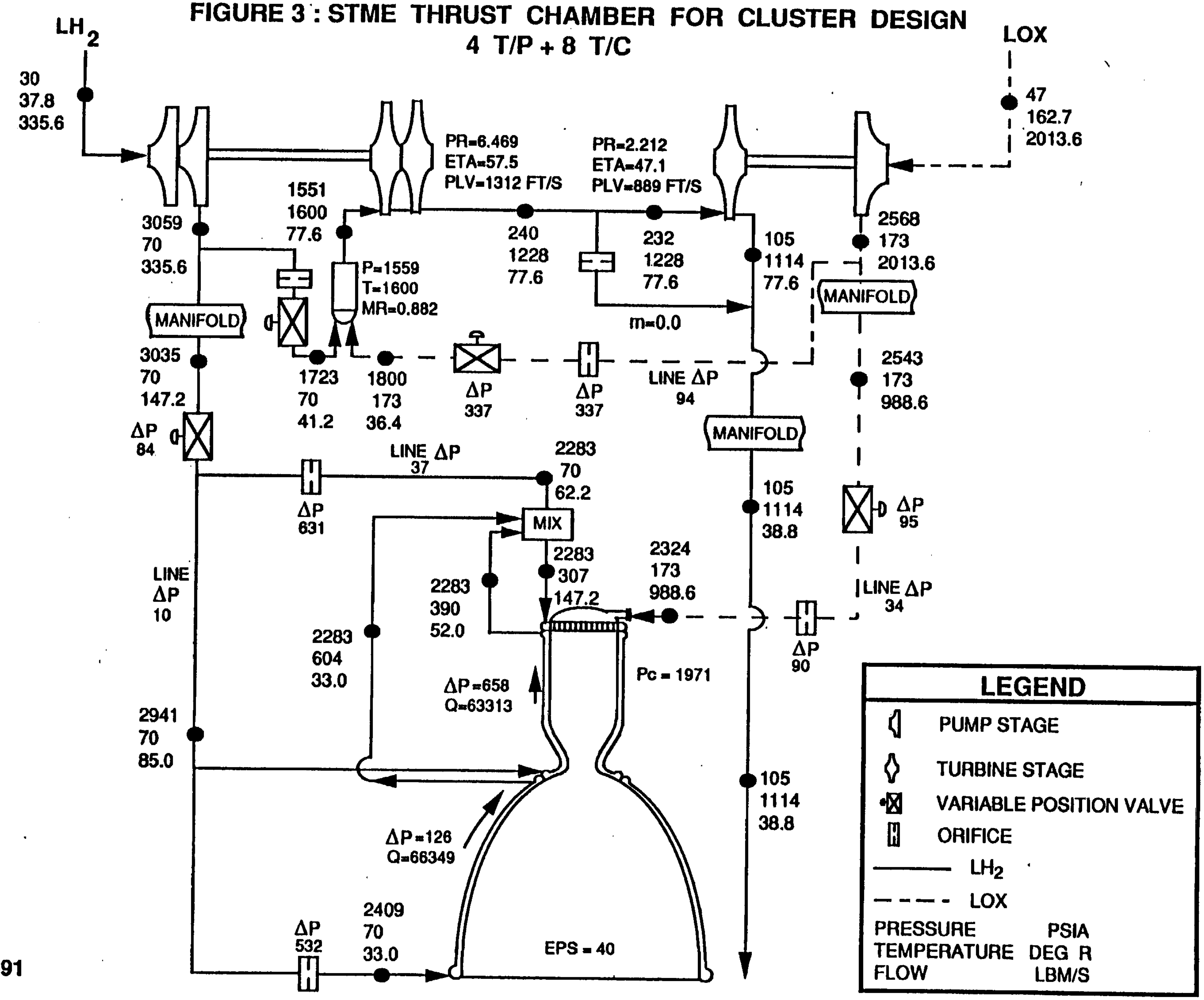

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Table 1

Comparison Between Transient Model Steady State Conditions And Design Balance at 497 KLBF (Hydrogen Spin), Feb. 1990 Baseline For Gas Generator 1 / Thrust Chambers 1 and 2

Parameter	Transient Model	Design Balance
Fuel Side		
Tank Discharge Pressure (psia)	40	40
Pump Inlet Pressure (psia)	31	30
Pump Discharge Pressure (psia)	3037	3056
Pump Flowrate (lb/sec)	331	336
Pump Discharge Valve Discharge Pressure (psia)	2997	3015
Pump Discharge Valve Flowrate (lb/sec)	290	294.4
Manifold Pressure (psia) Element 1	2960	2975
Manifold Pressure (psia) Element 2	2957	2975
T/C 1 Inlet Valve Discharge Pressure (psia)	2926	2940
T/C 2 Inlet Valve Discharge Presure (psia)	2923	2940
T/C 1 Inlet Valve Flowrate (lb/sec)	144	147.2
T/C 2 Inlet Valve Flowrate (lb/sec)	144	147.2
T/C 1 Combustor Coolant Channel Discharge Pres (psia)	2606	2612
T/C 2 Combustor Coolant Channel Discharge Pres (psia)	2605	2612
T/C 1 Combustor Coolant Channel Flowrate (lb/sec)	144	147.2
T/C 2 Combustor Coolant Channel Flowrate (lb/sec)	144	147.2
T/C 1 Injector Inlet Pressure (psia)	1954	1971
T/C 2 Injector Inlet Pressure (psia)	1954	1971
Gas Generator Injector Inlet Pressure (psia)	1569	1559
Gas Generator Flowrate (lb/sec)	40.8	41.2
Pump Speed (rpm)	14,644	14,644
Oxidizer Side		
Tank Discharge Pressure (psia)	62	62
Pump Inlet Pressure (psia)	47	47
Pump Discharge Pressure (psia)	2570	2565
Pump Flowrate (lb/sec)	2019	2014
Pump Discharge Valve Discharge Pressure (psia)	2488	2483
Pump Discharge Valve Flowrate (lb/sec)	1983	1978
Manifold Pressure (psia) Element 1	2386	2404
Manifold Pressure (psia) Element 2	2386	2404
T/C 1 Inlet Valve Flowrate (lb/sec)	988	989
T/C 2 Inlet Valve Flowrate (lb/sec)	988	989
T/C 1 Injector Inlet Pressure (psia)	1954	1971
T/C 2 Injector Inlet Pressure (psia)	1954	1971
Gas Generator Injector Inlet Pressure (psia)	1569	1559
Gas Generator Flowrate (lb/sec)	36.3	36.4
Pump Speed (rpm)	5526	5526

Table 1 (continued)

Comparison Between Transient Model Steady State Conditions And Design Balance at 497 KLBF (Hydrogen Spin), Feb. 1990 Baseline For Gas Generator 1 / Thrust Chambers 1 and 2

Parameter	Transient Model	Design Balance
Hot Gas Side		
T/C 1 Pressure (psia)	1954	1971
T/C 2 Pressure (psia)	1954	1971
T/C 1 Temperature (deg R)	6017	6000
T/C 2 Temperature (deg R)	6017	6000
Gas Generator Pressure (psia)	1569	1559
Gas Generator Temperature (deg R)	1631	1600
T/C 1 Mixture Ratio (lox/fuel)	6.85	6.7
T/C 2 Mixture Ratio (lox/fuel)	6.85	6.7
Gas Generator Mixture Ratio (lox/fuel)	0.89	0.882
Fuel Turbine Inlet Pressure (psia)	1561	1551
Fuel Turbine Flowrate (lb/sec)	77	77.6
Oxidizer Turbine Inlet Pressure (psia)	235	232
Oxidizer Turbine Inlet Temperature (deg R)	1268	1228
Oxidizer Turbine Flowrate (lb/sec)	77	77.6
Oxidizer Turbine Discharge Pressure (psia)	107	105
Oxidizer Turbine Discharge Temperature (deg R)	1156	1114
Fuel Turbine Torque (in-lb)	337,283	336,518
Oxidizer Turbine Torque (in-lb)	274,363	274,128

Note : The steady state engine balance for the model is similar for the other three vehicle engine elements, i.e. for gas generator 2 with thrust chambers 3 and 4, for gas generator 3 with thrust chambers 5 and 6, and for gas generator 4 with thrust chambers 7 and 8.

Table 2
Configuration Geometry

Fuel Feed System:

Element	Length (in)	Diameter (in)	Volume (in**3)
pump inlet line	20	5	--
pump discharge valve inlet line	15	5	--
gas generator inlet line	15	1.5	--
ring manifold element inlet line	15	5	--
ring manifold element	93	8	--
thrust chamber inlet valve inlet line	15	5	--
combustor cooling channels	100	5	8500
manifold	15	1.5	1500
injector	15	2	--

combustor cooling channels wall weight (lb):

ambient side	187
hot gas side	94

Oxidizer Feed System:

Element	Length (in)	Diameter (in)
pump discharge valve inlet line	15	5
gas generator inlet line	15	1.5
ring manifold element inlet line	107	5
ring manifold element	107	8
thrust chamber inlet valve inlet line	15	5

Pumps, Turbines, Thrust Chamber:

fuel turbine inlet line volume (in**3)	1272
oxidizer turbine inlet line volume (in**3)	4000
oxidizer turbine discharge line volume (in**3)	1000
main combustion chamber volume (in**3)	12500
throat area (in**2)	132.5
area ratio	39:1
fuel pump inertia (lb-in-sec**2)	14.3
oxidizer pump inertia (lb-in-sec**2)	17.4

Table 3

Valve Flow Areas

Valves	Position At 497 KLBF (%)	Fully Opened Effective Area (in**2) System 1	Fully Opened Effective Area (in**2) Systems 2,3 , and 4
Fuel Pump Discharge (4)	100	30.88	35.17
Ox Pump Discharge (4)	100	38.70	39.40
Fuel Gas Generator (4)	100	0.756	0.781
Oxidizer Gas Generator (4)	100	0.233	0.263
Fuel Thrust Chamber Inlet (8)	100	16.68	16.68
Ox Thrust Chamber Inlet (8)	100	19.60	19.60

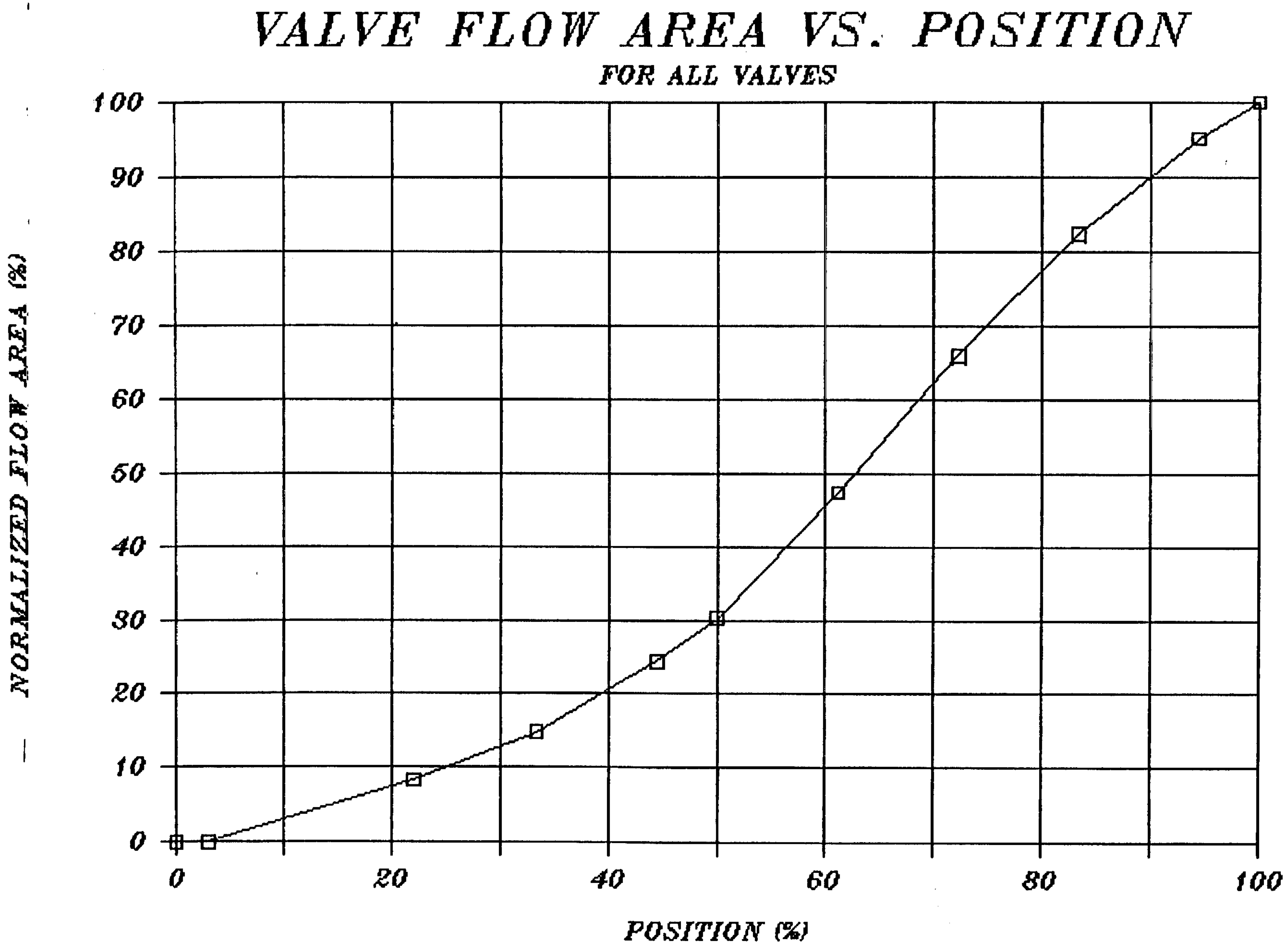
VALVE FLOW AREA VS. POSITION
FOR ALL VALVES
NORMALIZED FLOW AREA (%)
100
90
80
70
60
50
40
30
20
10
0
0
20
40
60
80
100
POSITION (%)

Figure 4

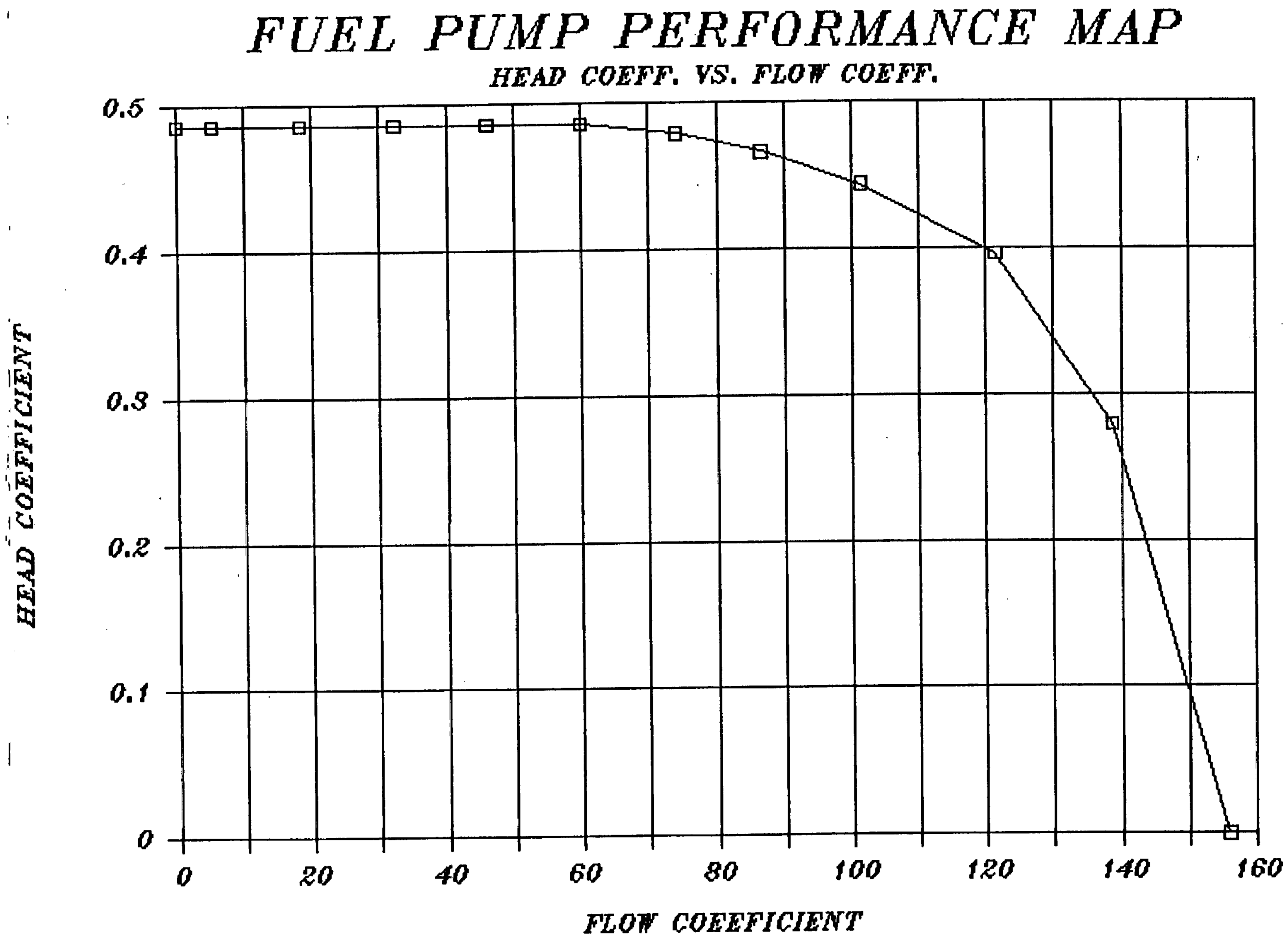
FUEL PUMP PERFORMANCE MAP
HEAD COEFF. VS. FLOW COEFF.
HEAD COEFFICIENT
0.5
0.4
0.3
0.2
0.1
0
0
20
40
60
80
100
120
140
160
FLOW COEFFICIENT

Figure 5

FUEL PUMP PERFORMANCE MAP

TORQUE COEFF. VS. FLOW COEFF.

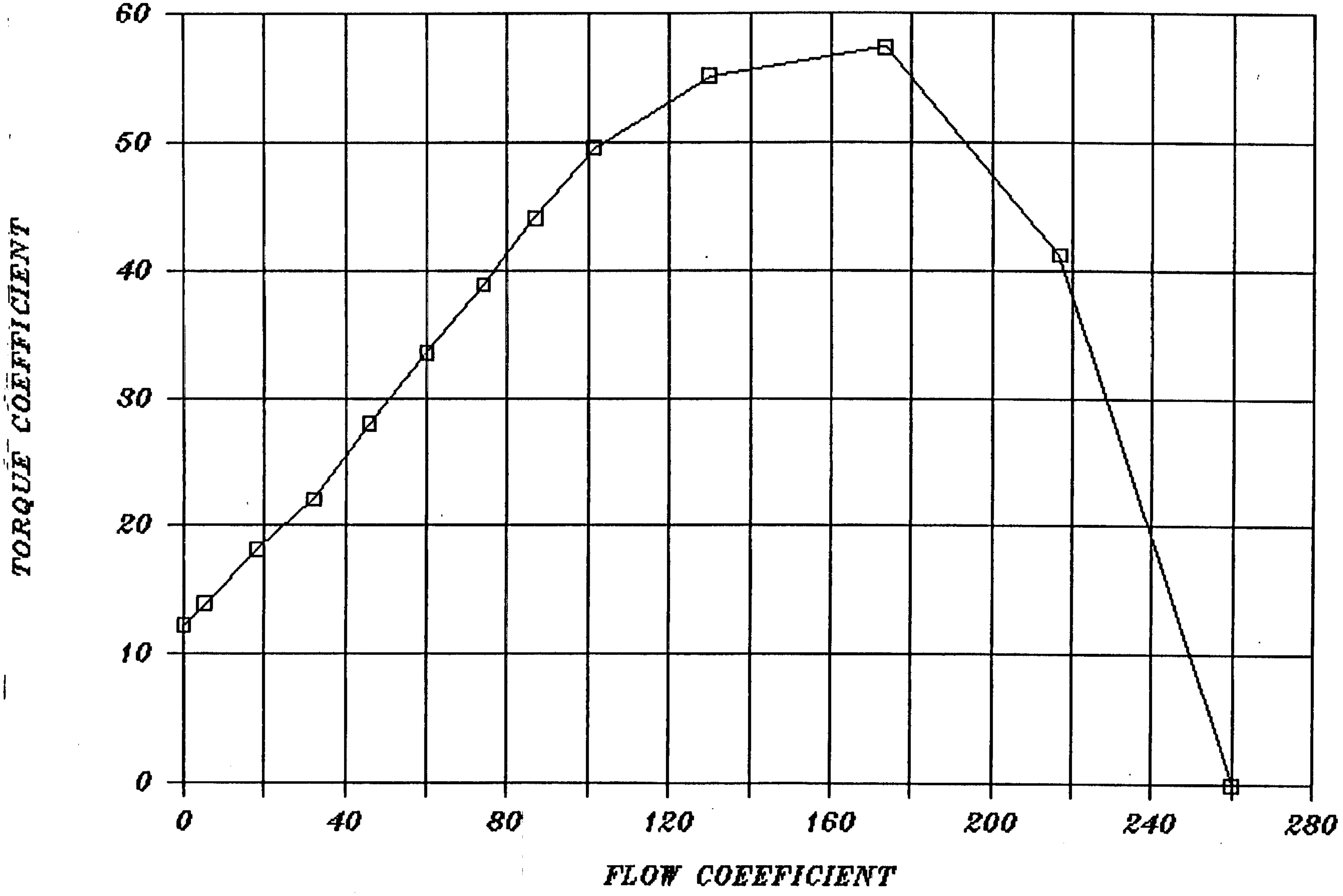

Figure 6

LOX PUMP PERFORMANCE MAP

HEAD COEFF. VS. FLOW COEFF.

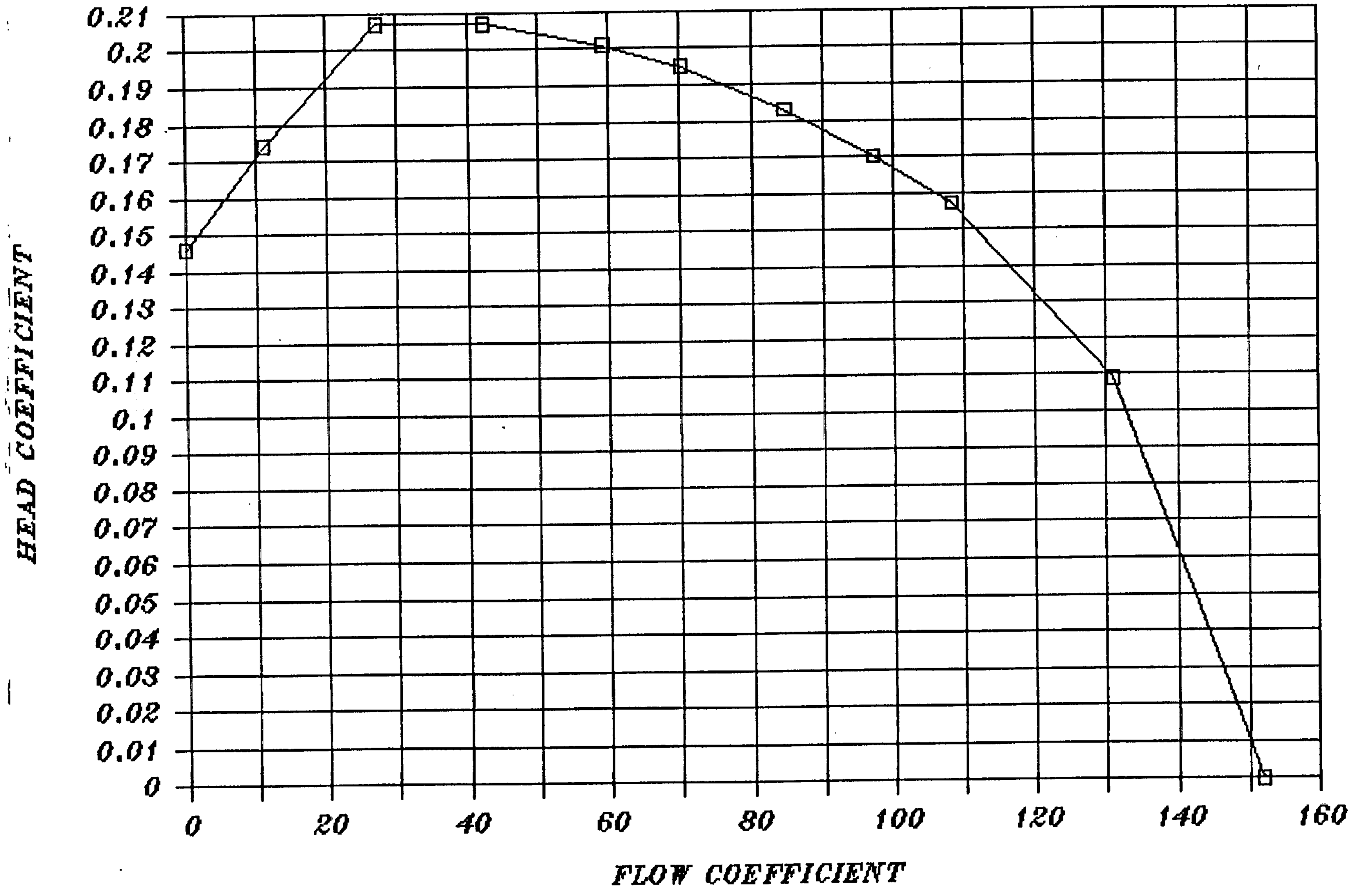

Figure 7

LOX PUMP PERFORMANCE MAP

TORQUE COEFF. VS. FLOW COEFF.

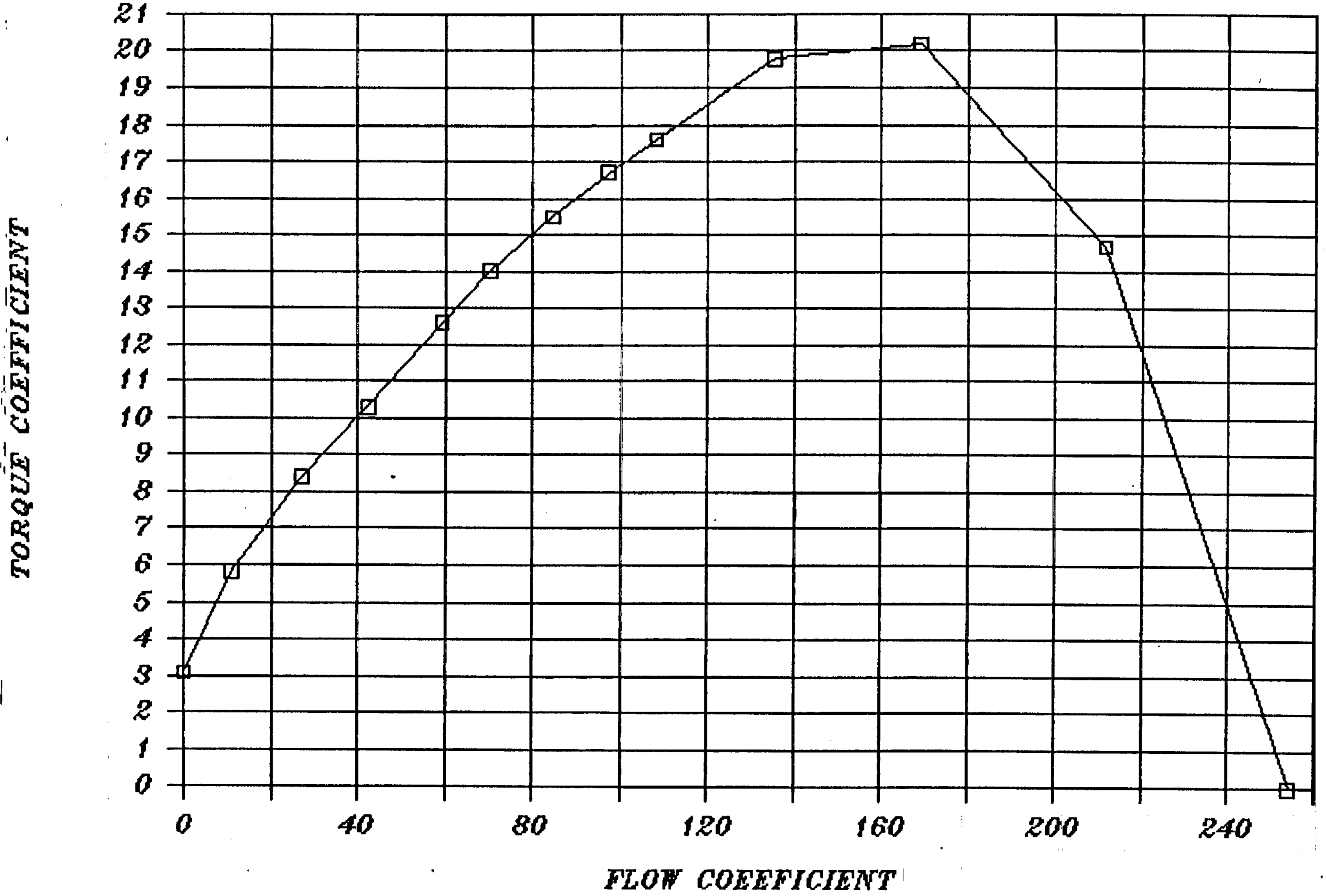

Figure 8

Discussion and Results

Nominal Start Transient

In order to start the fuel and oxidizer pumps, a hydrogen spin is used on each of the four gas generators to generate initial turbine speed. 15 lbs of hydrogen is used between 0.1 and 1.6 seconds to assist in start. For each of the four engine systems, the same valve sequences are used since all four GGs are started simultaneously with the same hydrogen-spin sequence (Figures A20, B13, C13, D13). The duration for the gas flow to assist in a spin start is based on two criteria: (1) The fuel pump discharge pressure should be greater than the critical pressure (~186 psia), and (2) The GG chamber pressure should be operating between 150 psia and 200 psia to achieve spark ignition.

The valve schedules for start are shown in Table 4. The results, presented in Appendices A through D, indicate satisfactory transient behavior. Mainstage is reached around 3.5 seconds. The fuel and oxidizer pump discharge valves are 100% and 55% open from start, respectively, so that the ring manifolds are chilled at start. In the first trial start simulations, the fuel and oxidizer valves were 100% open at start. This valve sequence was modified, however, to eliminate flow oscillations in the oxidizer feedsystem which were occurring around 0.5 seconds. For an engine system with multiple pumps and parallel feedsystems coupled by ring manifolds, the oxidizer feedsystem flow oscillations are difficult to eliminate due to the reduced available damping of the lower feedsystem. By throttling the oxidizer pump discharge valves upstream of the ring manifold rather than having them full open at start, the flow oscillations were eliminated by allowing for more damping in the feedsystem downstream of the manifold. The oxidizer pump discharge valves are then ramped from 55% to full open in 1.2 seconds, beginning at 2.2 seconds. At 1.0 second, the fuel GG valves are ramped open in 0.5 seconds. At 1.2 seconds the LOX GG valves are ramped open in 2.0 seconds. The slower opening rate for the LOX GG valves keeps the GG mixture ratios (Figures A8,B8,C8,D8) at desirable levels and prevents excessive turbine temperatures. The thrust chamber inlet fuel valves are ramped open in 0.3 seconds at start. The thrust chamber inlet oxidizer valves are ramped to 40% open in 0.5 seconds at start, throttled at 40% for 2.0 seconds, and then ramped to full open in 1.3 seconds. These valves are opened gradually in two stages in order to keep the thrust chamber mixture ratios (Figures A7,B7,C7,D7) from increasing too rapidly as well as to avoid excessive overshoots.

One of the concerns during start is a fuel pump stall condition. At low flows, hydrogen axial pumps have performance behavior characterized by abrupt pressure loss for reduced flow, which results in stall. This behavior is described on the H-Q (head versus flow) pump performance curve as a positive slope in the low flow region of the curve. Stall can be avoided by insuring that the pumps are not operated in this region. By maintaining a high enough flow coefficent, operation of the fuel pumps will be in the negative-slope region of the H-Q performance curve and stall can be avoided.

Table 4
Valve Schedules During Hydrogen Spin-Assisted Start

Valves	Start/End (sec)	Rate (%/sec)	Final Position (%)
Fuel Pump Discharge (4)	0. /0.	instantaneous	100.
Ox Pump Discharge (4)	0. /0.	instantaneous	55.
	2.1/3.4	35	100.
Fuel Gas Generator (4)	0. /1.0	0	0.
	1.0 /1.5	200	100.
Ox Gas Generator (4)	0. /1.2	0	0.
	1.2 /3.2	50	100.
Fuel Thrust Chamber Inlet (8)	0. /0.3	333	100.
Ox Thrust Chamber Inlet (8)	0. /0.1	0	0
	0.1 /0.5	100	40.
	0.5 /2.5	0	40.
	2.5/ 3.8	46	100.

Nominal Cutoff Transient

The valve schedules for cutoff are shown in Table 5. The initial part of the shutdown sequence for a gas generator engine cycle is to close off flow to the turbines. This is partly a safety issue to minimize turbine energy if a malfunction was to occur. As Table 5 indicates, closing of all of the valves was initiated together, at 5.0 seconds for this particular simulation. The gas generator valves were closed most rapidly, in 0.5 seconds for the fuel side, and in 0.3 seconds for the oxidizer side. The fuel valves are closed more slowly than the oxidizer valves to insure a fuel-rich shutdown. Upon closing the GG valves, it would be desirable to purge out the LOX quickly while the GG fuel valve is still open. For larger GG chamber volumes, this becomes increasingly significant to prevent the possibility of vaporizing LOX at high GG mixture ratios, which could damage the turbine blades.

When flow to the GG is terminated, the pump speeds and consequently the pump discharge pressures decay rapidly. In order for the downstream pressures to drop, some of the hydrogen propellant in the system needs to bleed into the main chamber. If the pump speeds decay too rapidly, the pump discharge pressures will tend to drop faster than the downstream pressures. As a result, the flowrates decay faster than the pump speeds (flow coefficients drop too low relative to mainstage) raising the concern of hydrogen boil-out in the pumps. If the pump speed is too high, the energy of the pump will cause the hydrogen to boil out and possibly damage the bearings. A simulation run in which the GG oxidizer valves were closed in 0.1 seconds resulted in fuel flow coefficients of less than 40% (mainstage values). By slowing down the GG oxidizer valve closing rate to 0.3 seconds, termination of GG power was not quite as rapid. The pump speed decay rates were less, keeping the fuel flow coefficients from dropping below 50% of mainstage which should be acceptable based on SSME data.

The pump discharge valves and the thrust chamber inlet valves were closed together in 0.8 seconds on the fuel side, and in 0.7 seconds on the oxidizer side. The transient profiles for the valve sequence of Table 5, shown in Appendices A through D, represent satisfactory transient behavior during cutoff.

Table 5
Valve Schedules During Engine Cutoff

Valves	Start/End (sec)	Rate (%/sec)	Start/Final Position (%
Fuel Pump Discharge (4)	5.0 /5.8	125	100. /0.
Ox Pump Discharge (4)	5.0/5.7	143	100. /0.
Fuel Gas Generator (4)	5.0 /5.5	200	100. /0.
Ox Gas Generator (4)	5.0 /5.3	333	100. /0.
Fuel Thrust Chamber Inlet (8)	5.0 /5.8	125	100. /0.
Ox Thrust Chamber Inlet (8)	5.0 /5.7	143	100. /0.

Thrust Chamber Failure Condition

The advantage of an integrated propulsion system becomes apparent in the event of a component failure. During nominal operation, the pumps and thrust chambers operate at throttled down conditions. In the event that a component fails, the remaining components can be powered up to overcome the loss. Thus, an entire engine is not lost due to the loss of a single component.

For the simulation of one thrust chamber failure, a nominal start simulation was made and allowed to run for 5 seconds to mainstage. When a thrust chamber fails, both the fuel and oxidizer valves supplying the failed thrust chamber must be closed. The propellant flow which would nominally supply this thrust chamber is thus diverted via the ring manifolds to the other seven chambers. Under the assumption that failure of thrust chamber #3 occurred just prior to 5 seconds, closing of the fuel and oxidizer chamber inlet valves (#3) was initiated at 5 seconds. An effort was made to find a single valve sequence for the main chamber inlet valves which could be used both for cutoff of a single thrust chamber in the case of a failure and of all thrust chambers during nominal conditions.

Appendices E through H show the results when the main chamber (#3) inlet valves are closed in 0.8 and 0.7 seconds, on the fuel and oxidizer sides, respectively. This is the same sequence for these valves used for a nominal shutdown, shown in Table 5. Figure E5 and E7 show the main chamber (#3) pressure and mixture ratio decay, due to the shutdown of this chamber. The operating level of the pumps and remaining chambers increased as a result, as shown in the profiles of Appendices E through H. Slight mixture ratio overshoots from the design value of 6.7 to as high as 7.4 in the seven remaining chambers, and slight GG mixture ratio overshoots from 0.88 to as high as 0.94, resulted. These overshoots are probably acceptable although a detailed heat transfer analysis of the effect on the thrust chambers and GGs is reccommended.

Several other valve sequences were simulated prior to this selection. Valve closing rates of 0.5 and 0.3 seconds as well as 0.8 and 0.6 seconds for the fuel and oxidizer valves, respectively, resulted in excessive mixture ratios in the seven remaining chambers (8.0 and 7.7) and in the GGs (1.0 and 0.97). It was found that closing these valves at similar rates yielded the best results. Valve closing rates of 1.0 second for both the fuel and oxidizer valves was found to result in an acceptable shutdown, for example. This sequence was not selected, however, since a slightly faster closing rate for the oxidizer valve relative to the fuel valve is typically desirable to insure a fuel-rich shutdown for the main chamber, as stated earlier. In the case when one chamber is shut down, the objective is to maintain acceptable mixture ratios in the remaining chambers as well as in the failed chamber, so that the potential for further damage to the failed chamber is avoided.

When one chamber (#3) was shut down, the pressure in five of the remaining chambers (TC #2 and #4 excluded) increased to about 2208 psia which is about 95% rated thrust. Slightly higher thrust levels were achieved in the chambers adjacent to the chamber which was shut down. The pressures in TC #2 and #4 increased to 2226 psia and 2240 psia, respectively, which correspond to thrust levels of 96% and 97%. The adjacent chambers were affected slightly more by the flow which was diverted as a result of shutting down one thrust chamber, due to the closer proximity. Fuel pump speeds of 15500 rpm and oxidizer pump speeds of 5825 rpm were achieved for Systems 1, 3, and 4, which correspond to about 95% rated speed. A slightly higher operating level of about 96% was achieved for the System 2 pumps. Fuel and oxidizer pump speeds of 15670 rpm and 5892 rpm were achieved for System 2.

Recommendations/Conclusion

The results of the foregoing analysis indicate satisfactory transient behavior during both start and cutoff for the 8/4 integrated propulsion system. When one of the eight thrust chambers is shut down by closing the inlet valves, the simulation indicates an increase in main chamber thrust from 85% rated thrust to about 95% in the seven remaining chambers. Slight overshoots result in the GG and remaining main chamber mixture ratios. These overshoots are probably acceptable although a detailed heat transfer analysis of the effect on the thrust chambers and GGs is recommended prior to the development of a test program.

The start transient simulation was performed for a simultaneous gas spin-start of each of the four GGs. It is recommended that simulations be made for a staggered start of the GGs, in case a simultaneous start is not achieved. A tank head start option can also be evaluated as an alternative to a gas spin-start.

The integrated system is designed so that 100% nominal system thrust can be achieved in the case of a thrust chamber, a turbopump, or a combined thrust chamber/turbopump component failure. In the simulation of a single thrust chamber shutdown, 95% nominal system thrust was achieved. Simulations can be made for the other component shutdowns when funding becomes available. Further, refinements to the model as the components are better defined (e.g. pump maps, valve characteristics, geometry) will result in model results which are a better representation of the actual system behavior.

Victoria R. Kemp

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APPENDICES A THROUGH H
TRANSIENT ANALYTICAL RESULTS

Nominal Start/Cutoff Transient Analytical Results

For System 1:

Figure	Description
A1	Fuel and Oxidizer Pump Discharge Valve Positions
A2	Fuel and Oxidizer GG Valve Positions
A3	Thrust Chamber Inlet Fuel Valve Positions (two)
A4	Thrust Chamber Inlet Oxidizer Valve Positions (two)
A5	Main Chamber Pressures (two)
A6	GG Chamber Pressure
A7	Main Chamber Mixture Ratios (two)
A8	GG Chamber Mixture Ratio
A9	Fuel Pump Speed
A10	Oxidizer Pump Speed
A11	Fuel Pump Discharge Pressure
A12	Oxidizer Pump Discharge Pressure
A13	Fuel Pump Flowrate
A14	Oxidizer Pump Flowrate
A15	GG Chamber Temperature
A16	Oxidizer Turbine Inlet Temperature
A17	Oxidizer Turbine Discharge Temperature
A18	Fuel Pump Flow Coefficient
A19	Fuel Injector Inlet Temperatures (two)
A20	Hydrogen Gas Flow For GG Spin-Assisted Start

Nominal Start/Cutoff Transient Analytical Results

For System 2:

For System 3:

Nominal Start/Cutoff Transient Analytical Results

For System 4:

Figure	Description
D1	Fuel and Oxidizer Pump Discharge Valve Positions
D2	Fuel and Oxidizer GG Valve Positions
D3	Thrust Chamber Inlet Fuel Valve Positions (two)
D4	Thrust Chamber Inlet Oxidizer Valve Positions (two)
D5	Main Chamber Pressures (two)
D6	GG Chamber Pressure
D7	Main Chamber Mixture Ratios (two)
D8	GG Chamber Mixture Ratio
D9	Fuel Pump Speed
D10	Oxidizer Pump Speed
D11	Fuel Pump Flow Coefficient
D12	Fuel Injector Inlet Temperatures (two)
D13	Hydrogen Gas Flow For GG Spin-Assisted Start

Transient Analytical Results For Thrust Chamber (#3) Shutdown

For System 2:

Figure	Description
E1	Fuel and Oxidizer Pump Discharge Valve Positions
E2	Fuel and Oxidizer GG Valve Positions
E3	Thrust Chamber Inlet Fuel Valve Positions (two)
E4	Thrust Chamber Inlet Oxidizer Valve Positions (two)
E5	Main Chamber Pressures (two)
E6	GG Chamber Pressure
E7	Main Chamber Mixture Ratios (two)
E8	GG Chamber Mixture Ratio
E9	Fuel Pump Speed
E10	Oxidizer Pump Speed
E11	Fuel Pump Discharge Pressure
E12	Oxidizer Pump Discharge Pressure
E13	Fuel Pump Flowrate
E14	Oxidizer Pump Flowrate
E15	GG Chamber Temperature
E16	Oxidizer Turbine Inlet Temperature
E17	Oxidizer Turbine Discharge Temperature
E18	Fuel Pump Flow Coefficient
E19	Fuel Injector Inlet Temperatures (two)
E20	Hydrogen Gas Flow For GG Spin-Assisted Start

Transient Analytical Results For Thrust Chamber (#3) Shutdown

For System 1:

Figure	Description
F1	Fuel and Oxidizer Pump Discharge Valve Positions
F2	Fuel and Oxidizer GG Valve Positions
F3	Thrust Chamber Inlet Fuel Valve Positions (two)
F4	Thrust Chamber Inlet Oxidizer Valve Positions (two)
F5	Main Chamber Pressures (two)
F6	GG Chamber Pressure
F7	Main Chamber Mixture Ratios (two)
F8	GG Chamber Mixture Ratio
F9	Fuel Pump Speed
F10	Oxidizer Pump Speed
F11	Fuel Pump Flow Coefficient
F12	Fuel Injector Inlet Temperatures (two)
F13	Hydrogen Gas Flow For GG Spin-Assisted Start

For System 3:

Figure	Description
G1	Fuel and Oxidizer Pump Discharge Valve Positions
G2	Fuel and Oxidizer GG Valve Positions
G3	Thrust Chamber Inlet Fuel Valve Positions (two)
G4	Thrust Chamber Inlet Oxidizer Valve Positions (two)
G5	Main Chamber Pressures (two)
G6	GG Chamber Pressure
G7	Main Chamber Mixture Ratios (two)
G8	GG Chamber Mixture Ratio
G9	Fuel Pump Speed
G10	Oxidizer Pump Speed
G11	Fuel Pump Flow Coefficient
G12	Fuel Injector Inlet Temperatures (two)
G13	Hydrogen Gas Flow For GG Spin-Assisted Start

Transient Analytical Results For Thrust Chamber (#3) Shutdown

For System 4:

APPENDIX A

NOMINAL START/CUTOFF TRANSIENT ANALYTICAL RESULTS FOR SYSTEM 1

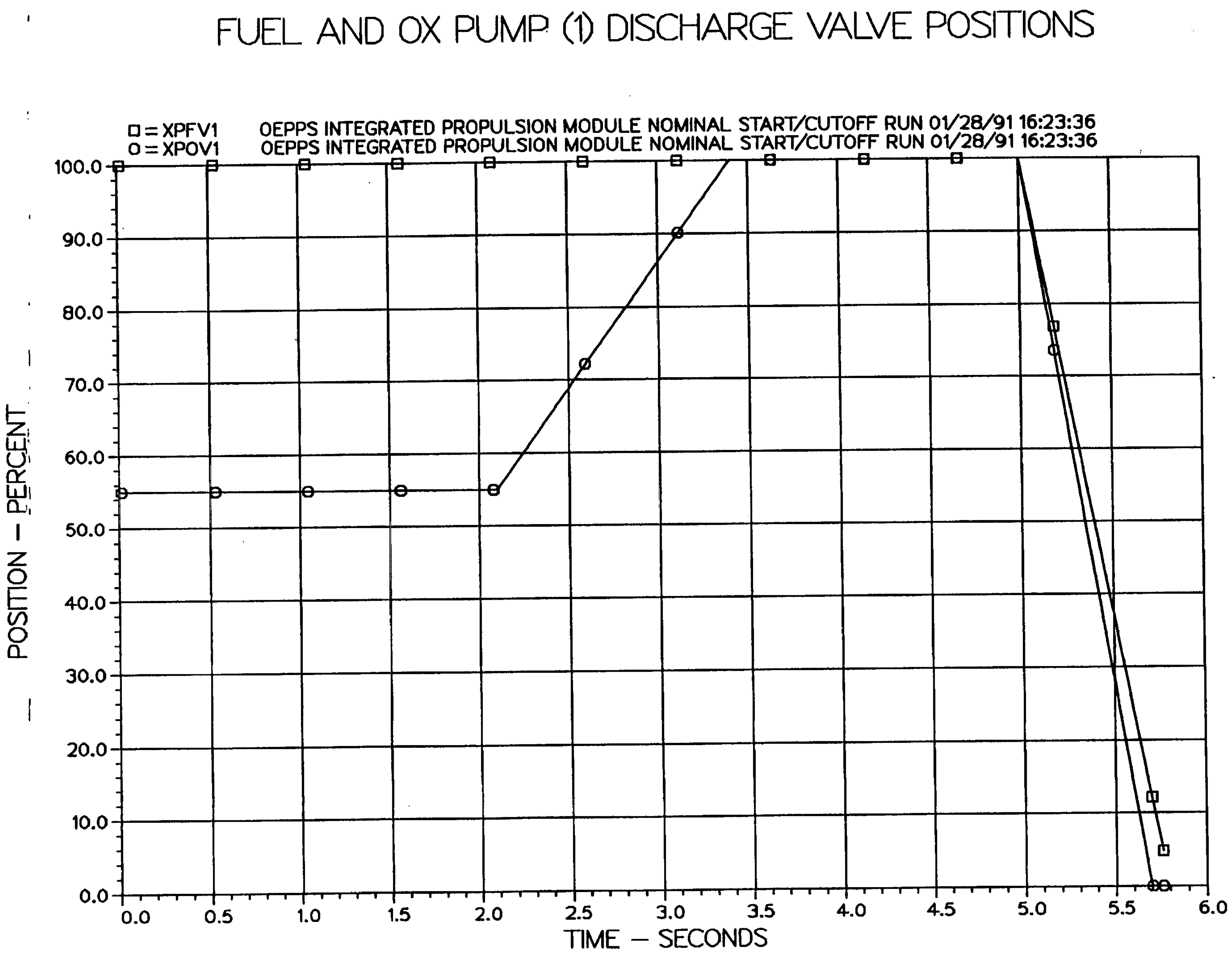


Figure A1

PLOT 2 10.03.43 TUES 29 JAN, 1991 JOB-r758335 , ISSCO DISSPLA 10.0

FUEL AND OX GAS GENERATOR (1) VALVE POSITIONS

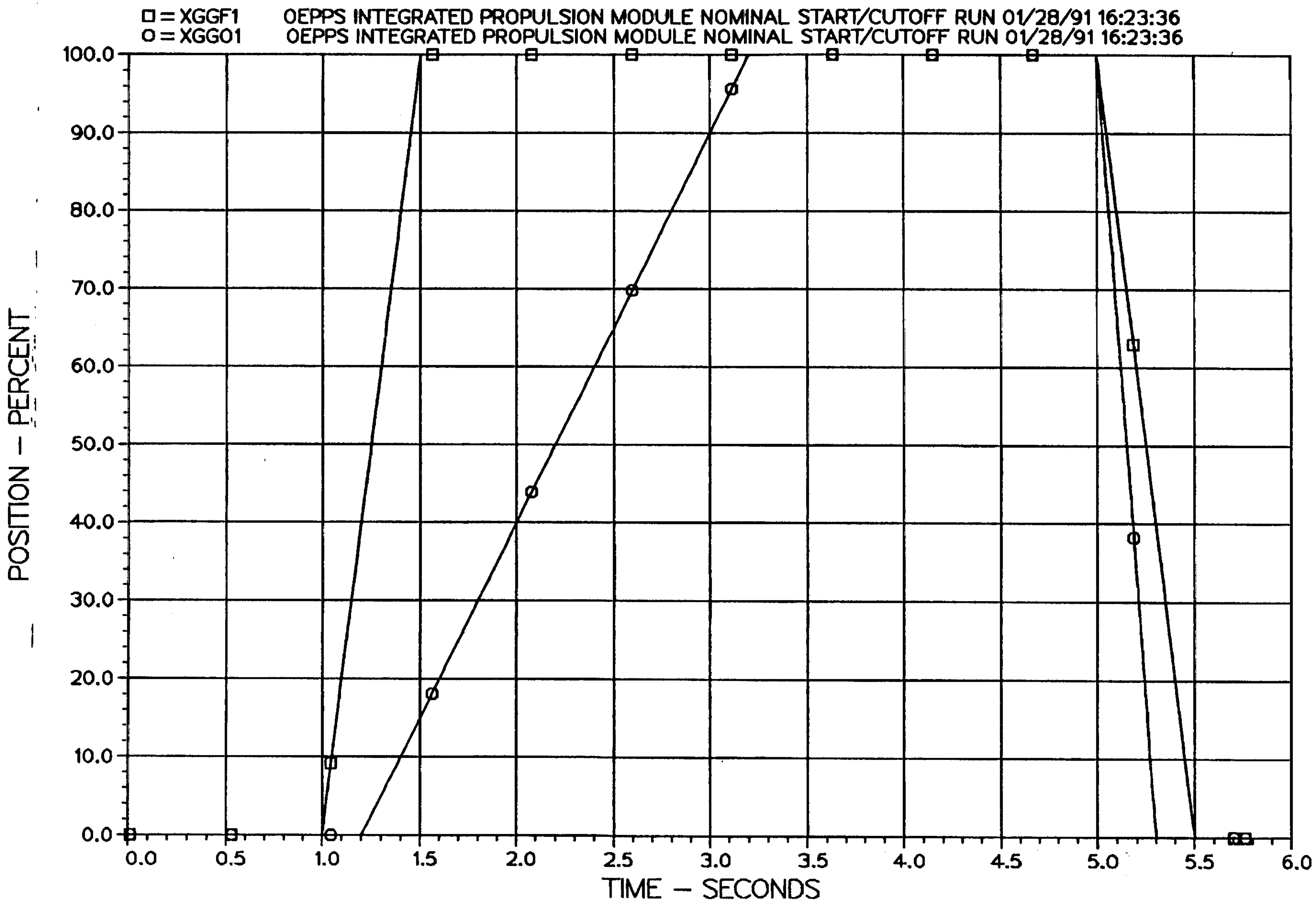


Figure A2

LOT 5 10.03.57 TUES 29 JAN, 1991 JOB-758335 , ISSCO DISSPLA 10.0

T/C (1,2) INLET FUEL VALVE POSITIONS

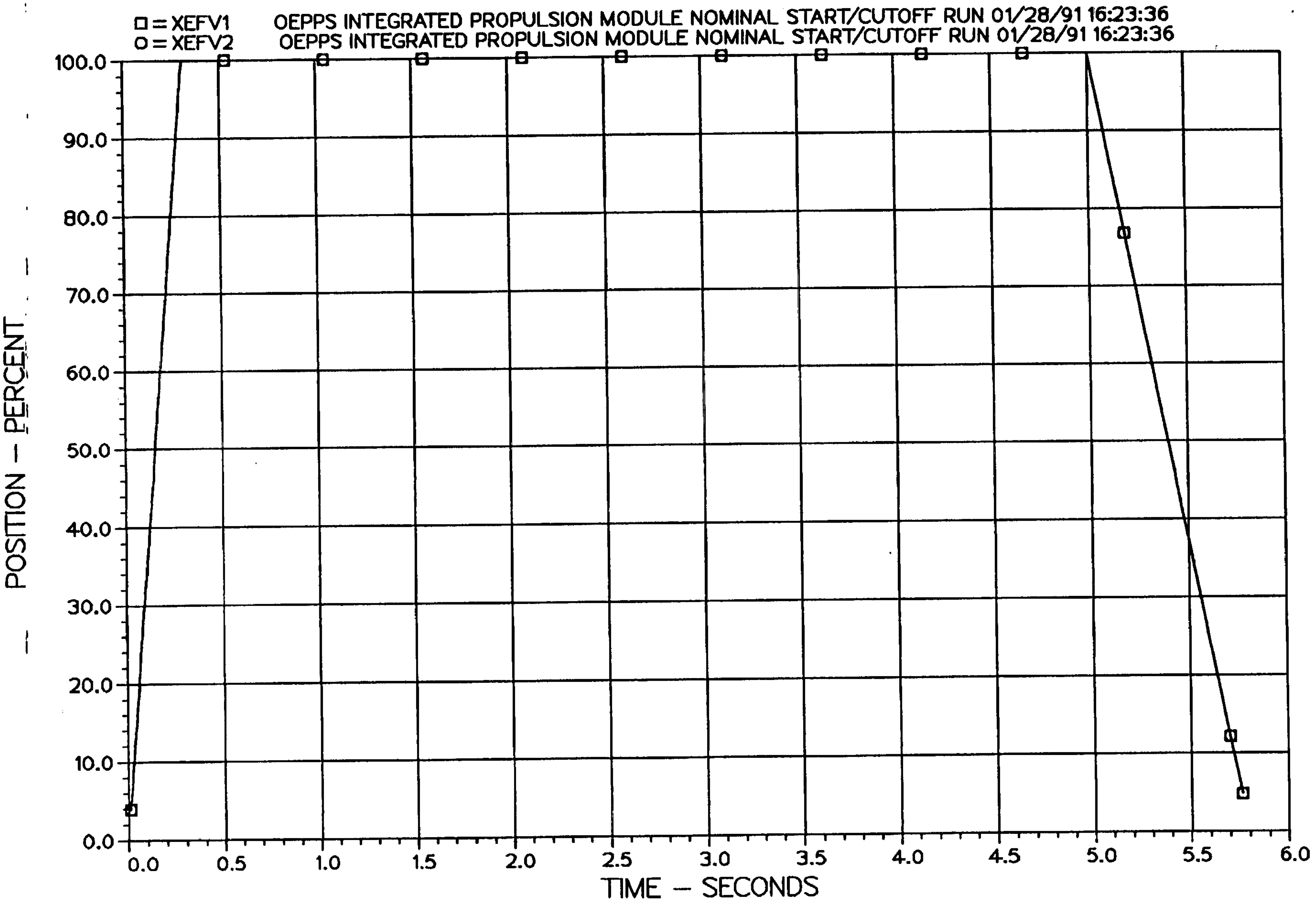


Figure A3

PLOT 3 10.03.48 TUES 29 JAN, 1991 JOB-758335 , ISSCO DISSPLA 10.0

T/C (1,2) INLET OX VALVE POSITIONS

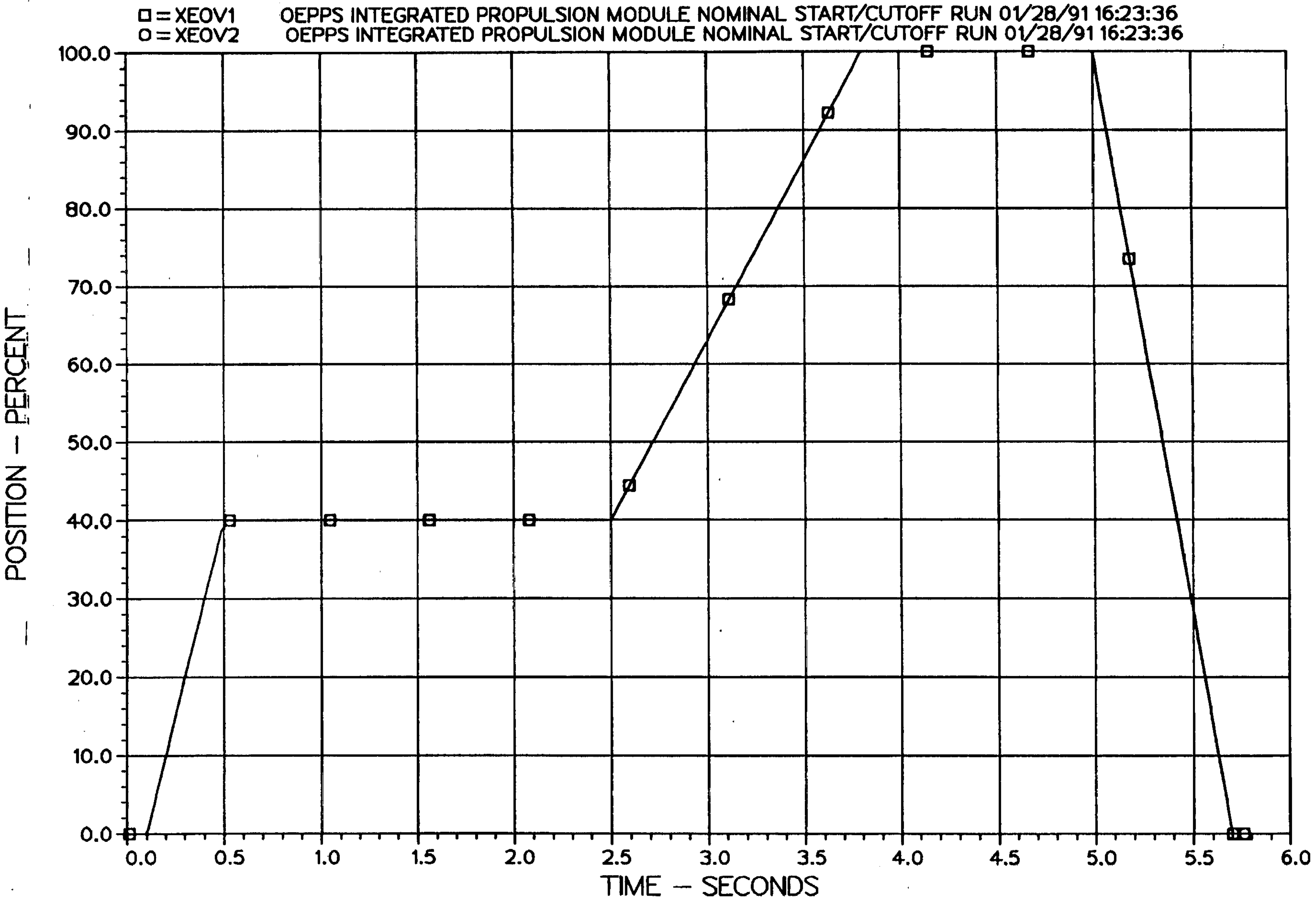
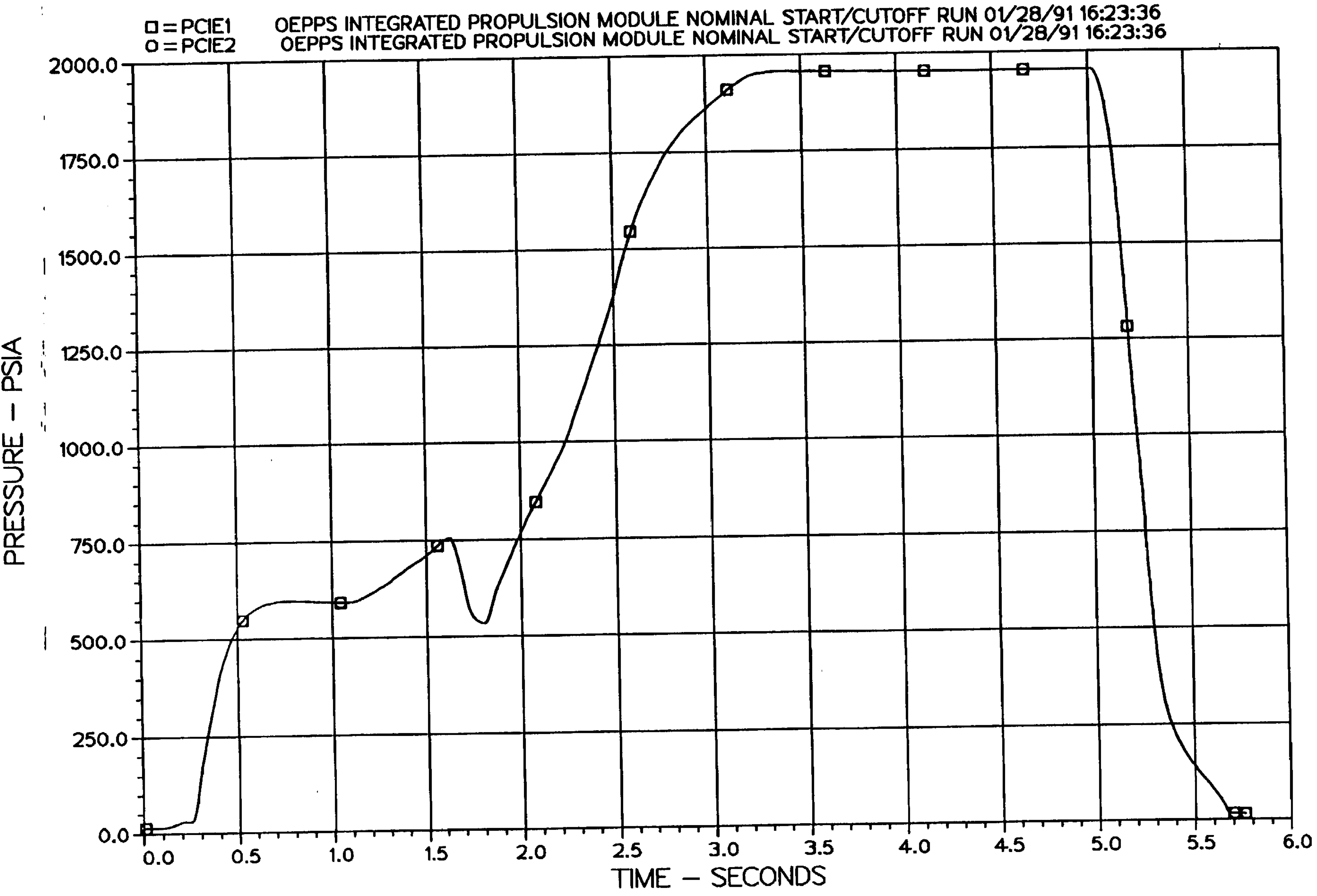


Figure 14

OT 4 10.03.52 TUES 29 JAN, 1991 JOB-r758335 , ISSCO DISSPLA 10.0

T/C (1,2) MAIN CHAMBER PRESSURES

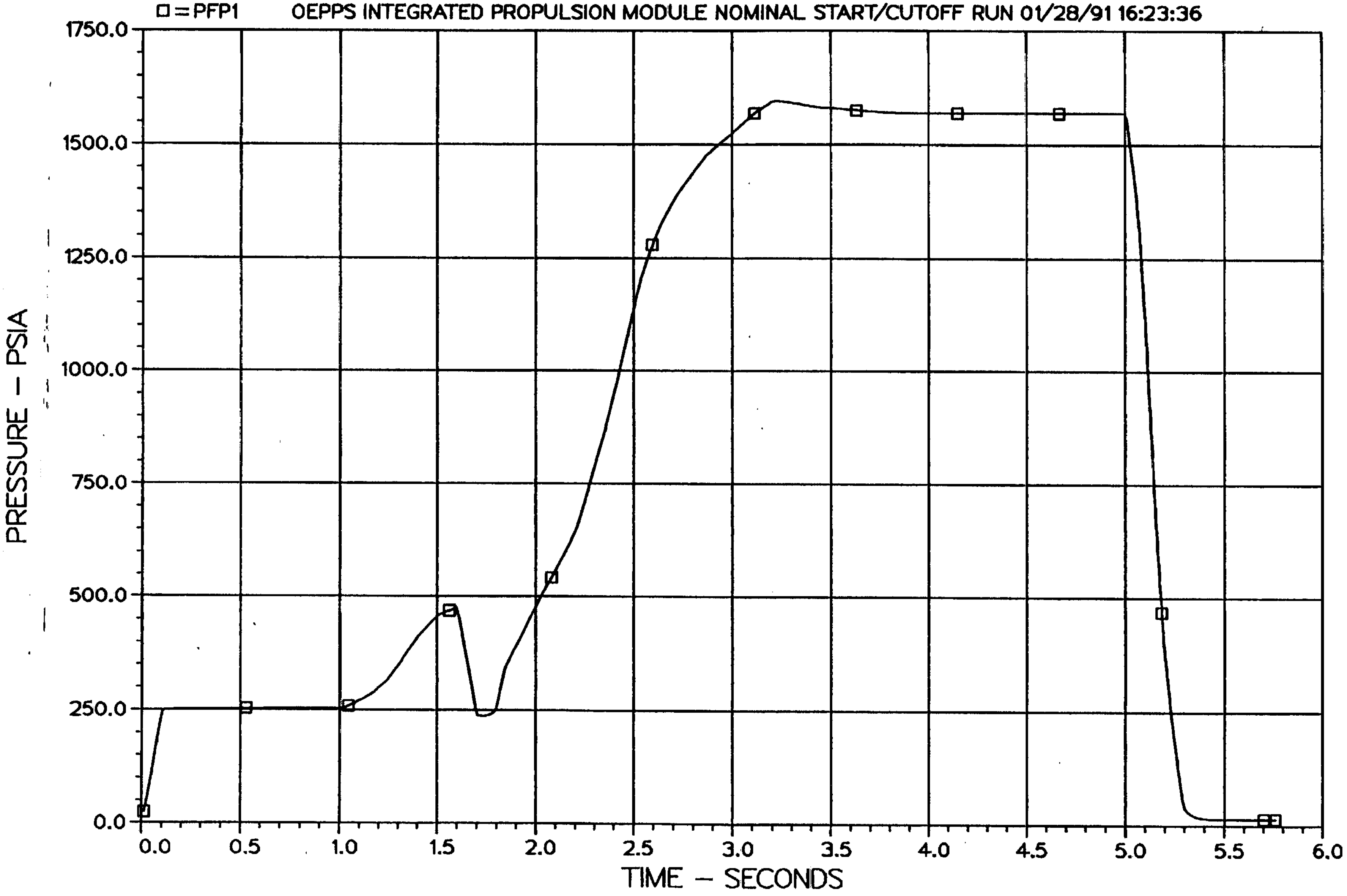


10.04.02 TUES 29 JAN, 1991 JOB-r758335 , ISSCO DISSPLA 10.0

PLOT 6

Figure A5

GAS GENERATOR (1) CHAMBER PRESSURE



10.04.05 TUES 29 JAN, 1991 JOB-758335 , ISSCO DISSPLA 10.0

LOT 7

Figure A6

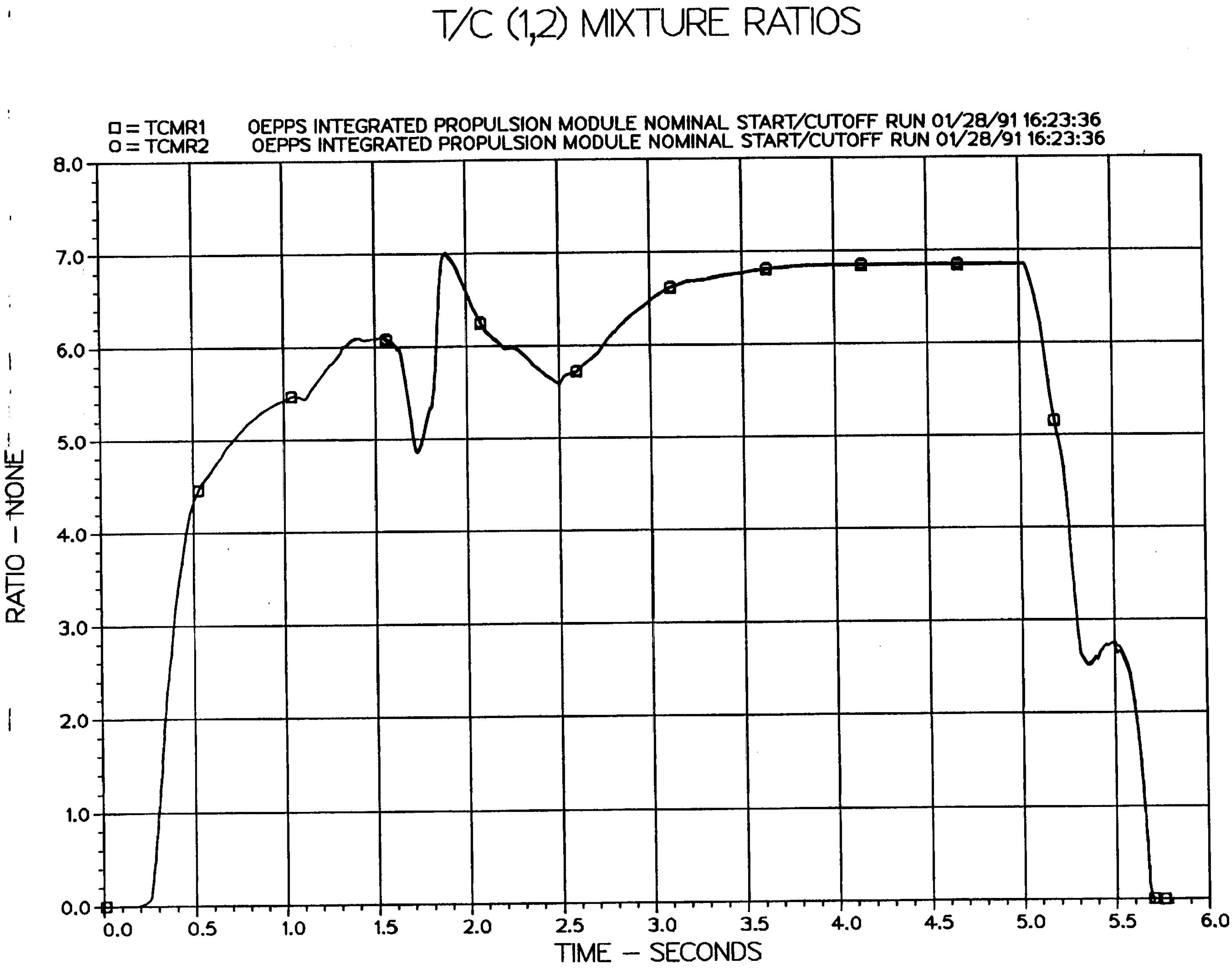


Figure A7

PLOT 8 10.04.09 TUES 29 JAN, 1991 JOB-r758335 , ISSCO DISSPLA 10.0

GAS GENERATOR (1) MIXTURE RATIO

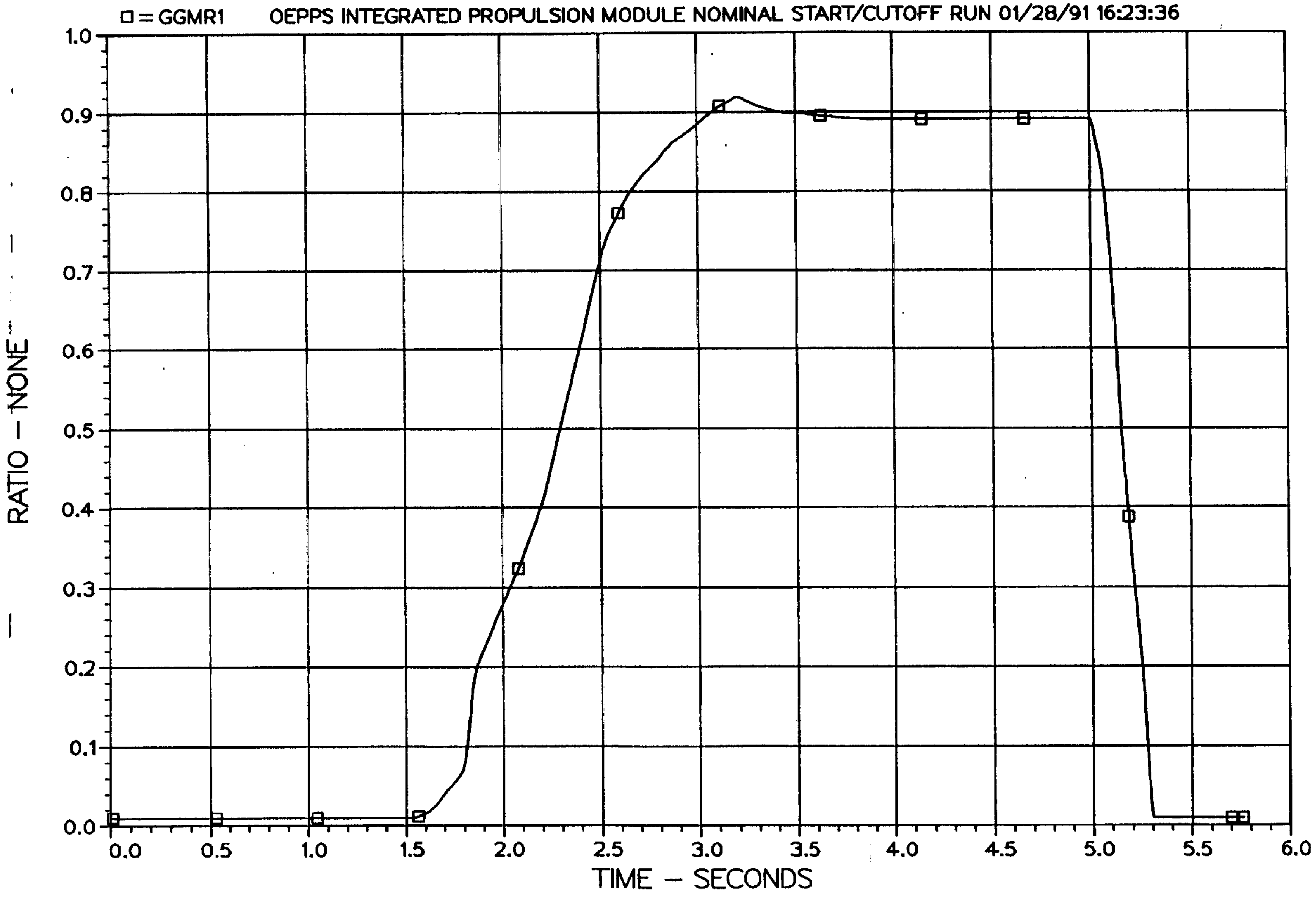


Figure A8

LOT 9   10.04.12 TUES 29 JAN, 1991   JOB-r758335 , ISSCO   DISSPLA 10.0

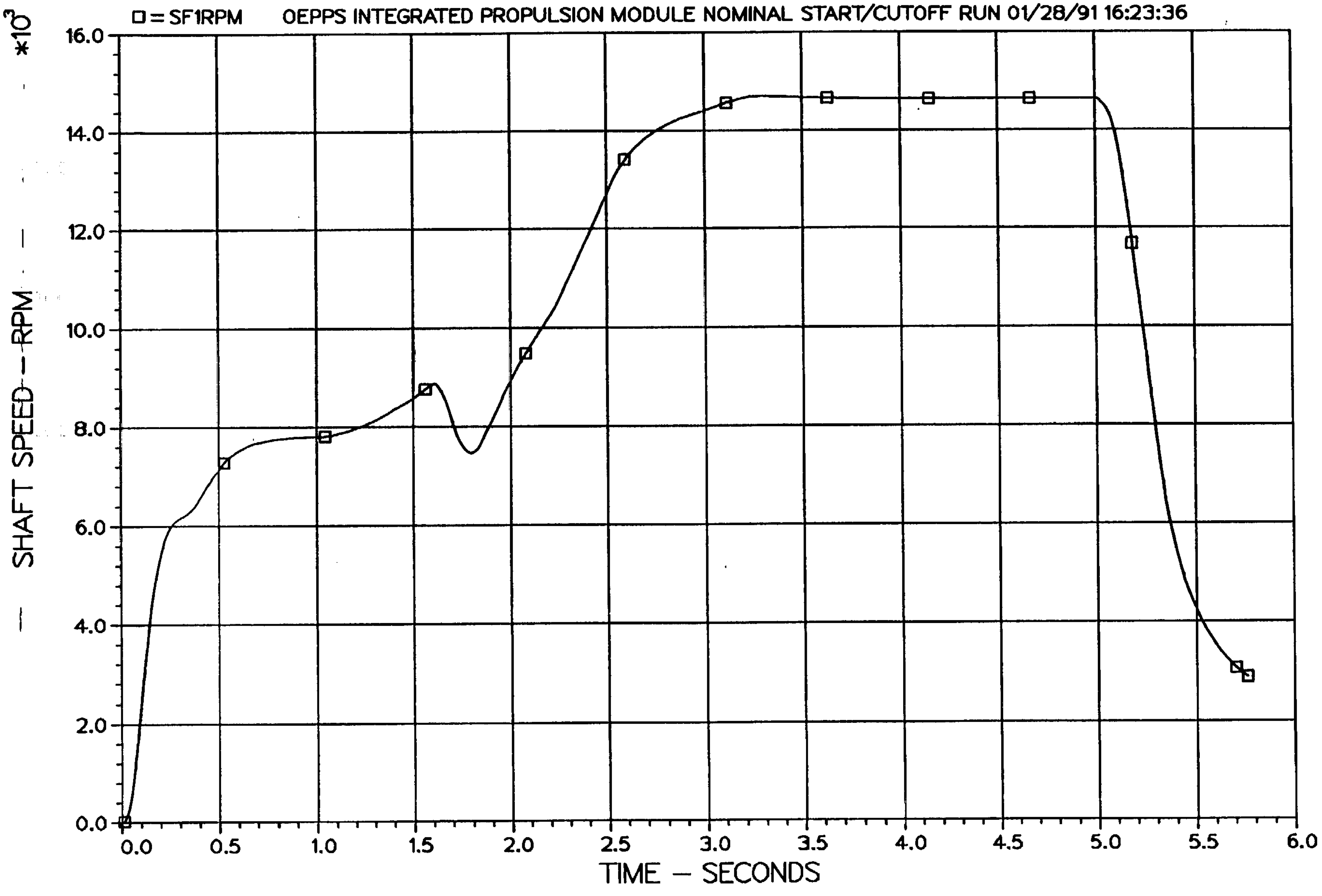

FUEL PUMP (1) SPEED

Figure A9

PLOT 10 10.04.15 TUES 29 JAN, 1991 JOB-758335 , ISSGO DISSPLA 10.0

LOX PUMP (1) SPEED

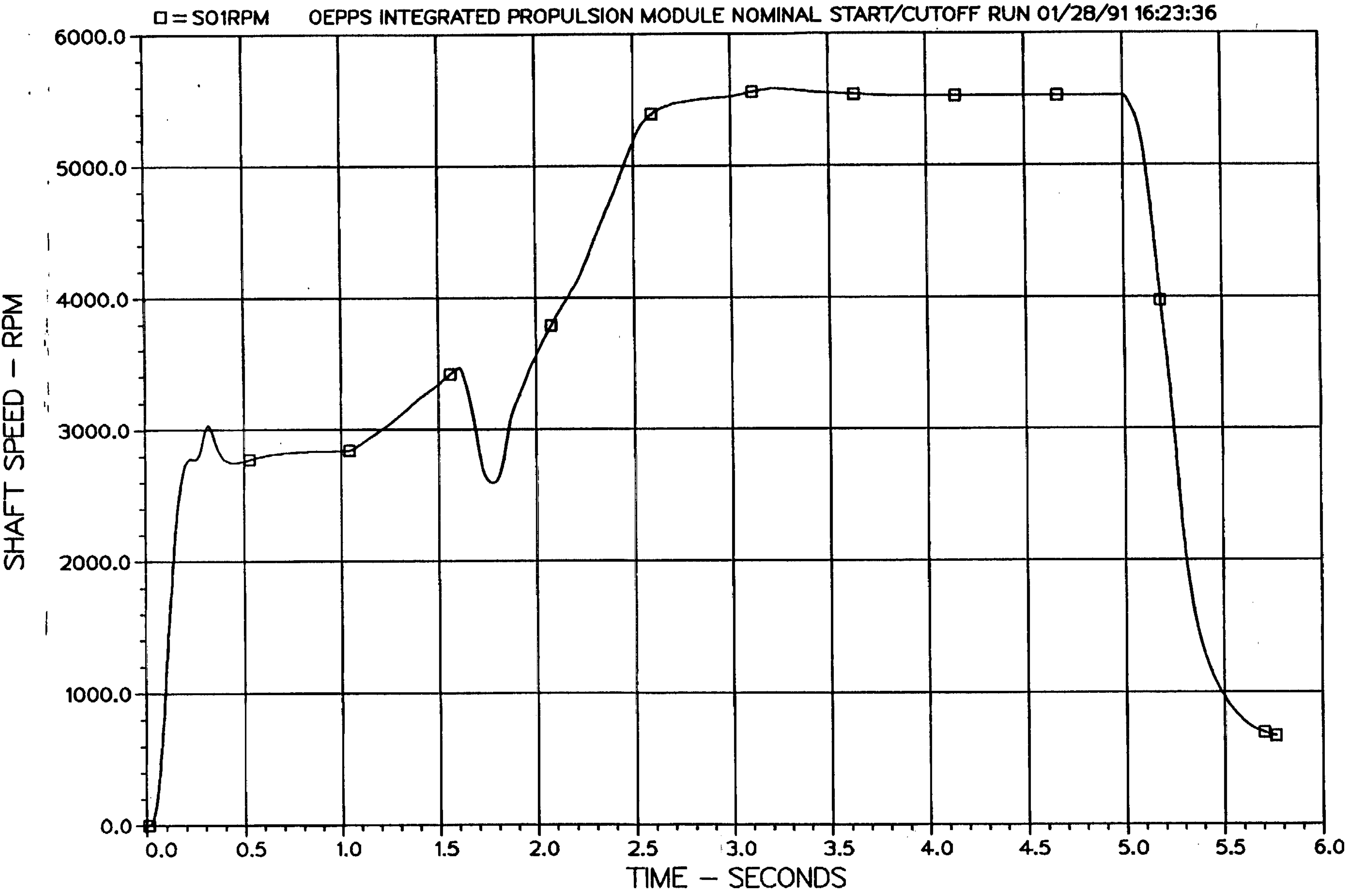


Figure A[illegible]

LOT 11 10.04.18 TUES 29 JAN, 1991 JOB-r758335 , ISSCO DISSPLA 10.0

FUEL PUMP (1) DISCHARGE PRESSURE

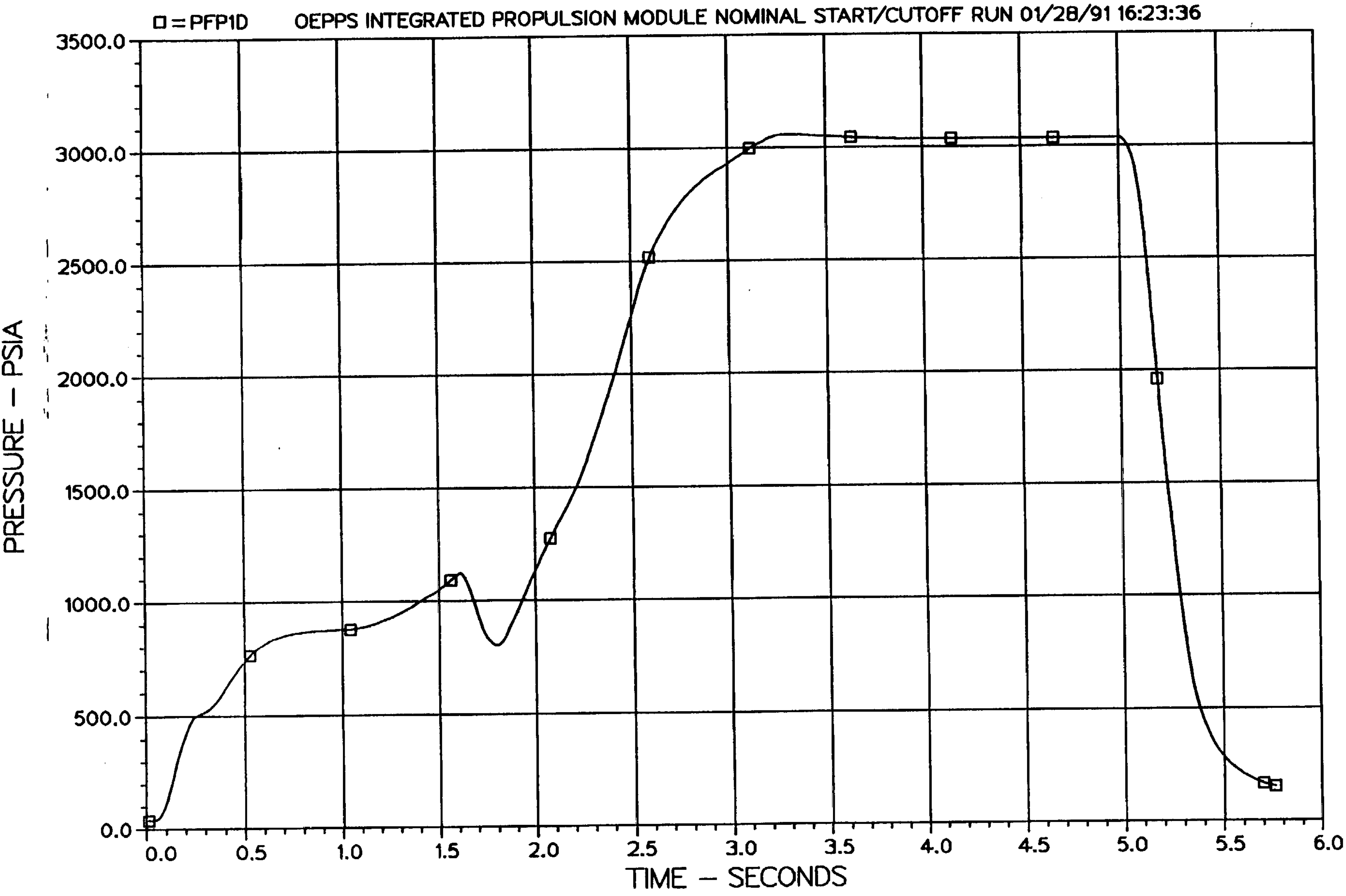
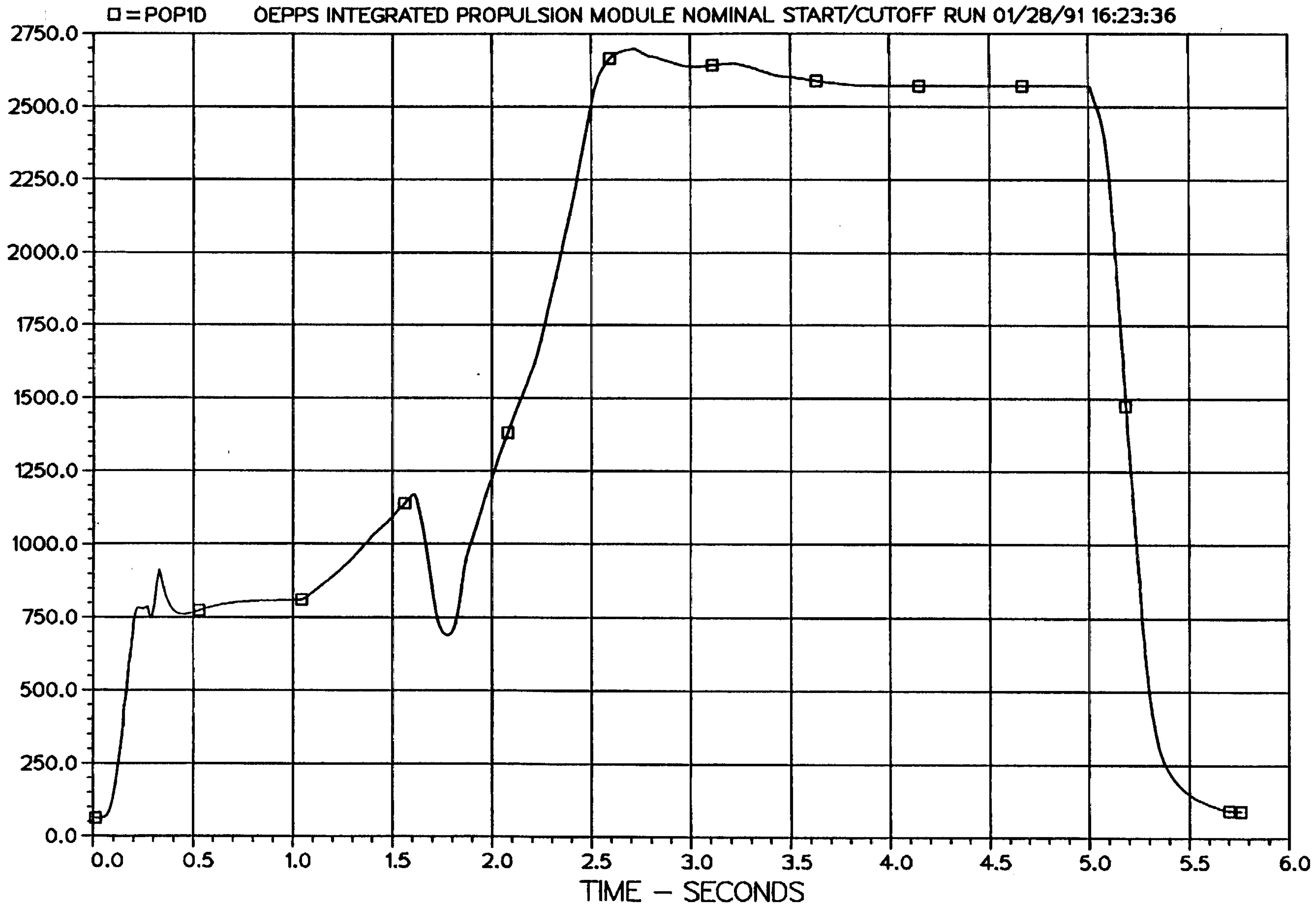


Figure A11

PLOT 12 10.04.21 TUES 29 JAN, 1991 JOB-r758335 , ISSCO DISSPLA 10.0

LOX PUMP (1) DISCHARGE PRESSURE



LOT 13 10.04.25 TUES 29 JAN, 1991 JOB-758335 , ISSCO DISSPLA 10.0

Figure A12

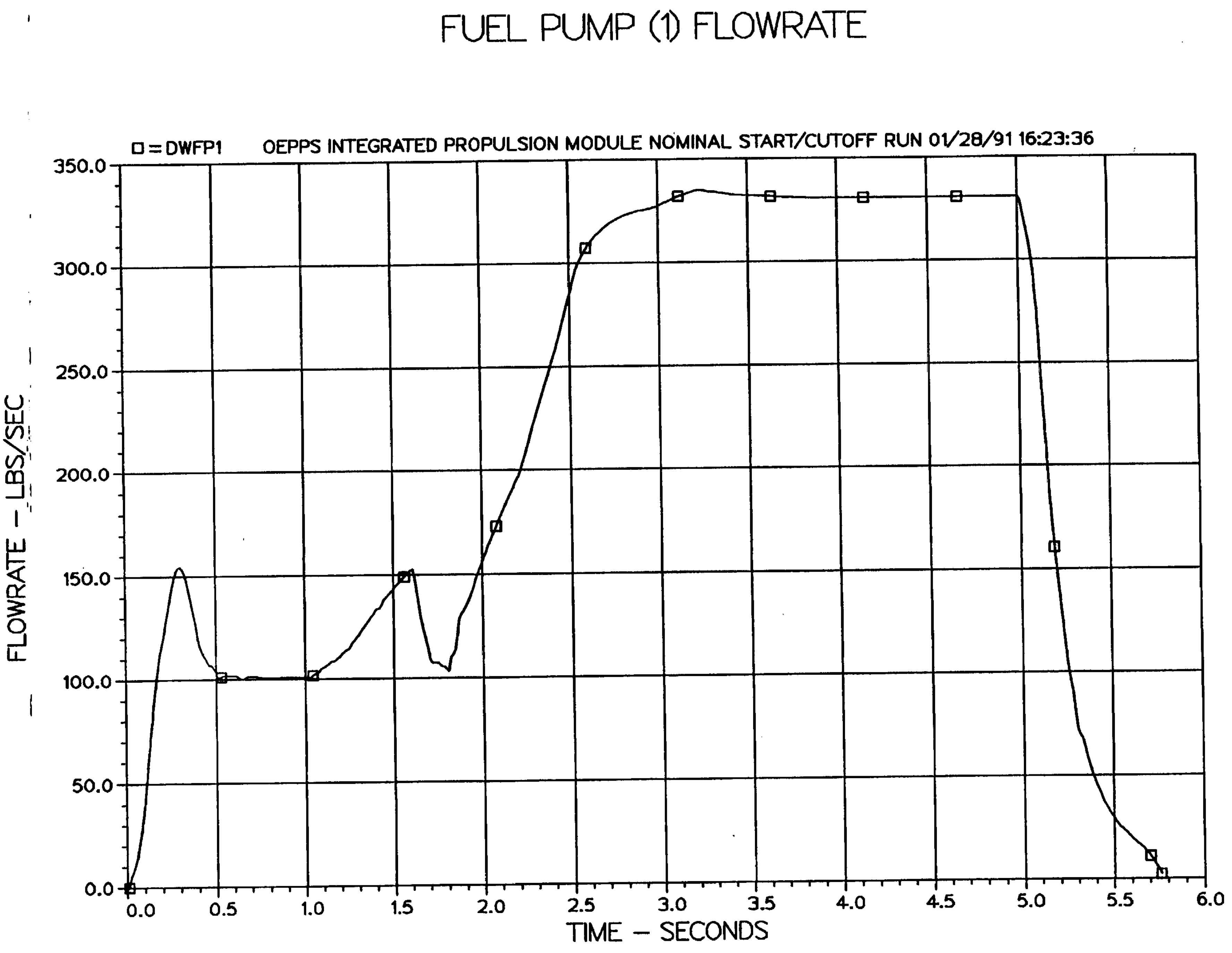
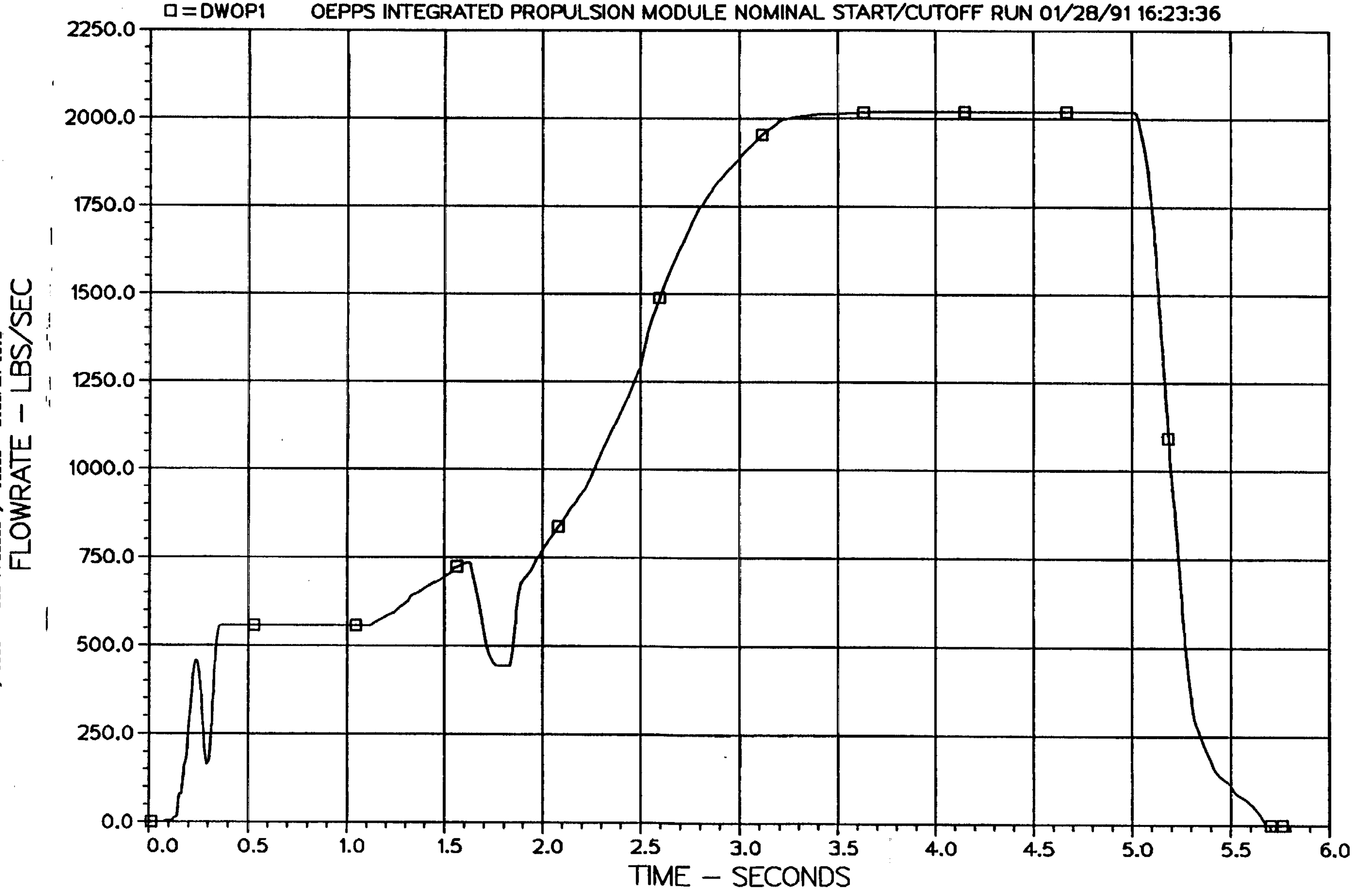


Figure A13

PLOT 14 10.04.29 TUES 29 JAN, 1991 JOB-r758335 , ISSCO DISSPLA 10.0

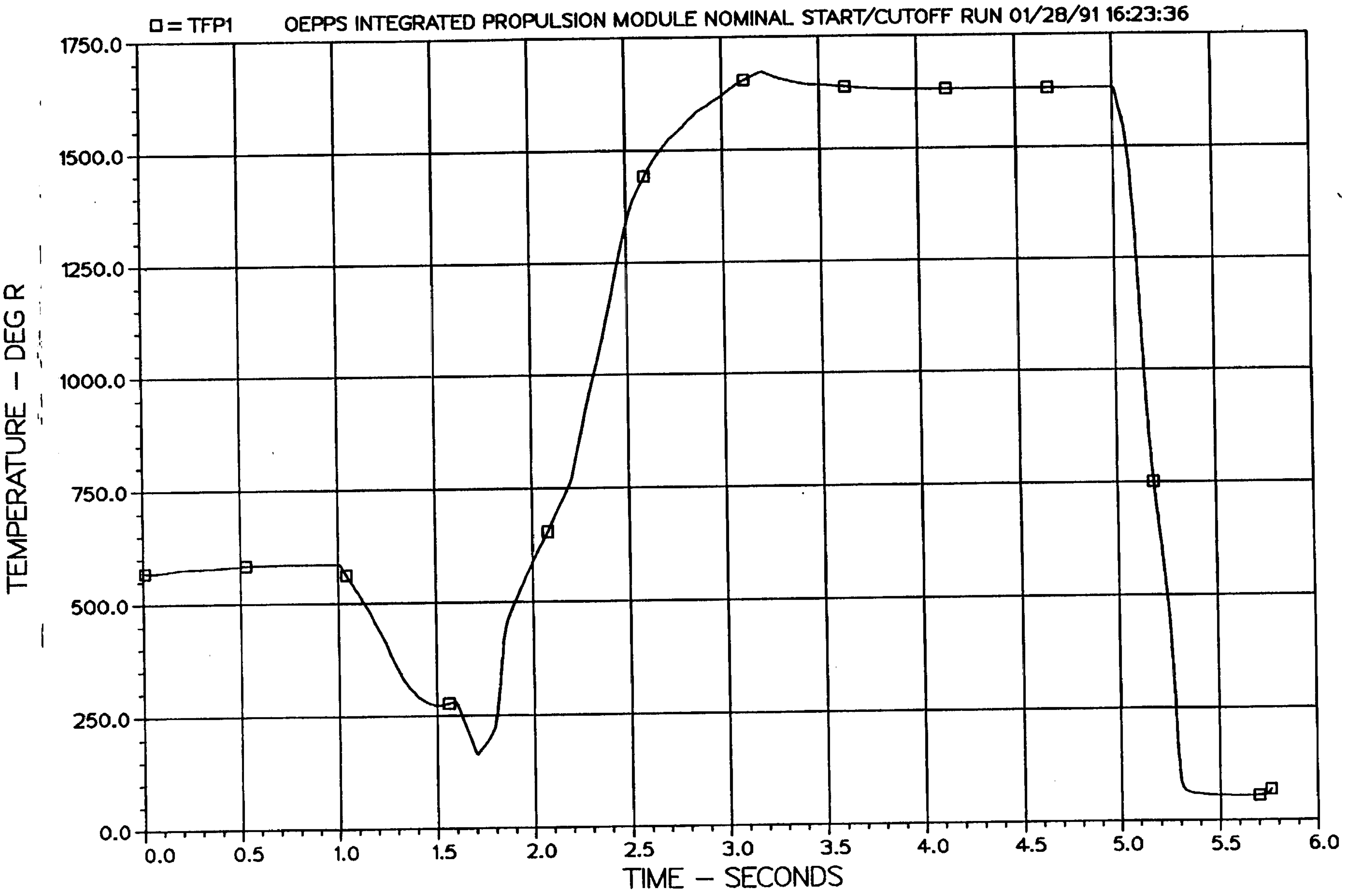
LOX PUMP (1) FLOWRATE



LOT 15 10.04.32 TUES 29 JAN, 1991 JOB-758335 , ISSCO DISSPLA 10.0

Figure A14

GAS GENERATOR (1) CHAMBER TEMPERATURE



PLOT 16 10.04.35 TUES 29 JAN, 1991 JOB-r758335 , ISSCO DISSPLA 10.0

Figure A15

LOX TURBINE (1) INLET TEMPERATURE

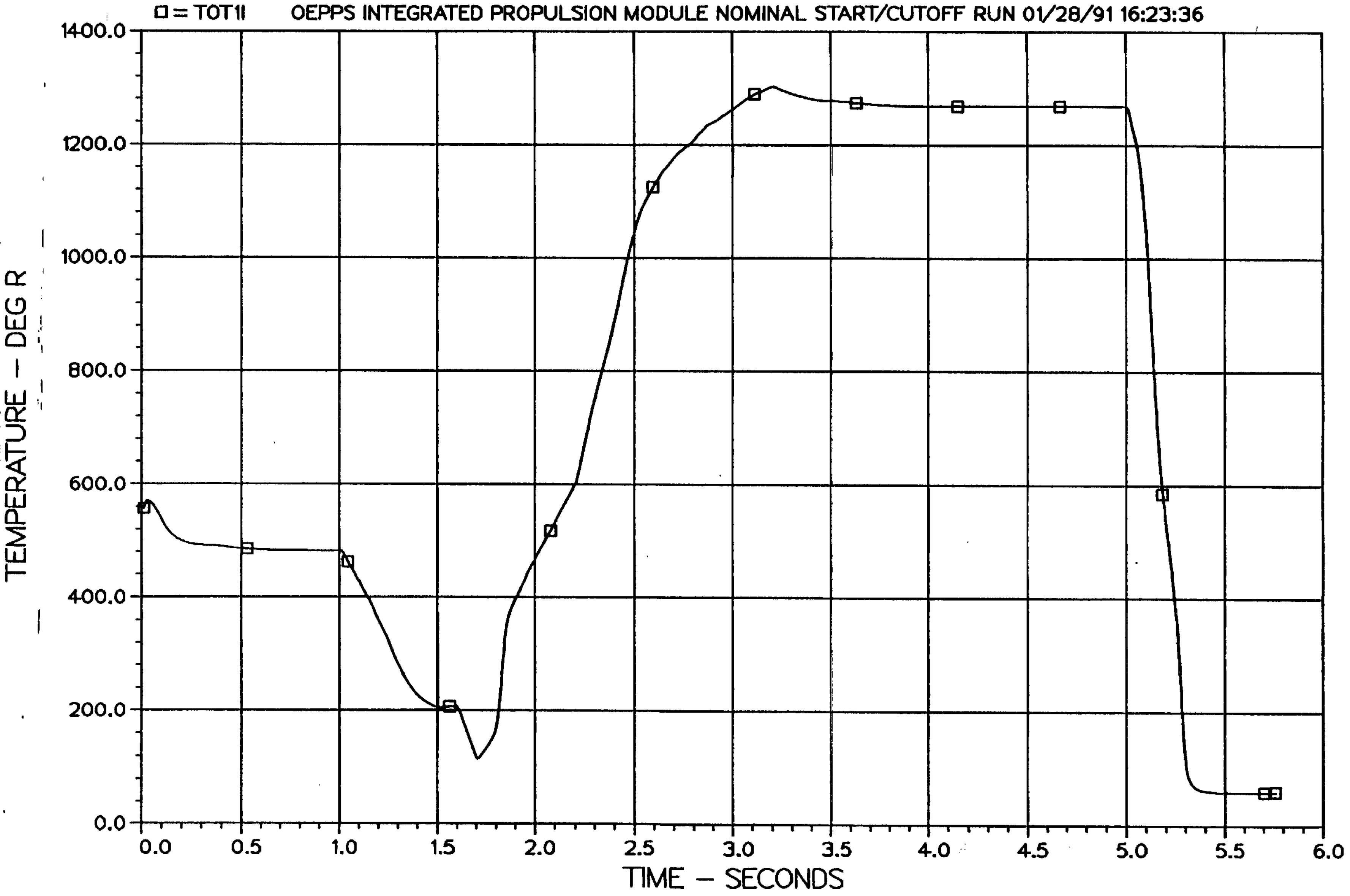


Figure A11

10.04.38 TUES 29 JAN, 1991 JOB-758335 , ISSCO DISSPLA 10.0

OT 17

LOX TURBINE (1) DISCHARGE TEMPERATURE

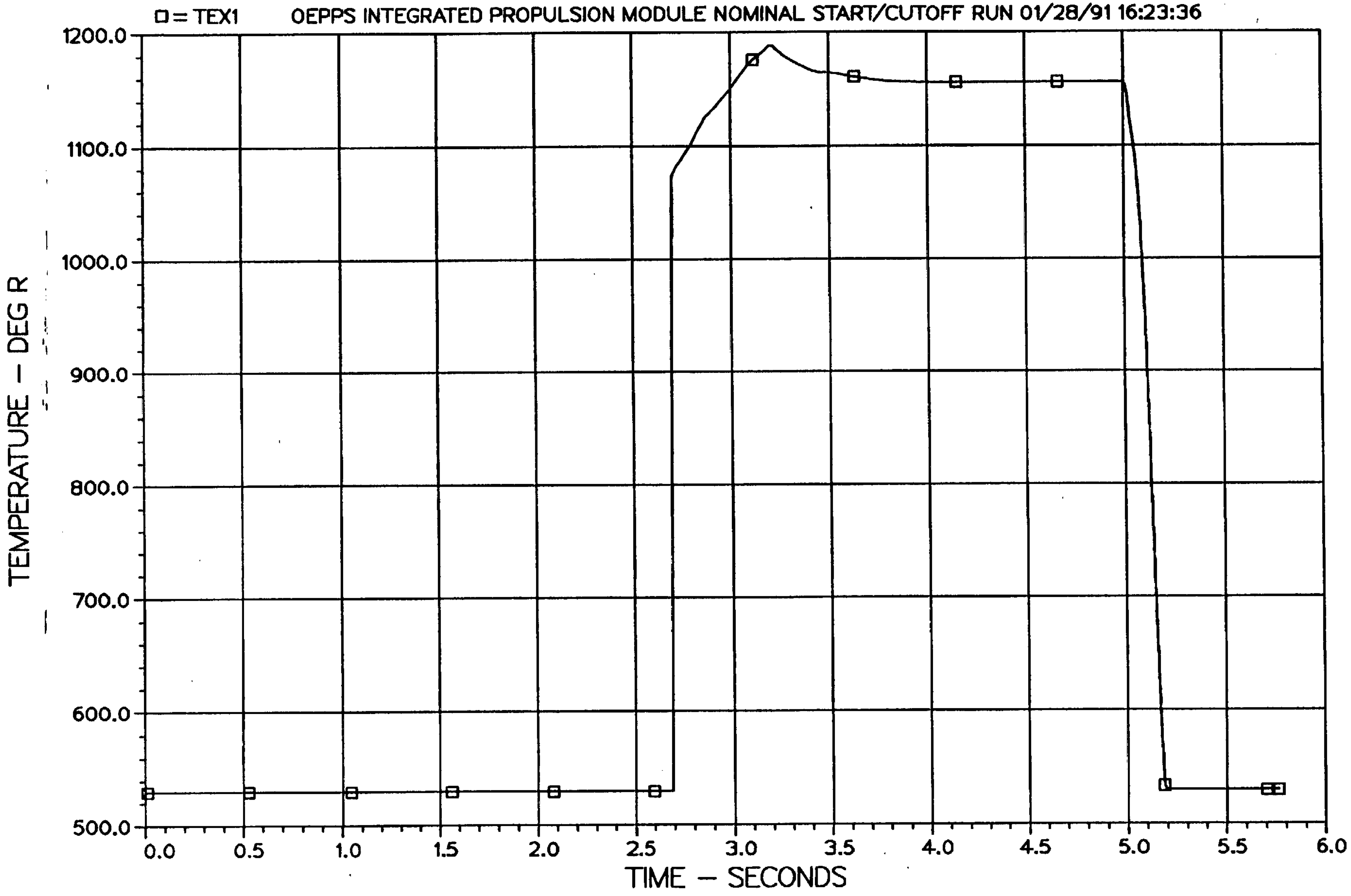


Figure A17

PLOT 18   10.04.42 TUES 29 JAN, 1991   JOB-r758335 , ISSCO   DISSPLA 10.0

FUEL PUMP (1) FLOW COEFFICIENT

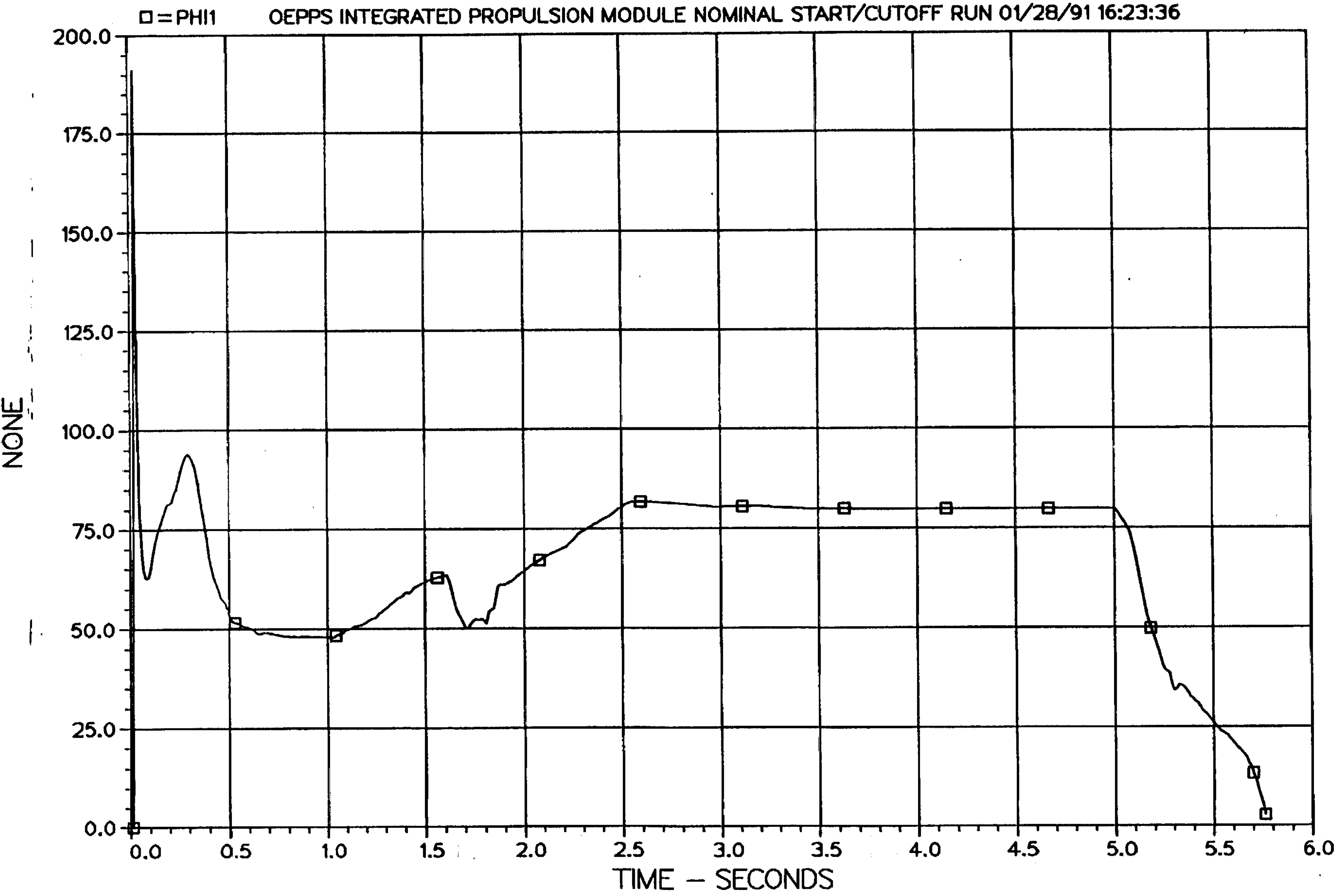


Figure A12

LOT 19 10.04.45 TUES 29 JAN, 1991 JOB-758335 , ISSCO DISSPLA 10.0

FUEL INJECTOR (1,2) TEMPERATURES

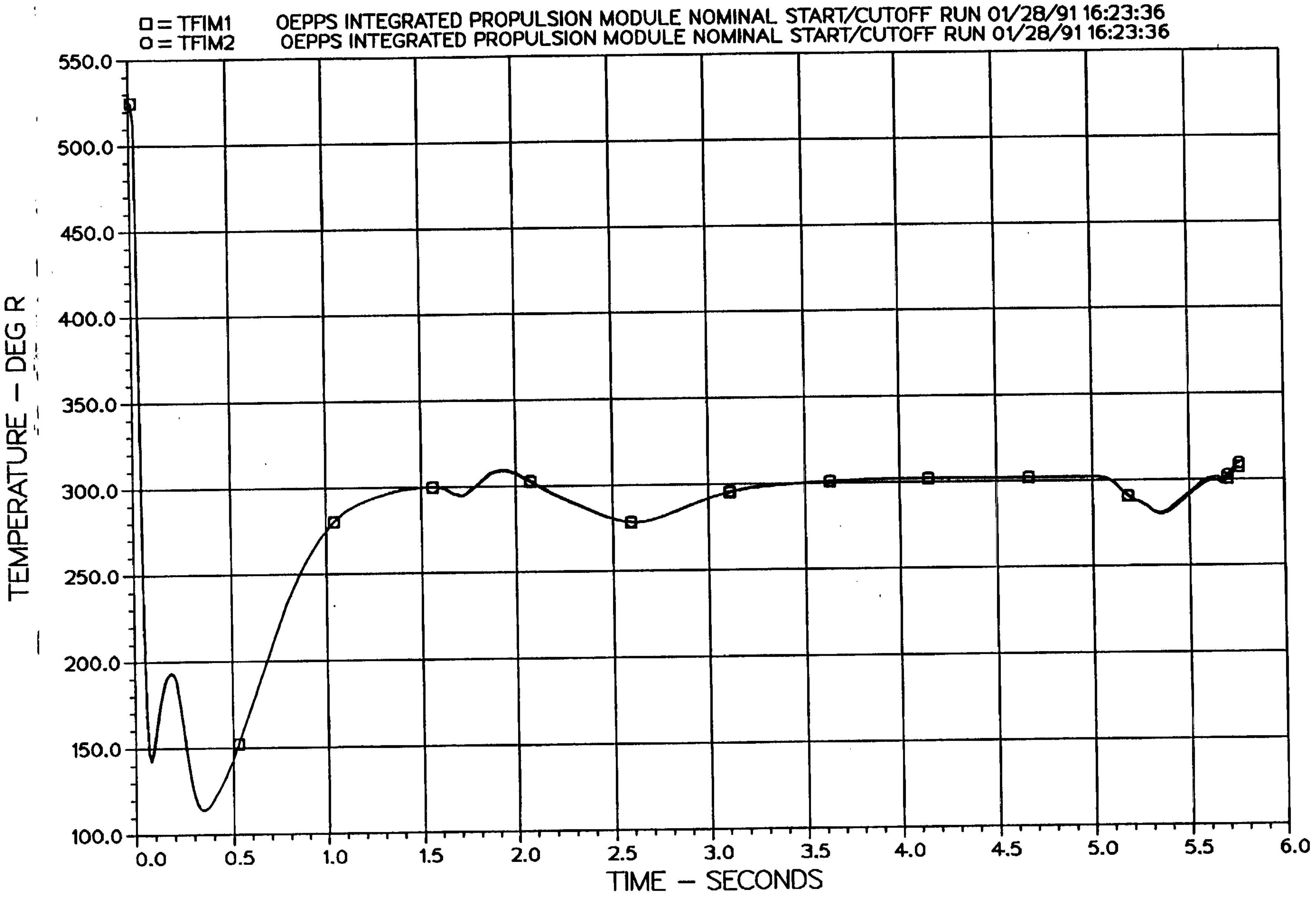


Figure A19

PLOT 20 10.04.50 TUES 29 JAN, 1991 JOB-r758335 , ISSCO DISSPLA 10.0

HYDROGEN GAS FLOW FOR GG (1) SPIN

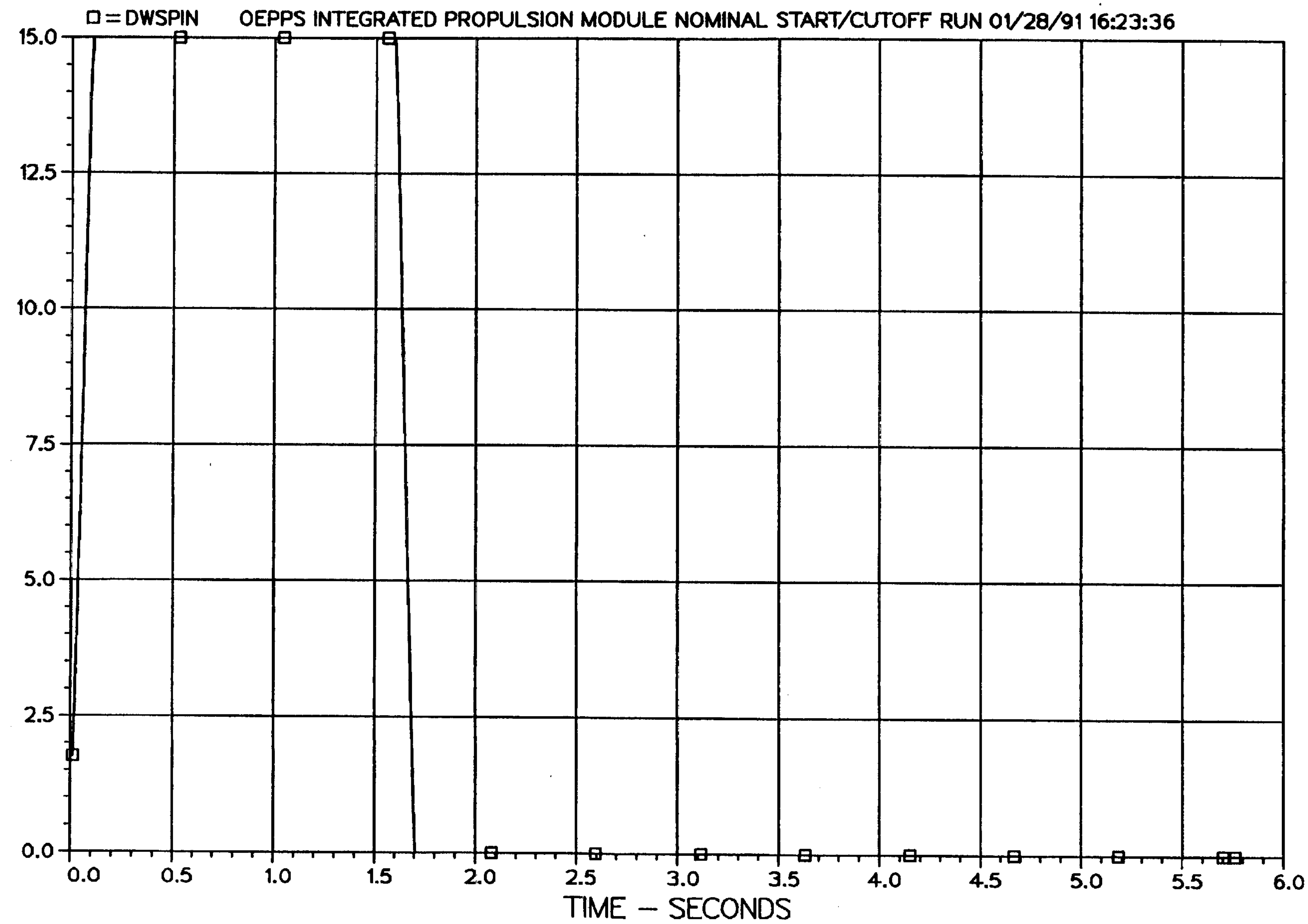


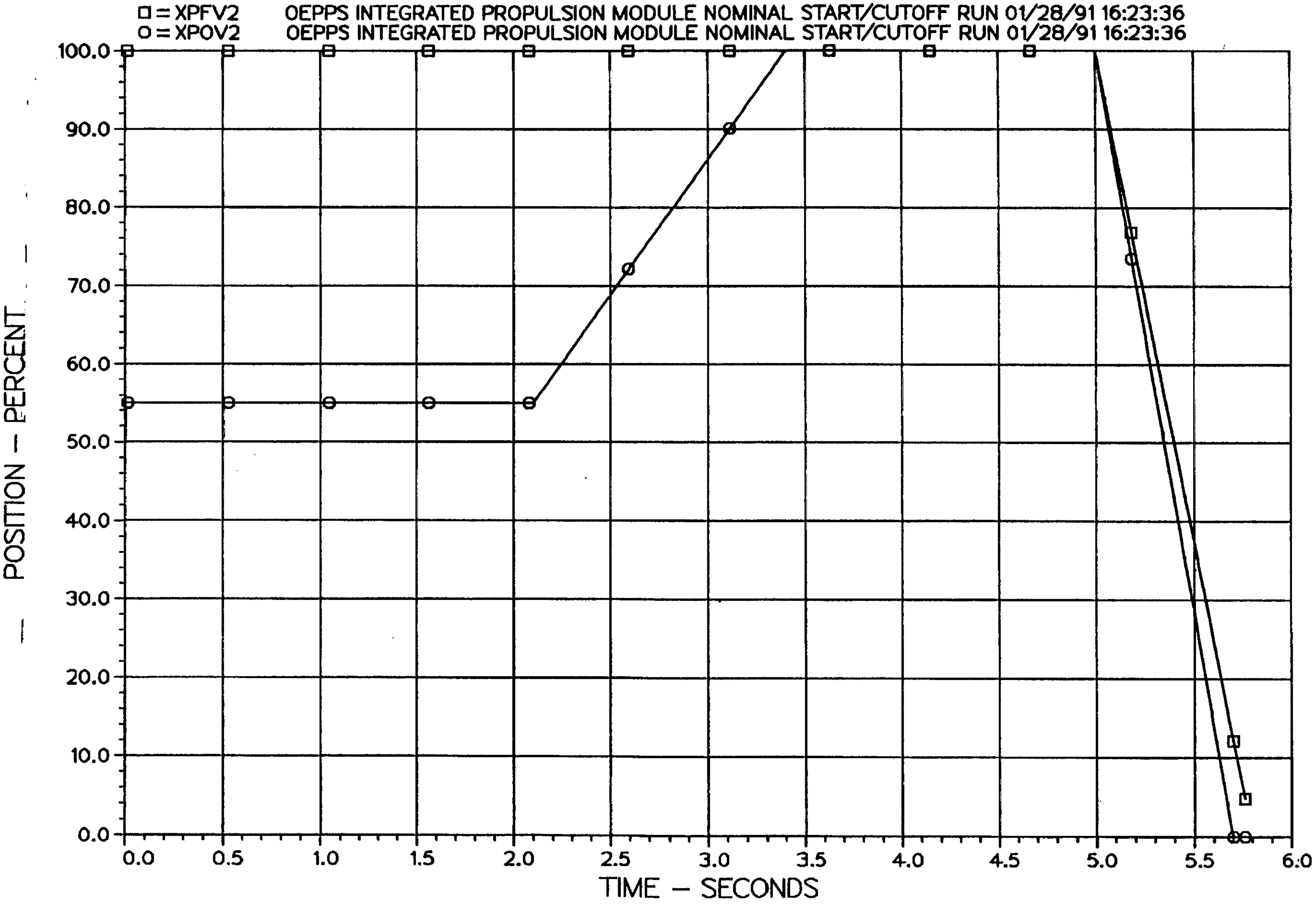
Figure P20

PLOT 21 10.04.53 TUES 29 JAN, 1991 JOB-758335 , ISSCO DISSPLA 10.0

APPENDIX B

NOMINAL START/CUTOFF TRANSIENT ANALYTICAL RESULTS FOR SYSTEM 2

FUEL AND OX PUMP (2) DISCHARGE VALVE POSITIONS



10.16.19 TUES 29 JAN, 1991 JOB-758335 , ISSCO DISSPLA 10.0

OT 2

Figure B1

FUEL AND OX GAS GENERATOR (2) VALVE POSITIONS

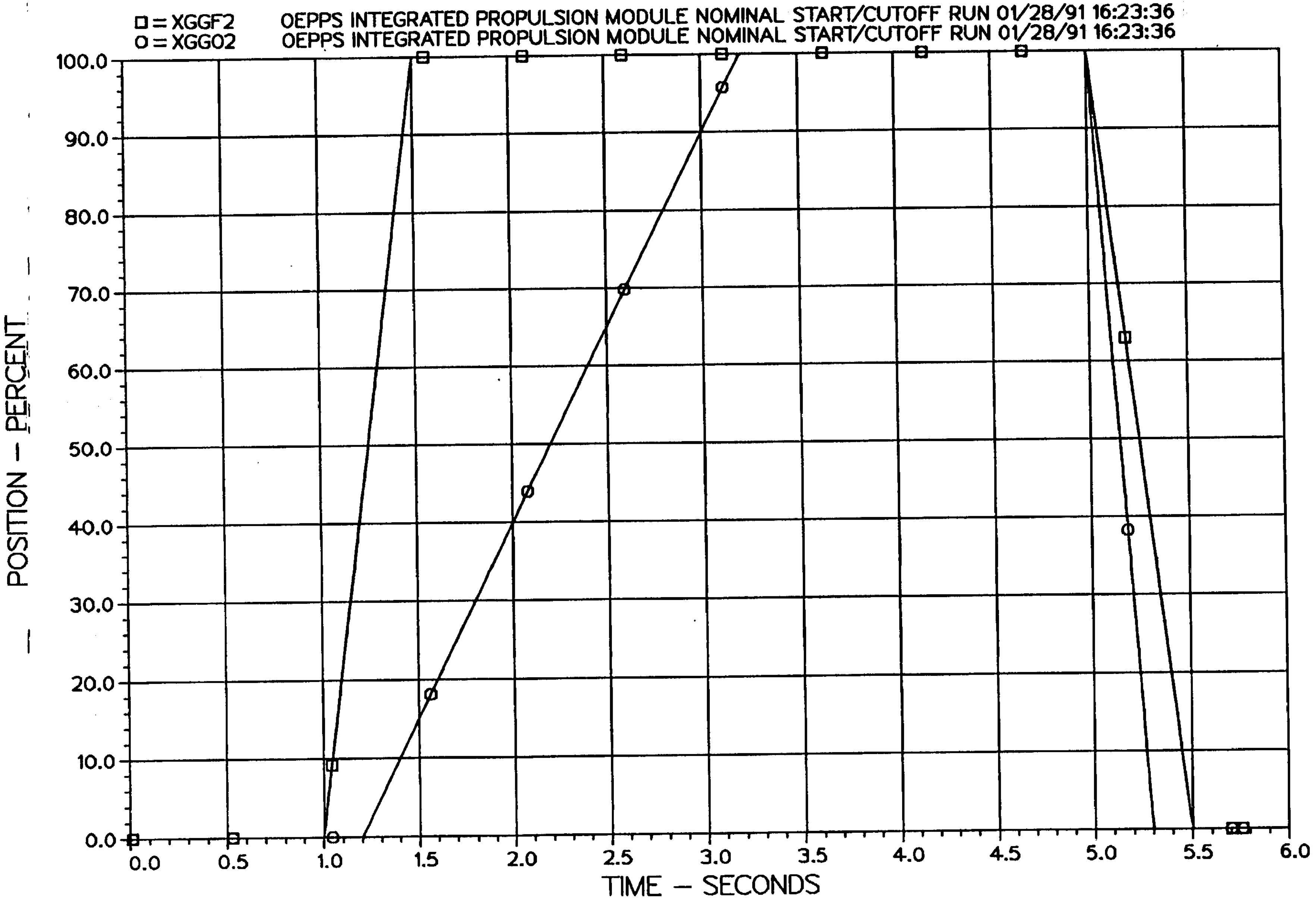


Figure B2

PLOT 5 10.16.32 TUES 29 JAN, 1991 JOB-758335 , ISSCO DISSPLA 10.0

T/C (3,4) INLET FUEL VALVE POSITIONS

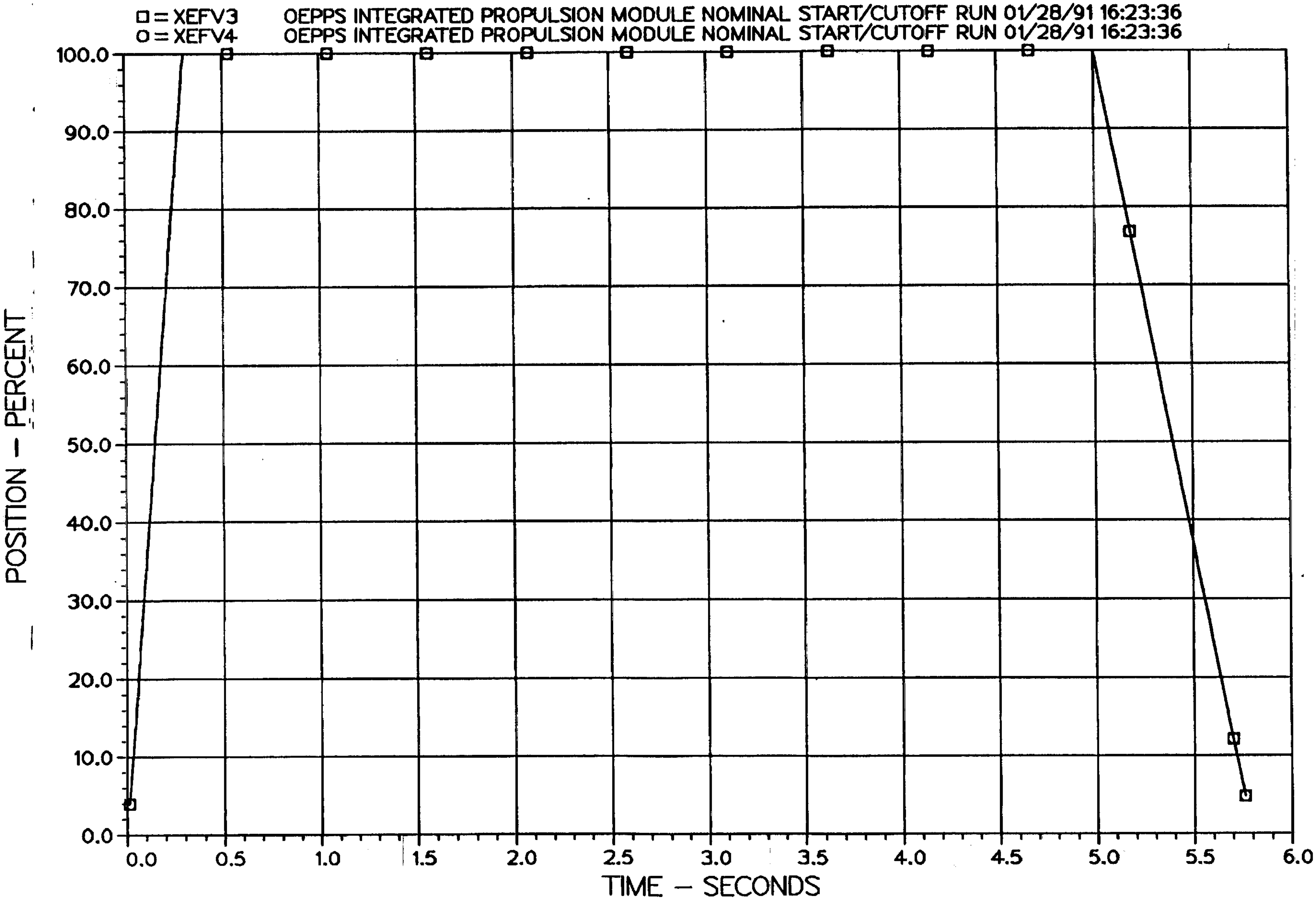


Figure B3

LOT 3 10.16.23 TUES 29 JAN, 1991 JOB–756335 , ISSCO DISSPLA 10.0

T/C (3,4) INLET OX VALVE POSITIONS

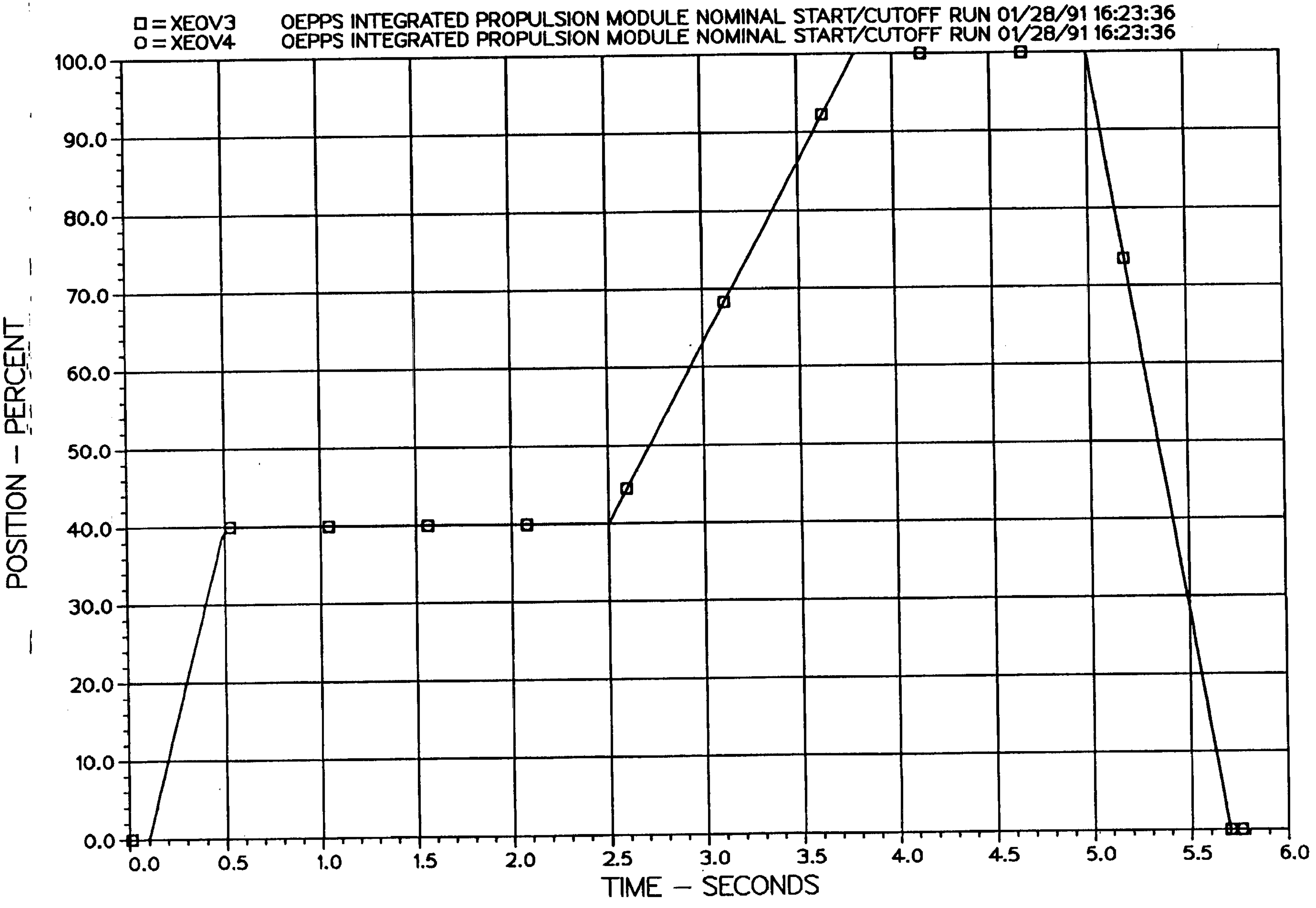


Figure B4

PLOT 4 10.16.27 TUES 29 JAN, 1991 JOB-758335 , ISSCO DISSPLA 10.0

T/C (3,4) MAIN CHAMBER PRESSURES

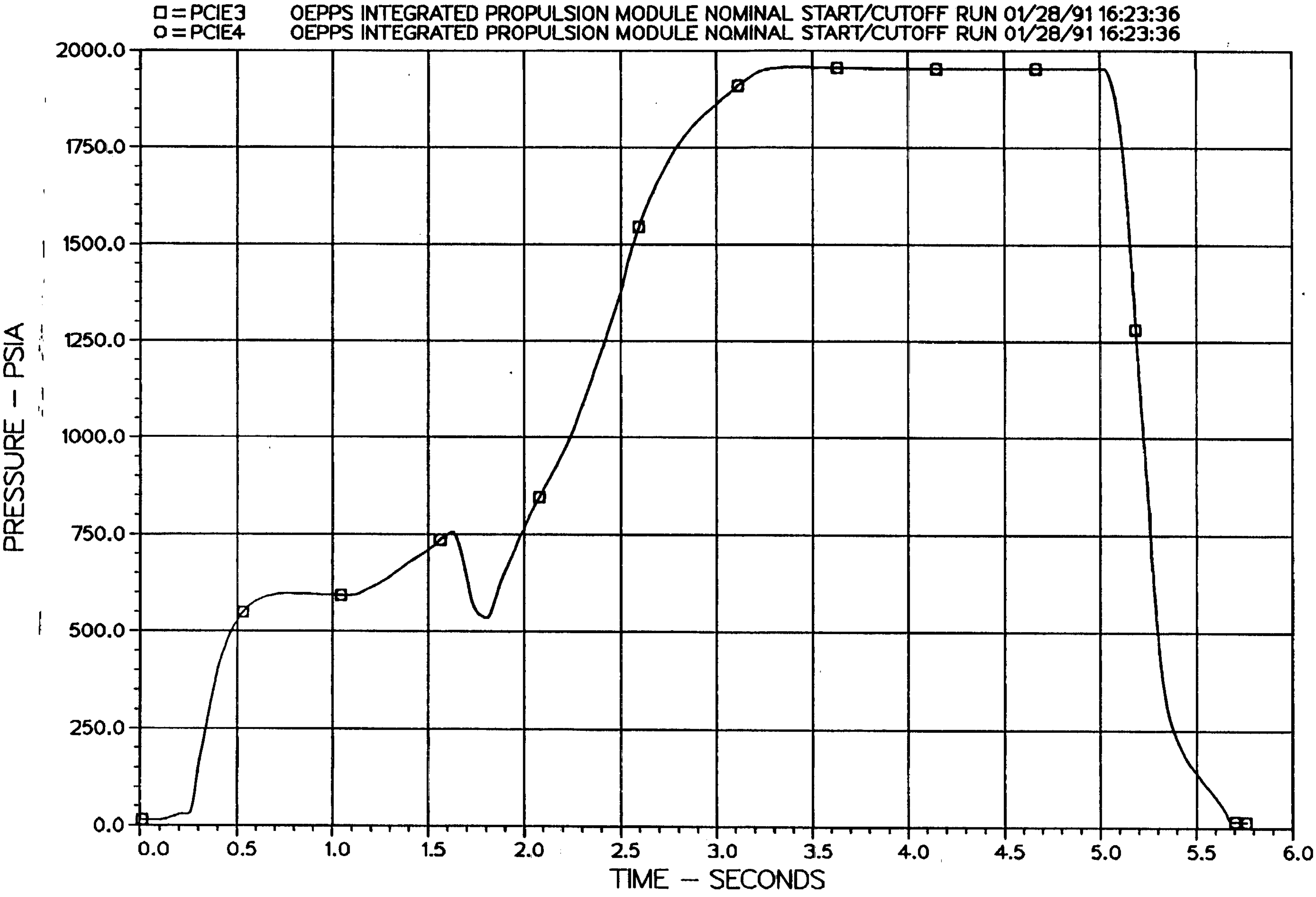


Figure 85

10.16.36 TUES 29 JAN, 1991 JOB-r758335 , ISSCO DISSPLA 10.0

OT 6

GAS GENERATOR (2) CHAMBER PRESSURE

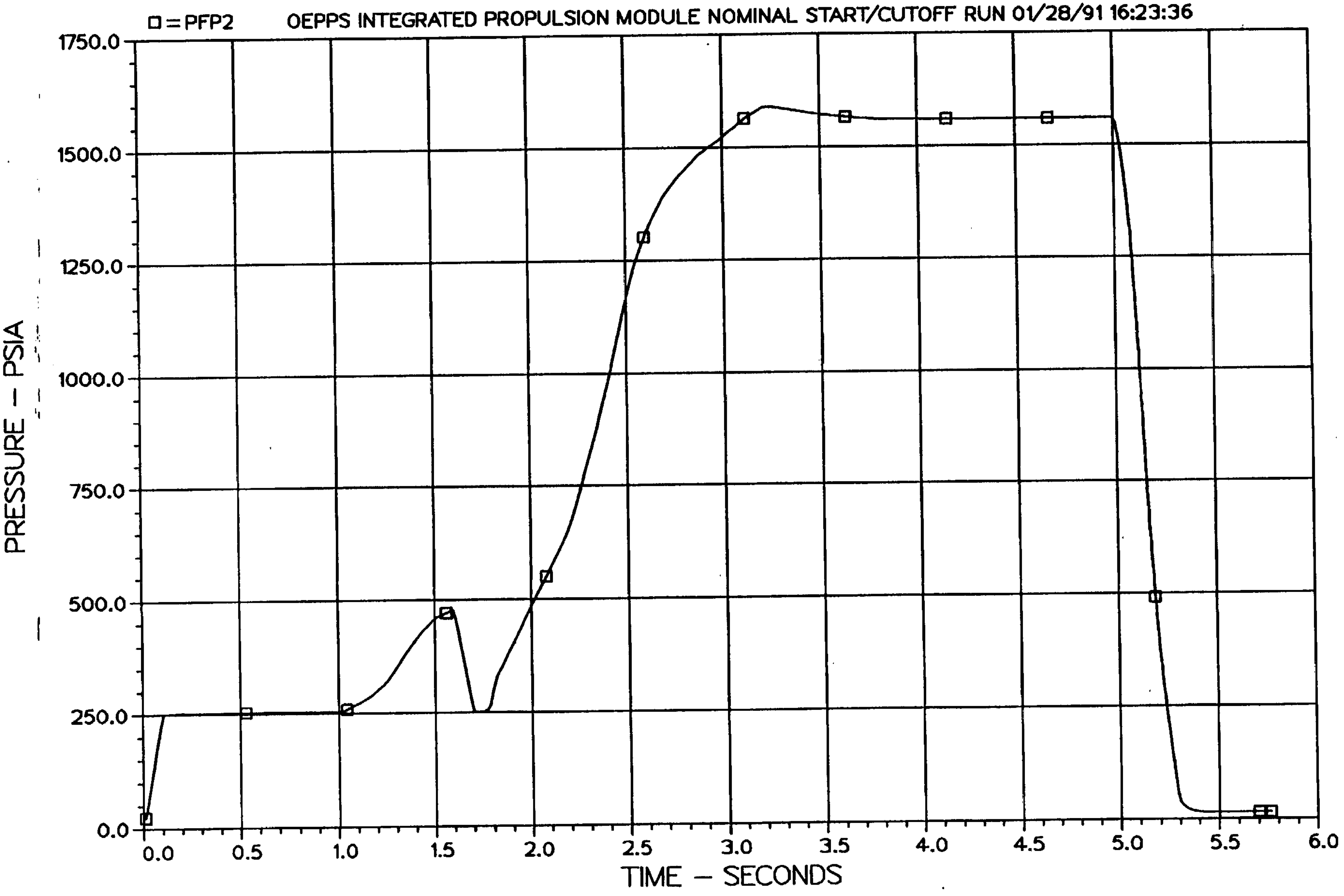


Figure B6

PLOT 7 10.16.39 TUES 29 JAN, 1991 JOB-758335 , ISSCO DISSPLA 10.0

T/C (3,4) MIXTURE RATIOS

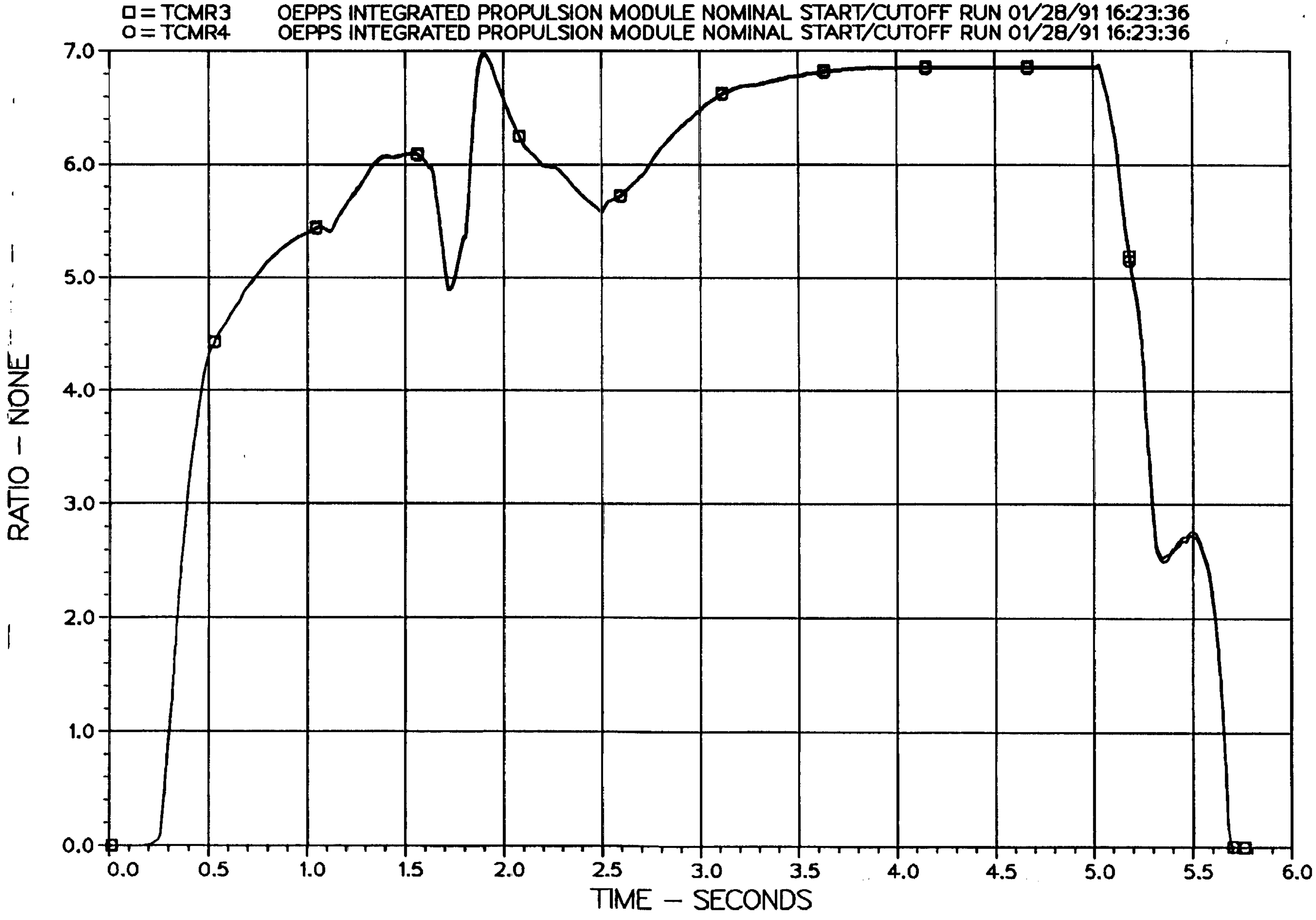


Figure B7

GAS GENERATOR (2) MIXTURE RATIO

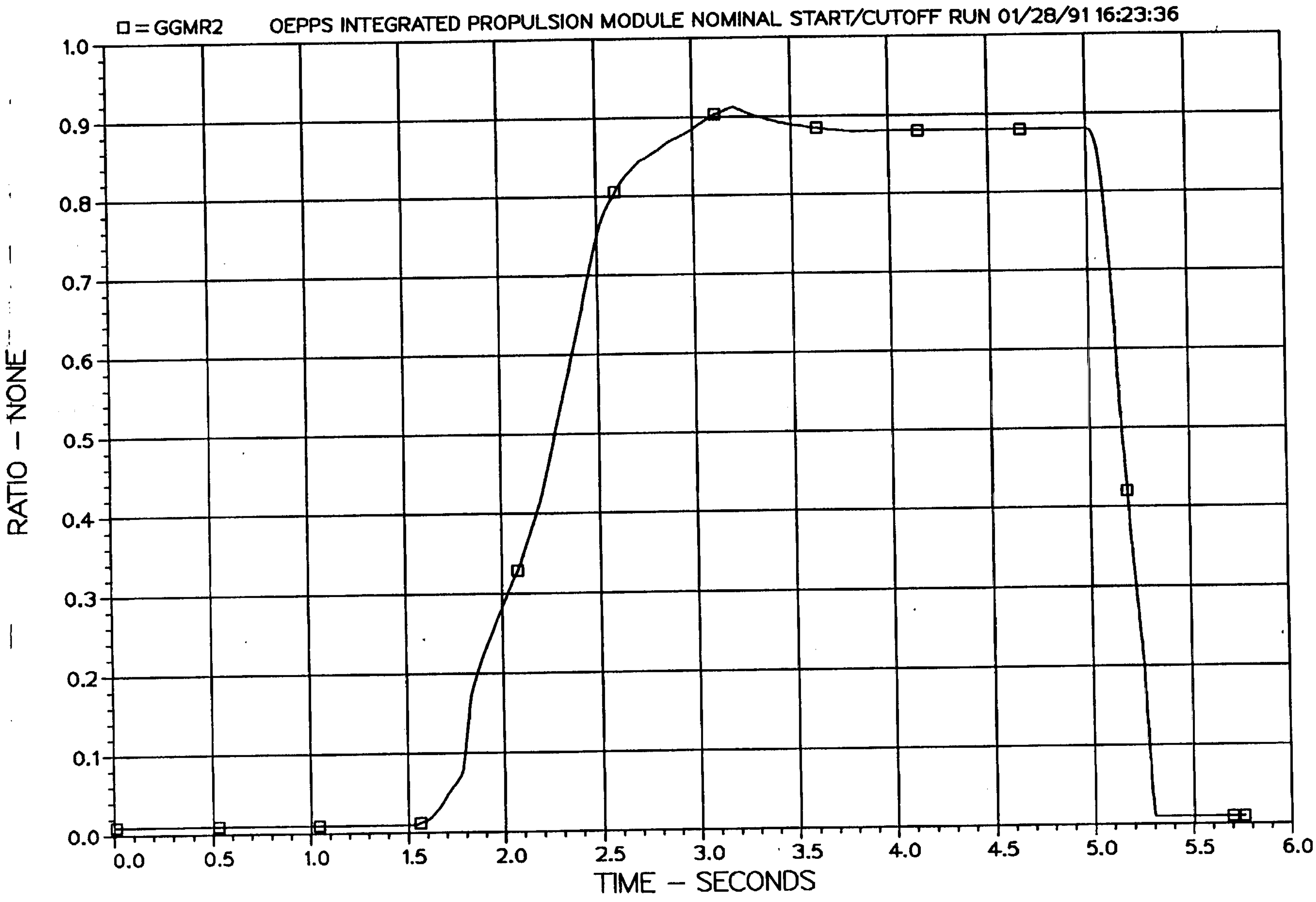


Figure B8

PLOT 9 10.16.46 TUES 29 JAN, 1991 JOB-758335 , ISSCO DISSPLA 10.0

FUEL PUMP (2) SPEED

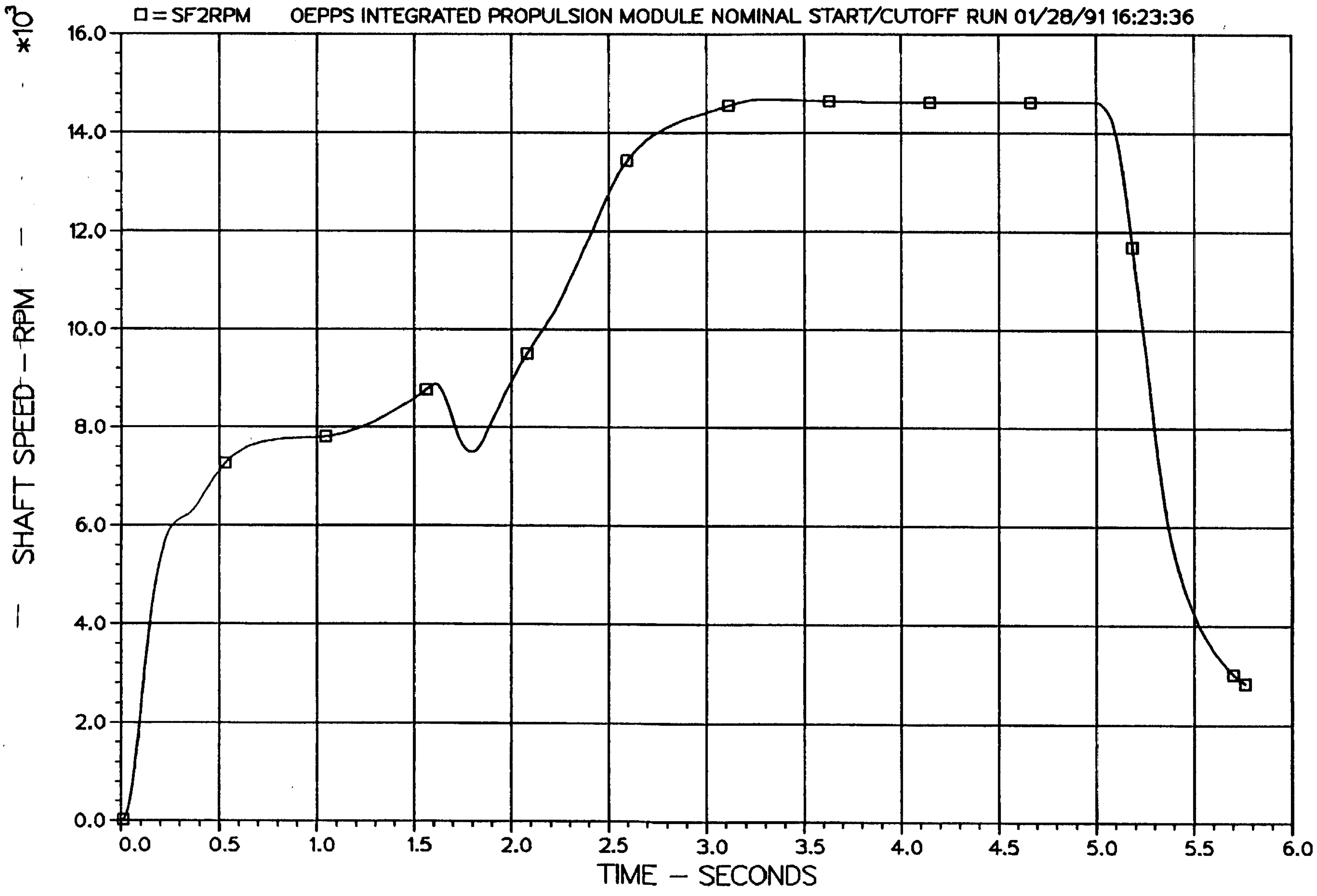


Figure 39

OT 10 10.16.49 TUES 29 JAN, 1991 JOB-758335 , ISSCO DISSPLA 10.0

LOX PUMP (2) SPEED

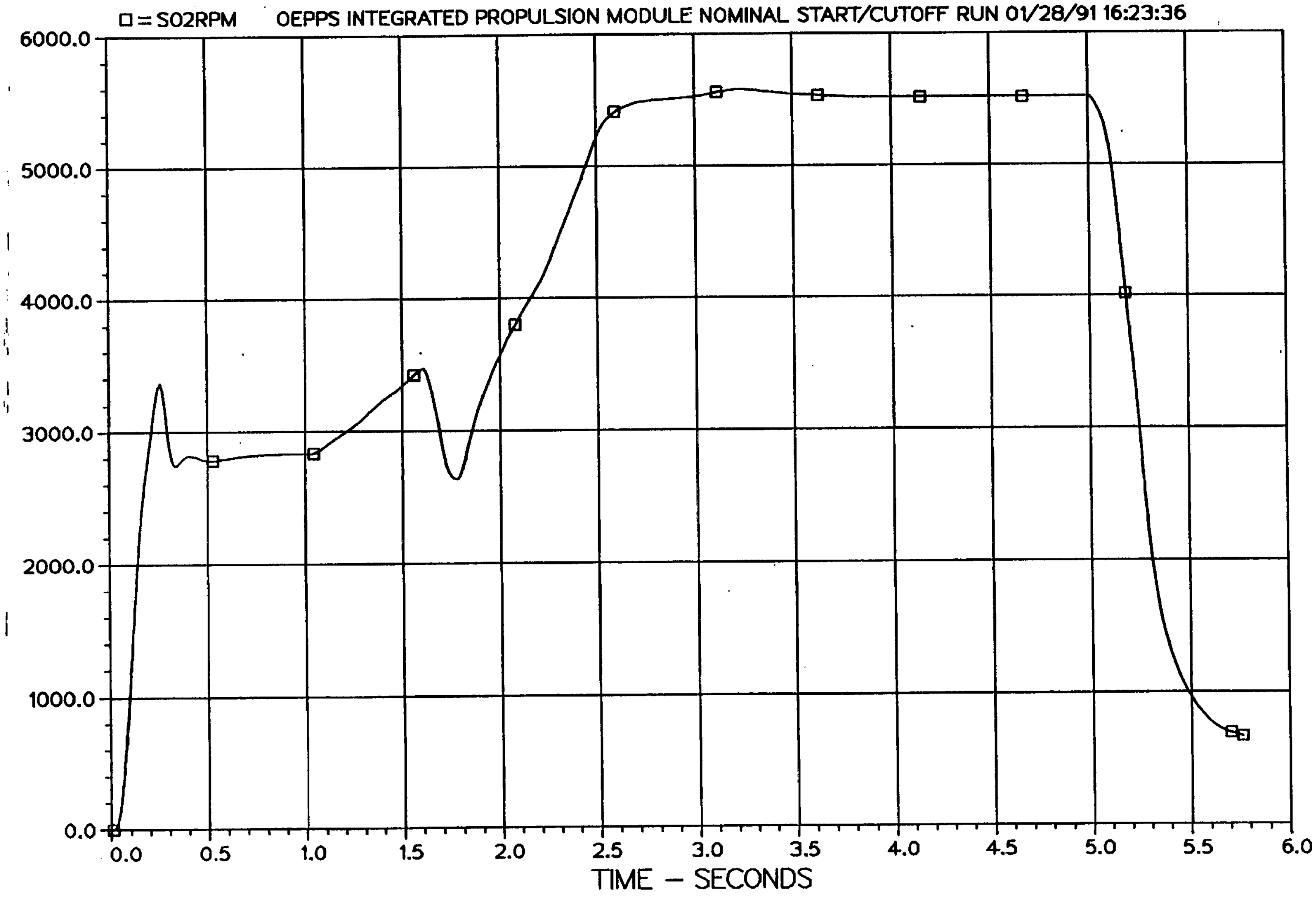


Figure 810

PLOT 11 10.16.52 TUES 29 JAN, 1991 JOB-r758335 , ISSCO DISSPLA 10.0

FUEL PUMP (2) FLOW COEFFICIENT

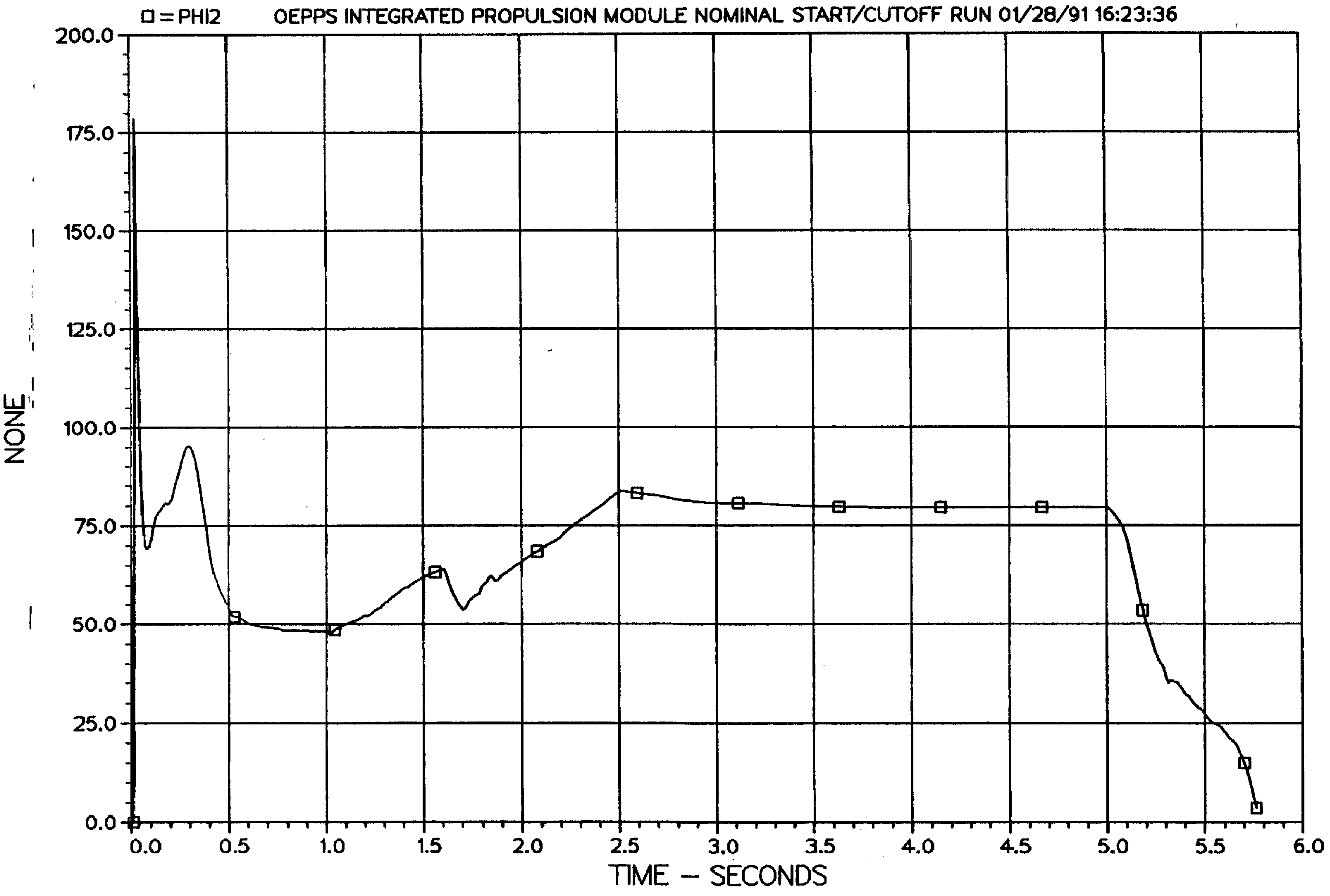
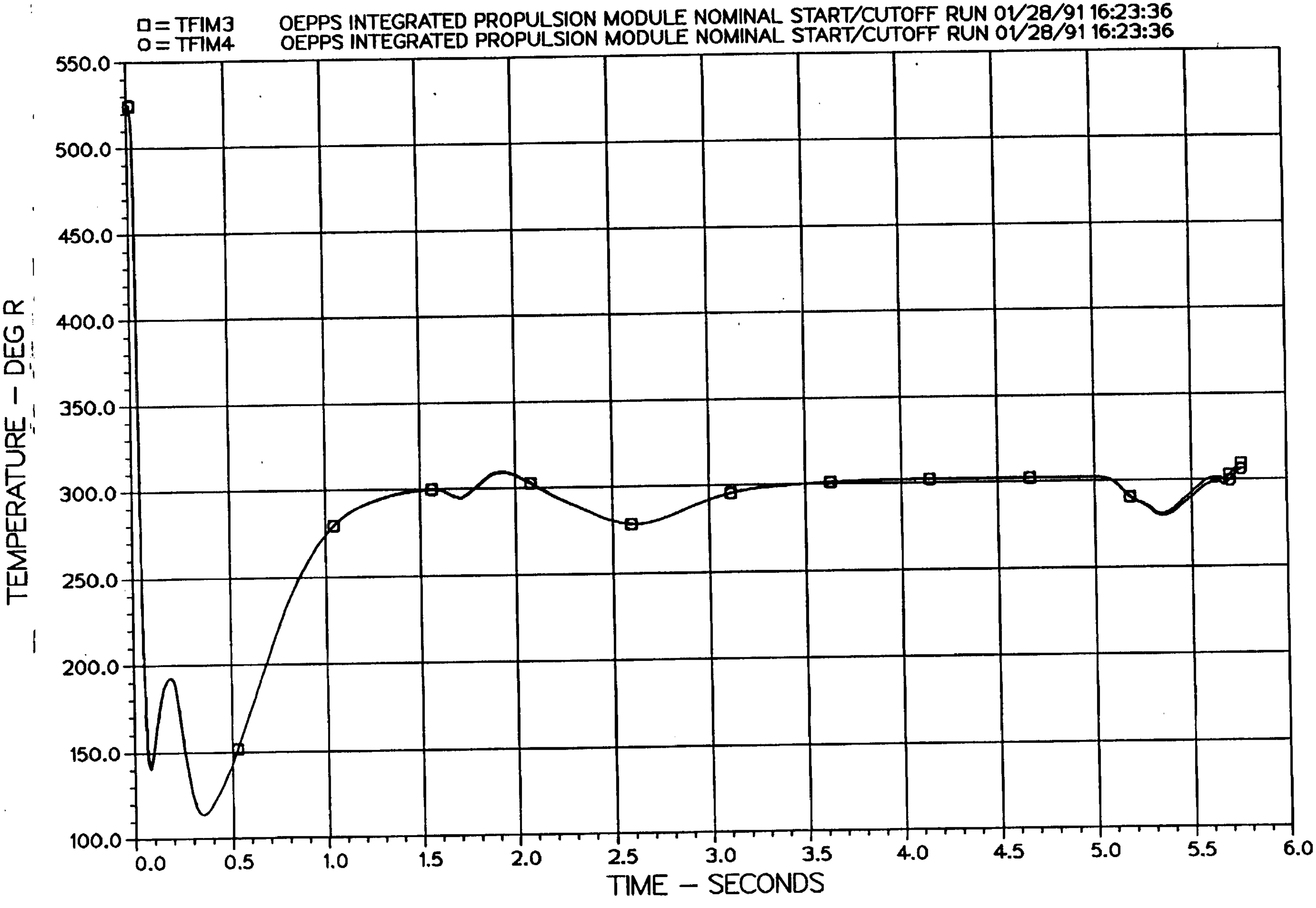


Figure B11

PLOT 19 10.17.16 TUES 29 JAN, 1991 JOB-758335 , ISSCO DISSPLA 10.0

FUEL INJECTOR (3,4) TEMPERATURES



PLOT 20 10.17.20 TUES 29 JAN, 1991 JOB-758335 , ISSCO DISSPLA 10.0

Figure B12

HYDROGEN GAS FLOW FOR GG (2) SPIN

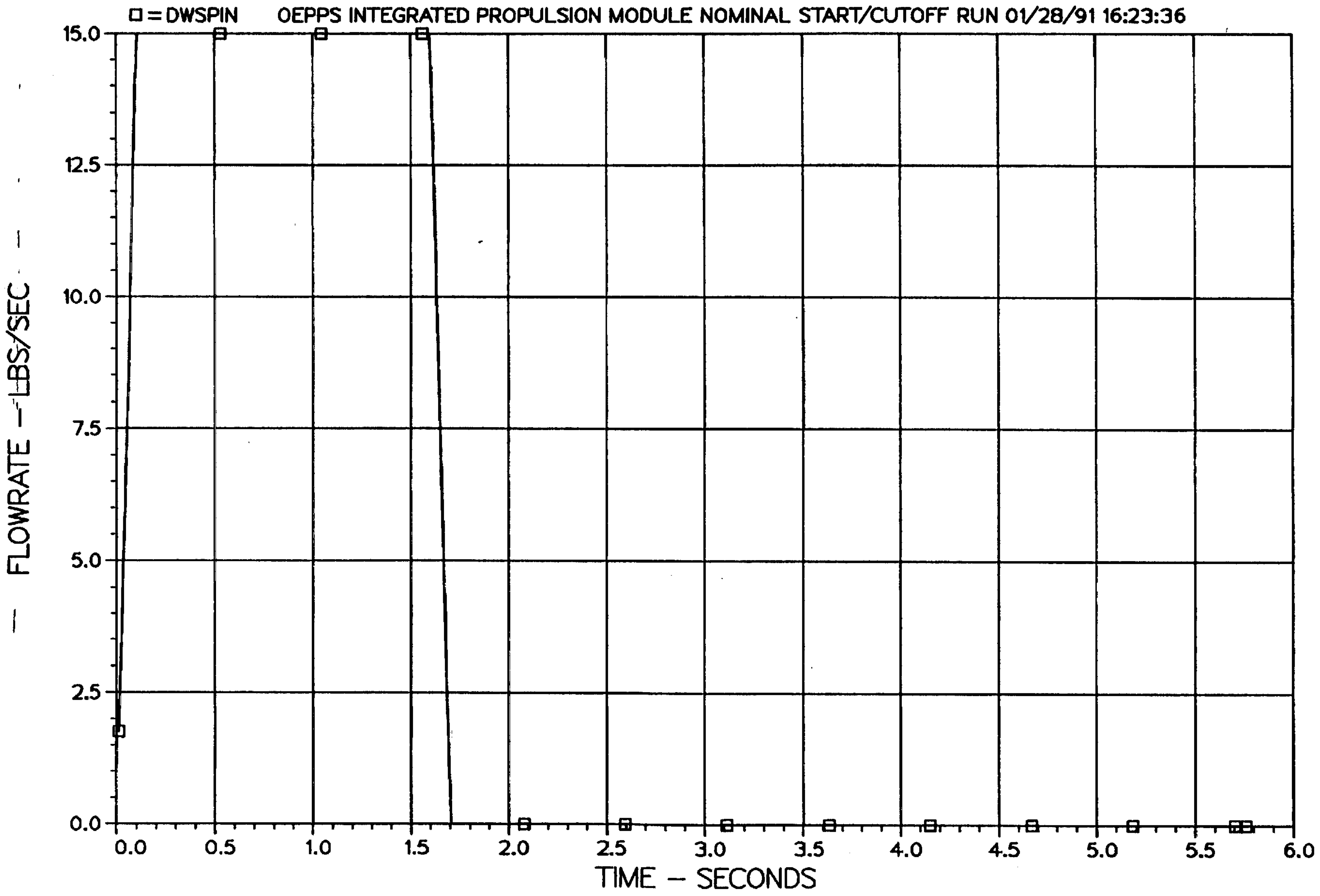


Figure B13

LOT 21 10.17.23 TUES 29 JAN, 1991 JOB-r758335 , ISSCO DISSPLA 10.0

APPENDIX C

NOMINAL START/CUTOFF TRANSIENT ANALYTICAL RESULTS FOR SYSTEM 3

FUEL AND OX PUMP (3) DISCHARGE VALVE POSITIONS

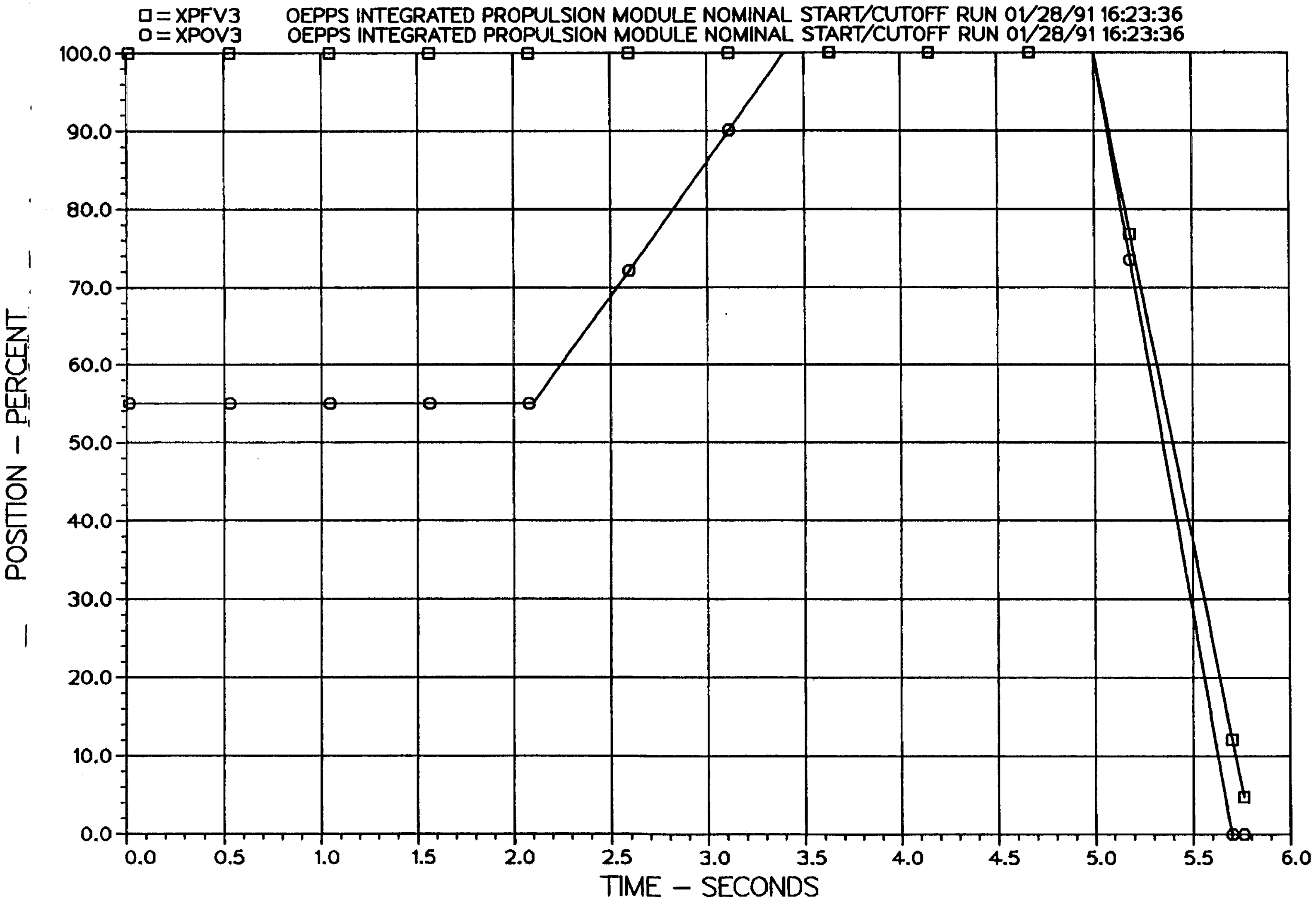


Figure C1

LOT 2 10.10.37 TUES 29 JAN, 1991 JOB-r758335 , ISSCO DISSPLA 10.0

FUEL AND OX GAS GENERATOR (3) VALVE POSITIONS

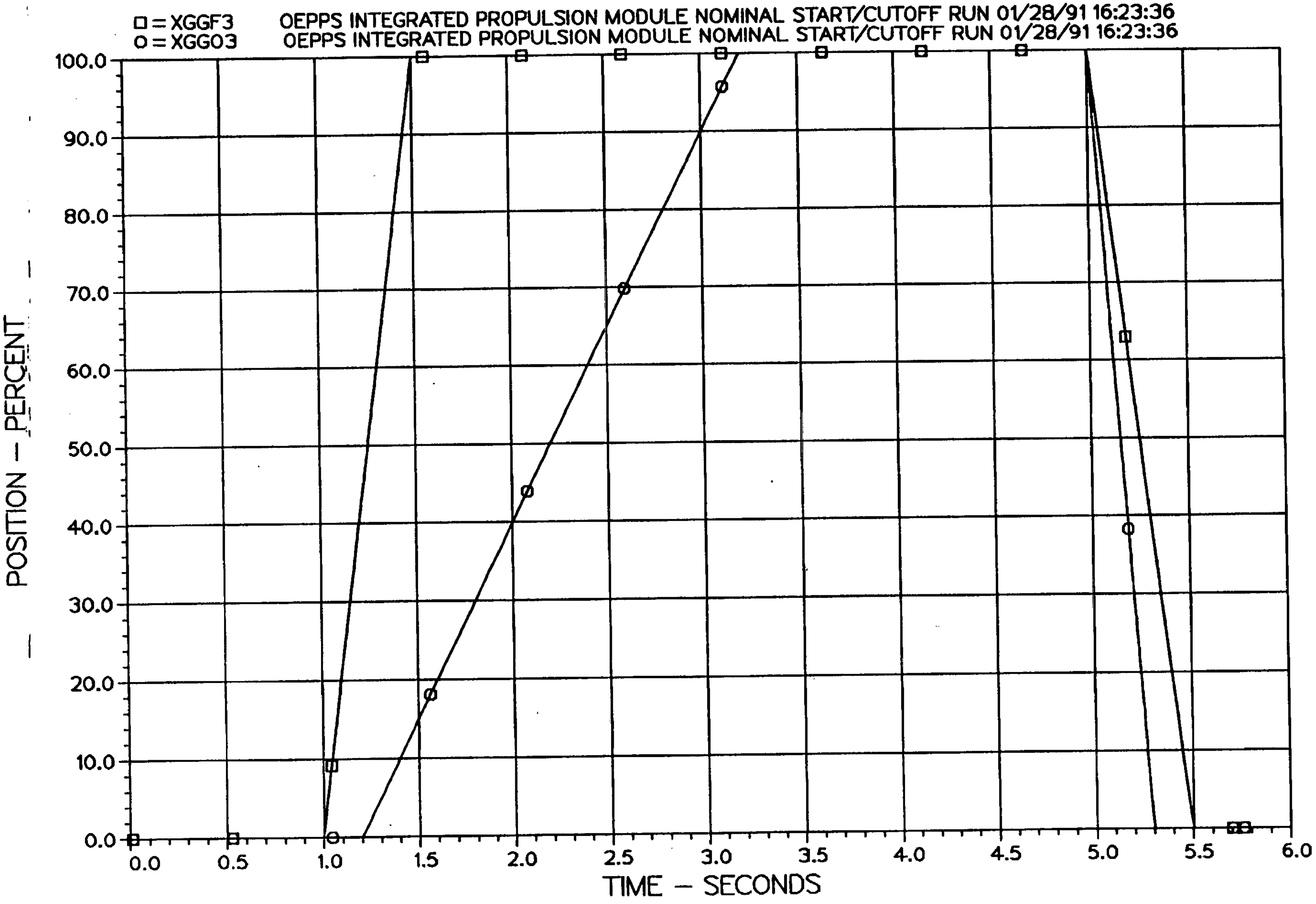


Figure C2

T/C (5,6) INLET FUEL VALVE POSITIONS

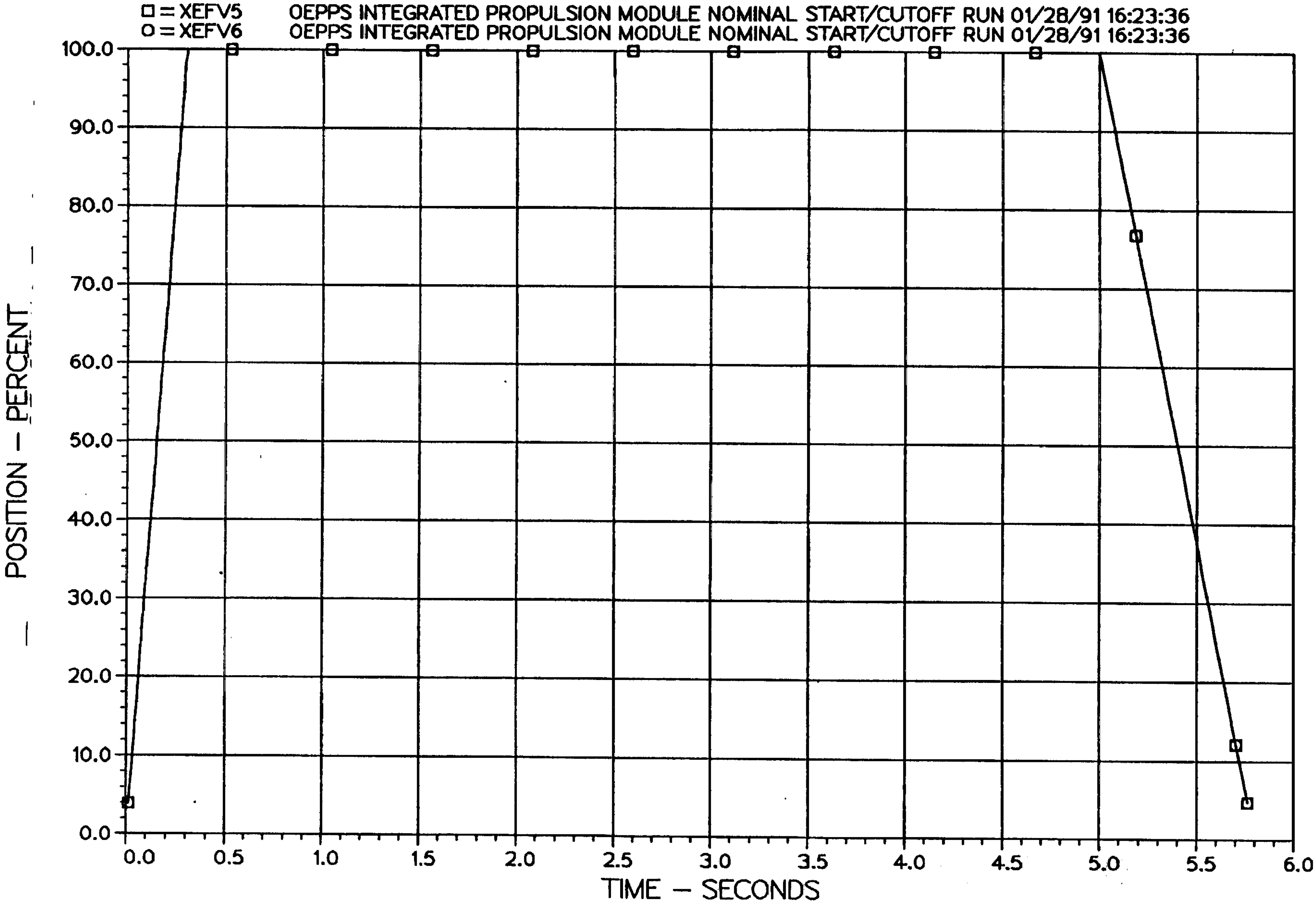


Figure C3

PLOT 3 10.10.41 TUES 29 JAN, 1991 JOB—758335 , ISSCO DISSPLA 10.0

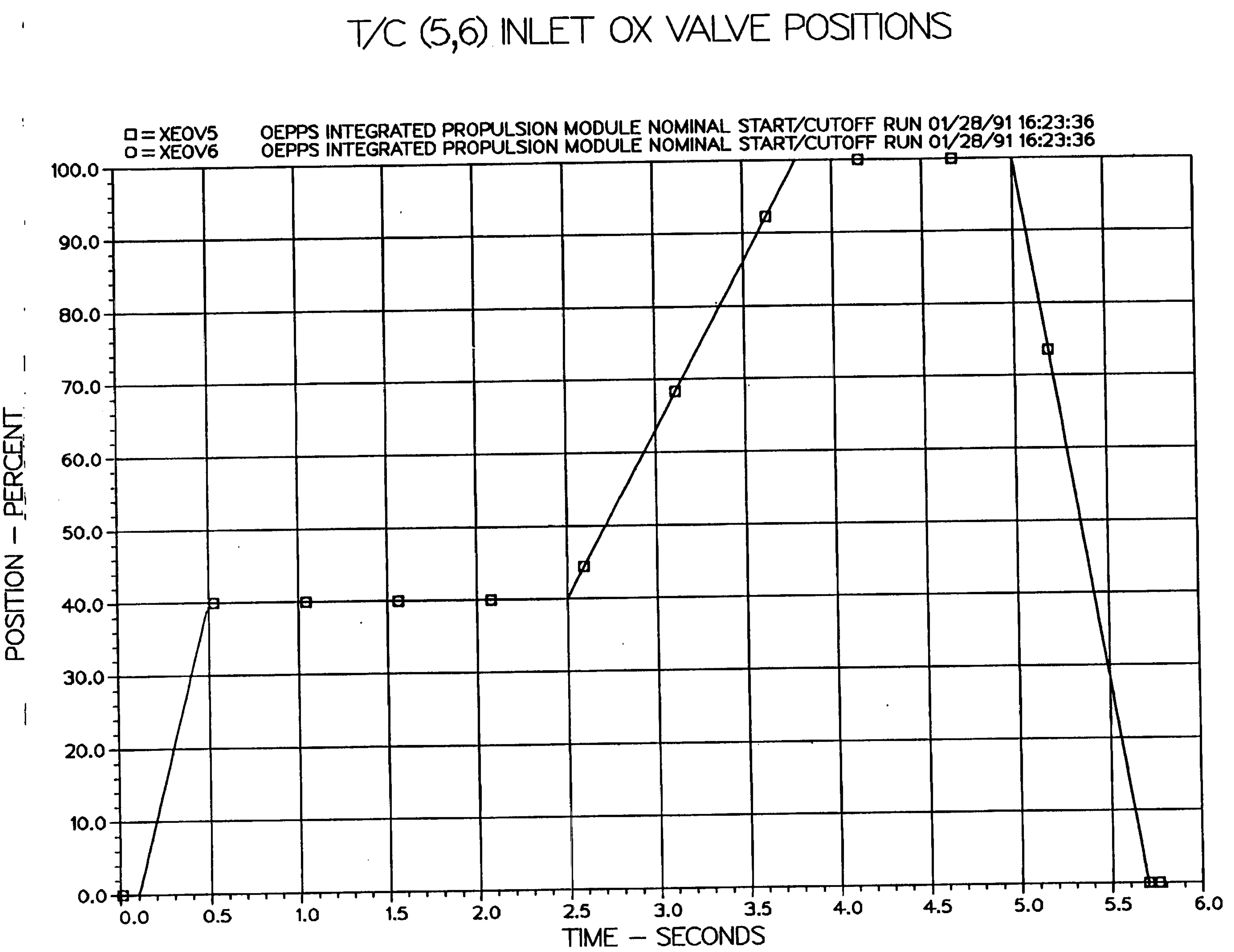
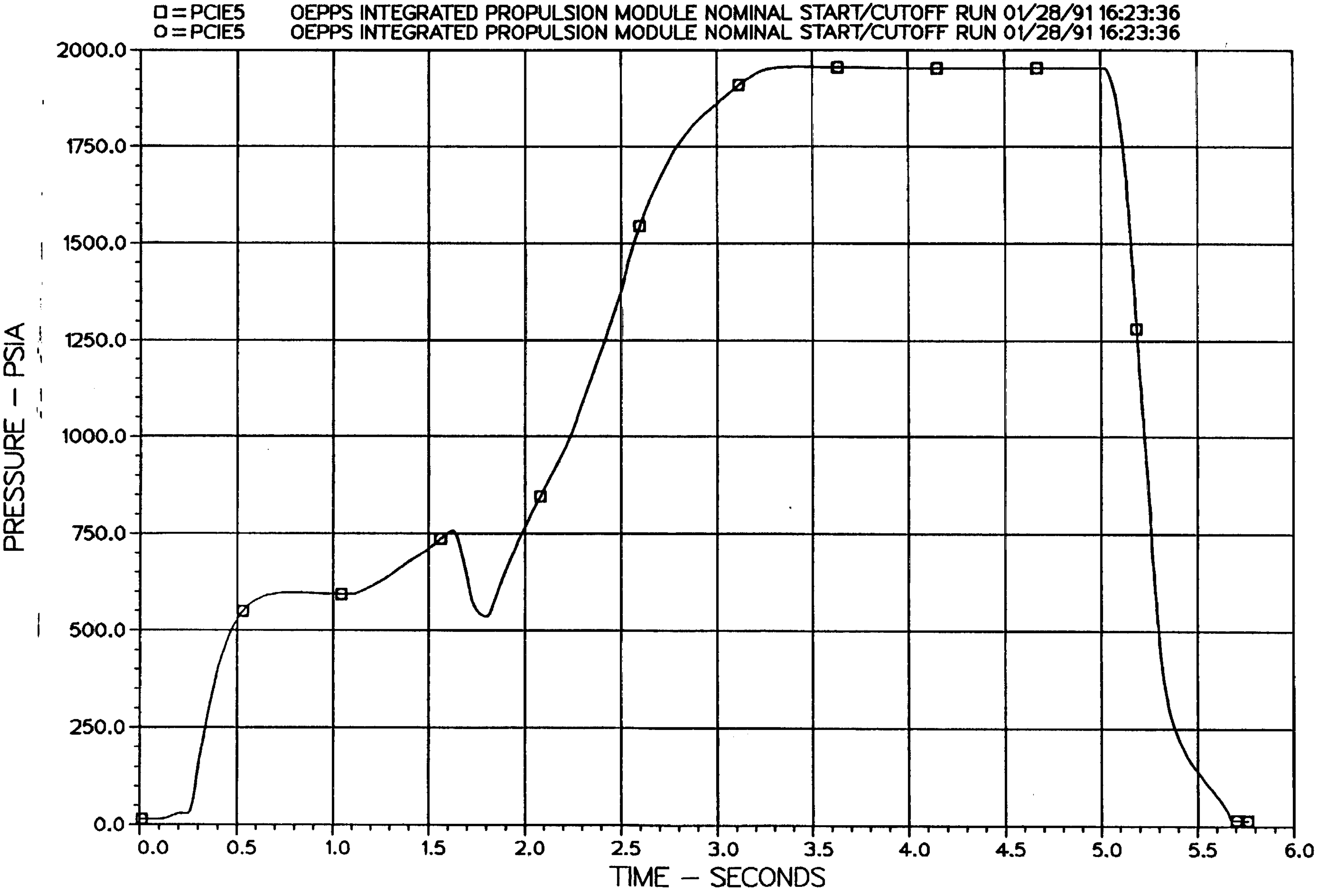


Figure c4

PLOT 4 10.10.45 TUES 29 JAN, 1991 JOB-758335 , ISSCO DISSPLA 10.0

T/C (5,6) MAIN CHAMBER PRESSURES

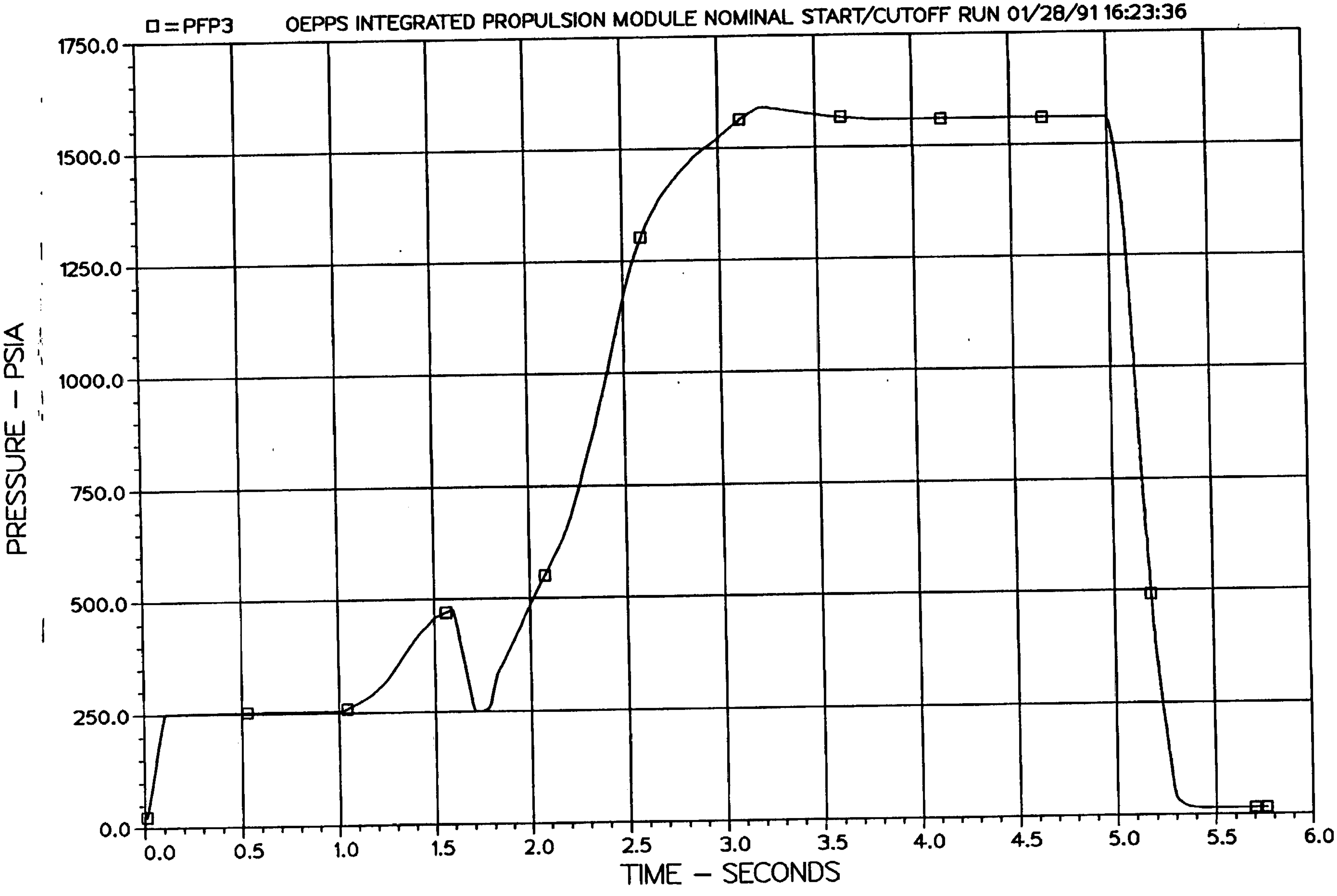


10.10.54 TUES 29 JAN, 1991 JOB-r758335 , ISSCO DISSPLA 10.0

OT 6

Figure C5

GAS GENERATOR (3) CHAMBER PRESSURE



PLOT 7 10.10.57 TUES 29 JAN, 1991 JOB-758335 , ISSCO DISSPLA 10.0

Figure C6

T/C (5,6) MIXTURE RATIOS

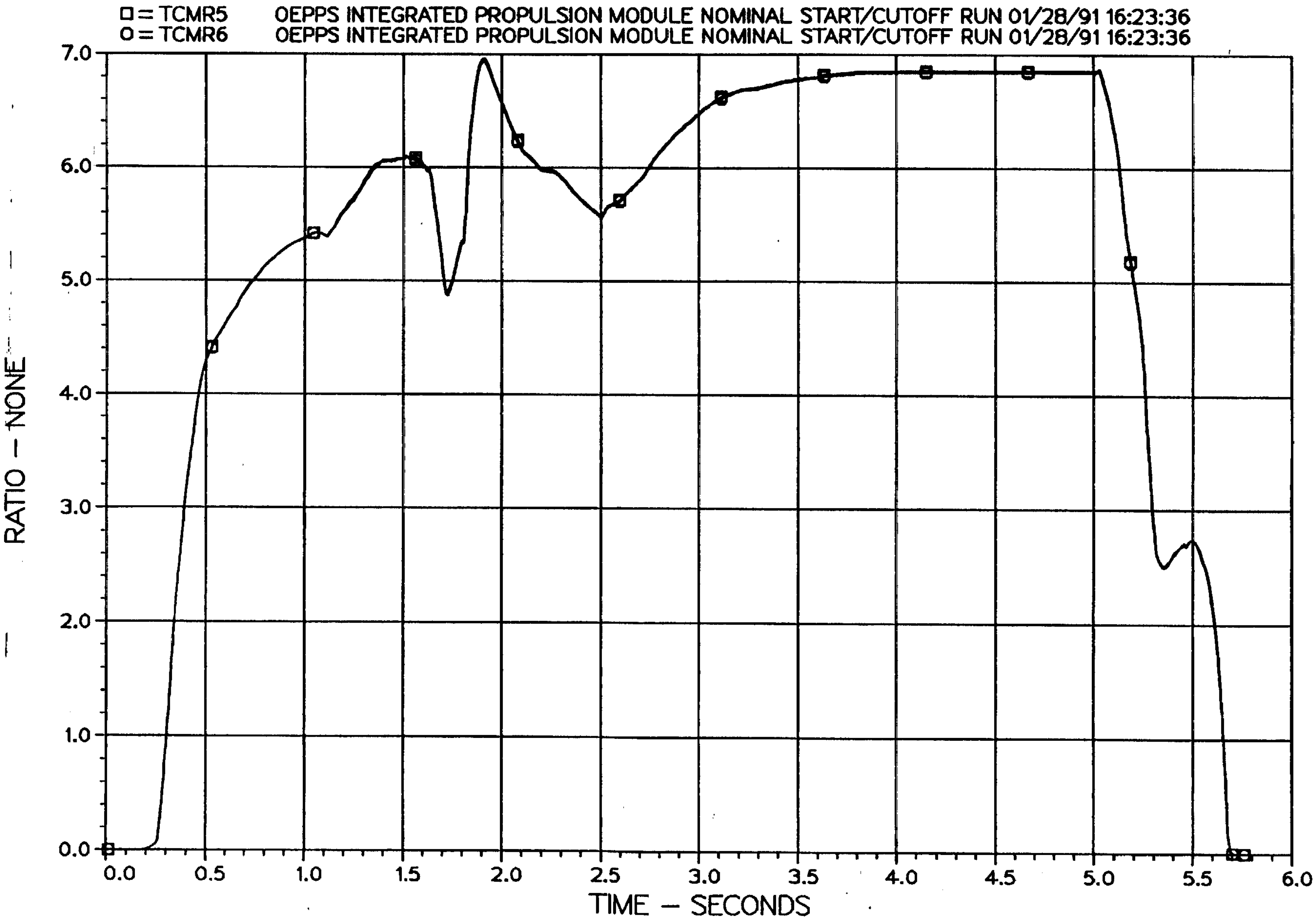


Figure G7

LOT 8 10.11.01 TUES 29 JAN, 1991 JOB-758335 , ISSCO DISSPLA 10.0

GAS GENERATOR (3) MIXTURE RATIO

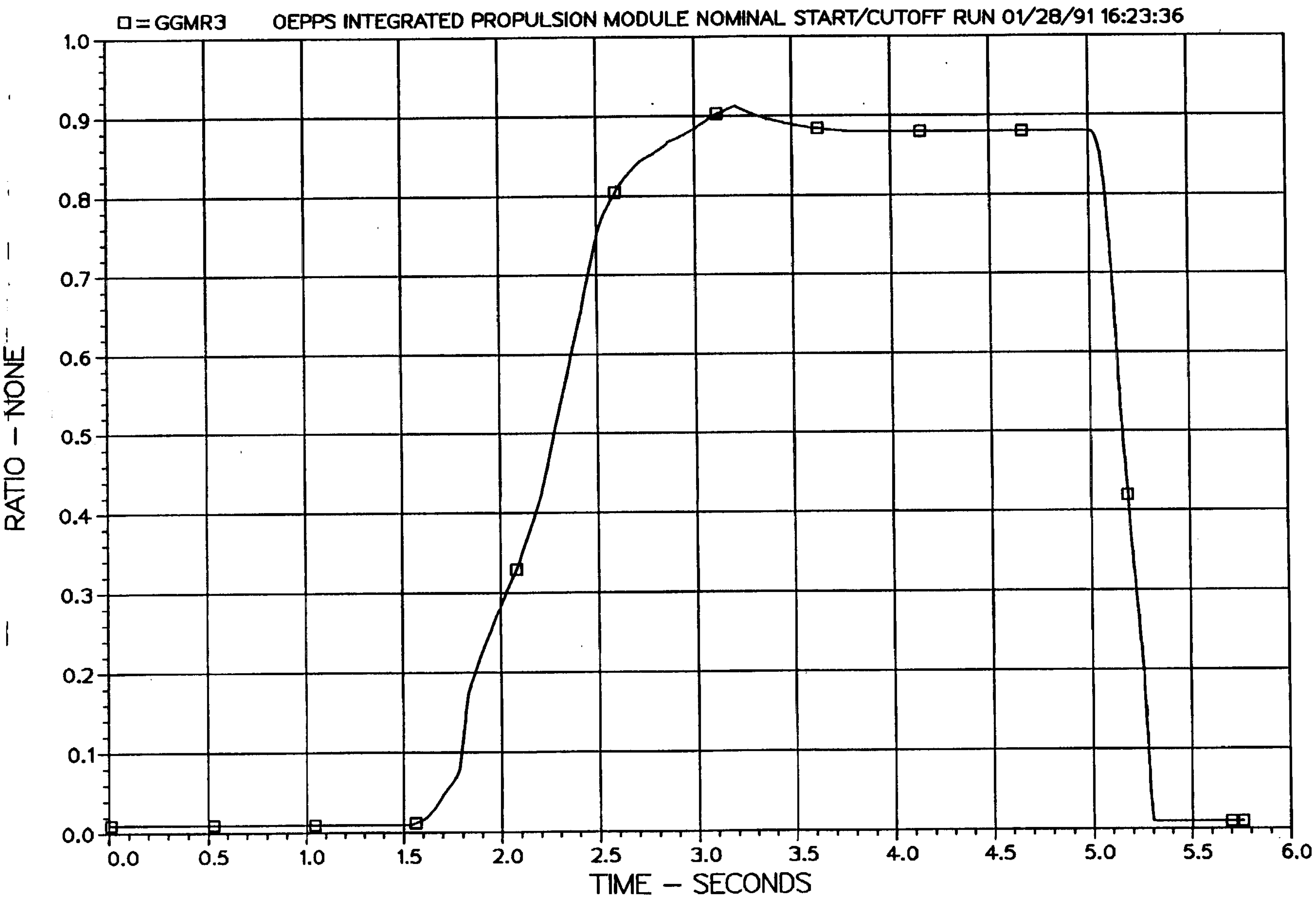


Figure C8

PLOT 9 10.11.04 TUES 29 JAN, 1991 JOB-758335 , ISSCO DISSPLA 10.0

FUEL PUMP (3) SPEED

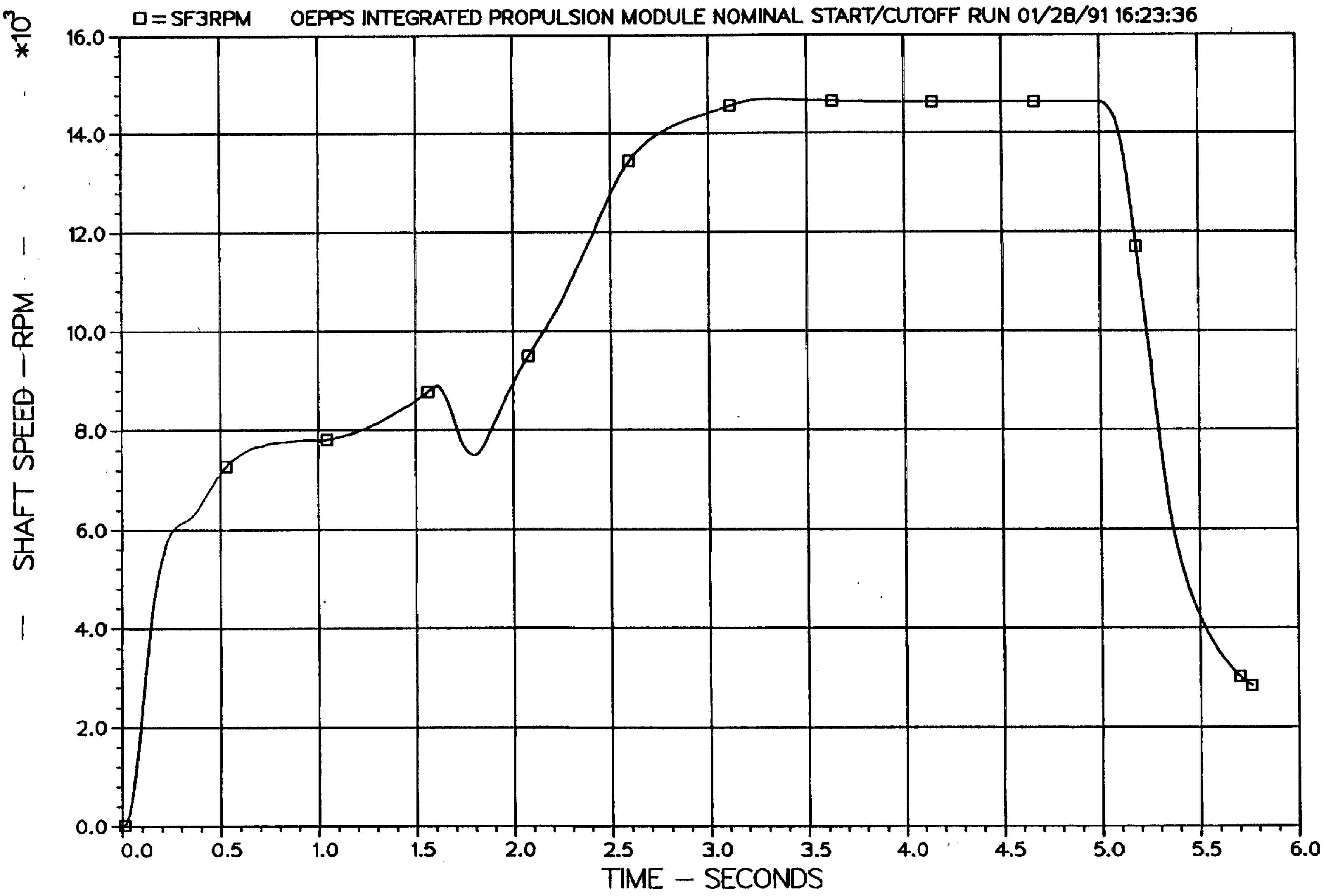


Figure C9

LOT 10 10.11.07 TUES 29 JAN, 1991 JOB-758335 , 15SGO DISSPLA 10.0

LOX PUMP (3) SPEED

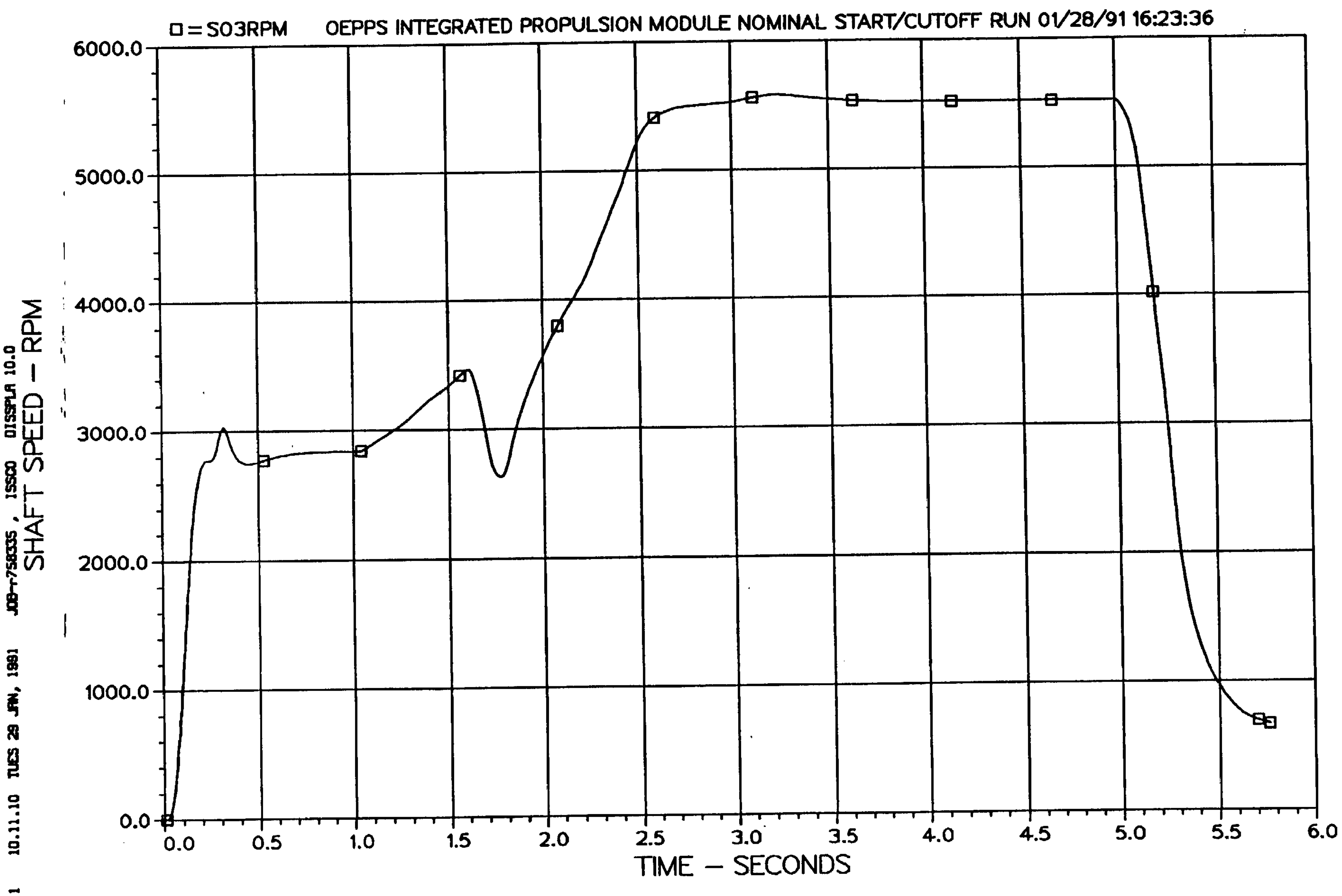


Figure C10

FUEL PUMP (3) FLOW COEFFICIENT

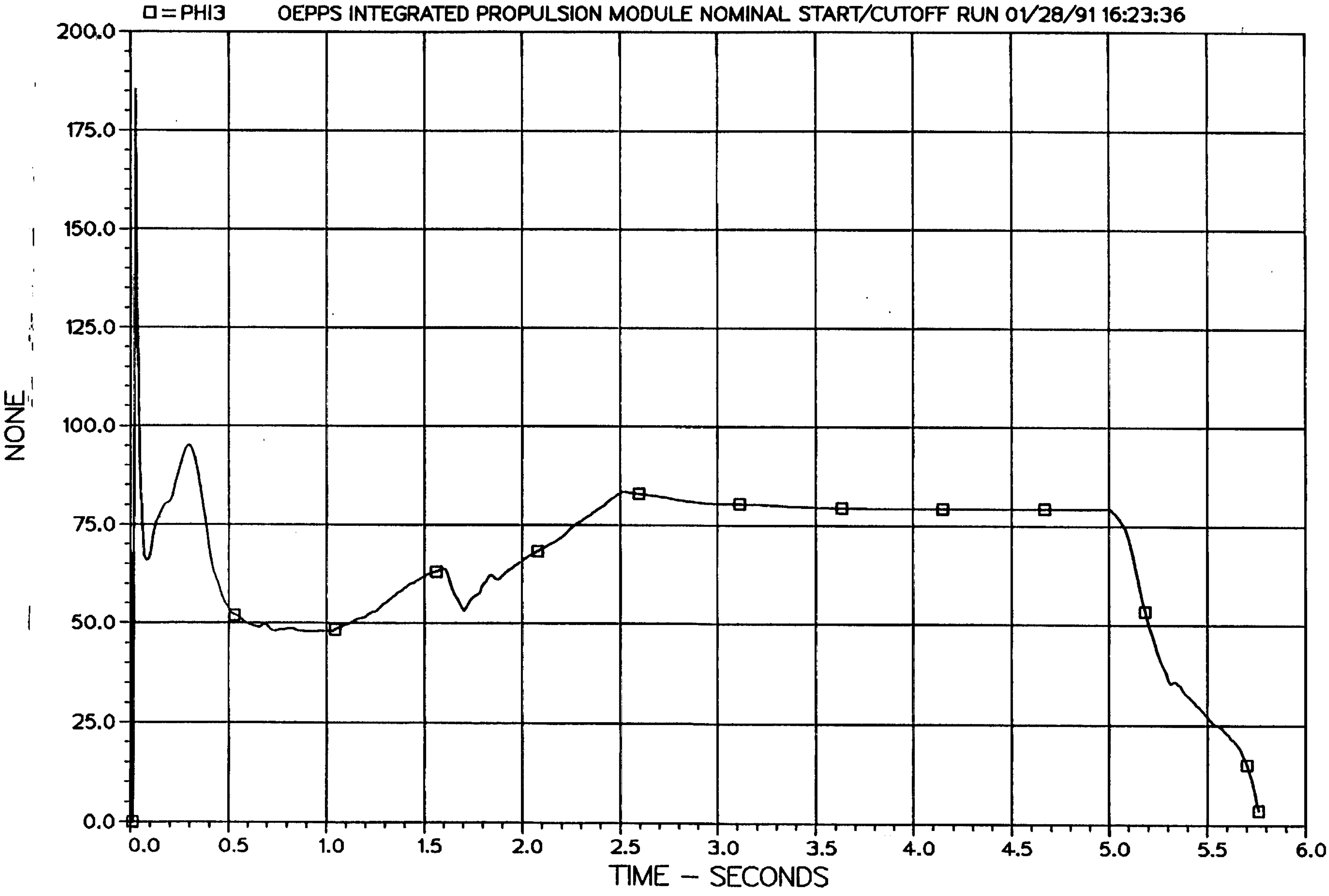


Figure C11

LOT 19 10.11.35 TUES 29 JAN, 1991 JOB-758335 , ISSCO DISSPLA 10.0

FUEL INJECTOR (5,6) TEMPERATURES

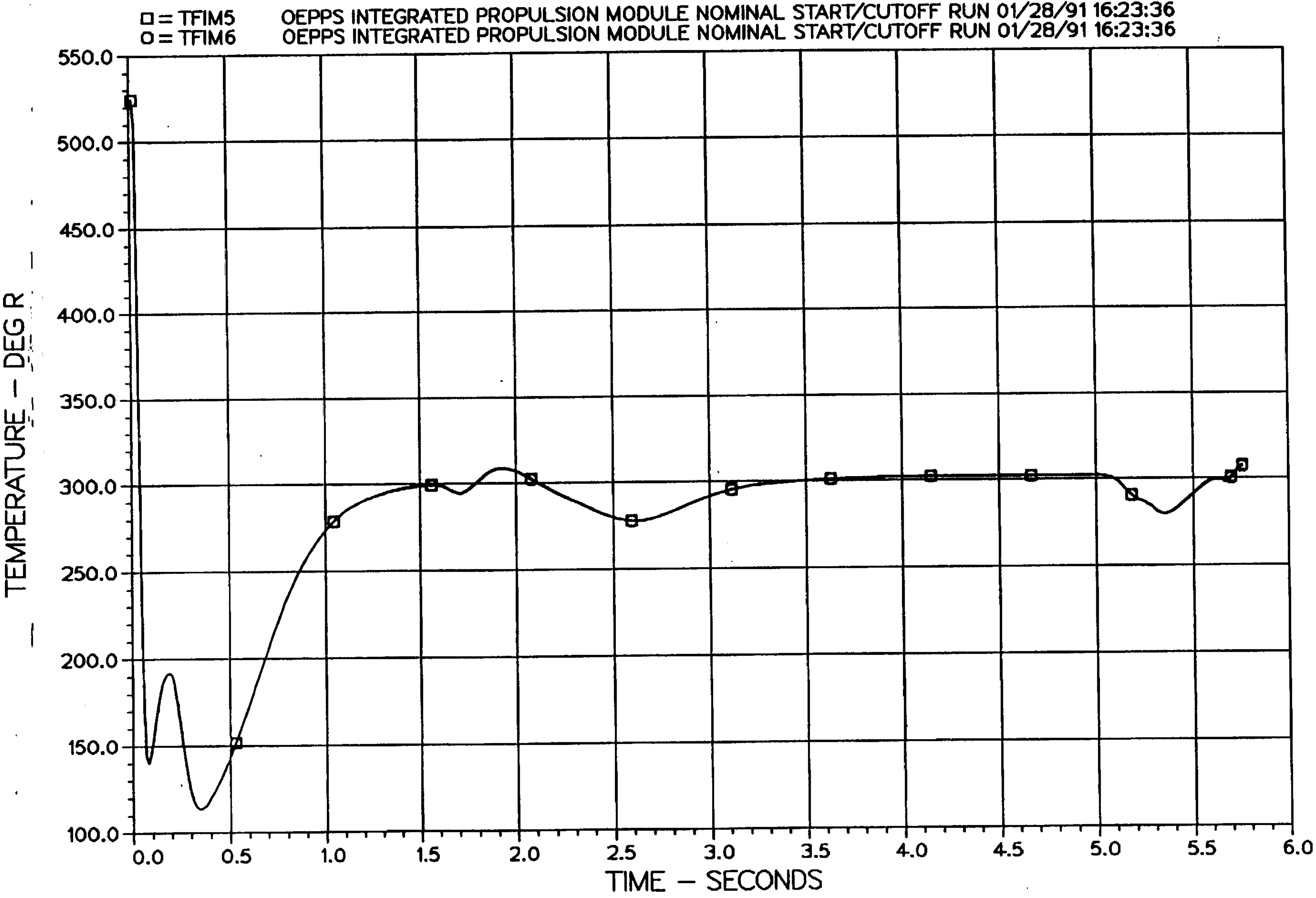


Figure C12

PLOT 20 10.11.40 TUES 29 JAN, 1991 JOB-7758335 , ISSCO DISSPLA 10.0

HYDROGEN GAS FLOW FOR GG (3) SPIN

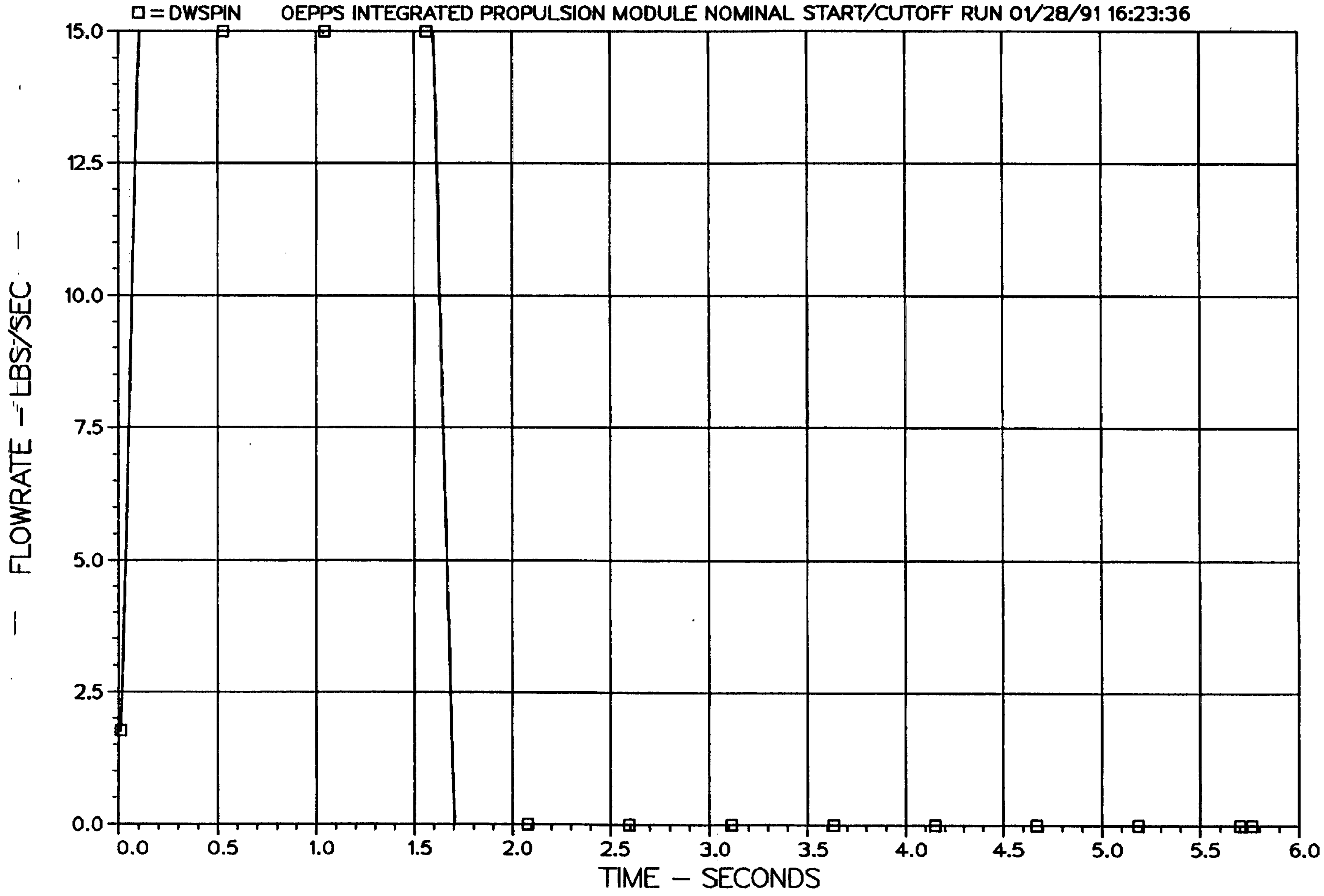


Figure C-13

LOT 21 10.11.42 TUES 29 JAN, 1991 JOB-758335 , ISSCO DISSPLA 10.0

APPENDIX D

NOMINAL START/CUTOFF TRANSIENT ANALYTICAL RESULTS FOR SYSTEM 4

FUEL AND OX PUMP (4) DISCHARGE VALVE POSITIONS

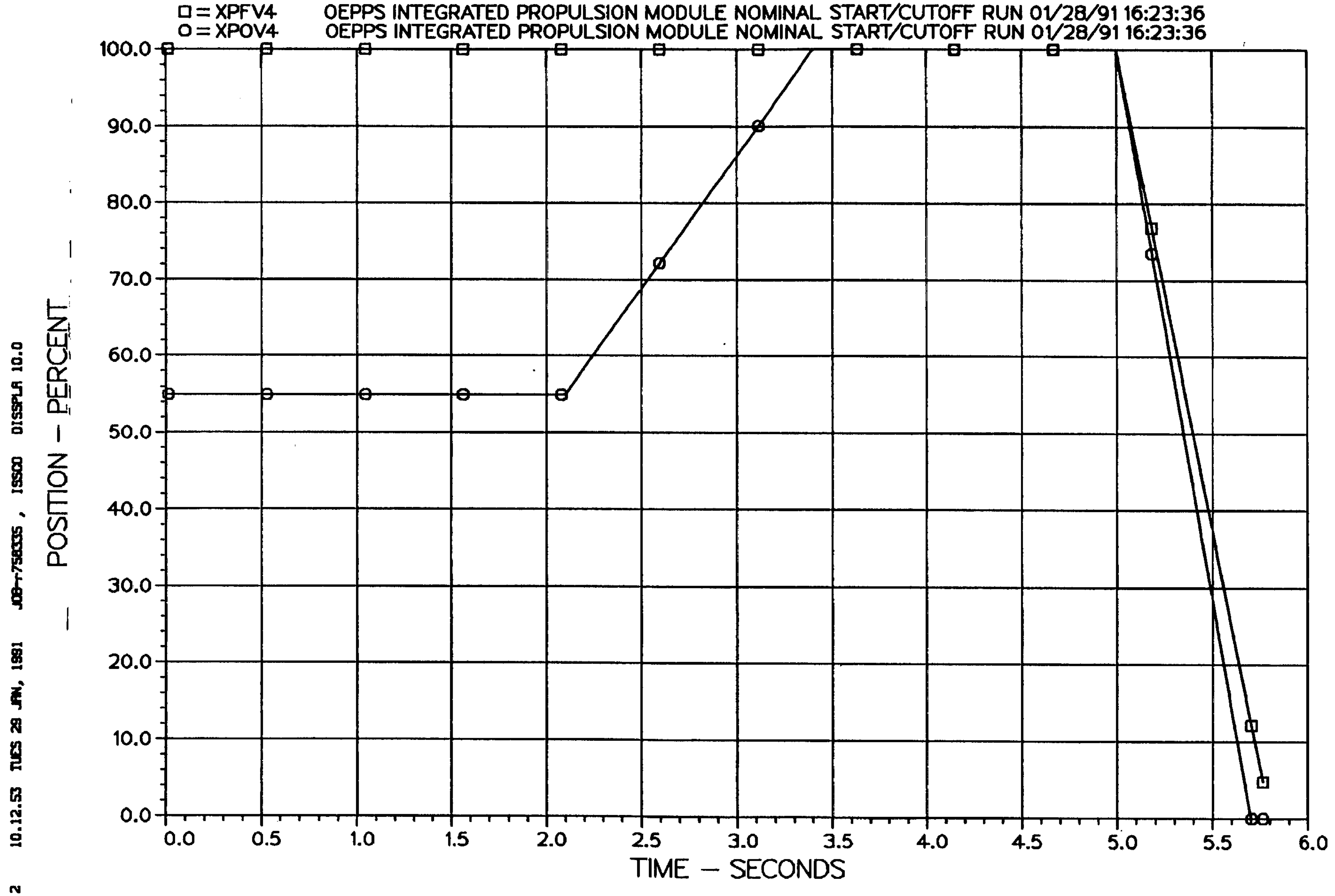
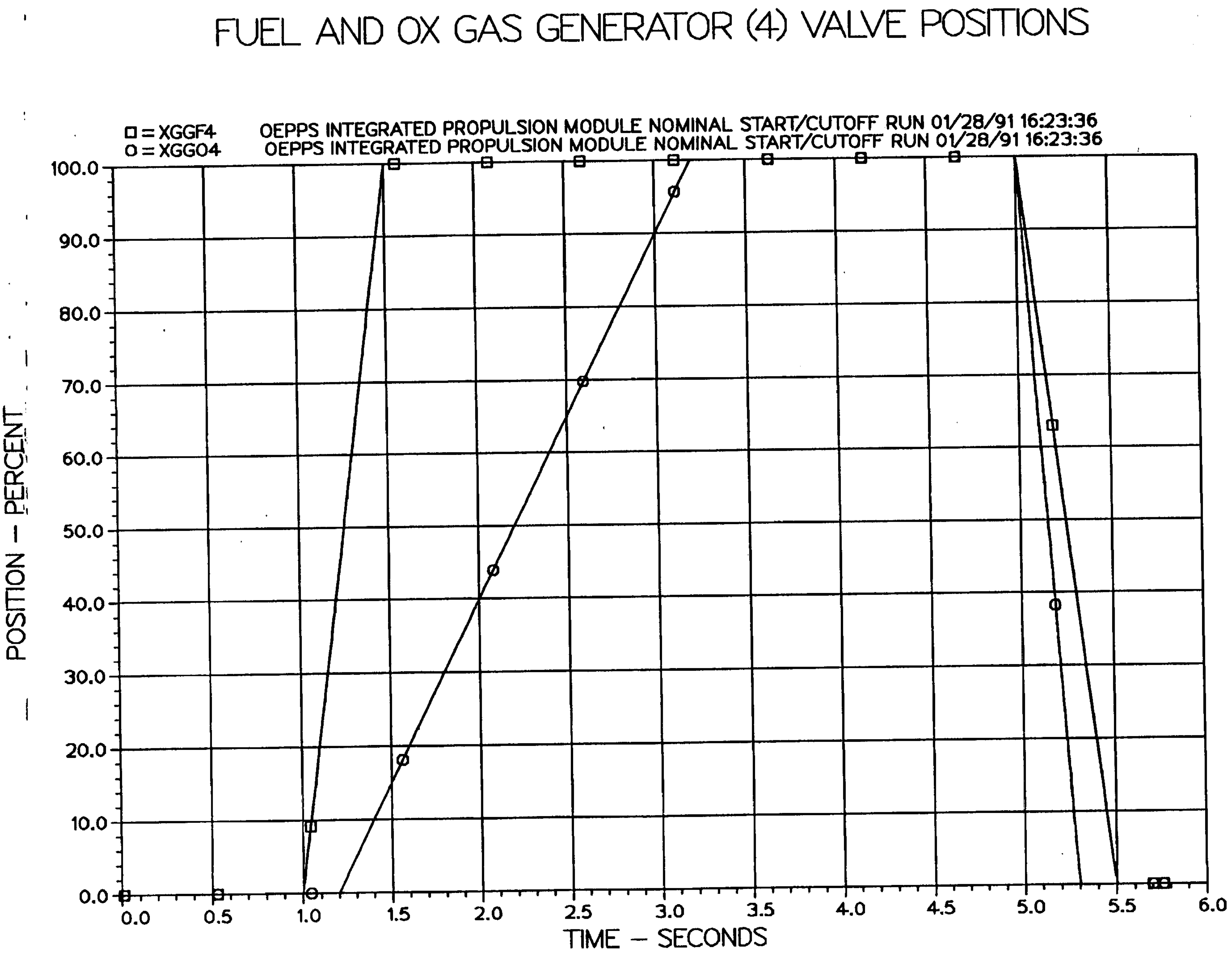


Figure D1



PLOT 5 10.13.06 TUES 29 JAN, 1991 JOB-758335 , ISSCO DISSPLA 10.0

Figure D2

T/C (7,8) INLET FUEL VALVE POSITIONS

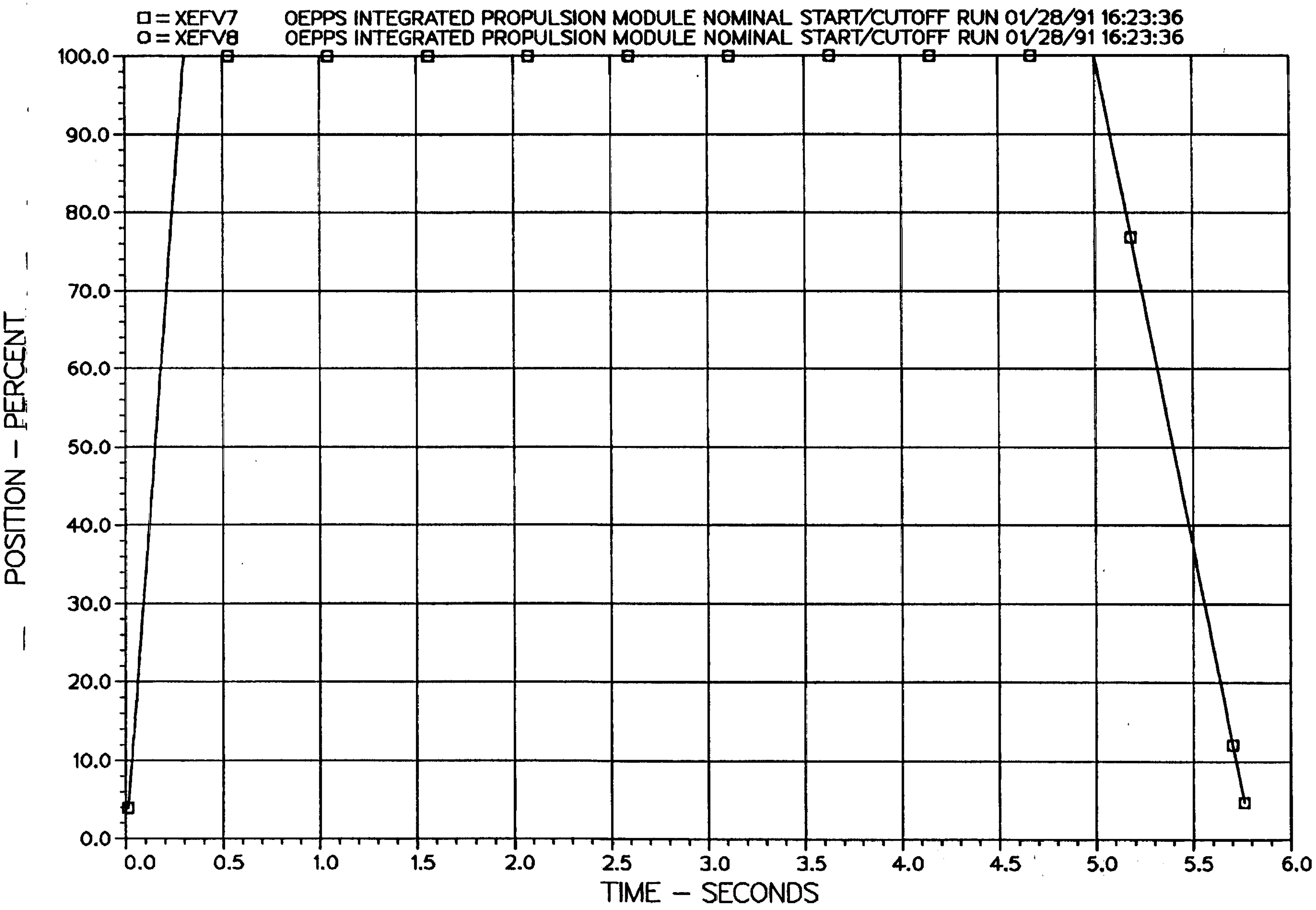


Figure A2

10.12.57 TUES 29 JAN, 1991 JOB-758335 , ISSCO DISSPLA 10.0

OT 3

T/C (7,8) INLET OX VALVE POSITIONS

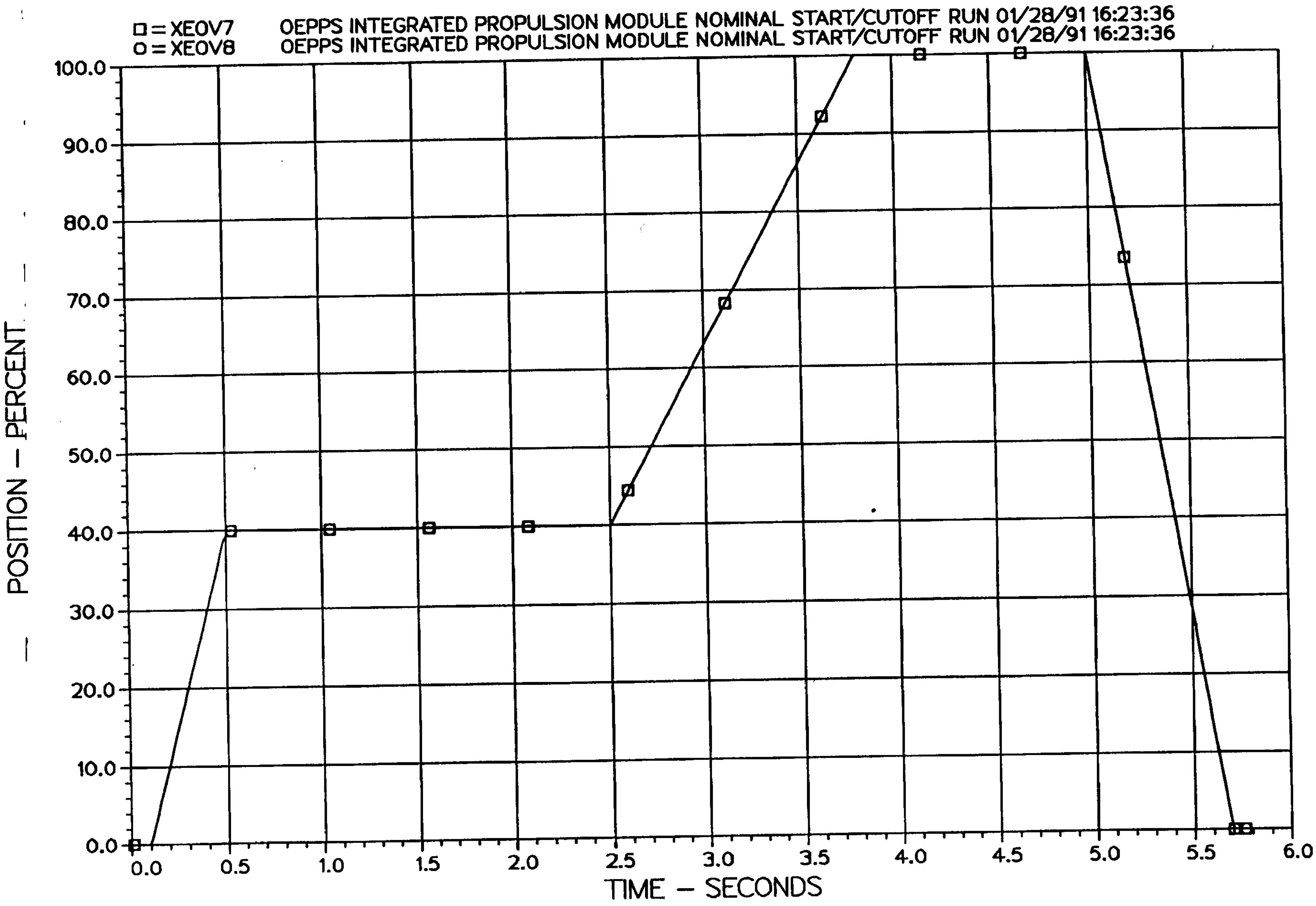


Figure D4

PLOT 4 10.13.02 TUES 29 JAN, 1991 JOB-758335 , ISSCO DISSPLA 10.0

T/C (7,8) MAIN CHAMBER PRESSURES

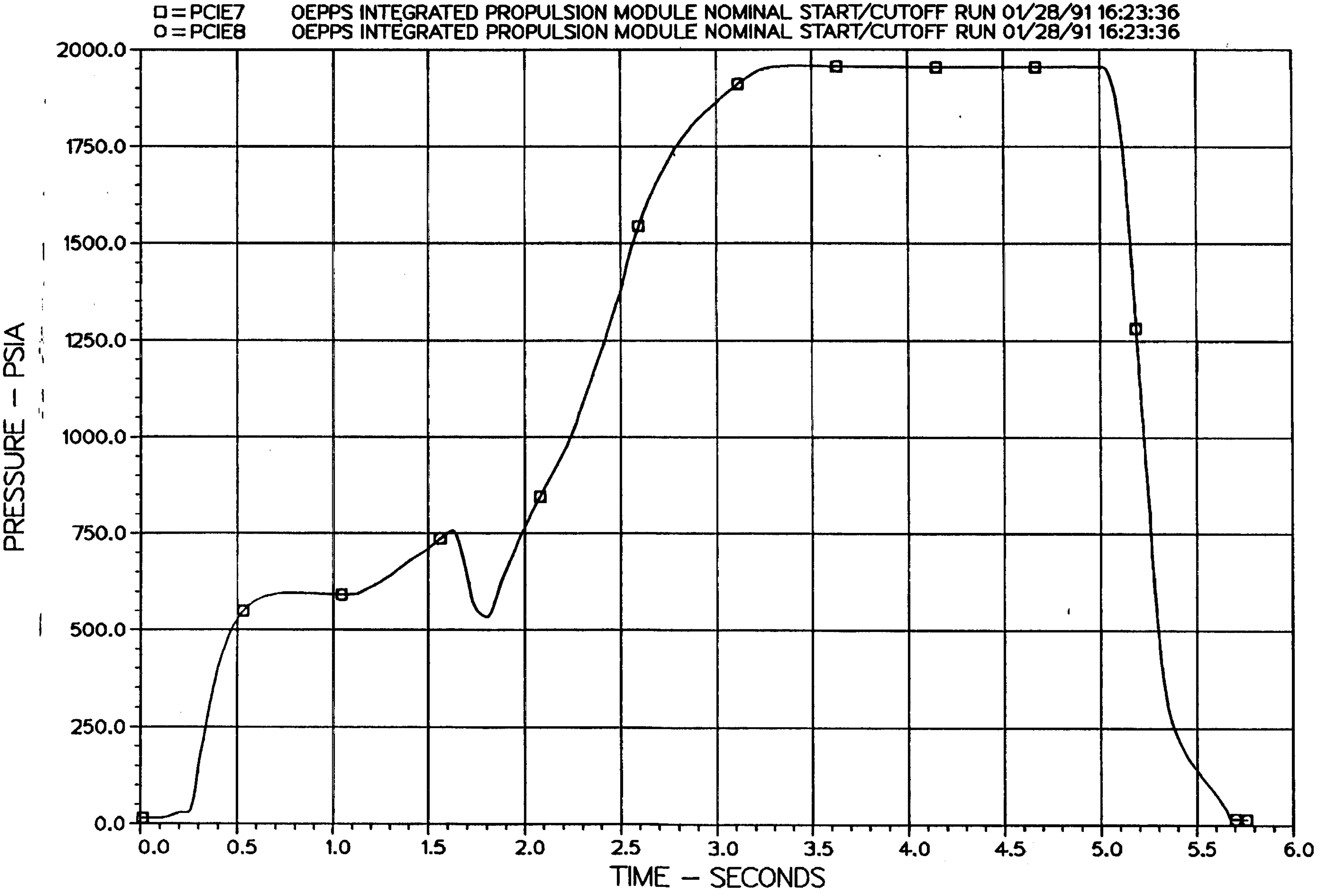


Figure 25

10.13.10 TUES 29 JAN, 1991 JOB-758335 , ISSCO DISSPLA 10.0

OT 6

GAS GENERATOR (4) CHAMBER PRESSURE

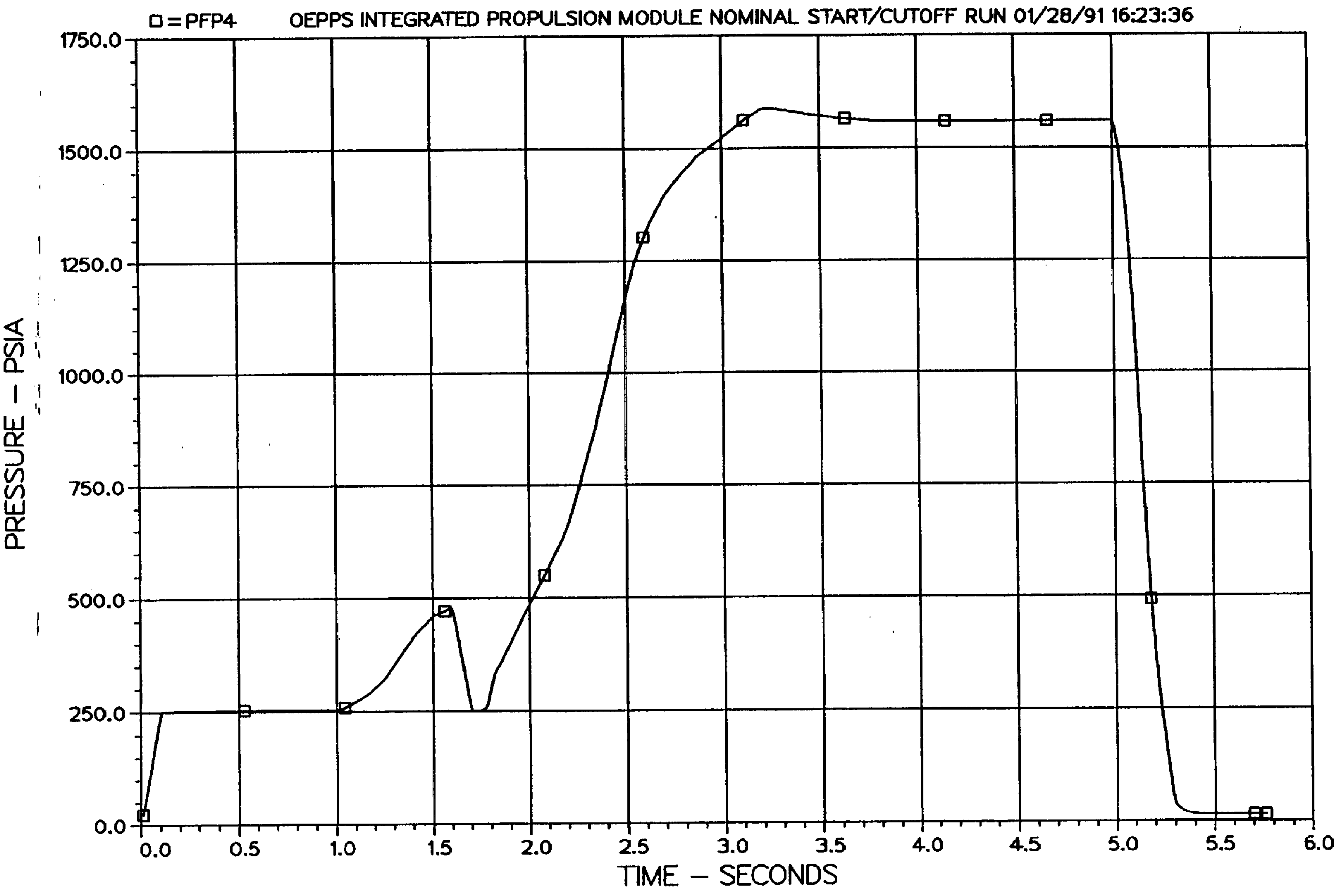


Figure 06

PLOT 7   10.13.15 TUES 29 JAN, 1991   JOB-r758335 , ISSCO DISSPLA 10.0

T/C (7,8) MIXTURE RATIOS

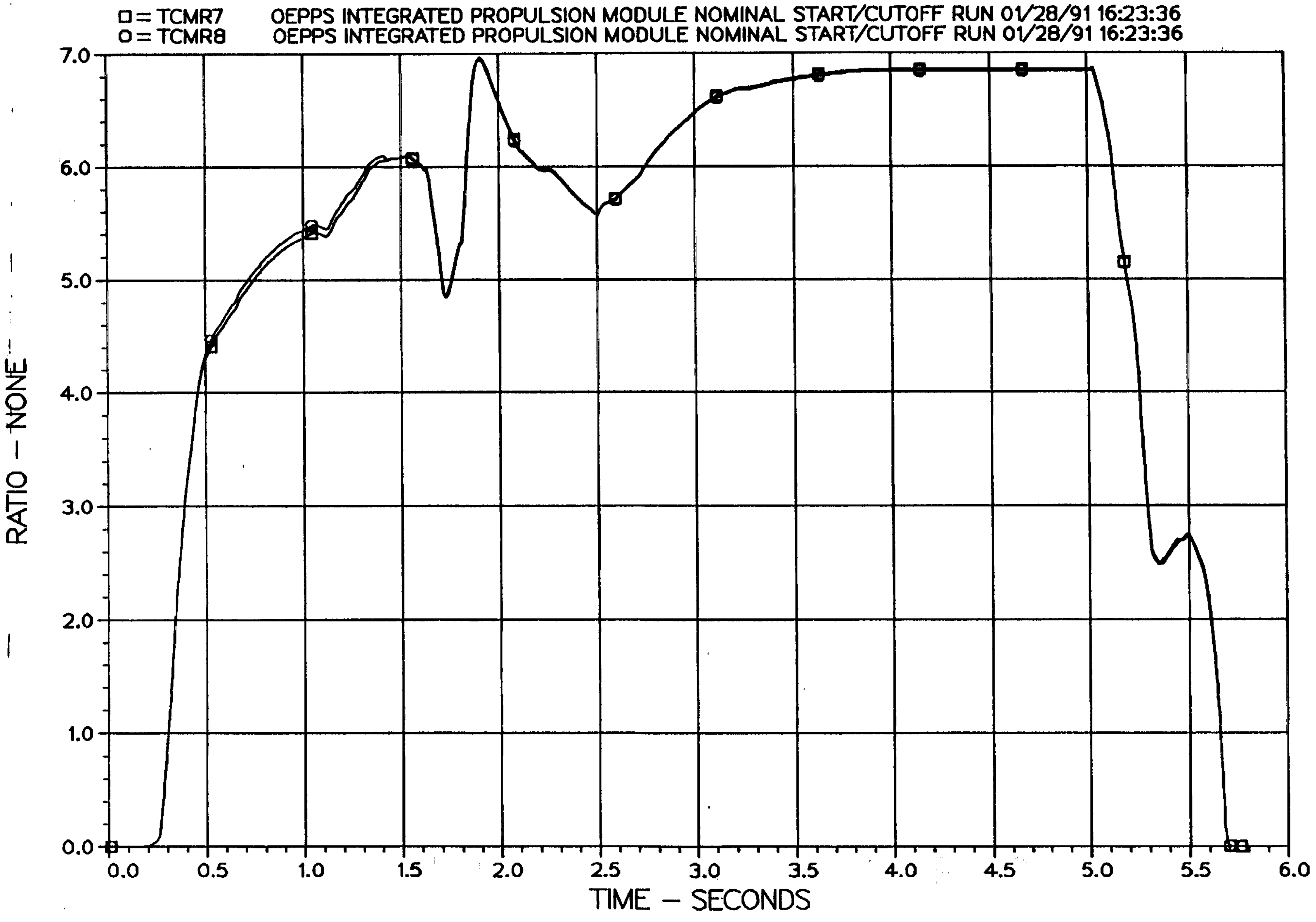


Figure D7

10.13.23 TUES 29 JAN, 1991 JOB-r758335 , ISSCO DISSPLA 10.0

PLOT 8

GAS GENERATOR (4) MIXTURE RATIO

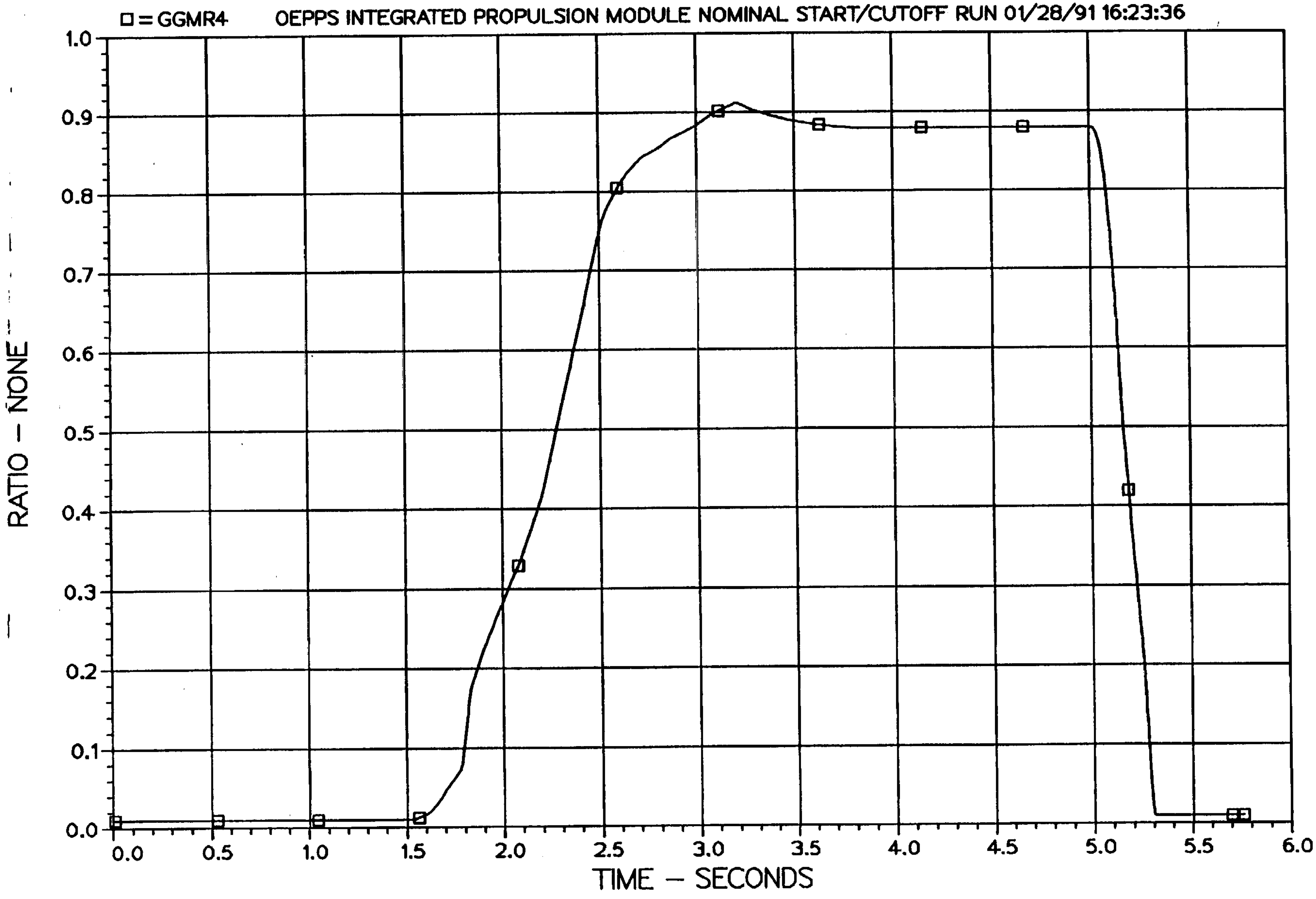
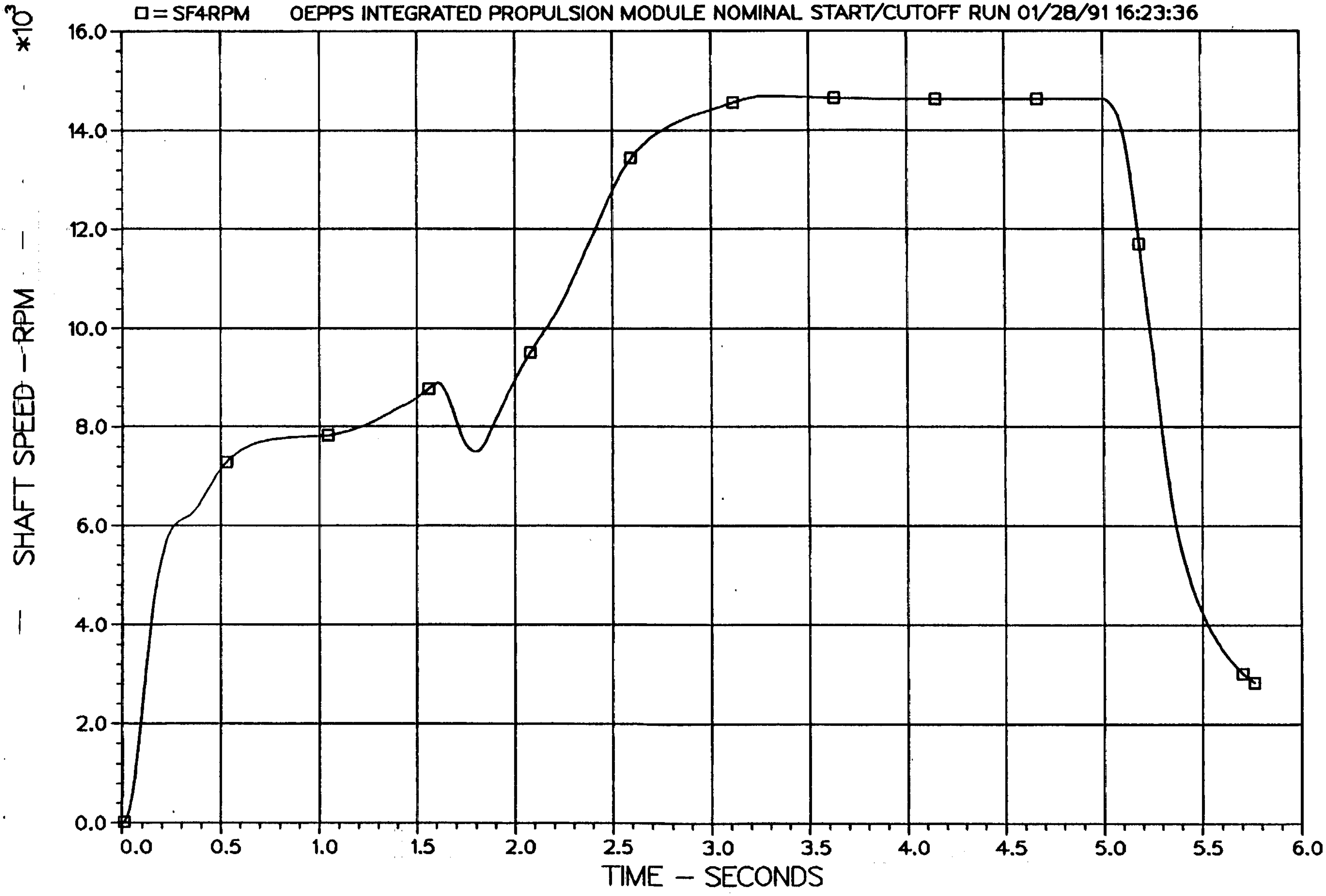


Figure D8

PLOT 9 10.13.28 TUES 29 JAN, 1991 JOB-r758335 , ISSCO DISSPLA 10.0

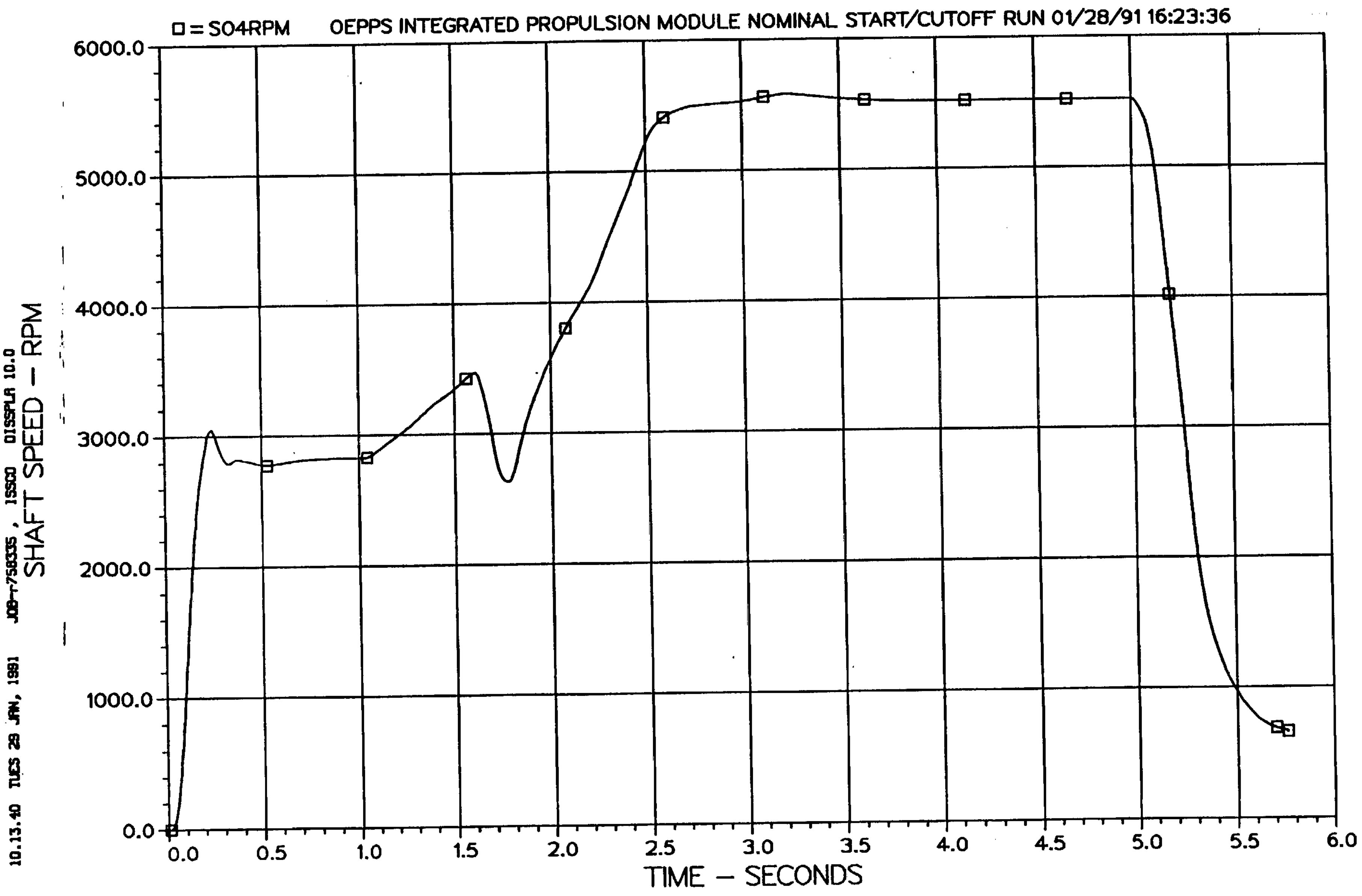
FUEL PUMP (4) SPEED



LOT 10 10.13.34 TUES 29 JAN, 1991 JOB-r758335 , ISSCO DISSPLA 10.0

Figure D9

LOX PUMP (4) SPEED



PLOT 11 10.13.40 TUES 29 JAN, 1991 JOB-758335 , ISSCO DISSPLA 10.0

Figure D10

FUEL PUMP (4) FLOW COEFFICIENT

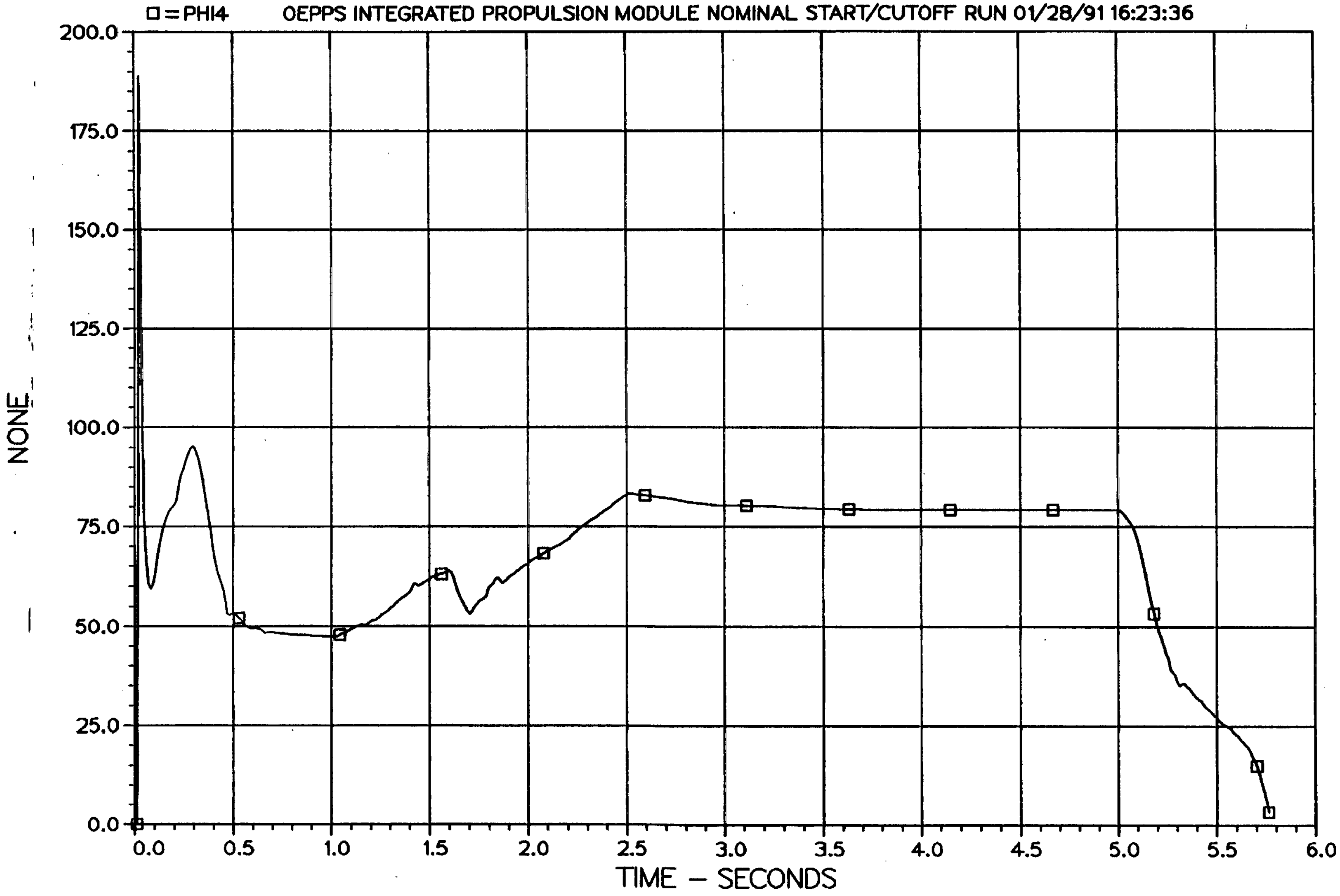
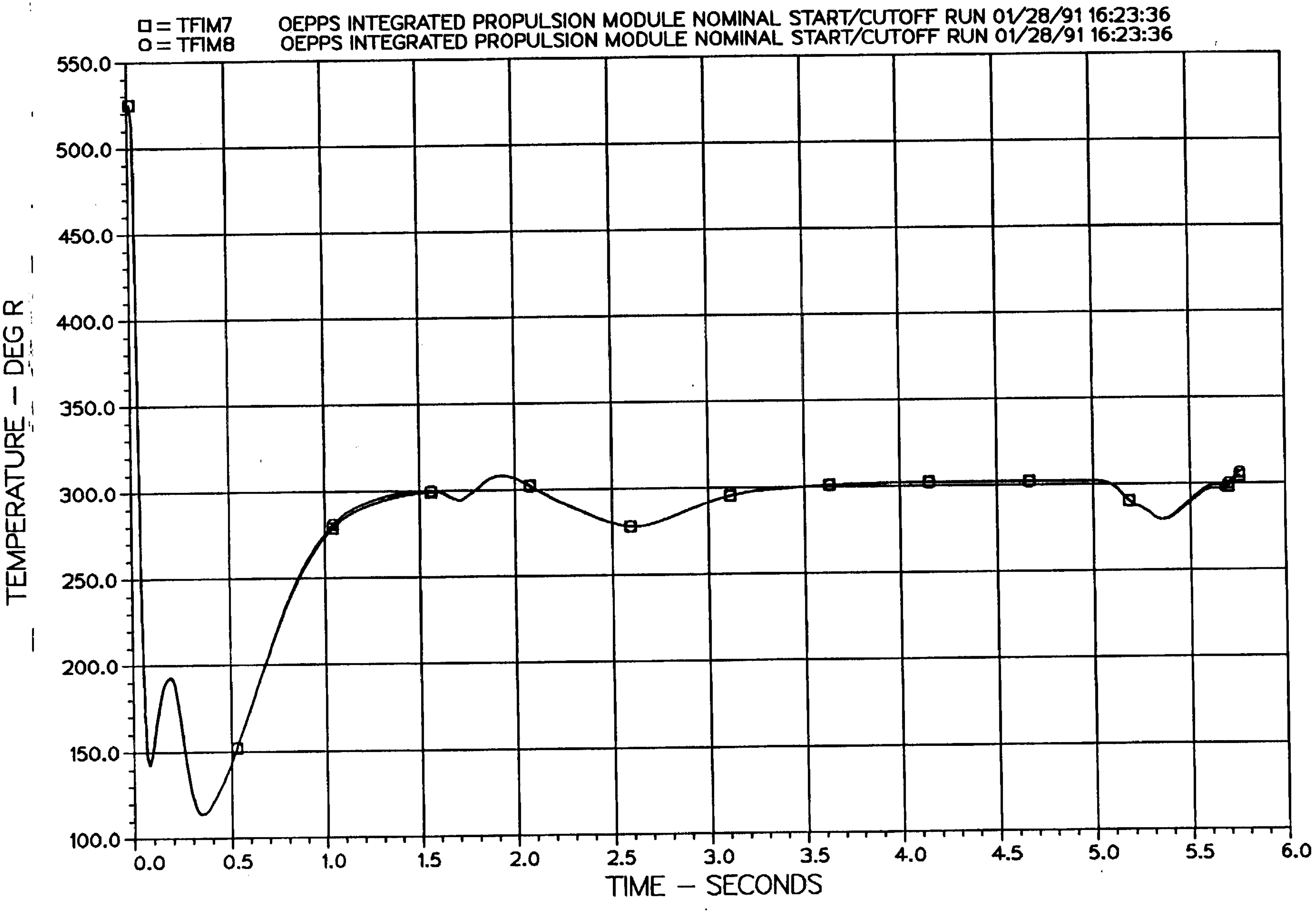


Figure 2[illegible]

OT 19 10.14.07 TUES 29 JAN, 1991 JOB-758335 , ISSCO DISSPLA 10.0

FUEL INJECTOR (7,8) TEMPERATURES



PLOT 20 10.14.11 TUES 29 JAN, 1991 JOB-7S8335 , ISSCO DISSPLA 10.0

Figure D12

HYDROGEN GAS FLOW FOR GG (4) SPIN

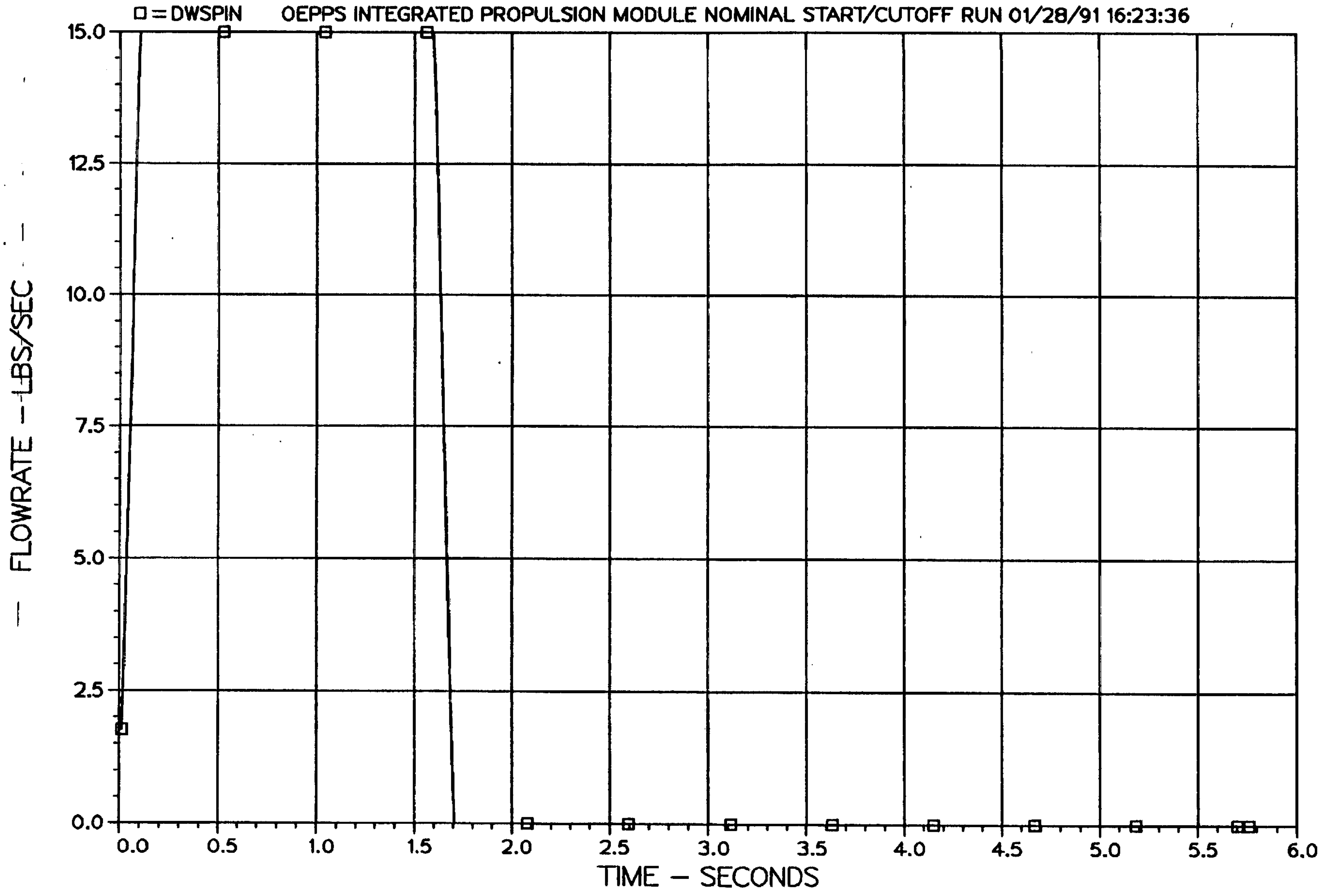


Figure D12

OT 21 10.14.14 TUES 29 JAN, 1991 JOB-r75833S , ISSCO DISSPLA 10.0

APPENDIX E

TRANSIENT ANALYTICAL RESULTS FOR THRUST CHAMBER #3 SHUTDOWN

FOR SYSTEM 2

FUEL AND OX PUMP (2) DISCHARGE VALVE POSITIONS

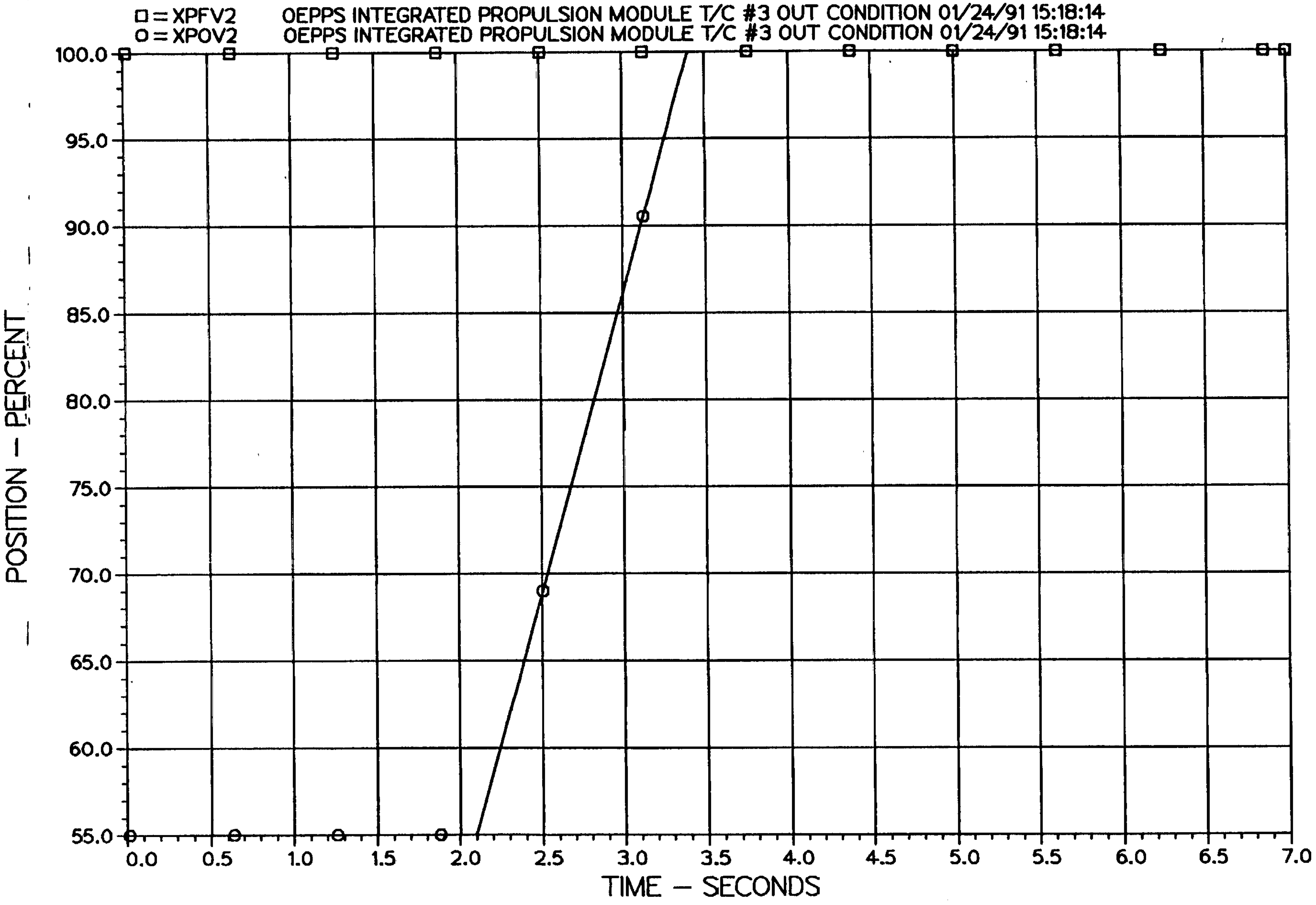
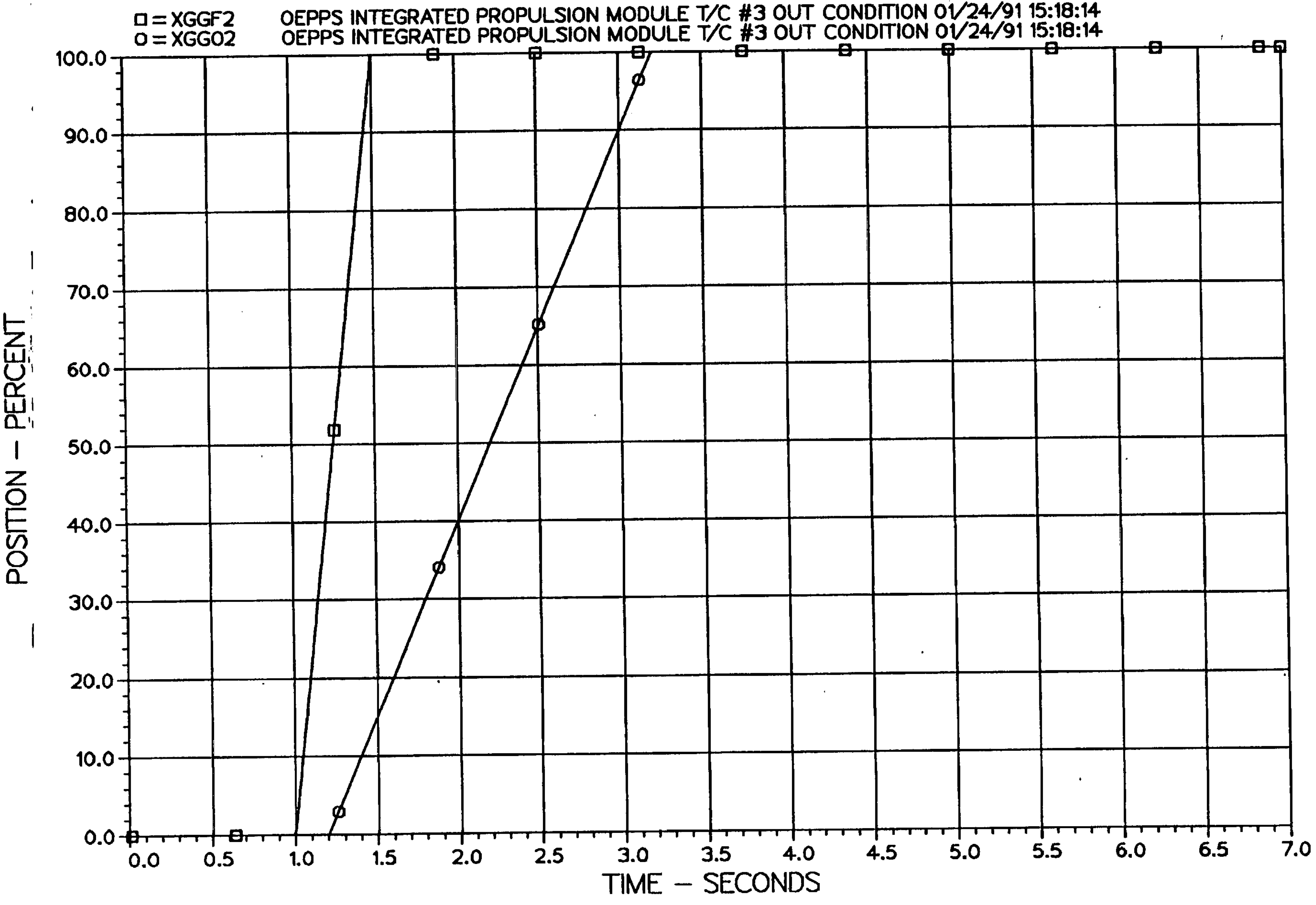


Figure E[illegible]

OT 2 10.01.52 MON 28 JAN, 1991 JOB-758335 , ISSCO DISSPLA 10.0

FUEL AND OX GAS GENERATOR (2) VALVE POSITIONS



PLOT 5 10.02.04 MON 28 JAN, 1991 JOB-756335 , ISSCO DISSPLA 10.0

Figure E2

T/C (3,4) INLET FUEL VALVE POSITIONS

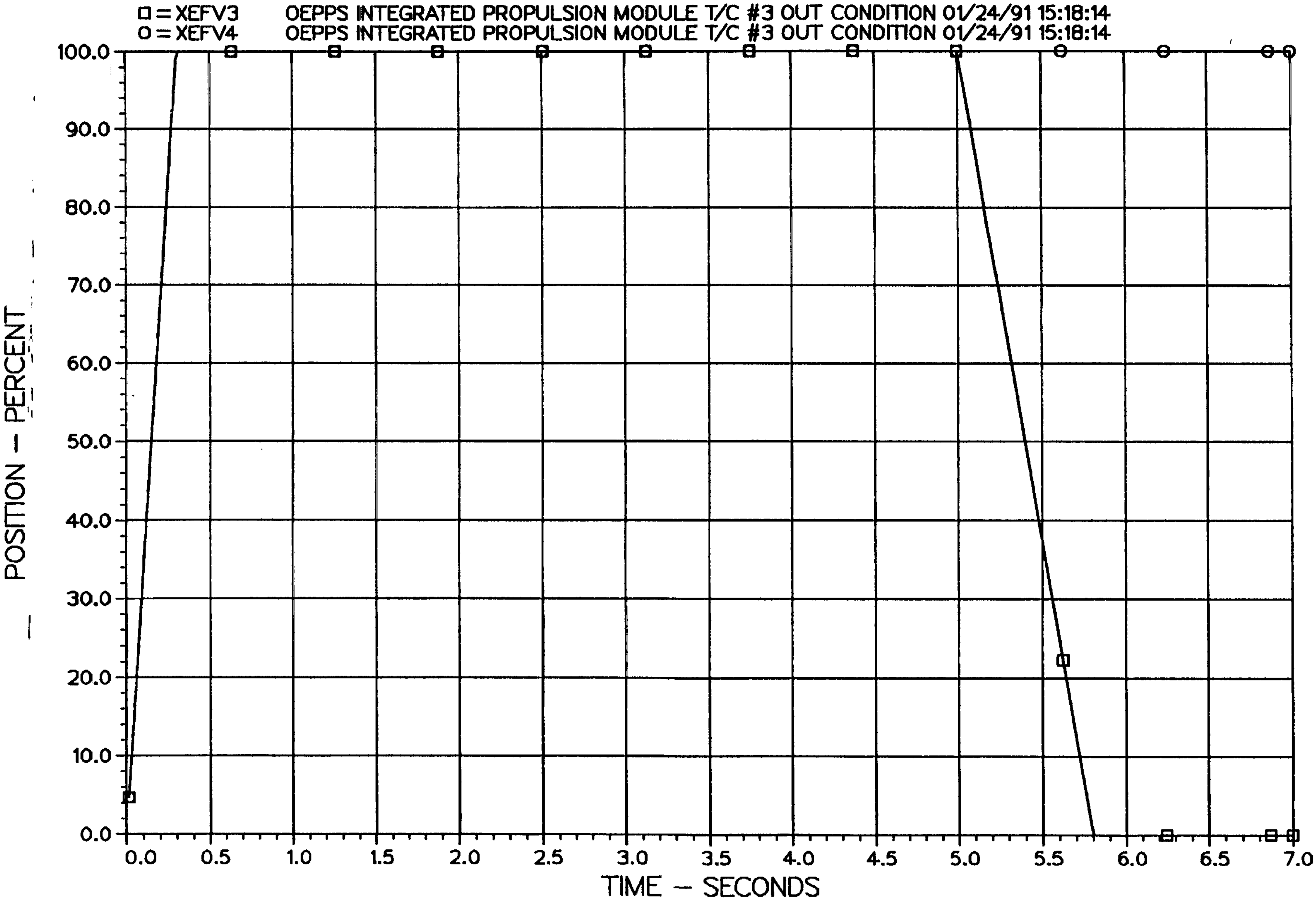


Figure F3

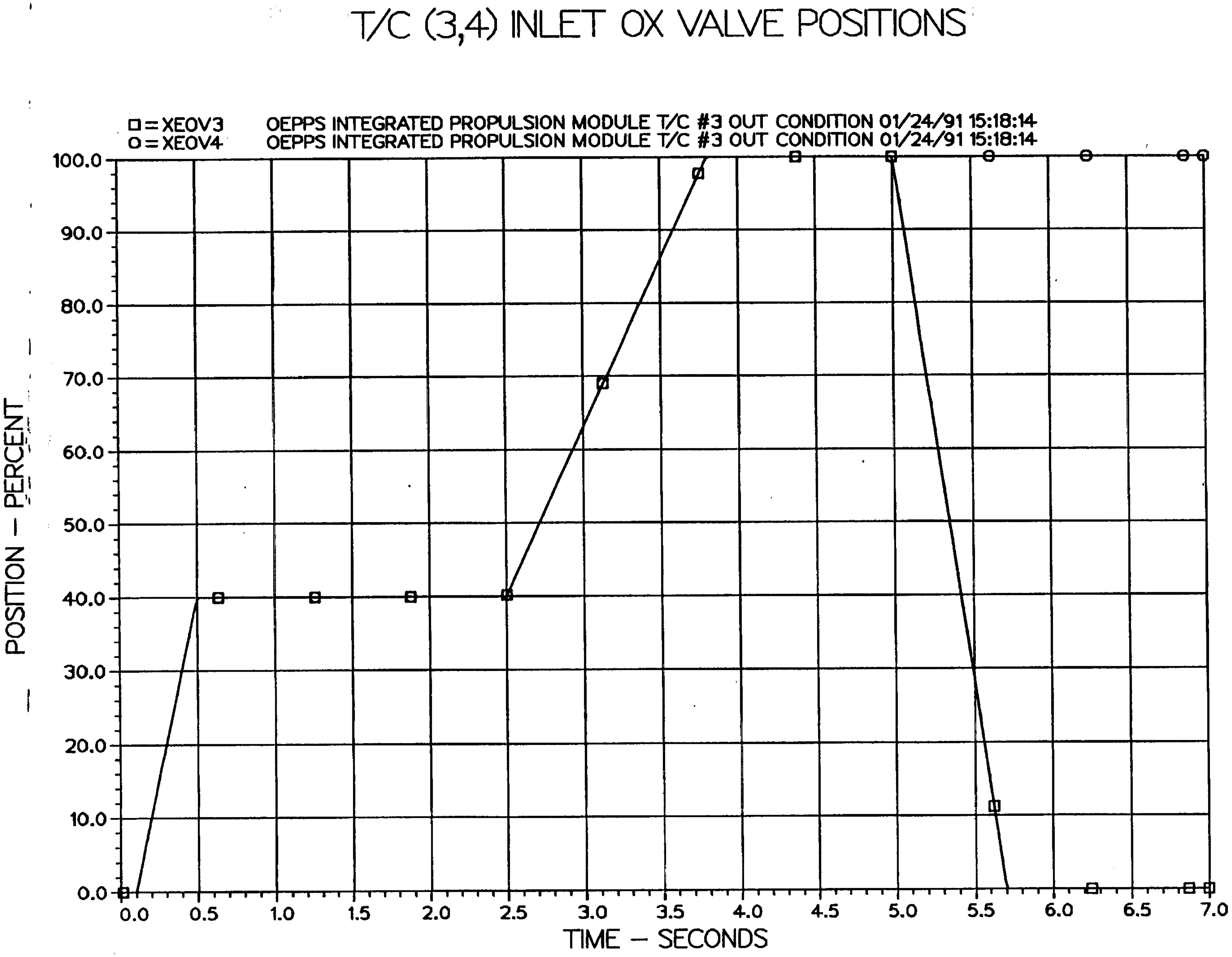


Figure E4

PLOT 4 10.02.00 MON 28 JAN, 1991 JOB-758335 , ISSCO DISSPLA 10.0

T/C (3,4) MAIN CHAMBER PRESSURES

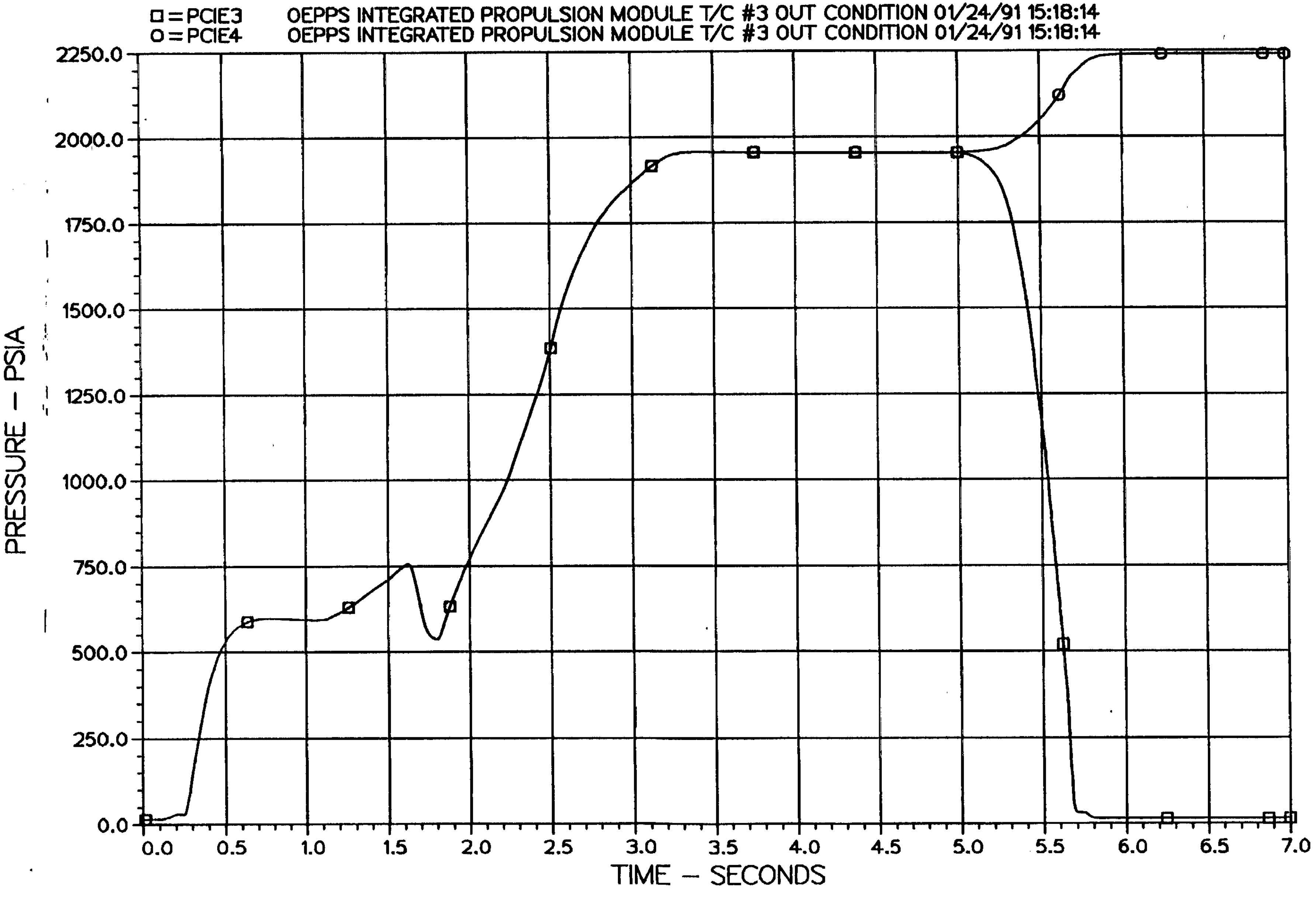


Figure E5

PLOT 6 10.02.08 MON 28 JAN, 1991 JOB-r758335 , ISSCO DISSPLA 10.0

GAS GENERATOR (2) CHAMBER PRESSURE

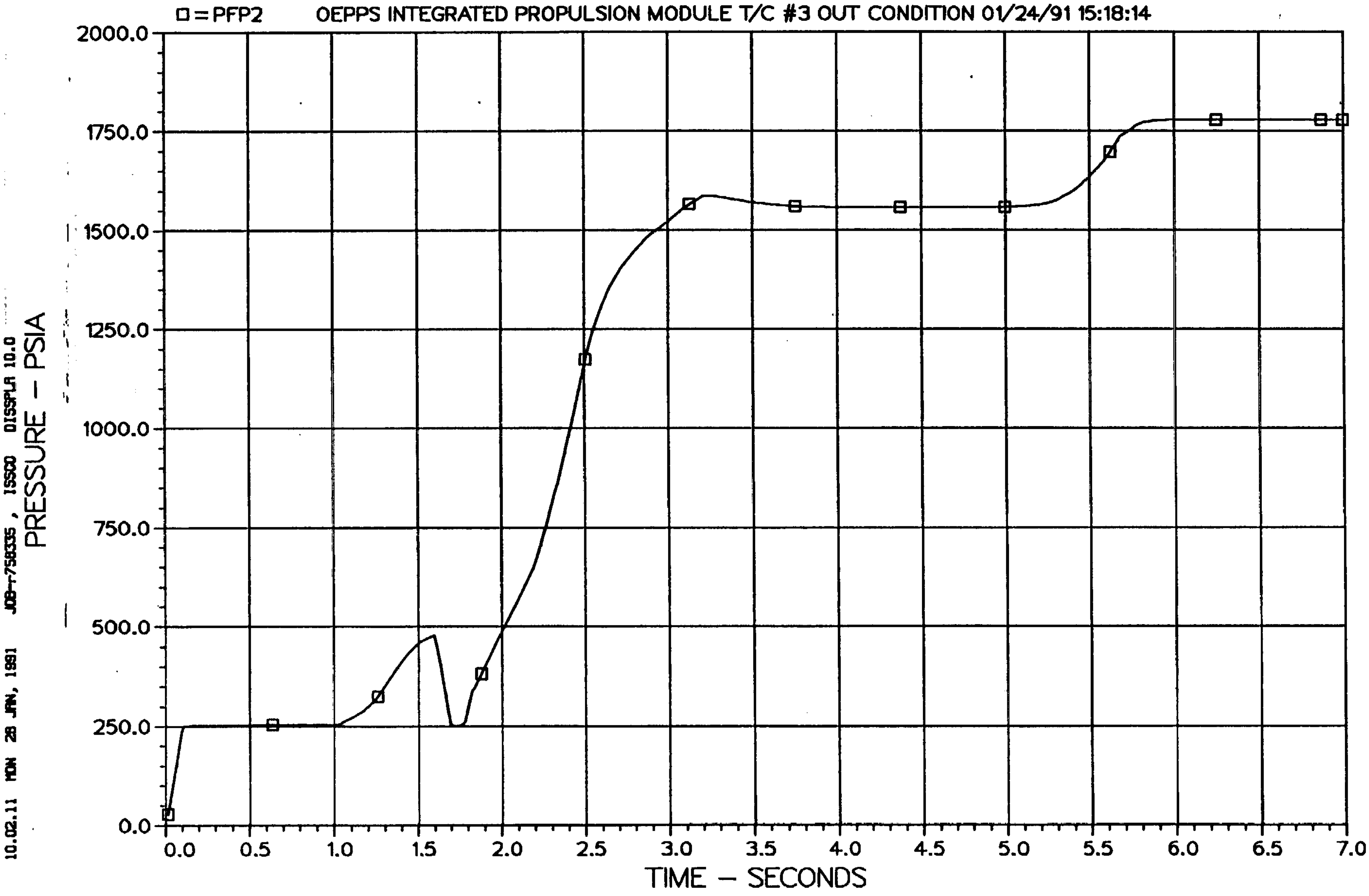


Figure E6

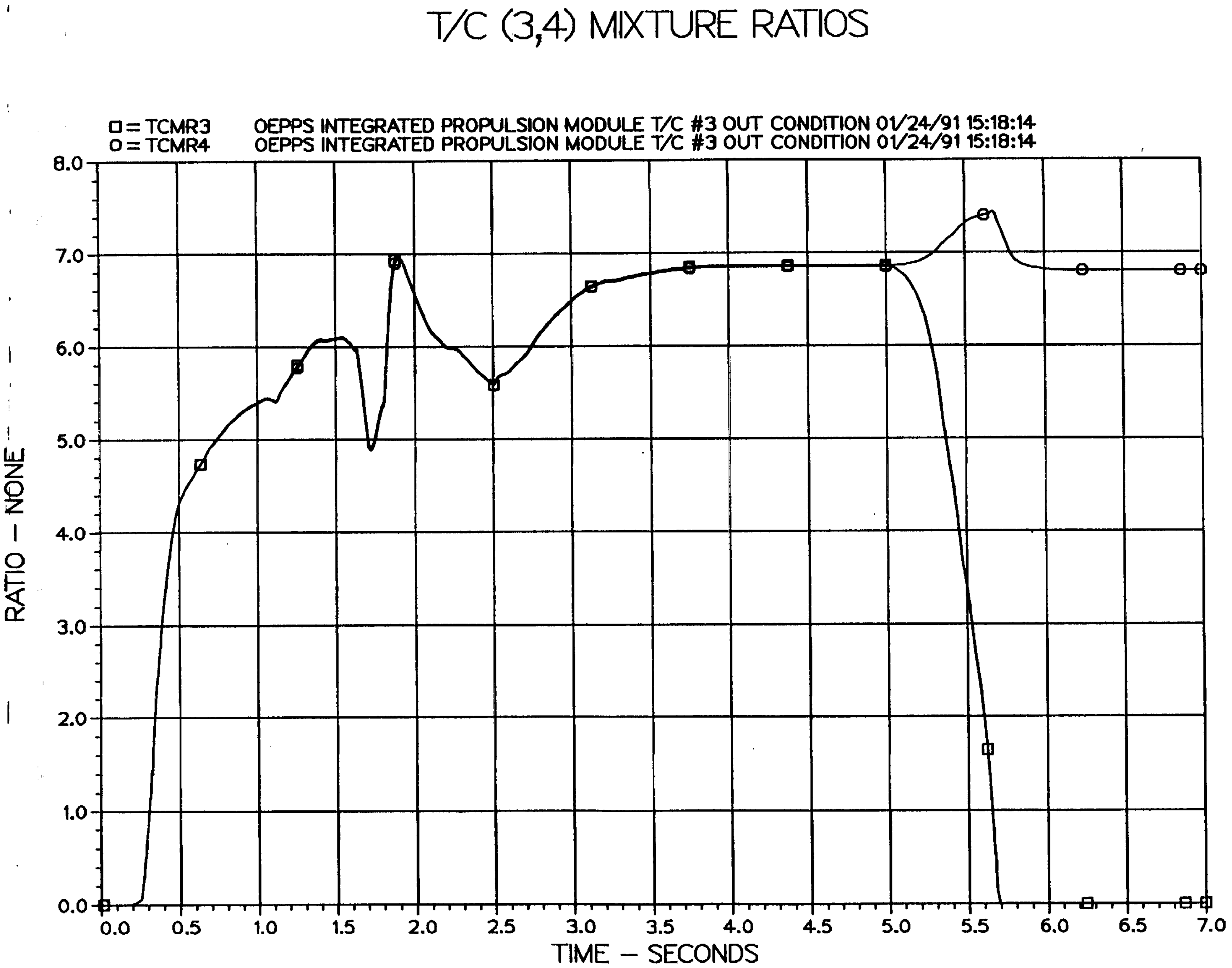


Figure E7

PLOT 8 10.02.15 MON 28 JAN, 1991 JOB-758335 , ISSCO DISSPLA 10.0

GAS GENERATOR (2) MIXTURE RATIO

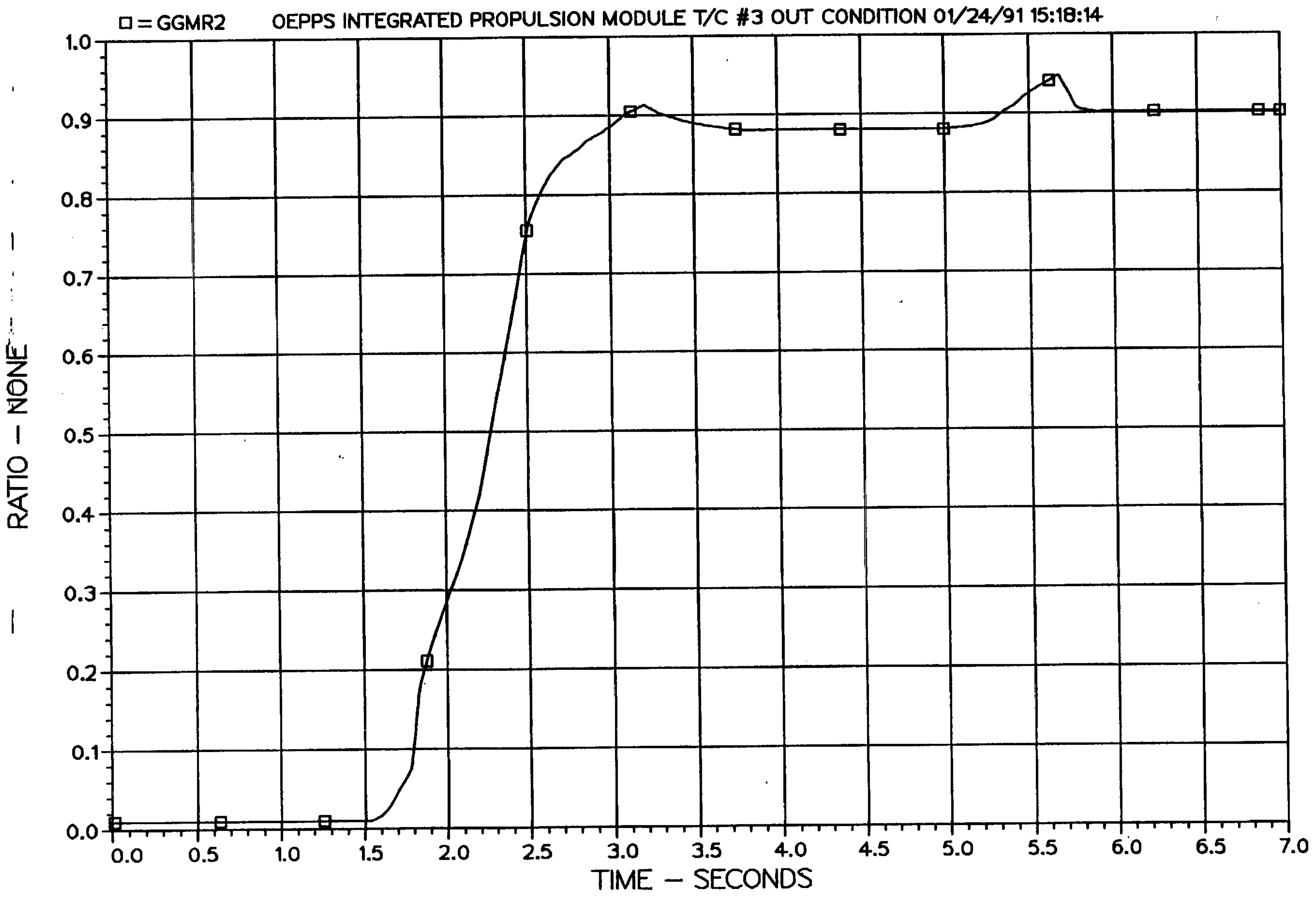


Figure E8

PLOT 9 10.02.18 MON 28 JAN, 1991 JOB-r758335 , ISSCO DISSPLA 10.0

FUEL PUMP (2) SPEED

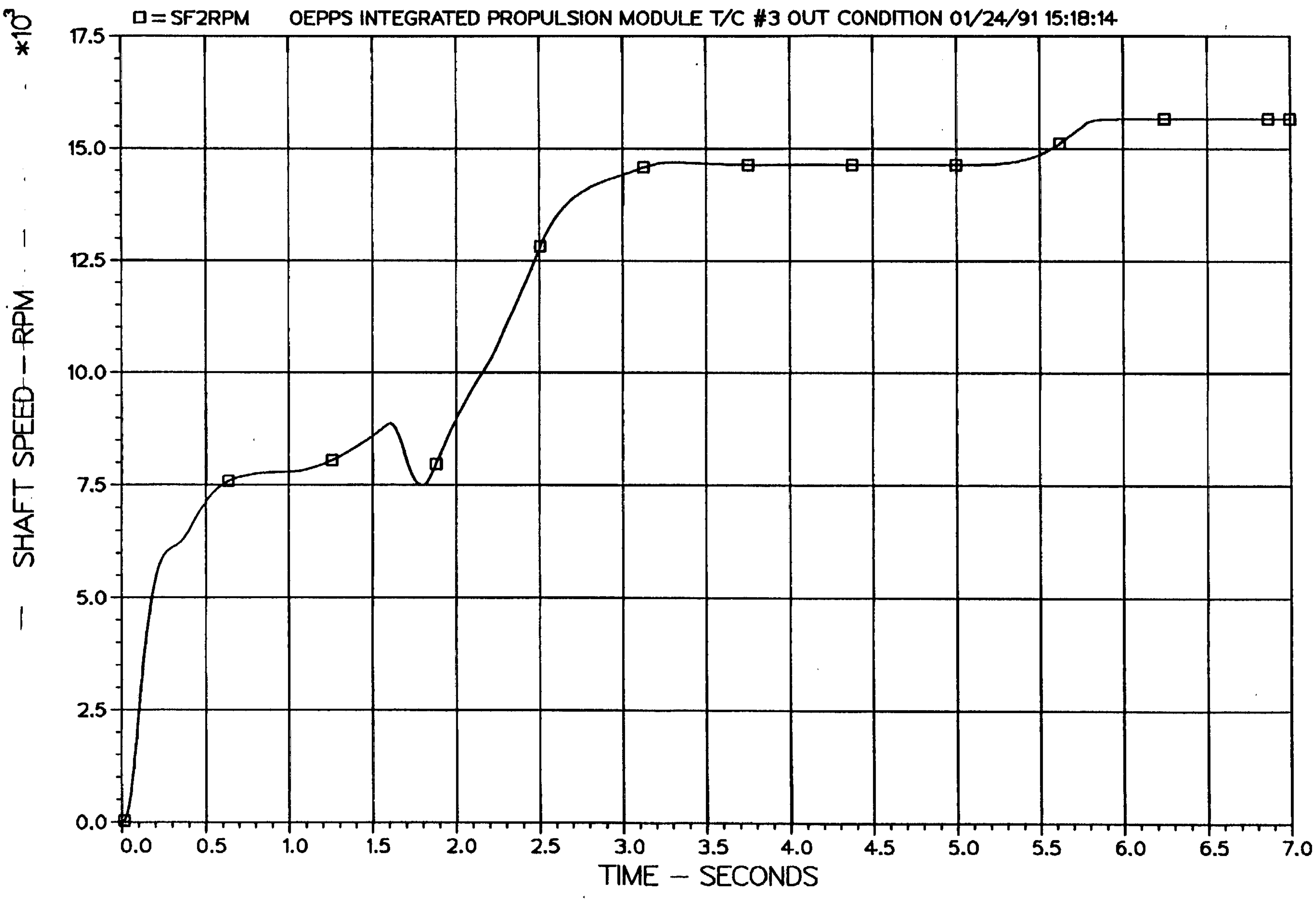


Figure E9

OT 10 10.02.21 MON 28 JAN, 1991 JOB-758335 , ISSCO DISSPLA 10.0

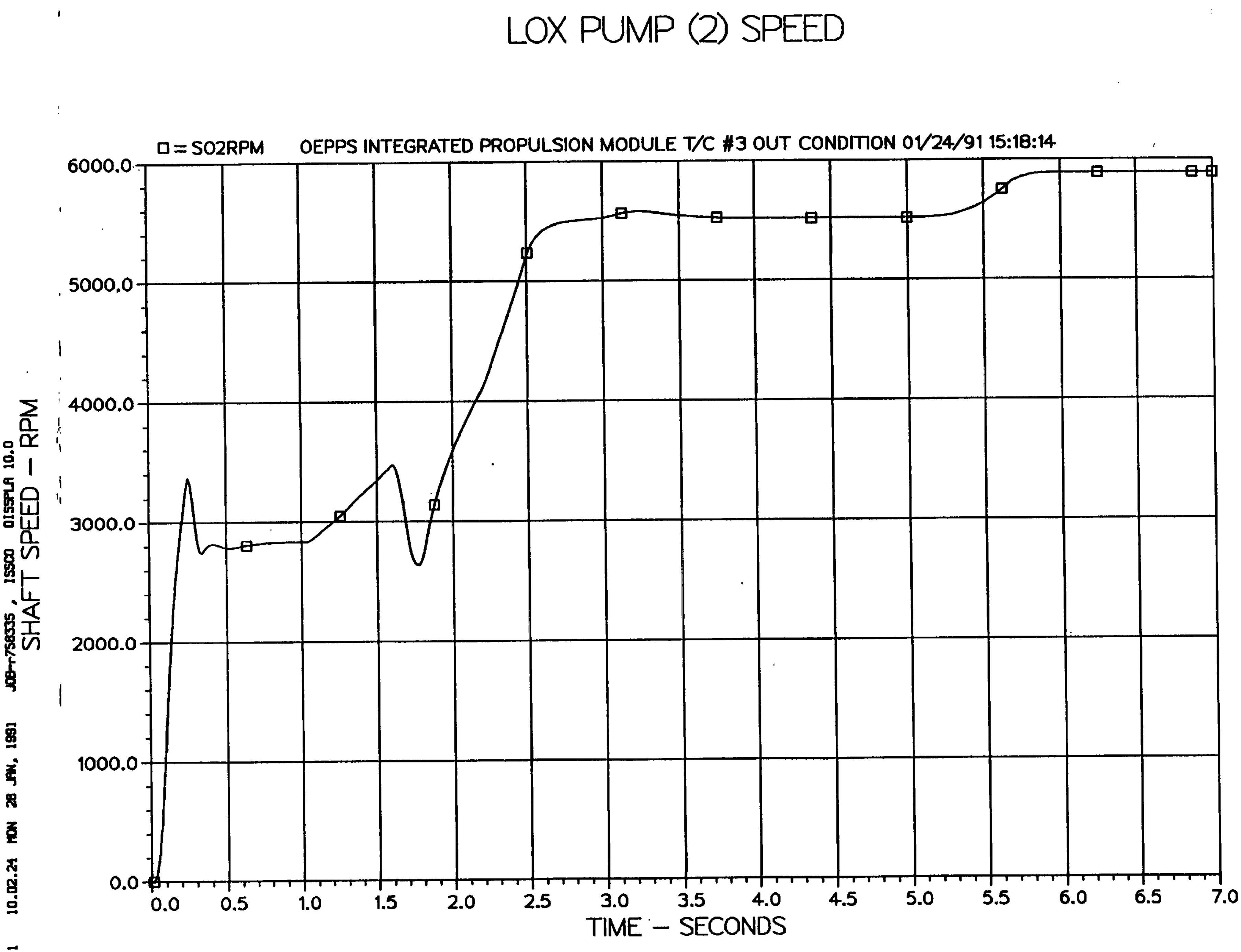

LOX PUMP (2) SPEED

Figure E10

FUEL PUMP (2) DISCHARGE PRESSURE

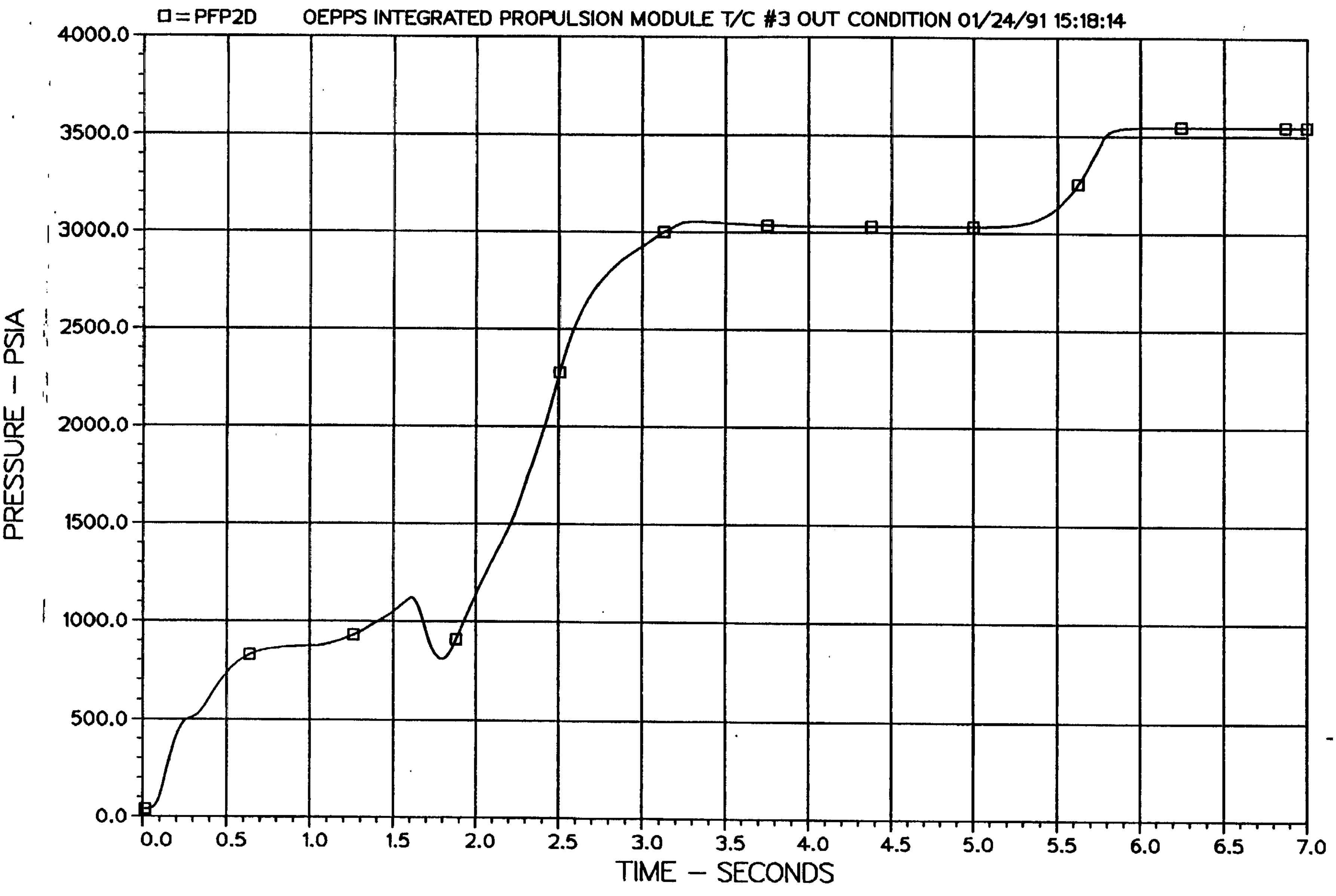
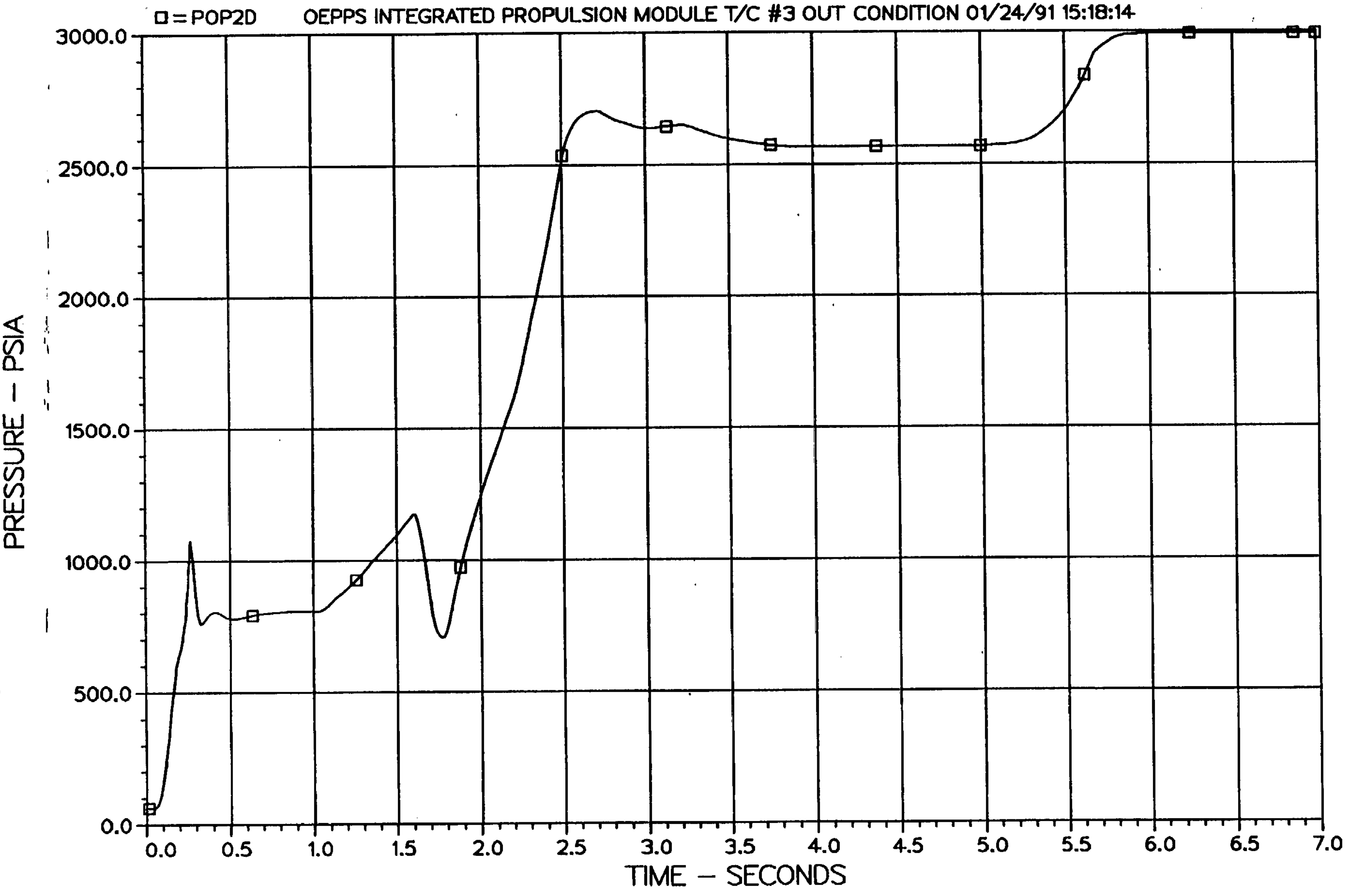


Figure E11

_OT 12 10.02.27 MON 28 JAN, 1991 JOB-758335 , ISSCO DISSPLA 10.0

LOX PUMP (2) DISCHARGE PRESSURE



PLOT 13 10.02.30 MON 28 JAN, 1991 JOB-r756335 , ISSCO DISSPLA 10.0

Figure E12

FUEL PUMP (2) FLOWRATE

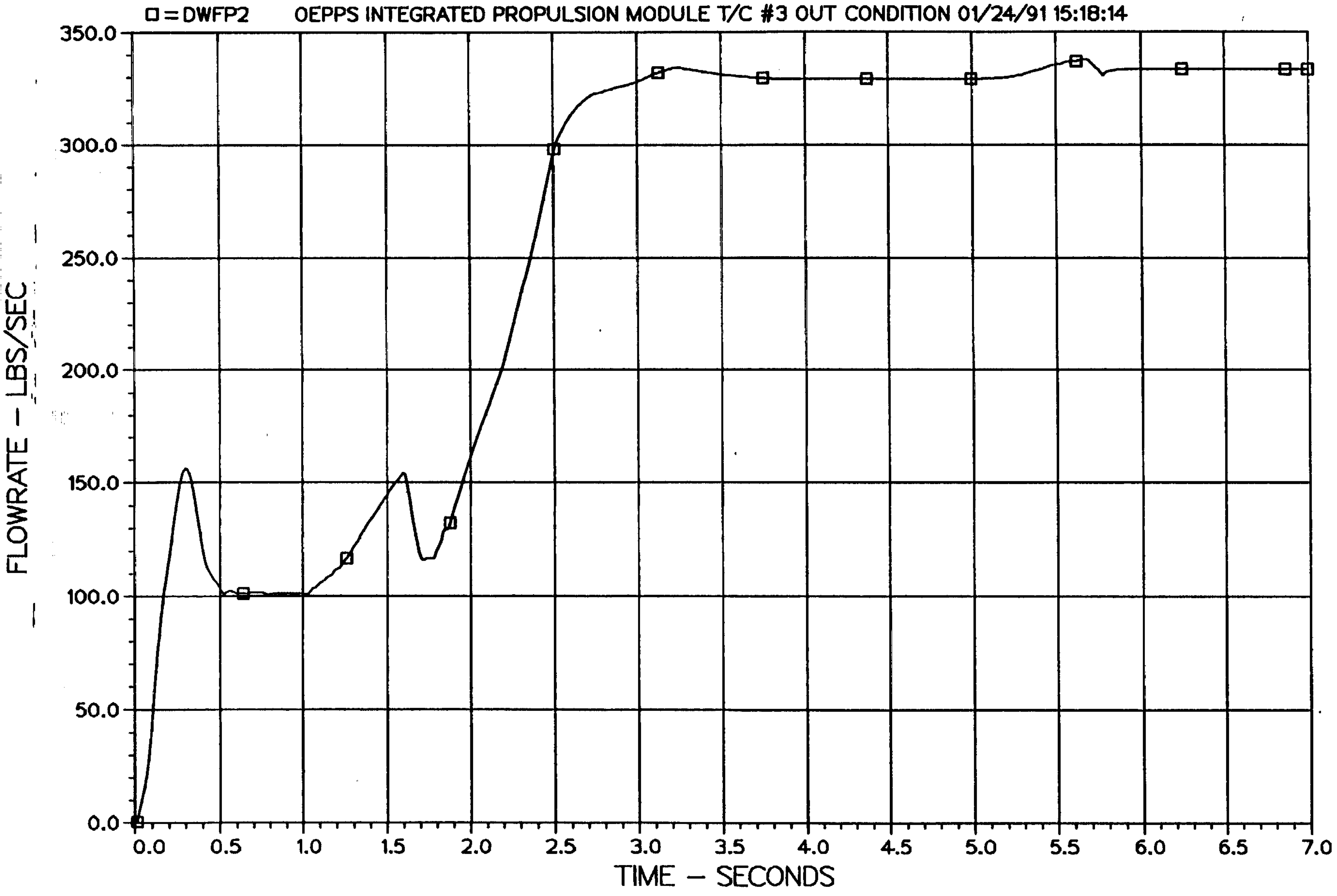


Figure E-[illegible]

LOX PUMP (2) FLOWRATE

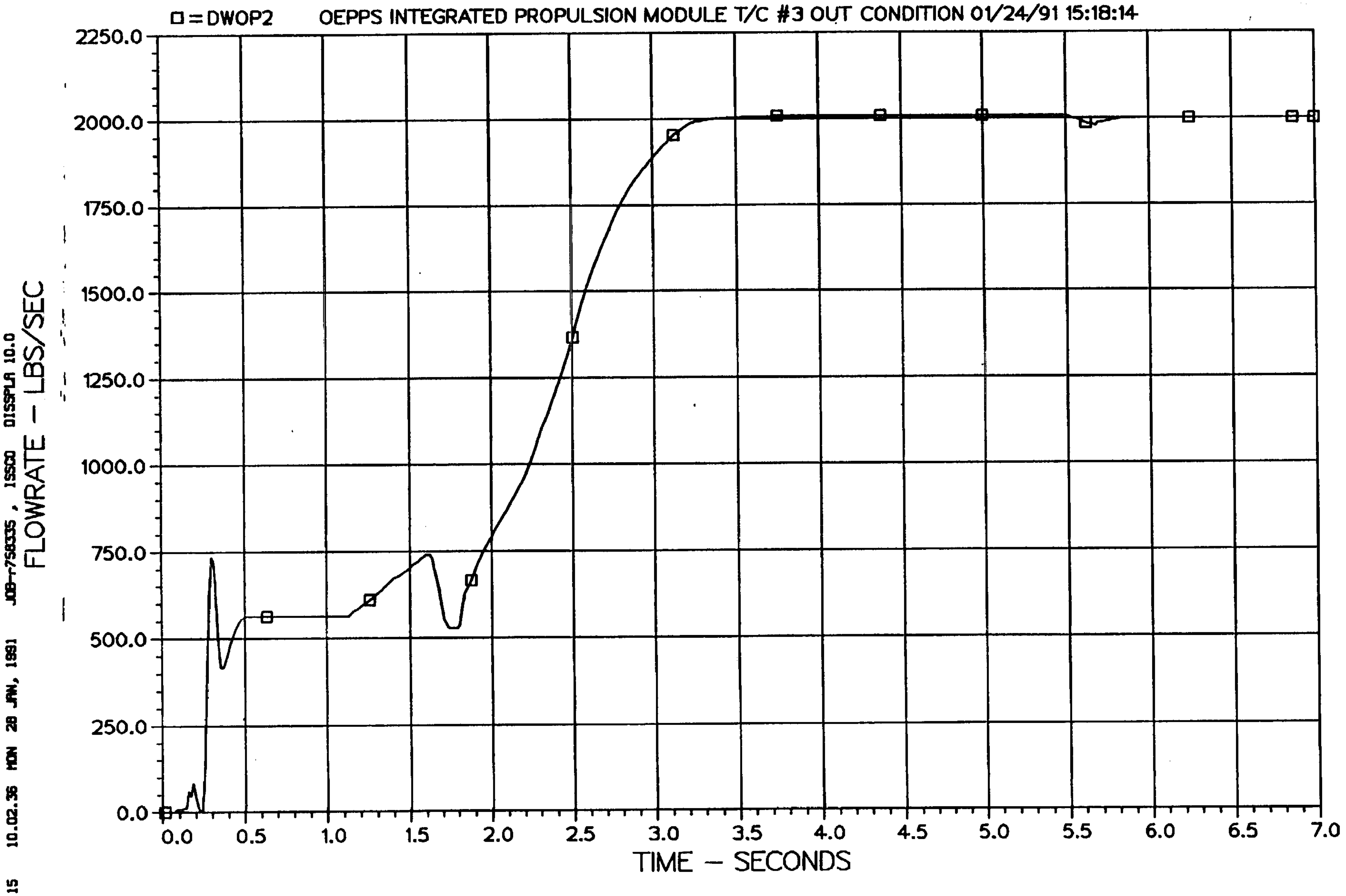
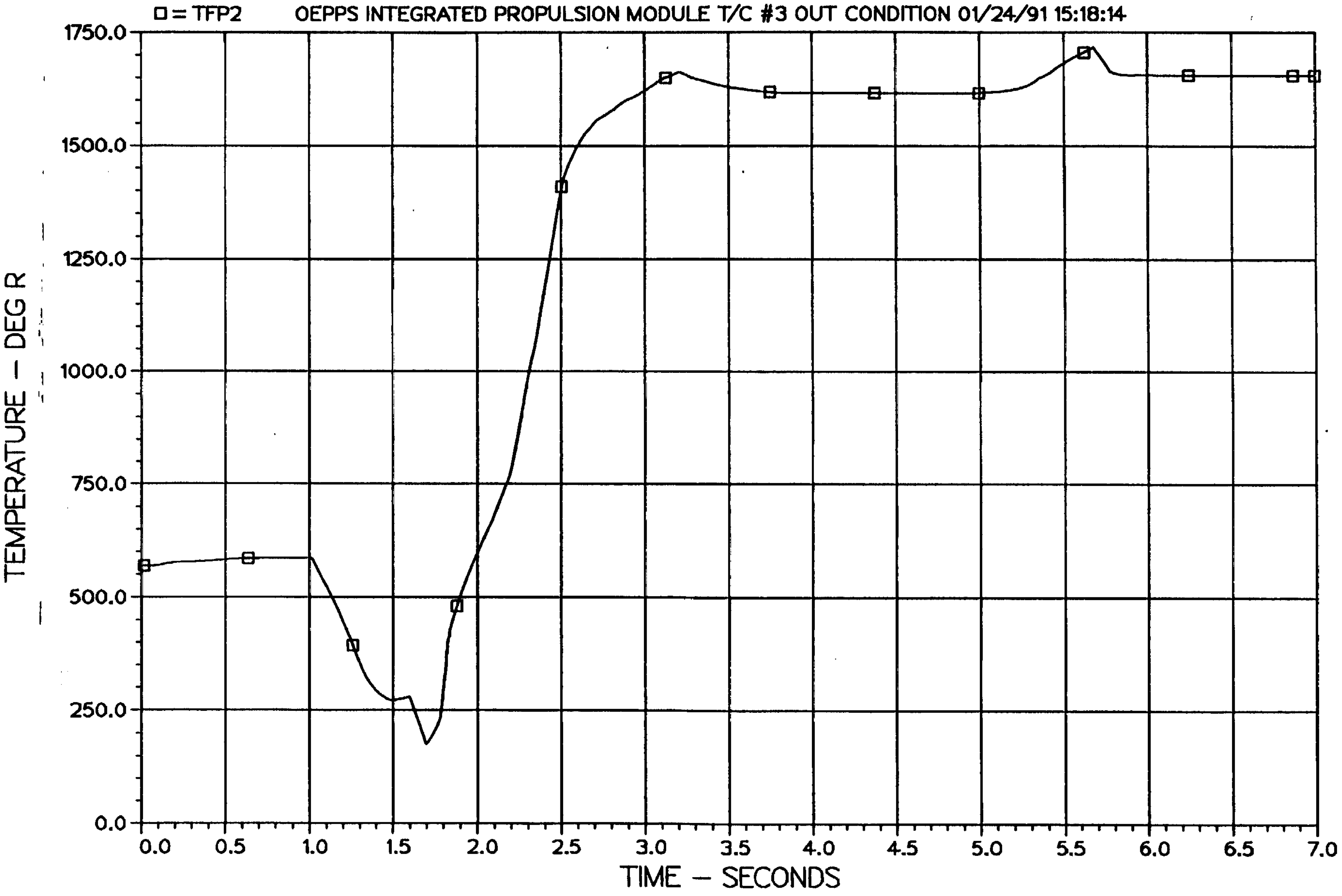


Figure E14

GAS GENERATOR (2) CHAMBER TEMPERATURE



10.02.39 MON 28 JAN, 1991 JOB-758335 , ISSCO DISSPLA 10.0

T 16

Figure 5.15

LOX TURBINE (2) INLET TEMPERATURE

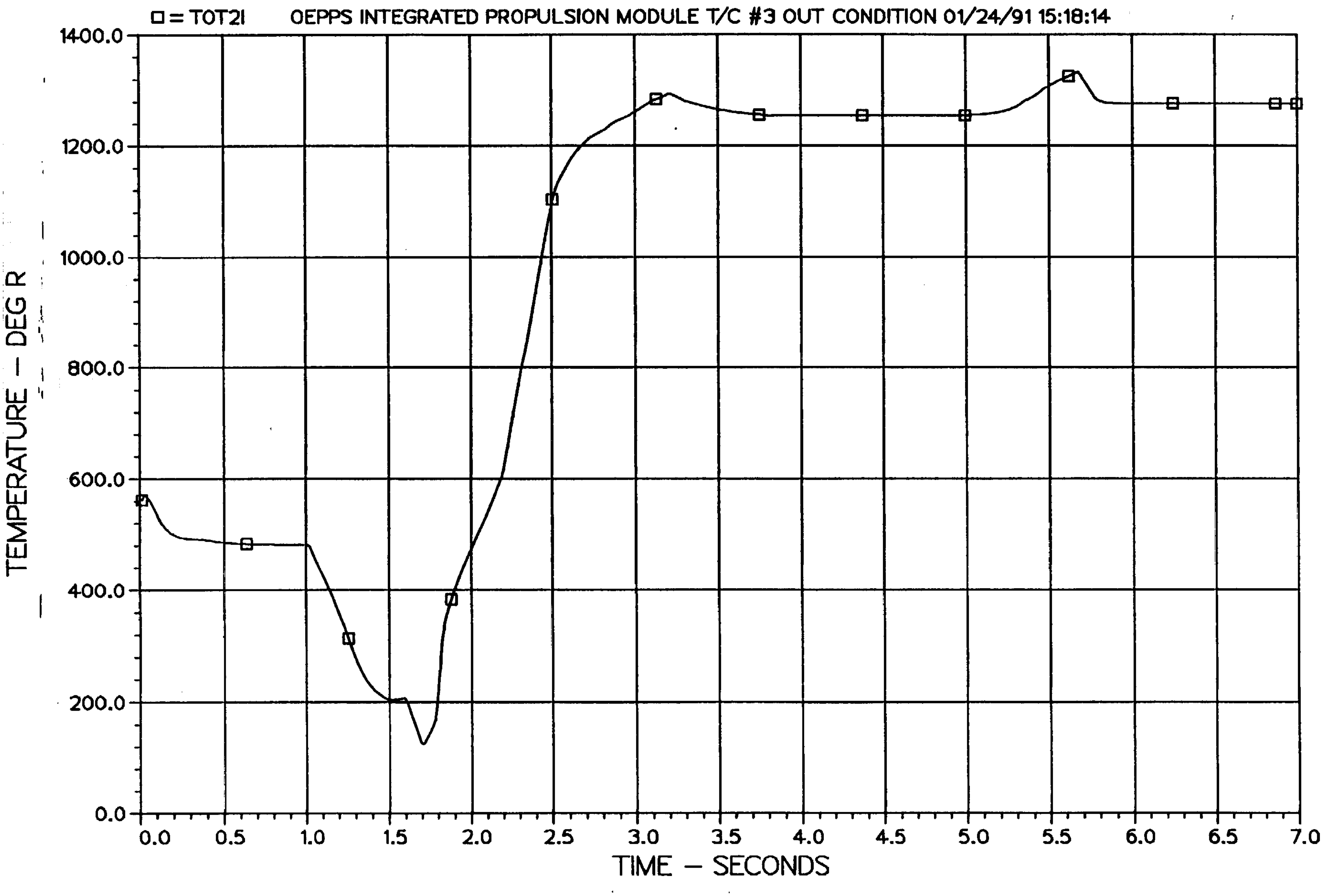
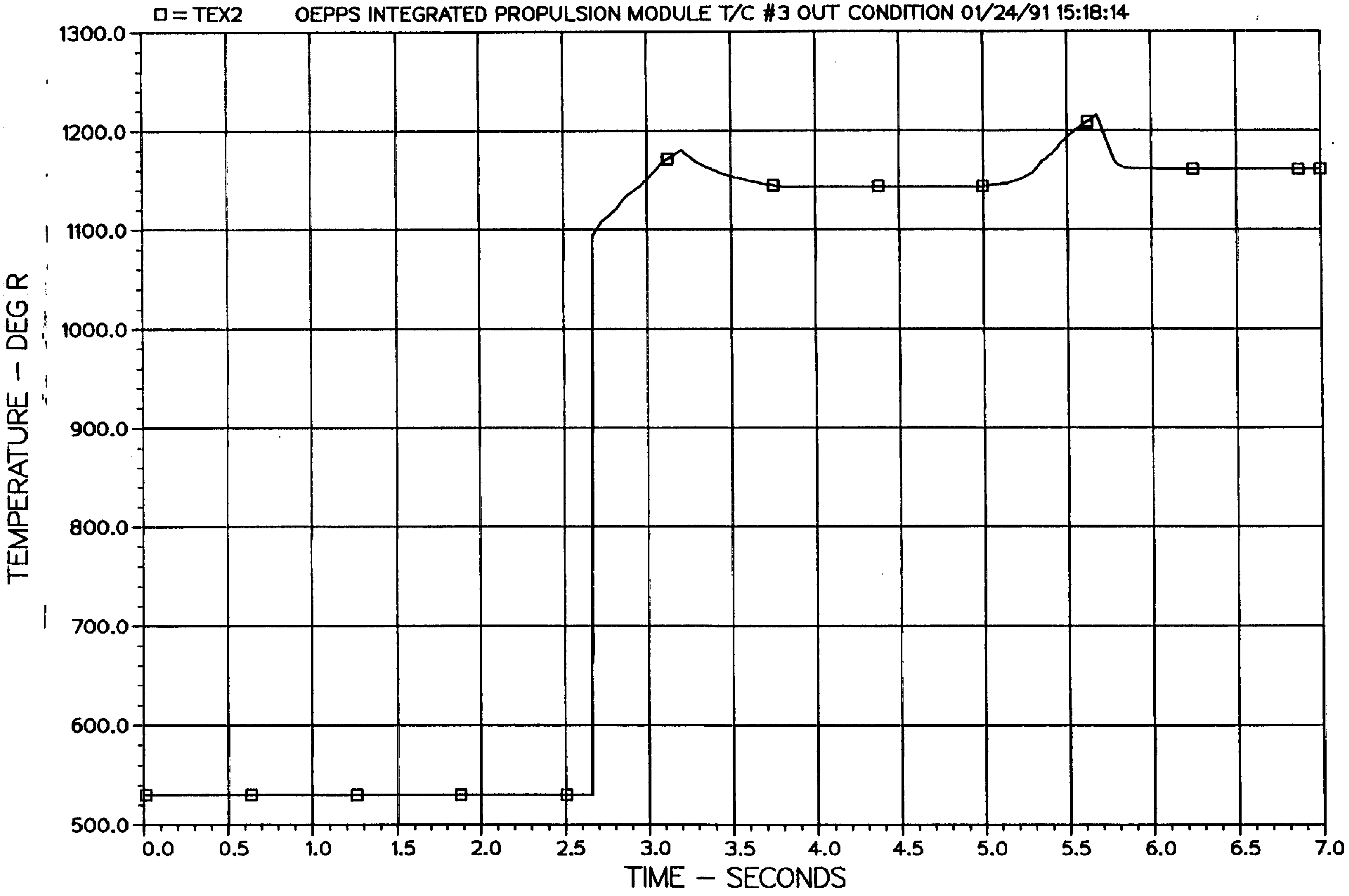


Figure E16

PLOT 17 10.02.42 MON 28 JAN, 1991 JOB-r758335 , ISSCO DISSPLA 10.0

LOX TURBINE (2) DISCHARGE TEMPERATURE



PLOT 18 10.02.45 MON 28 JAN, 1991 JOB-758335 , ISSCO DISSPLA 10.0

Figure E17

FUEL PUMP (2) FLOW COEFFICIENT

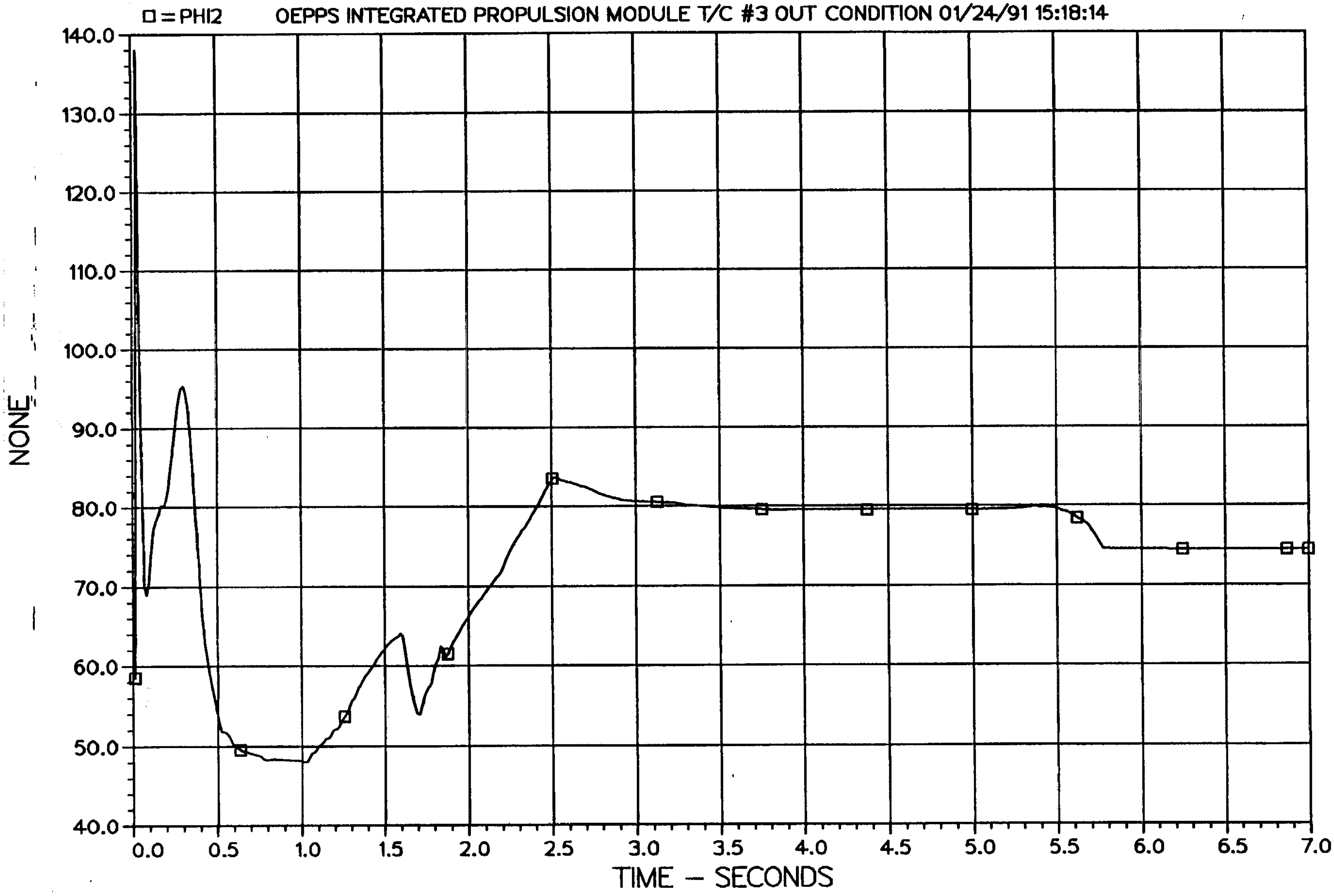
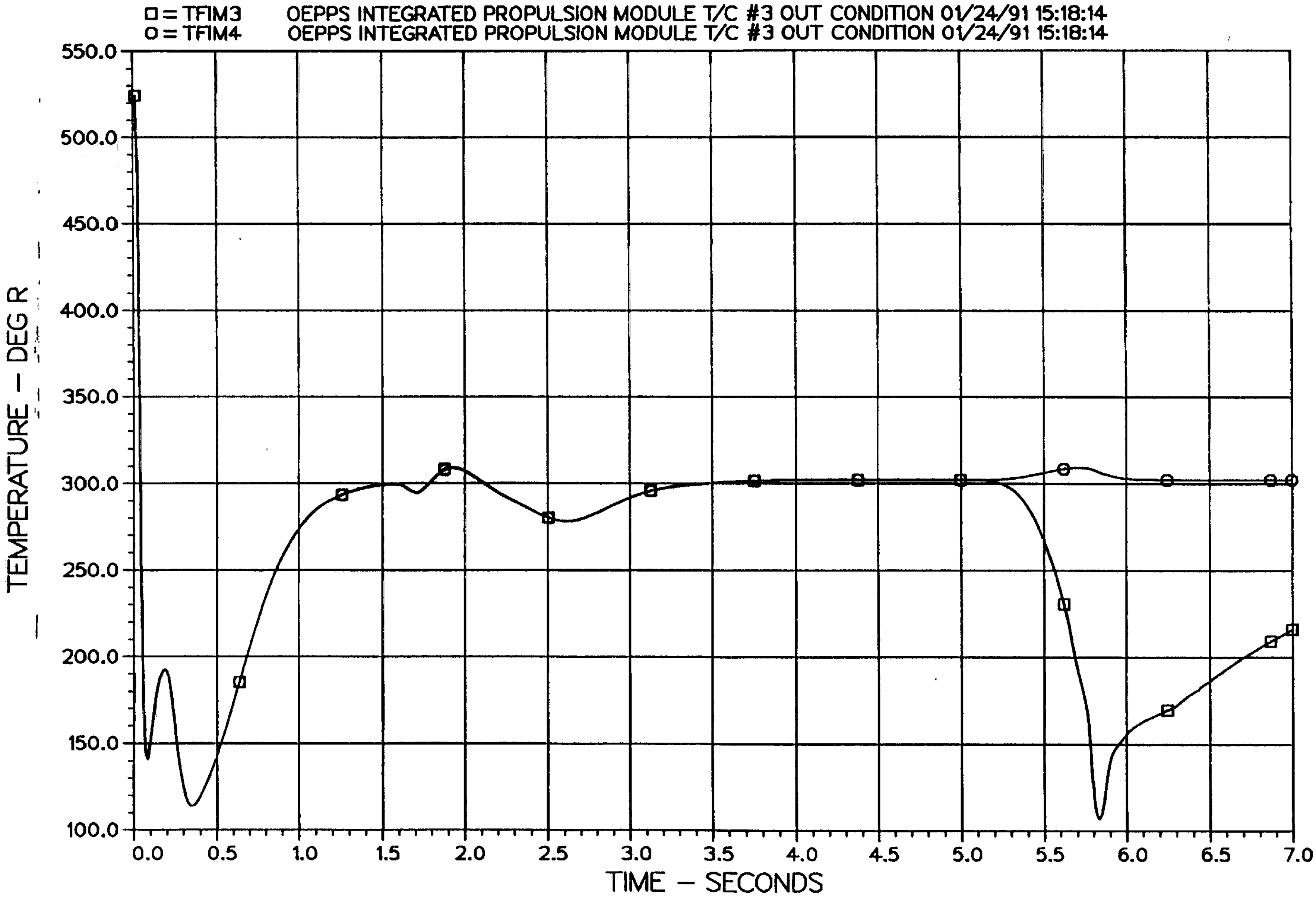


Figure E18

PLOT 19 10.02.48 MON 28 JAN, 1991 JOB-758335 , ISSCO DISSPLA 10.0

FUEL INJECTOR (3,4) TEMPERATURES



PLOT 21 10.02.55 MON 28 JAN, 1991 JOB-r758335 , ISSCO DISSPLA 10.0

Figure E19

HYDROGEN GAS FLOW FOR GG (2) SPIN

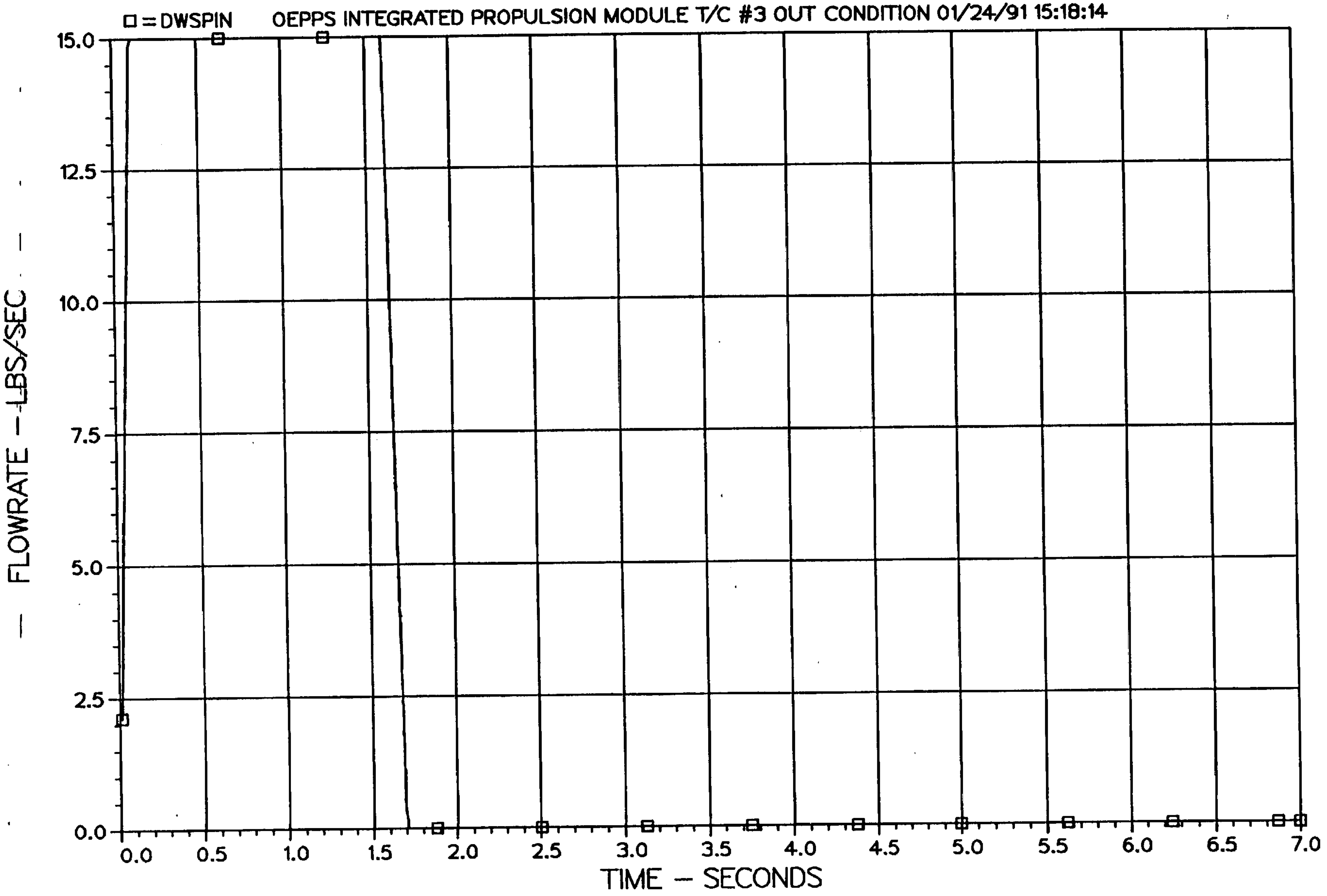


Figure E20

PLOT 21 13.37.01 FRI 1 FEB, 1991 JOB-r758335 , ISSCO DISSPLA 10.0

APPENDIX F

TRANSIENT ANALYTICAL RESULTS FOR THRUST CHAMBER #3 SHUTDOWN

FOR SYSTEM 1

FUEL AND OX PUMP (1) DISCHARGE VALVE POSITIONS

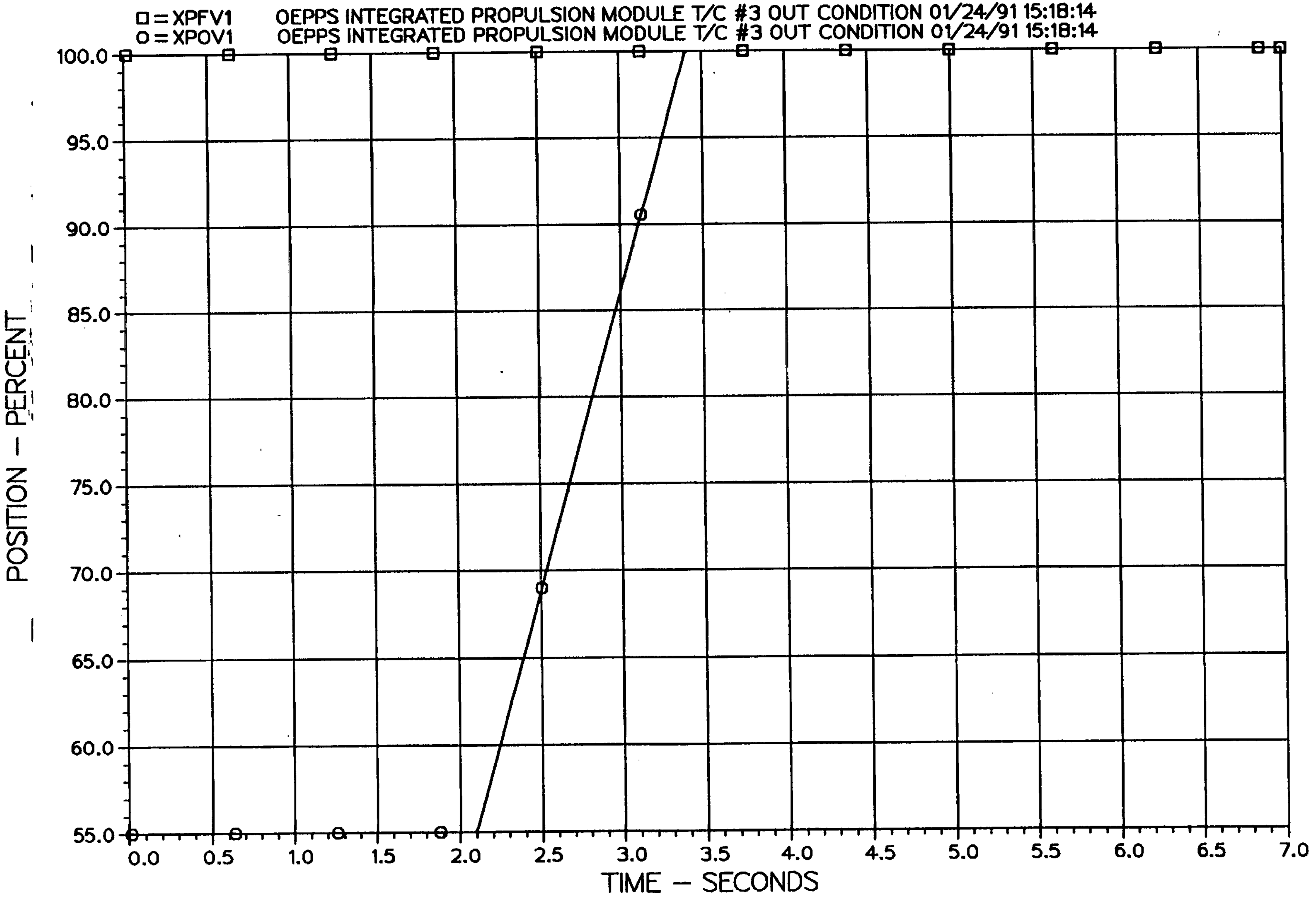


Figure F1

PLOT 2 15.57.37 FRI 25 JAN, 1991 JOB-758335 , ISSCO DISSPLA 10.0

FUEL AND OX GAS GENERATOR (1) VALVE POSITIONS

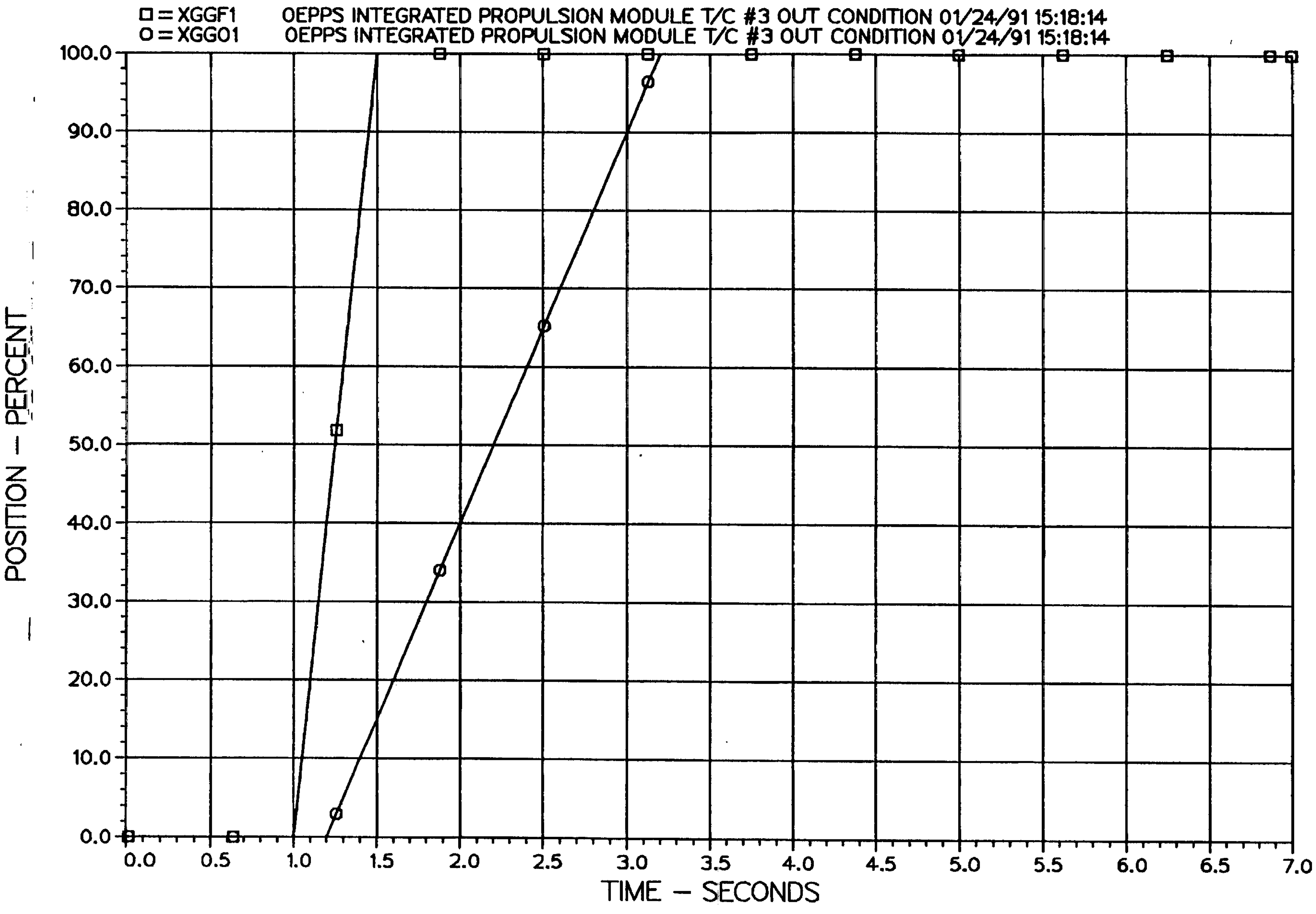


Figure 2

OT 5 15.58.10 FRI 25 JAN, 1991 JOB-758335 , ISSCO DISSPLA 10.0

T/C (1,2) INLET FUEL VALVE POSITIONS

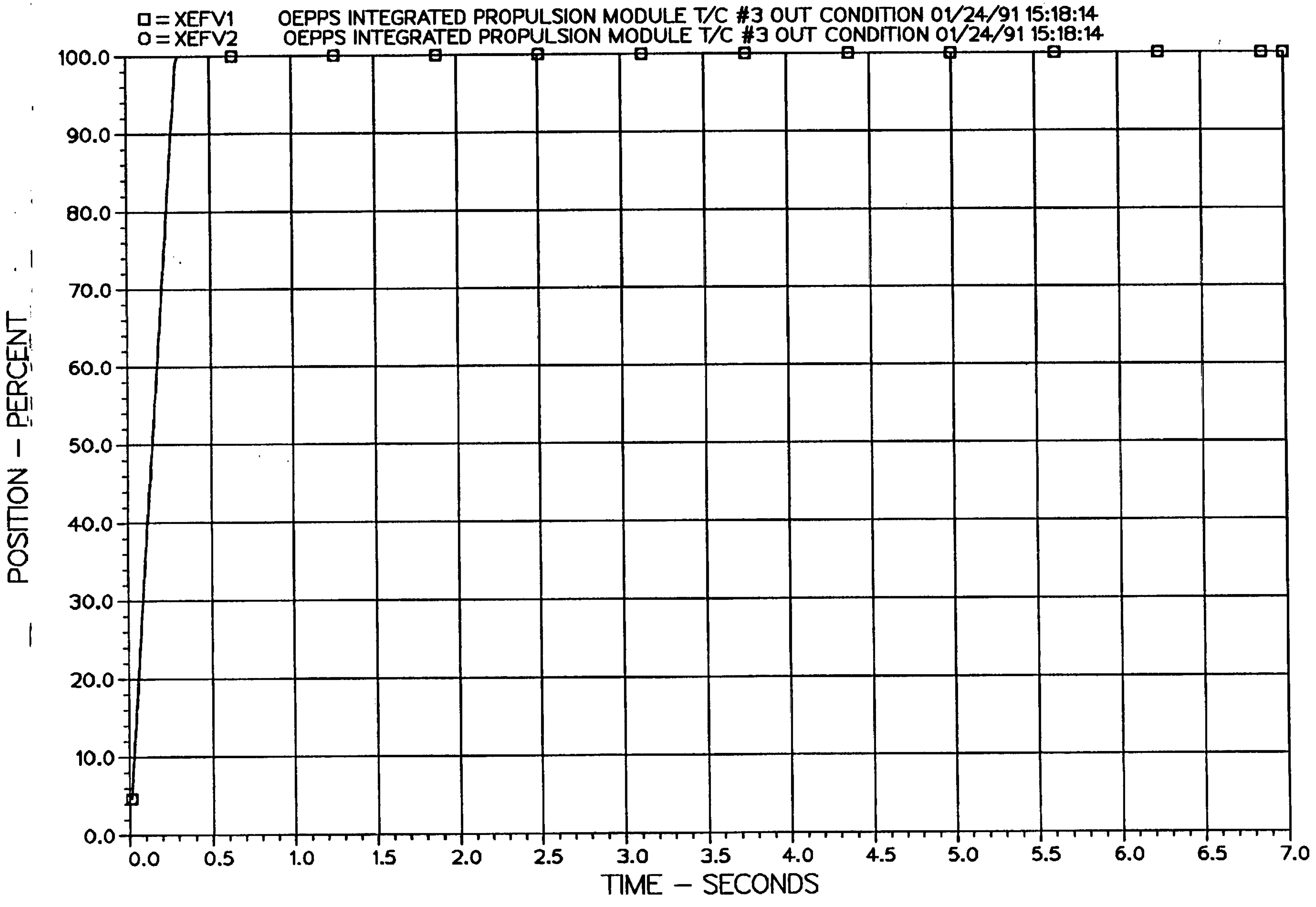


Figure F3

PLOT 3 15.57.46 FRI 25 JAN, 1991 JOB-r758335 , ISSCO DISSPLA 10.0

T/C (1,2) INLET OX VALVE POSITIONS

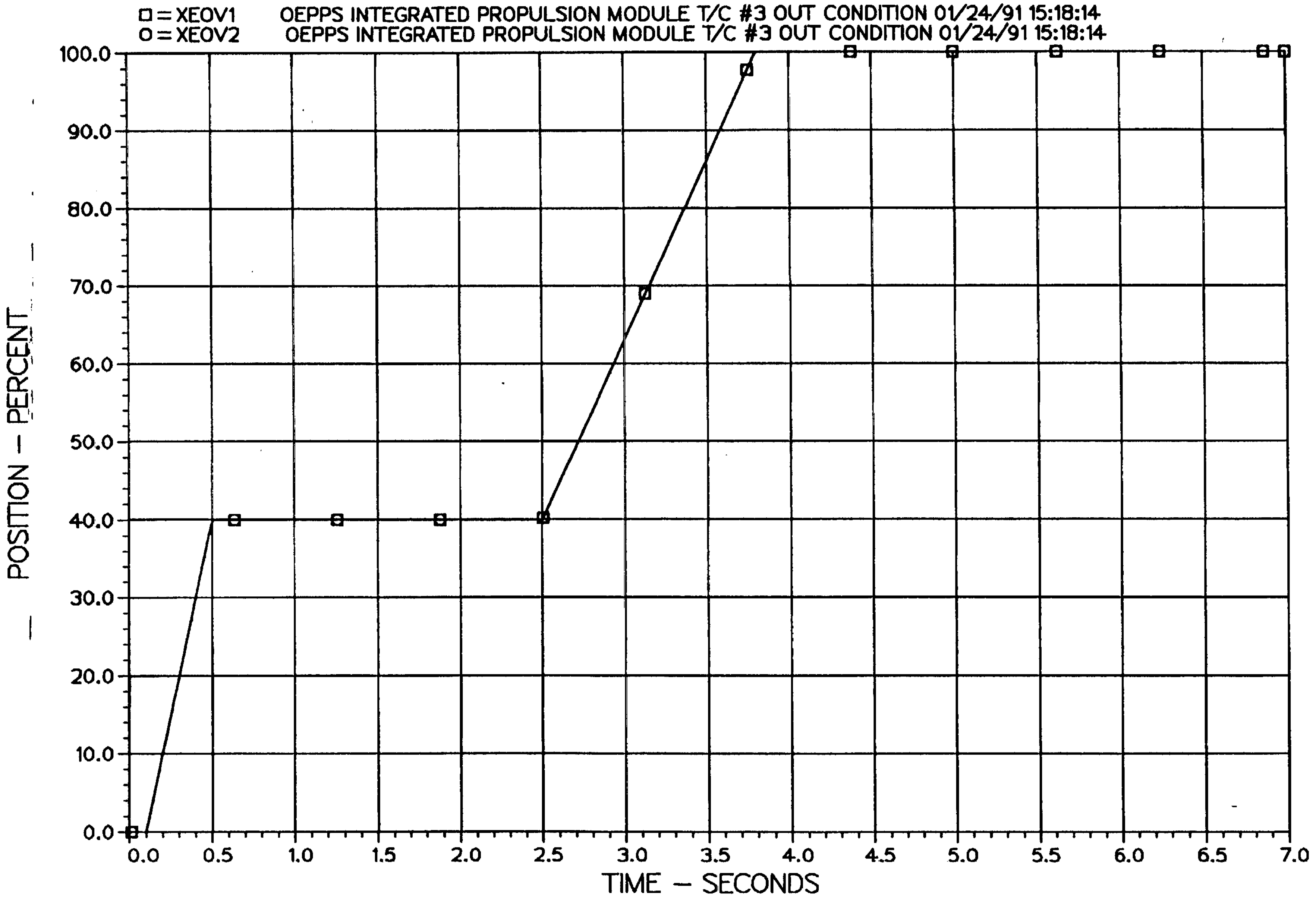


Figure F4

T/C (1,2) MAIN CHAMBER PRESSURES

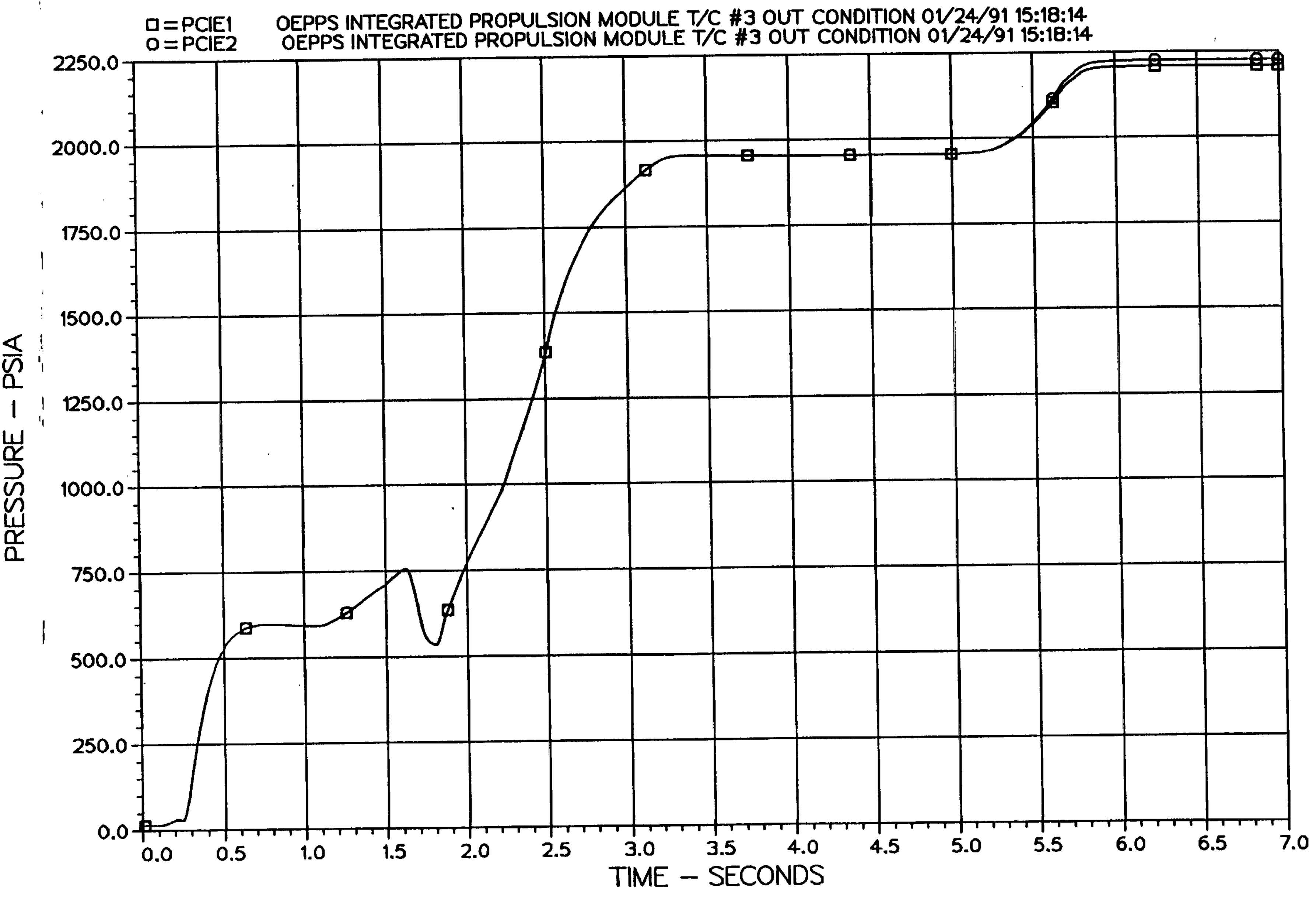
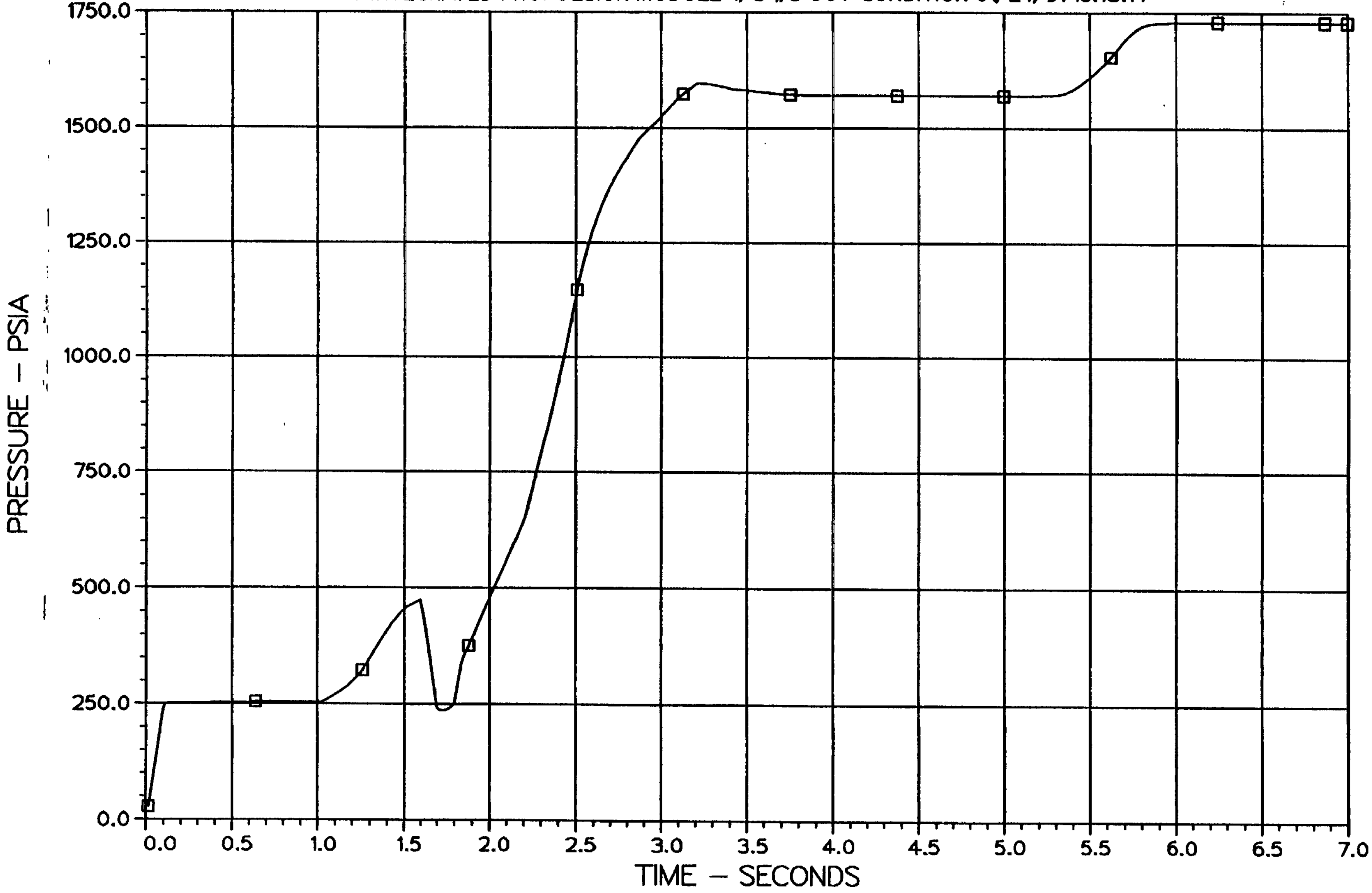


Figure F5

PLOT 6 15.58.19 FRI 25 JAN, 1991 JOB-758335 , ISSCO DISSPLA 10.0

GAS GENERATOR (1) CHAMBER PRESSURE

□ = PFP1 OEPPS INTEGRATED PROPULSION MODULE T/C #3 OUT CONDITION 01/24/91 15:18:14



15.58.25 FRI 25 JAN, 1991 JOB-r758335 , ISSCO DISSPLA 10.0

PLOT 7

Figure F6

T/C (1,2) MIXTURE RATIOS

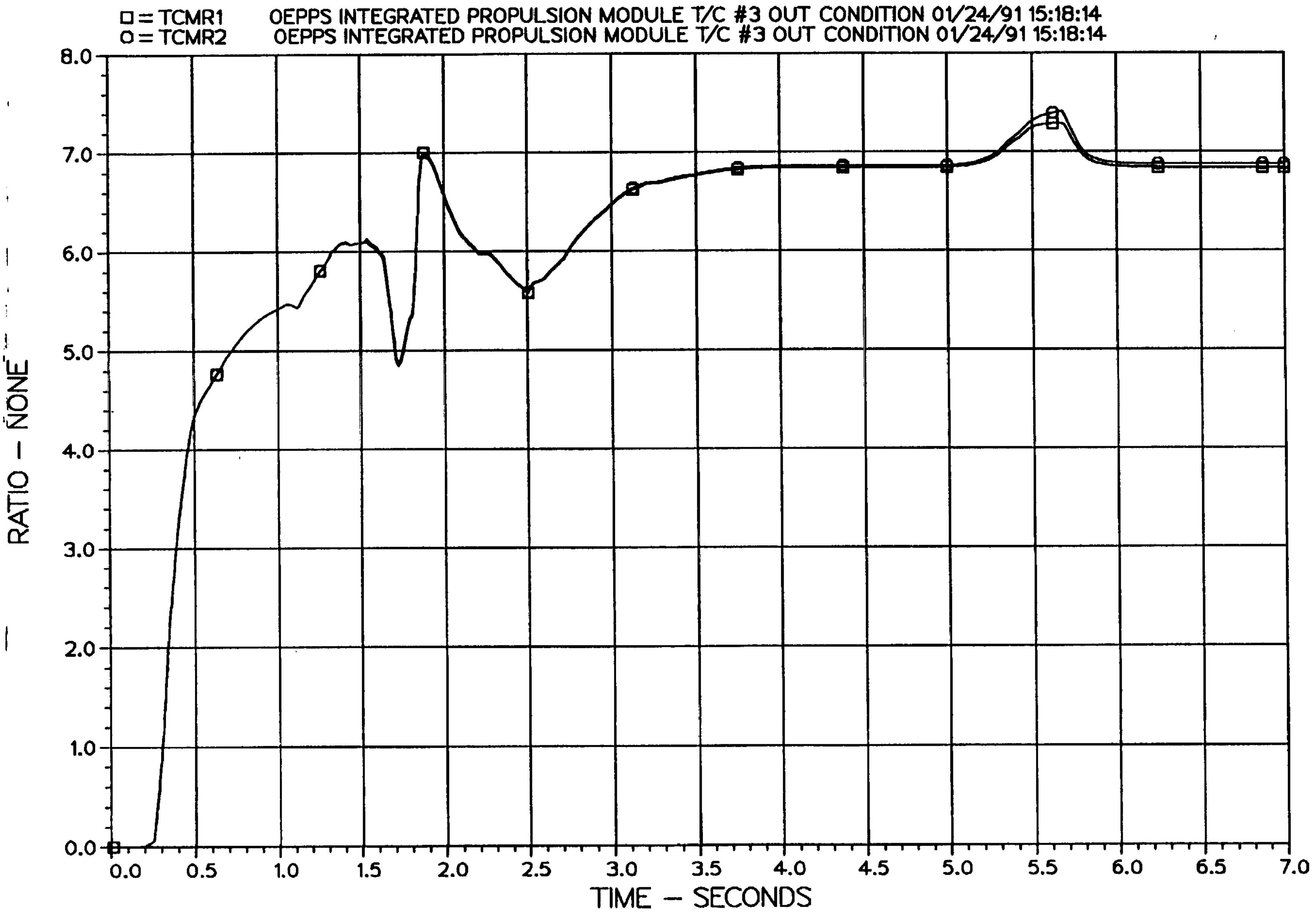


Figure F7

PLOT 8 15.58.33 FRI 25 JAN, 1991 JOB-758335 , ISSCO DISSPLA 10.0

GAS GENERATOR (1) MIXTURE RATIO

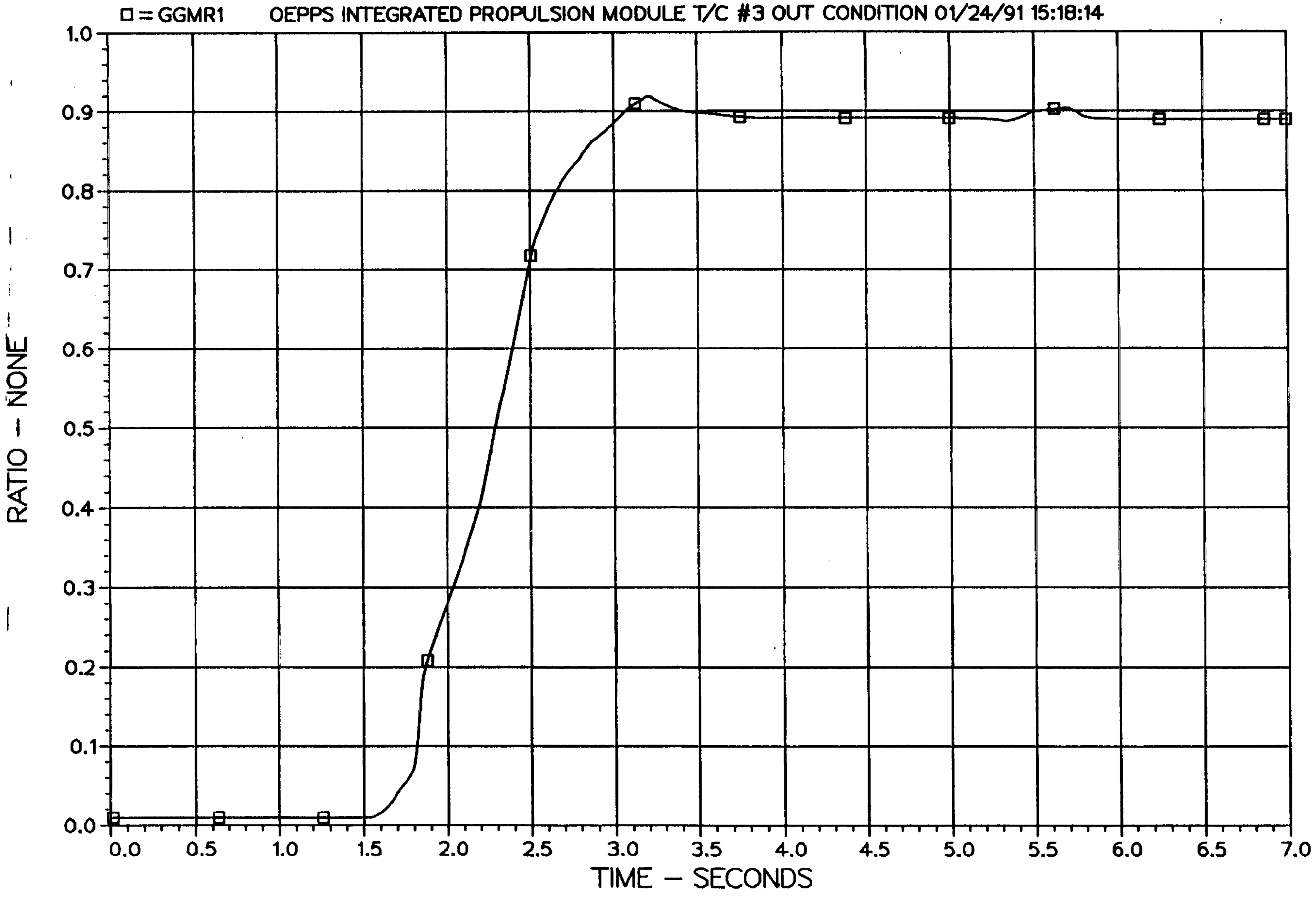


Figure F8

15.58.39 FRI 25 JAN, 1991 JOB-r758335 , ISSCO DISSPLA 10.0

OT 9

FUEL PUMP (1) SPEED

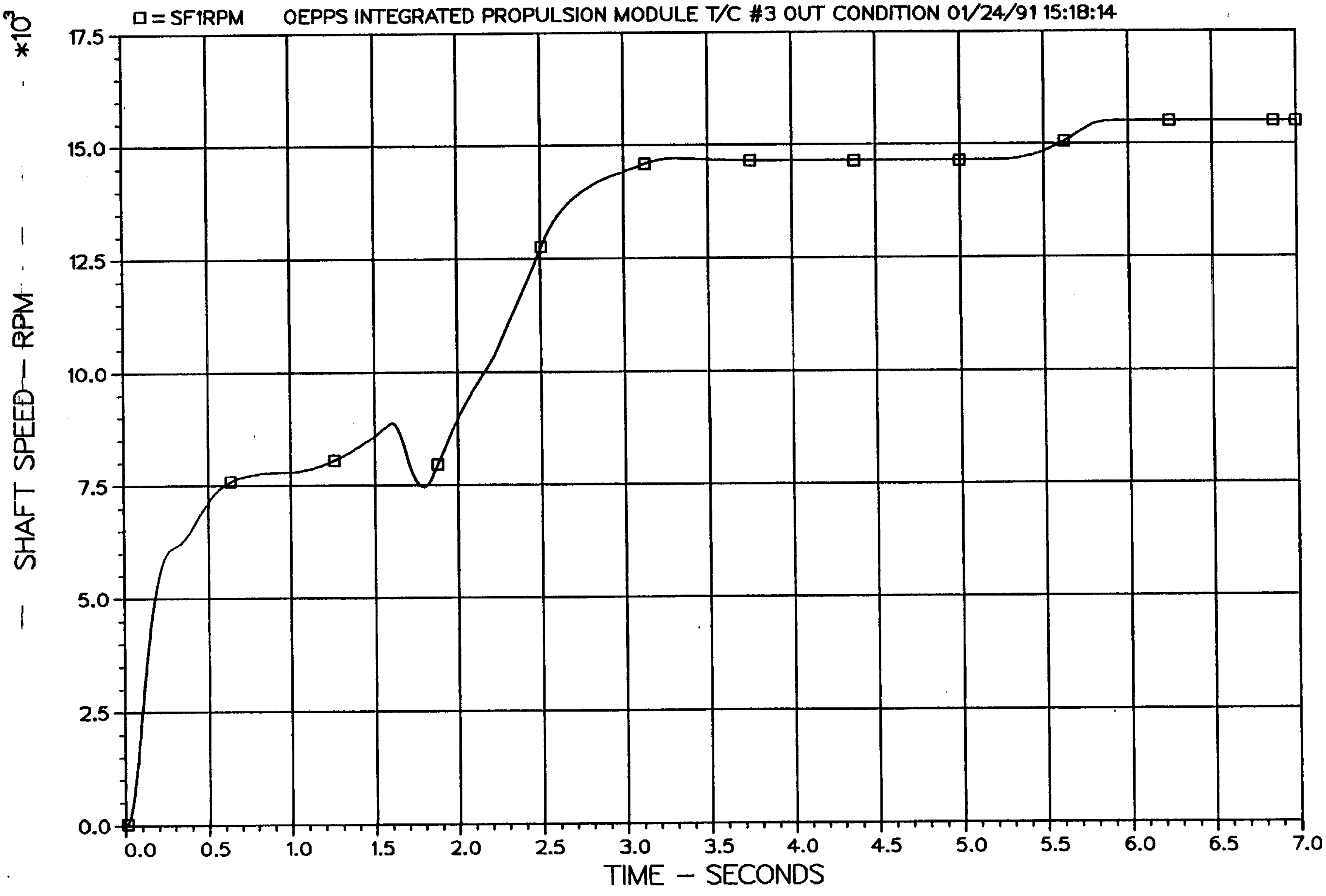


Figure F9

PLOT 10 15.58.46 FRI 25 JAN, 1991 JOB-758335 , ISSCO DISSPLA 10.0

LOX PUMP (1) SPEED

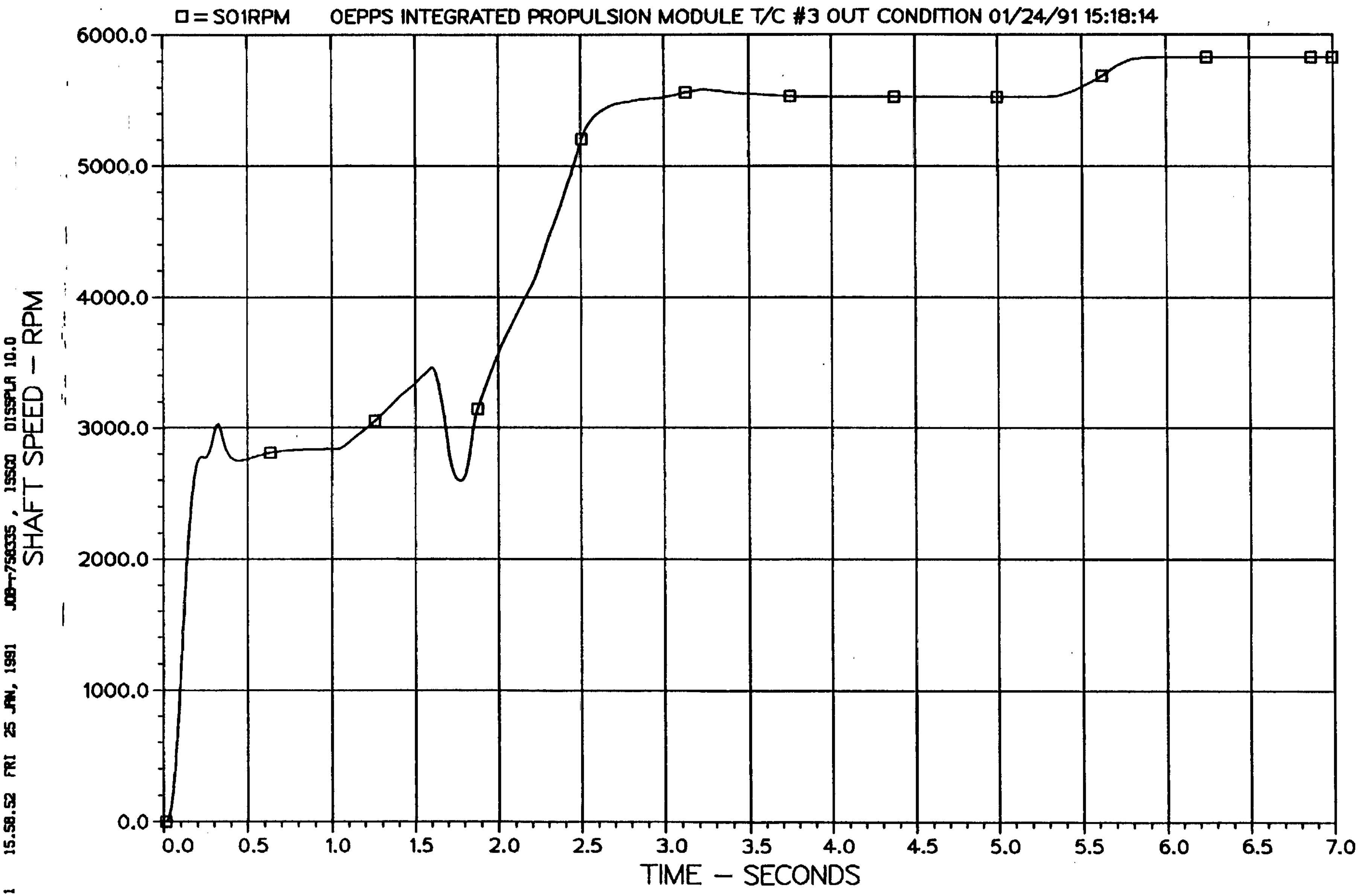


Figure E10

FUEL PUMP (1) FLOW COEFFICIENT

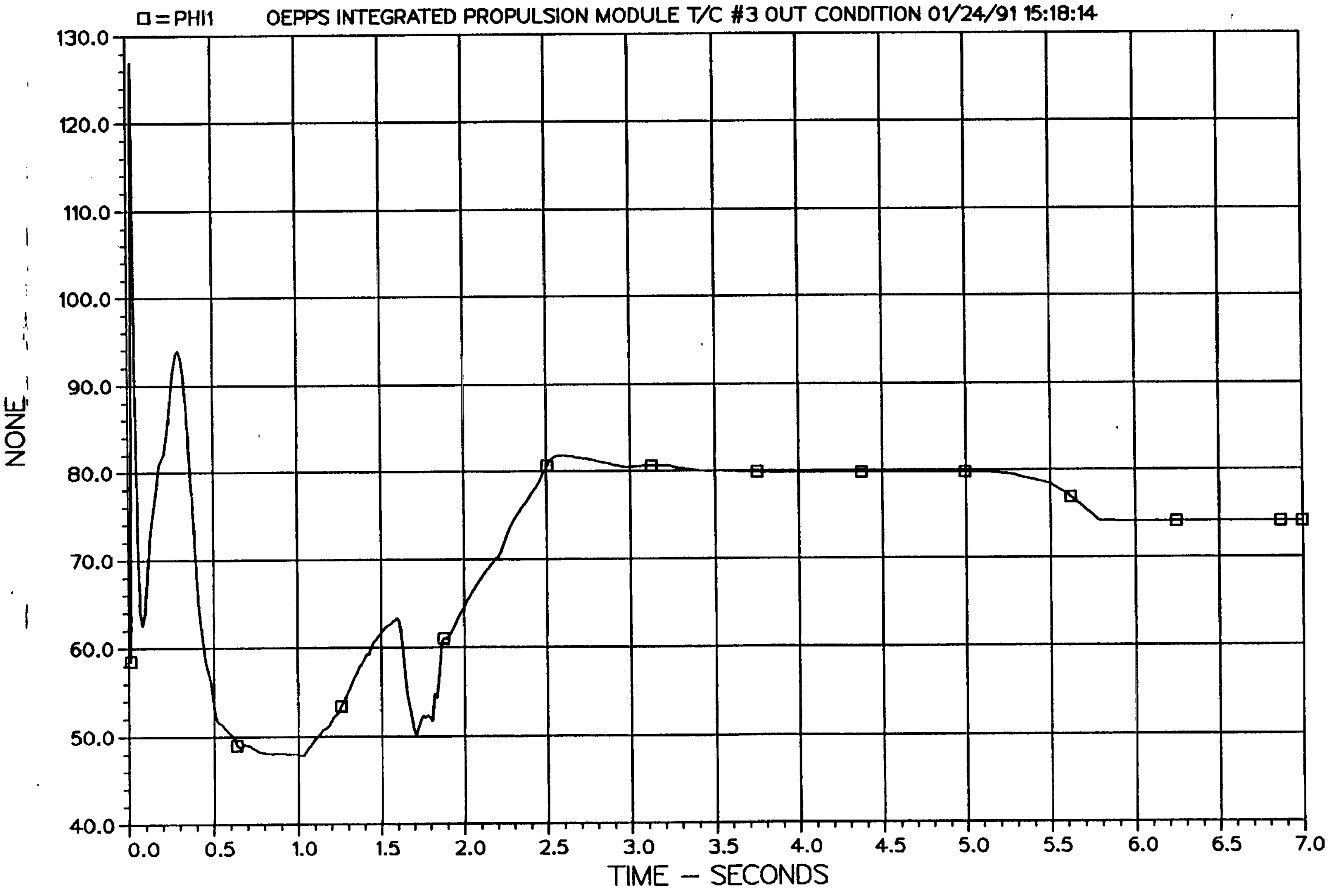


Figure F11

PLOT 19 16.00.07 FRI 25 JAN, 1991 JOB-758335 , ISSCO DISSPLA 10.0

FUEL INJECTOR (1,2) TEMPERATURES

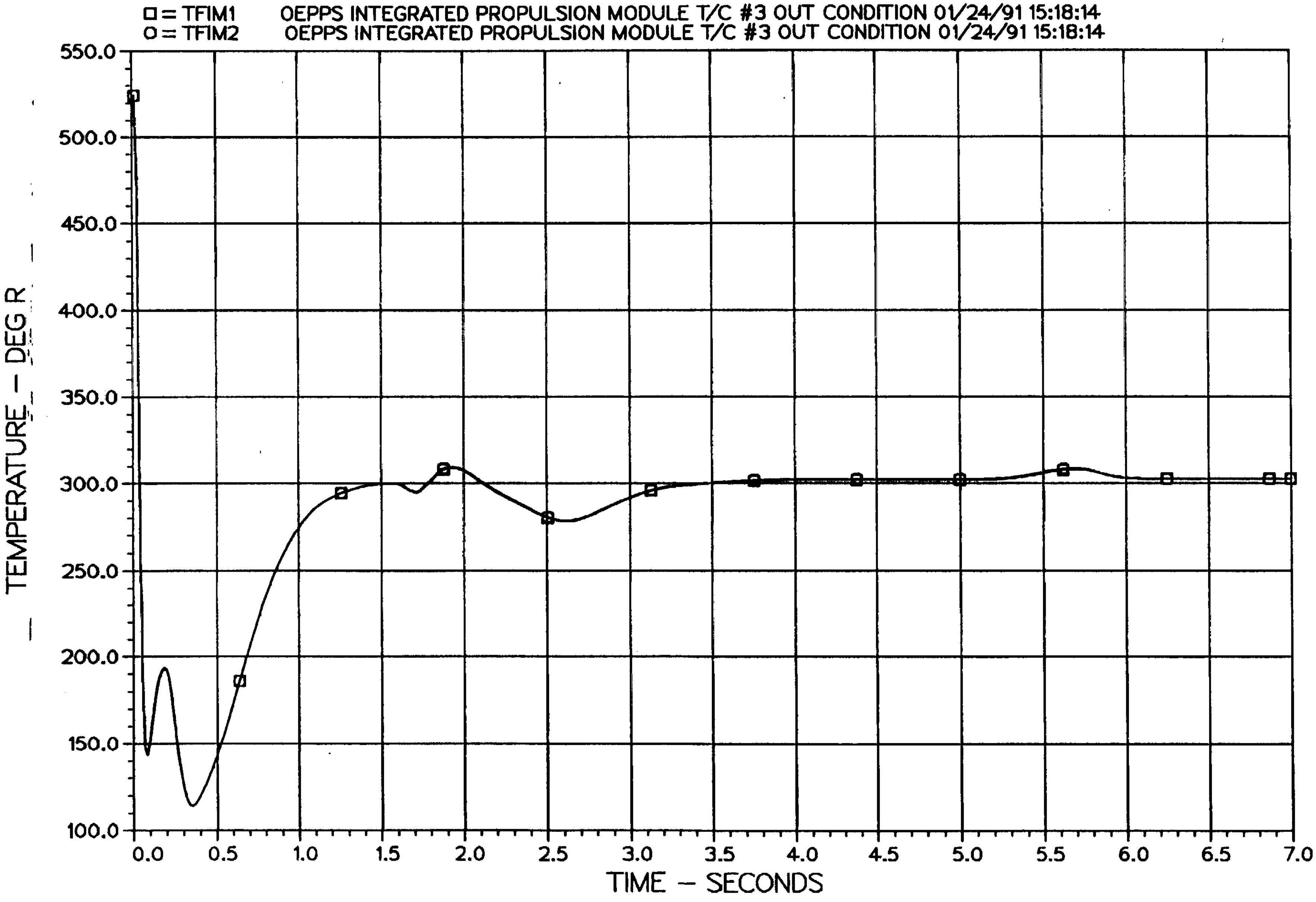


Figure E12

OT 21 16.00.30 FRI 25 JAN, 1991 JOB-758335 , ISSCO DISSPLA 10.0

HYDROGEN GAS FLOW FOR GG (1) SPIN

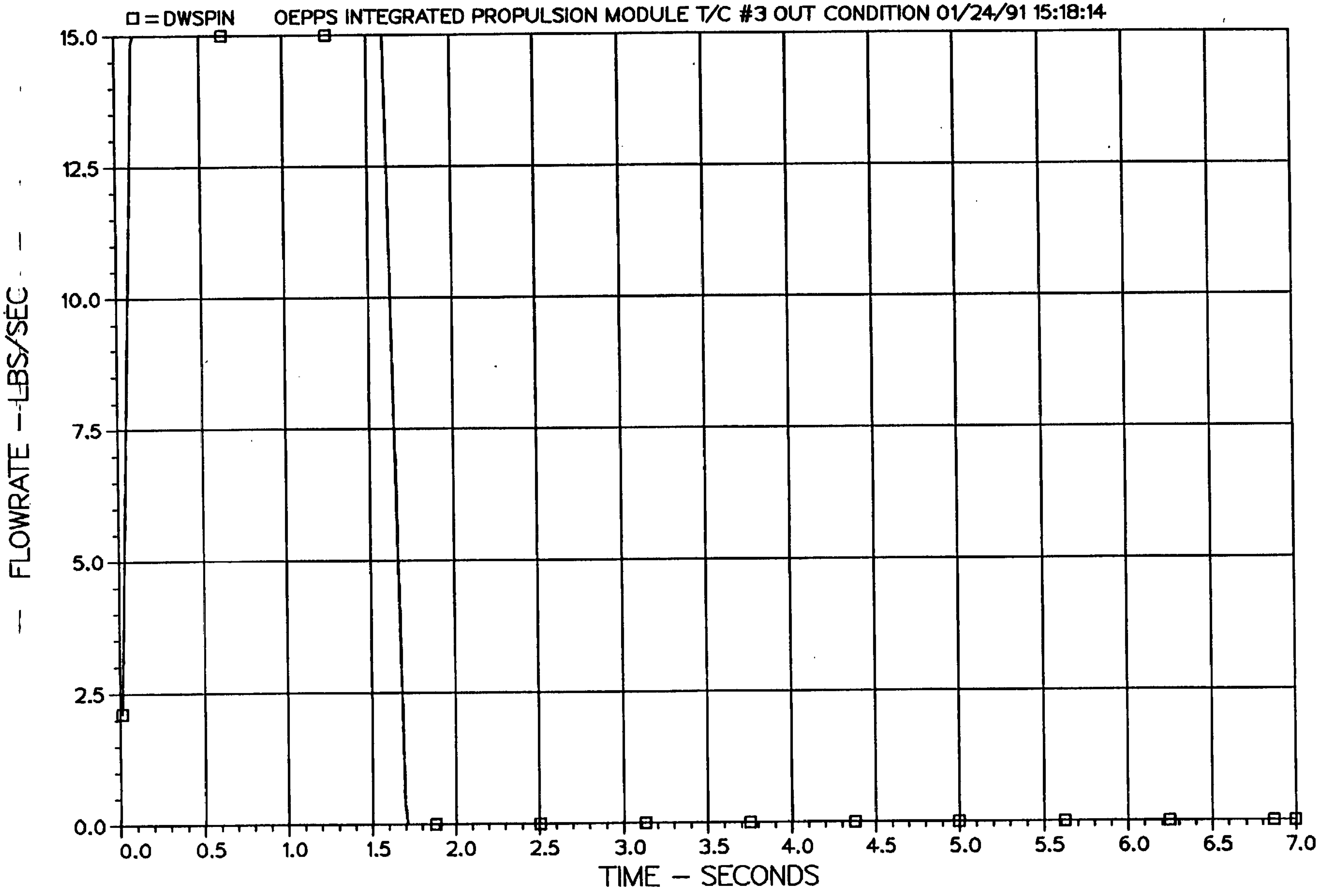


Figure F13

PLOT 21 13.14.56 FRI 1 FEB, 1991 JOB-r758335 , ISSCO DISSPLA 10.0

APPENDIX G

TRANSIENT ANALYTICAL RESULTS FOR THRUST CHAMBER #3 SHUTDOWN

FOR SYSTEM 3

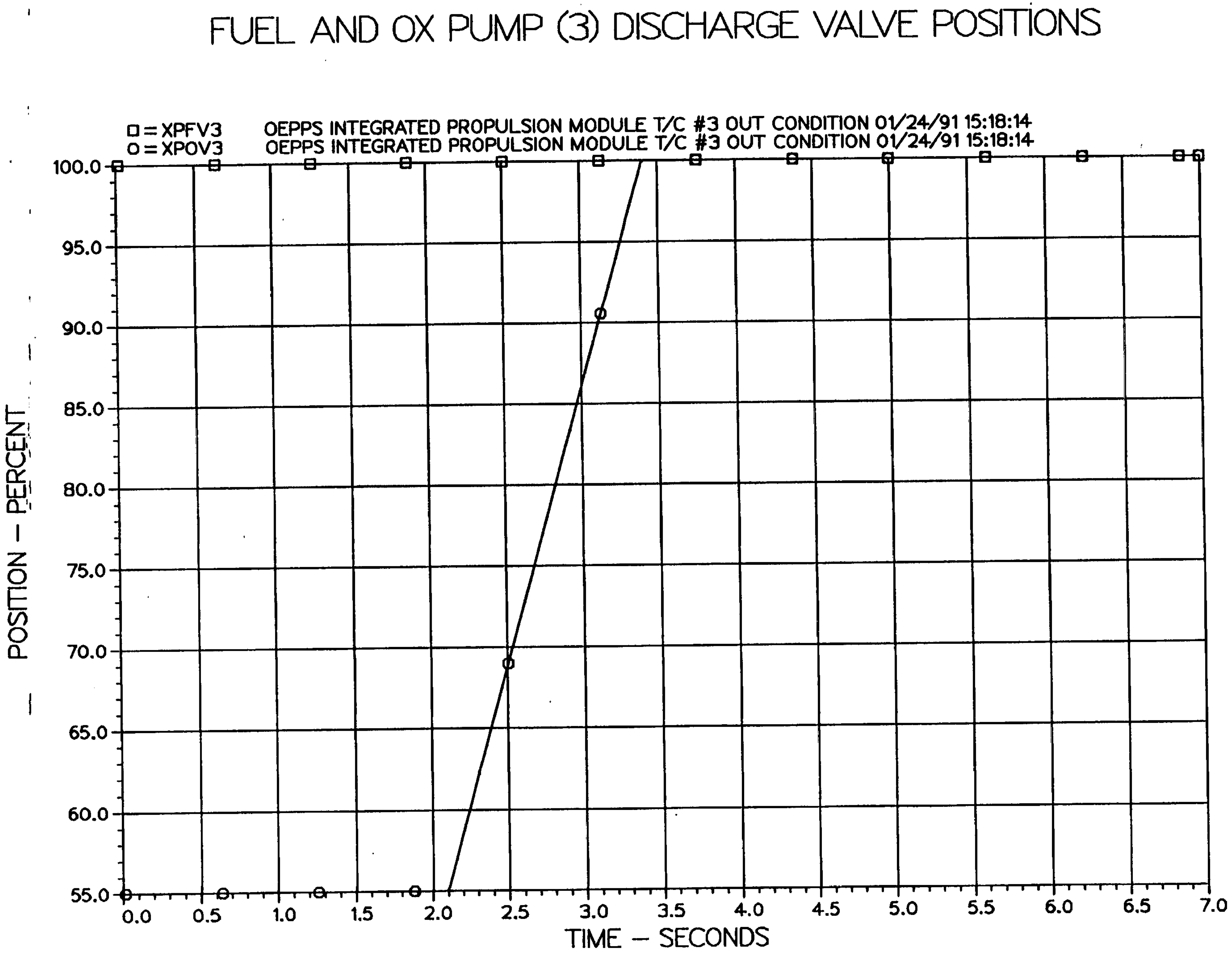


Figure 61

10.08.10 MON 28 JAN, 1991 JOB-758335 , ISSCO DISSPLA 10.0

PLOT 2

FUEL AND OX GAS GENERATOR (3) VALVE POSITIONS

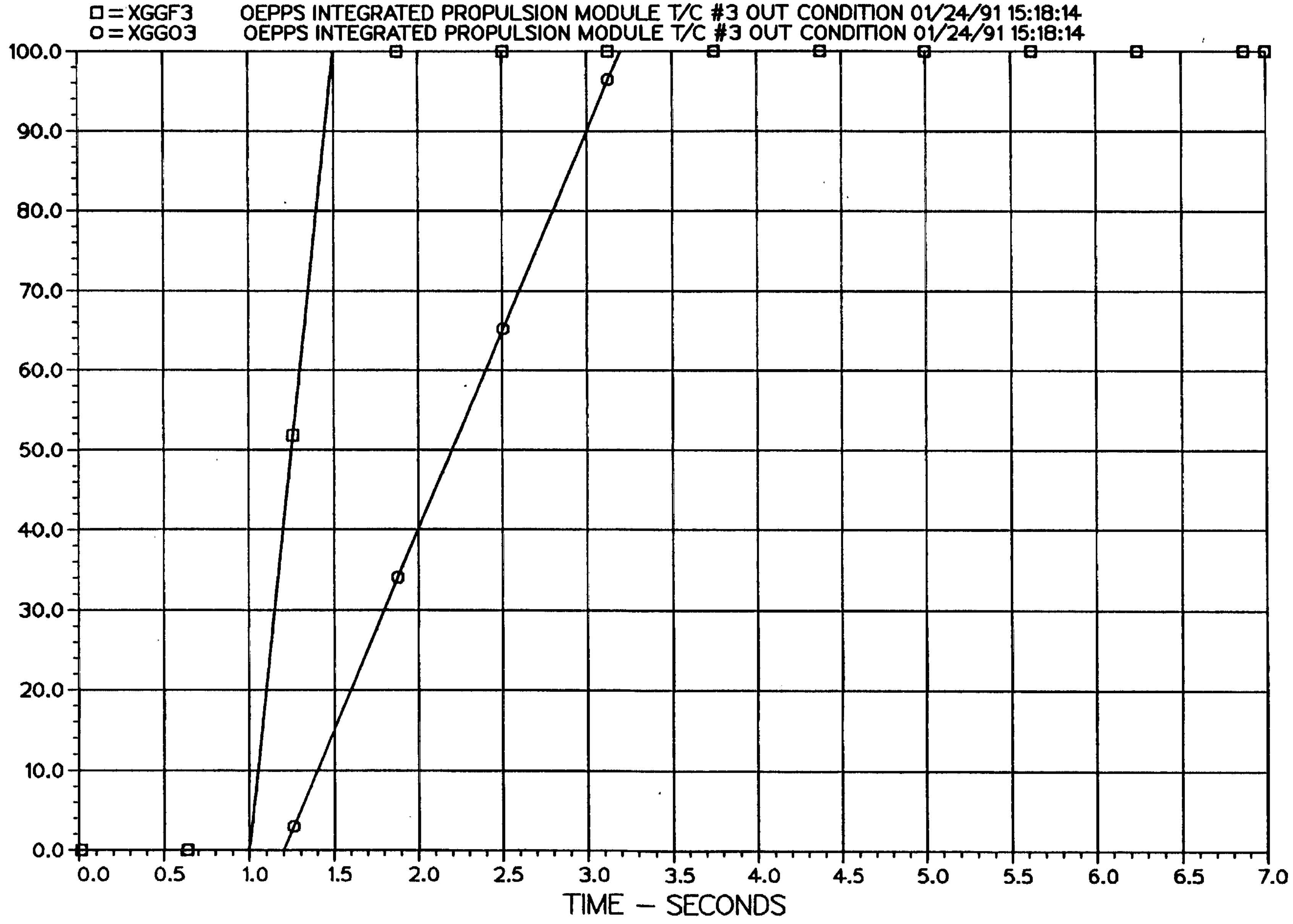


Figure G

T/C (5,6) INLET FUEL VALVE POSITIONS

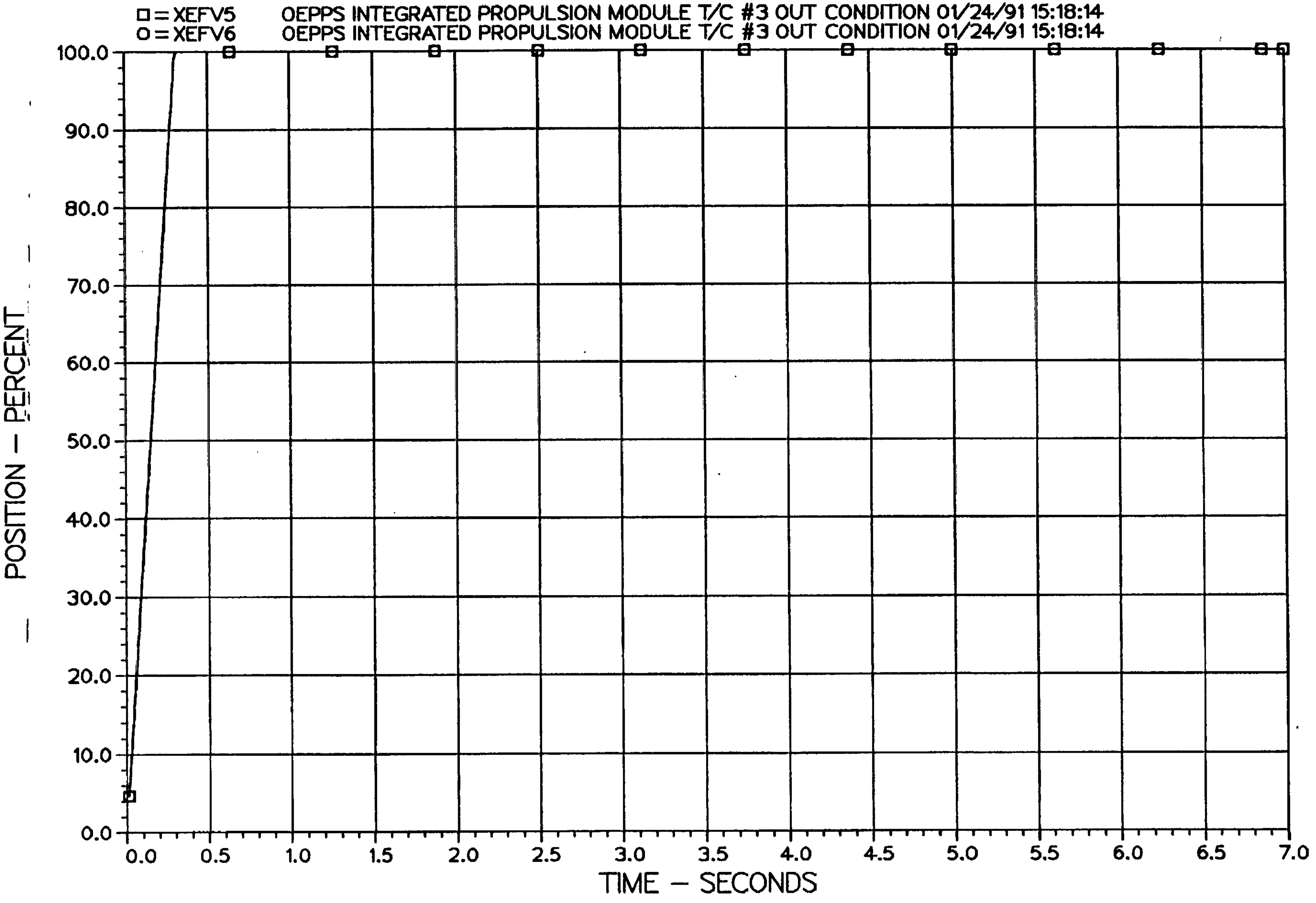


Figure G3

PLOT 3 10.08.17 MON 28 JAN, 1991 JOB-758335 , ISSCO DISSPLA 10.0

T/C (5,6) INLET OX VALVE POSITIONS

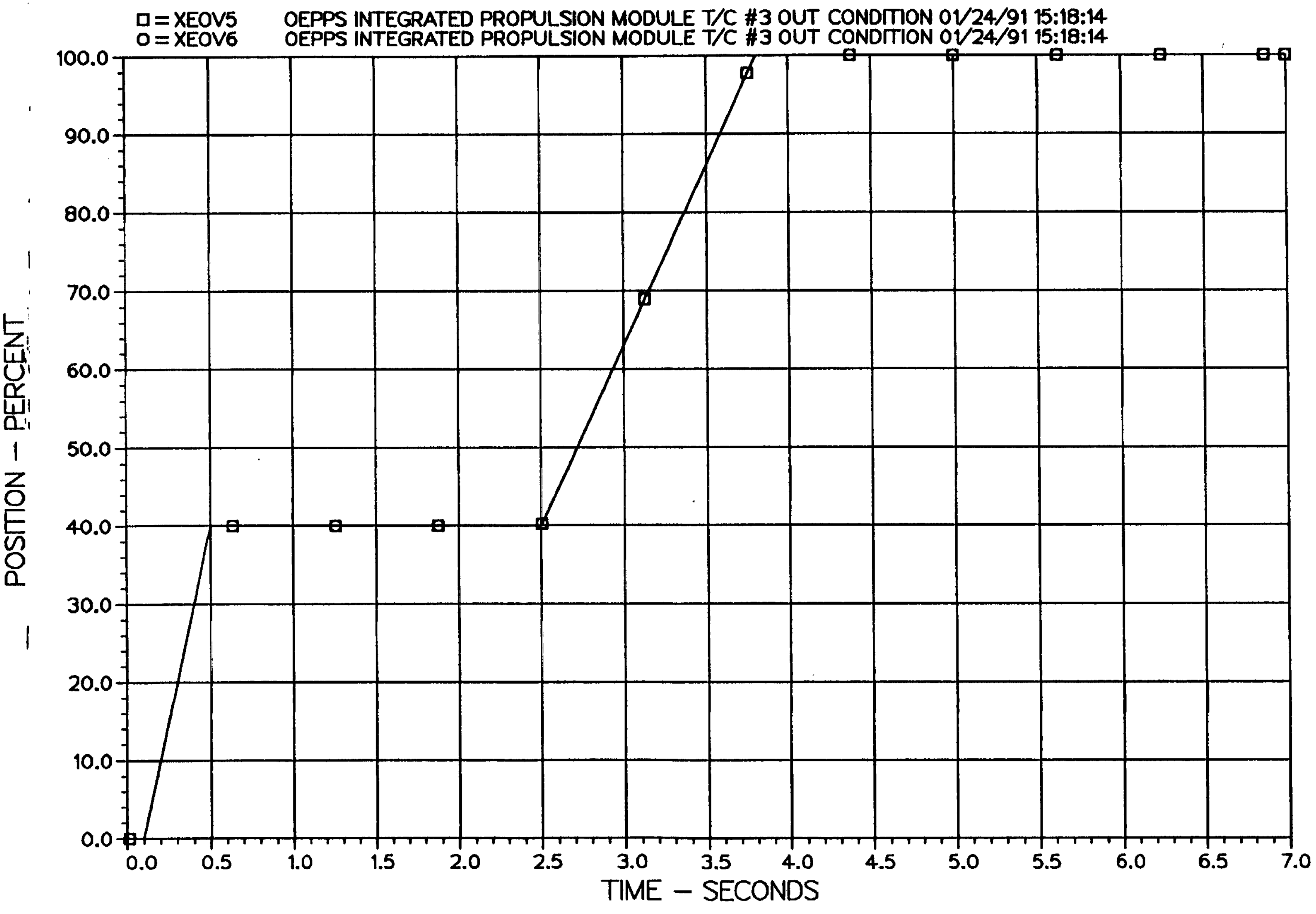


Figure 64

OT 4 10.08.23 MON 28 JAN, 1991 JOB-758335 , ISSCO DISSPLA 10.0

T/C (5,6) MAIN CHAMBER PRESSURES

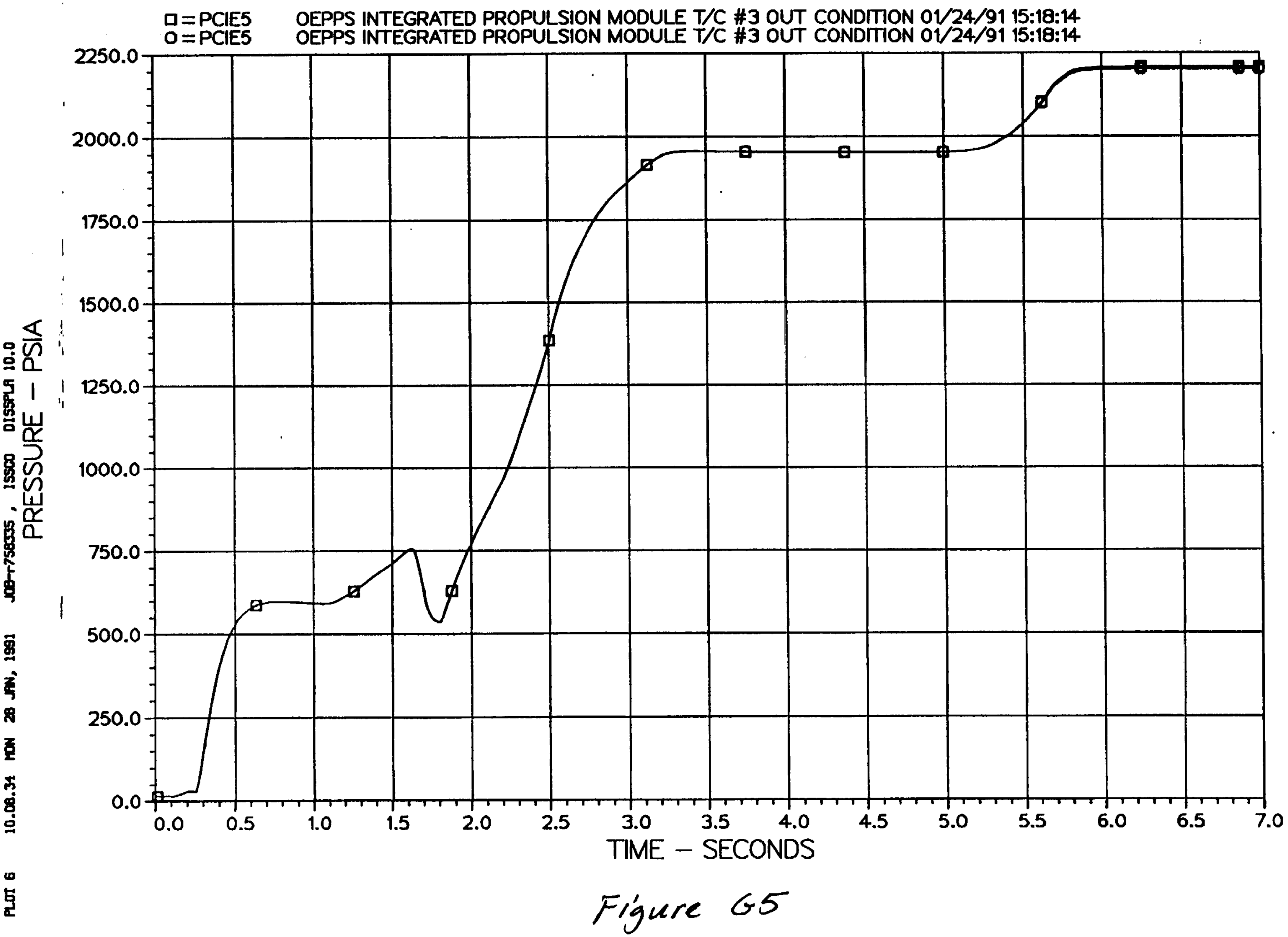


Figure G5

GAS GENERATOR (3) CHAMBER PRESSURE

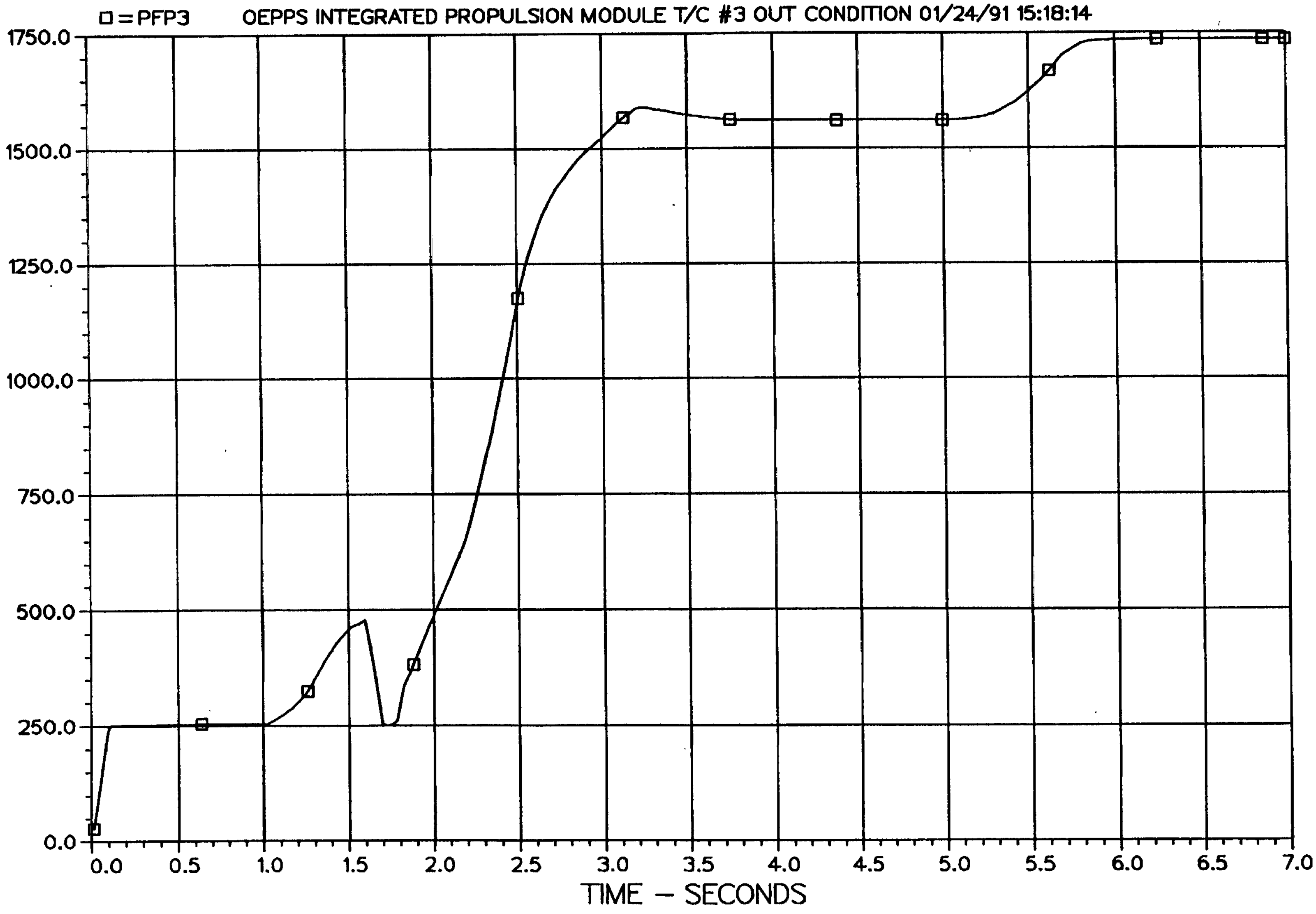


Figure G6

T/C (5,6) MIXTURE RATIOS

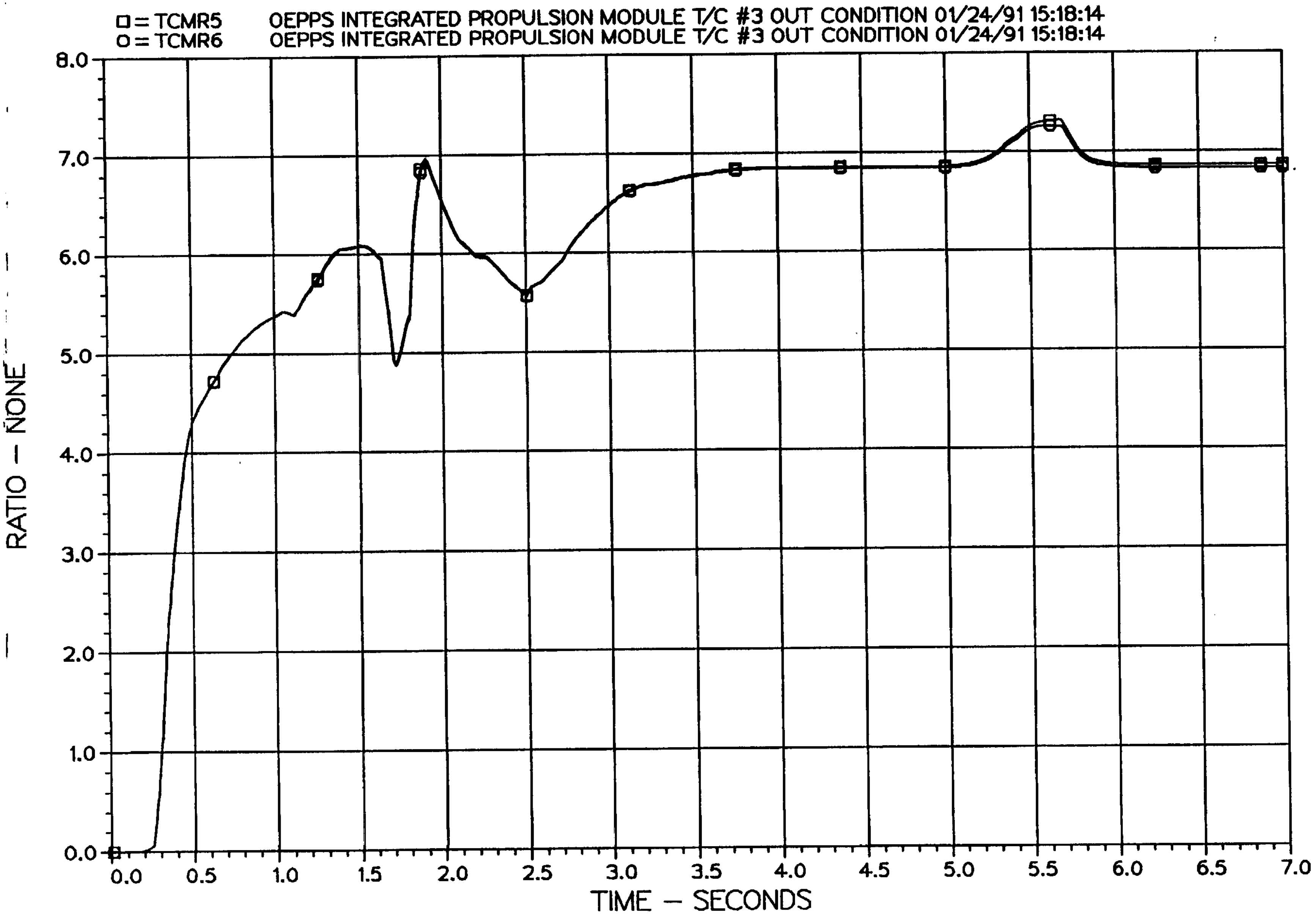


Figure G7

PLOT 8 10.08.43 MON 28 JAN, 1991 JOB-758335 , ISSCO DISSPLA 10.0

GAS GENERATOR (3) MIXTURE RATIO

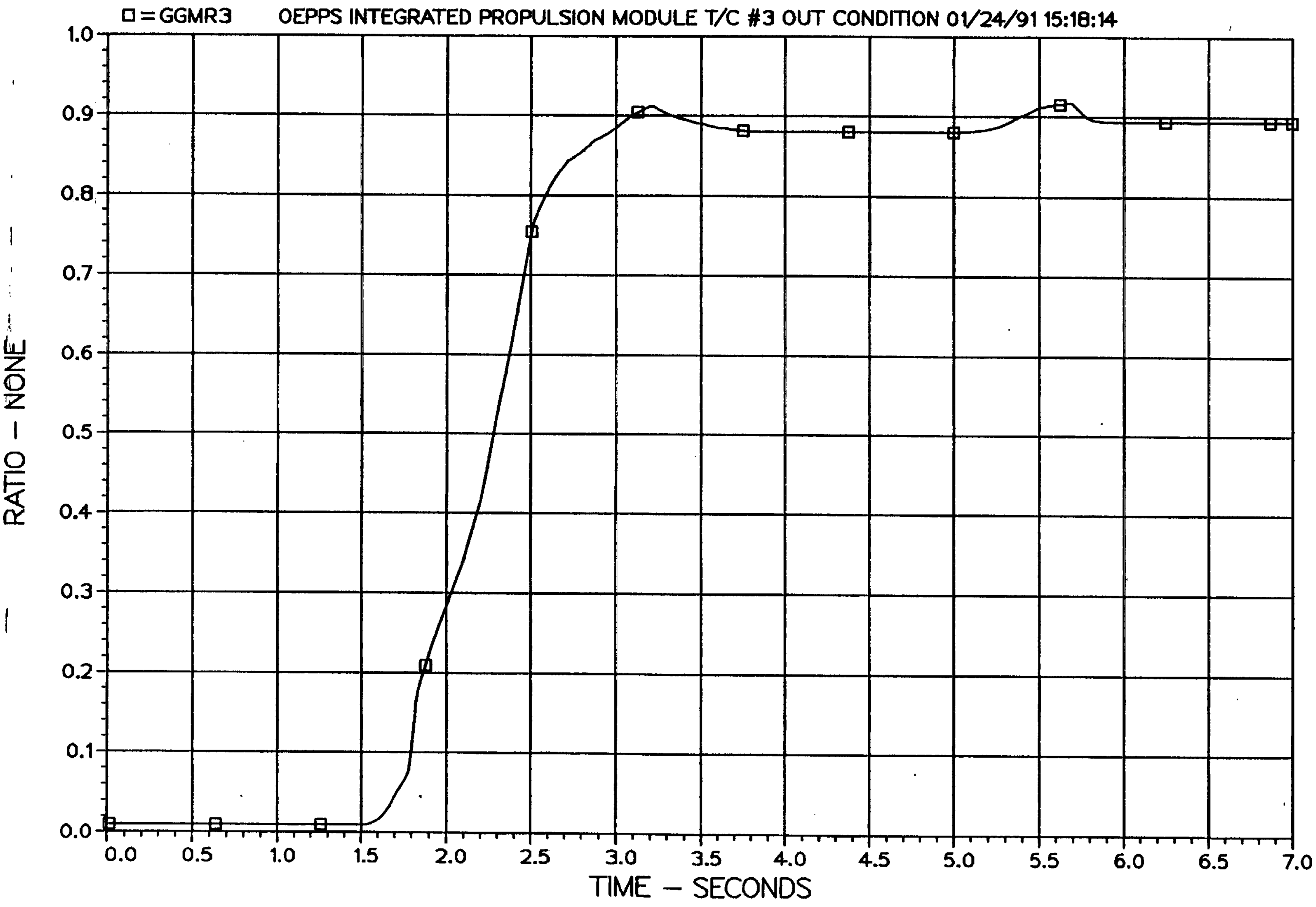


Figure G8

PLOT 9 10.08.48 MON 28 JAN, 1991 JOB-758335 , ISSCO DISSPLA 10.0

FUEL PUMP (3) SPEED

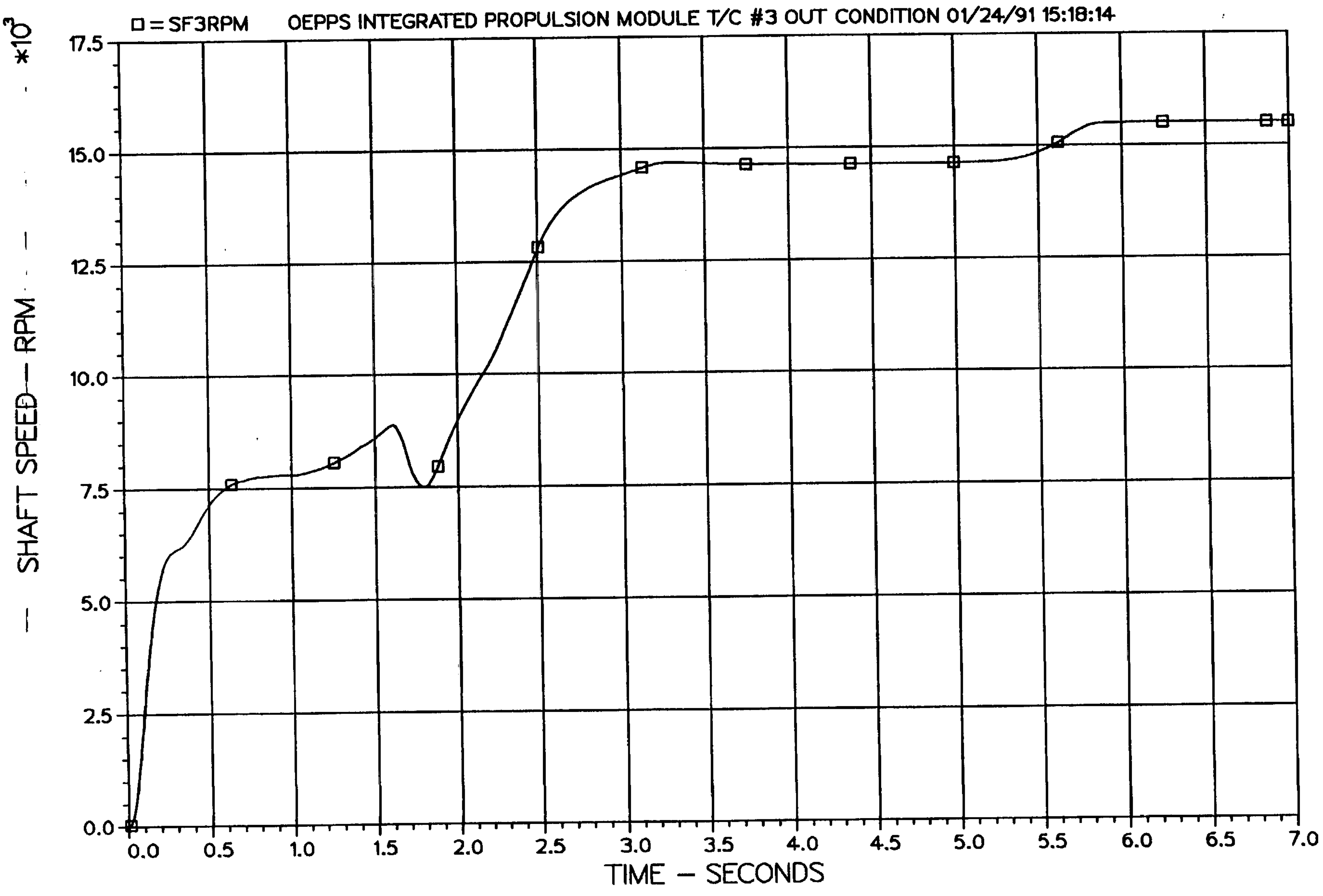


Figure G9

PLOT 10 10.08.55 MON 28 JAN, 1991 JOB-r758335 , ISSCO DISSPLA 10.0

LOX PUMP (3) SPEED

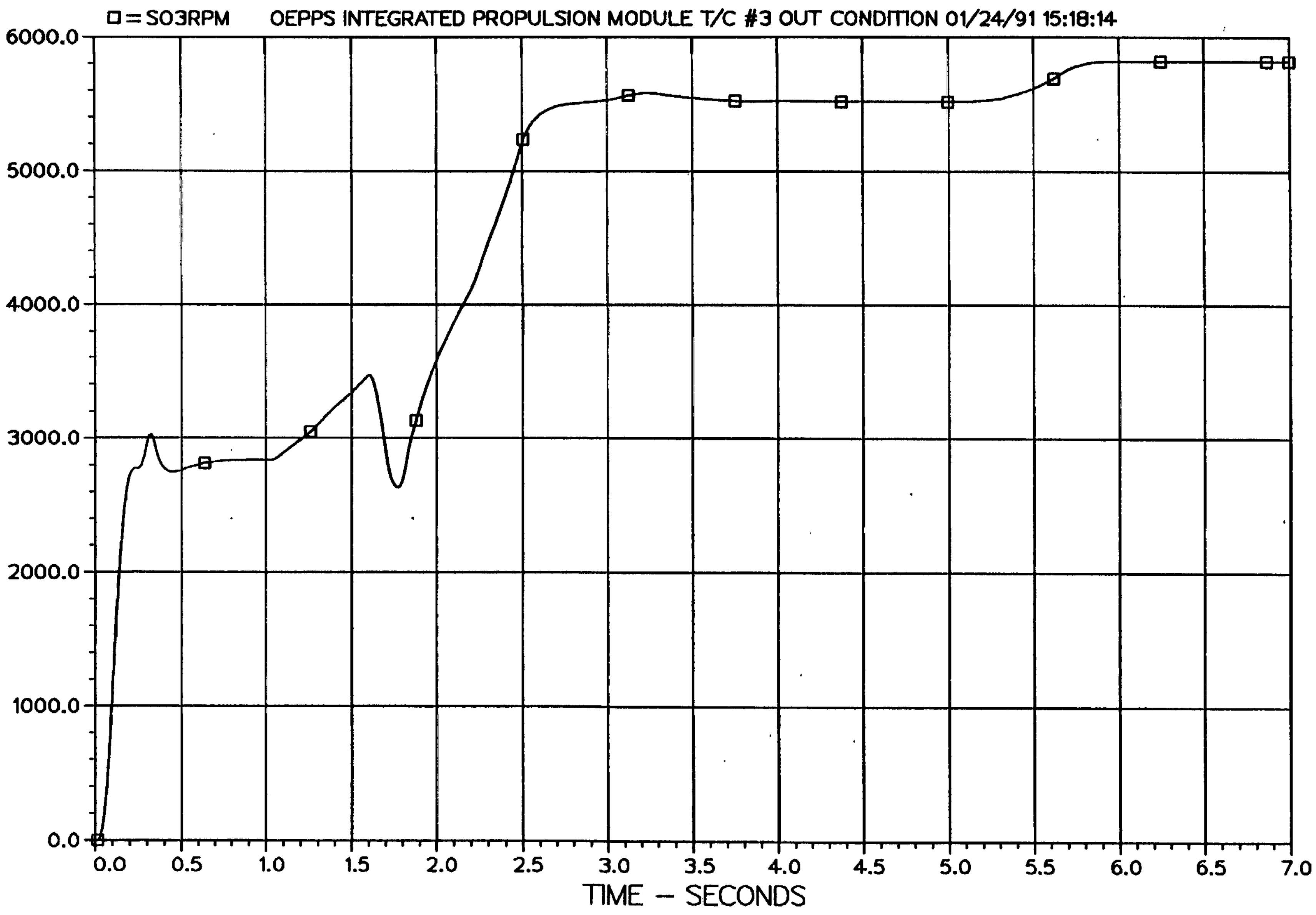


Figure 4.11

OT 11 10.08.59 MON 28 JAN, 1991 JOB-758335 , ISSCO DISSPLA 10.0

FUEL PUMP (3) FLOW COEFFICIENT

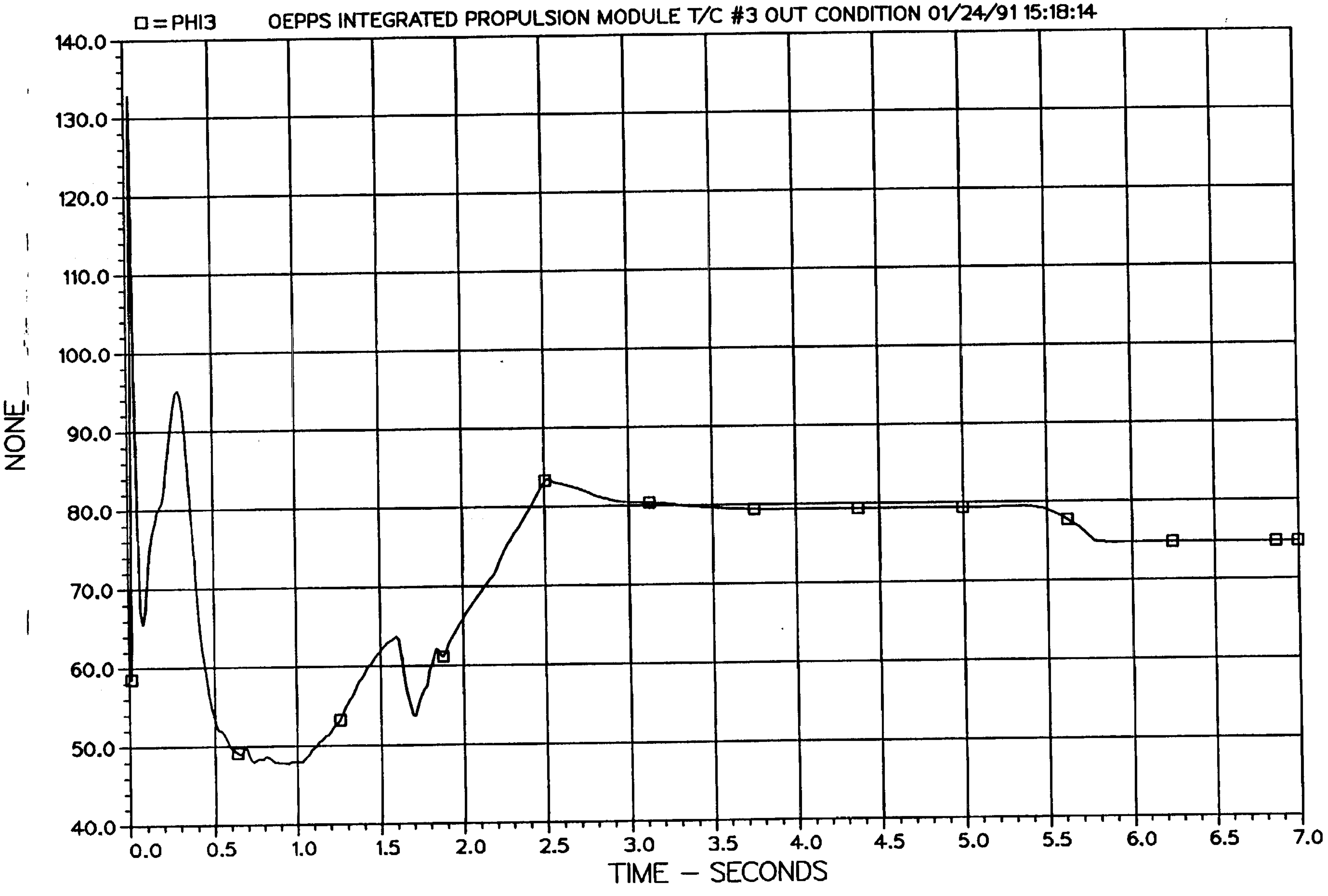


Figure G11

PLOT 19 13.50.45 FRI 1 FEB, 1991 JOB--758335 , ISSCO DISSPLA 10.0

FUEL INJECTOR (5,6) TEMPERATURES

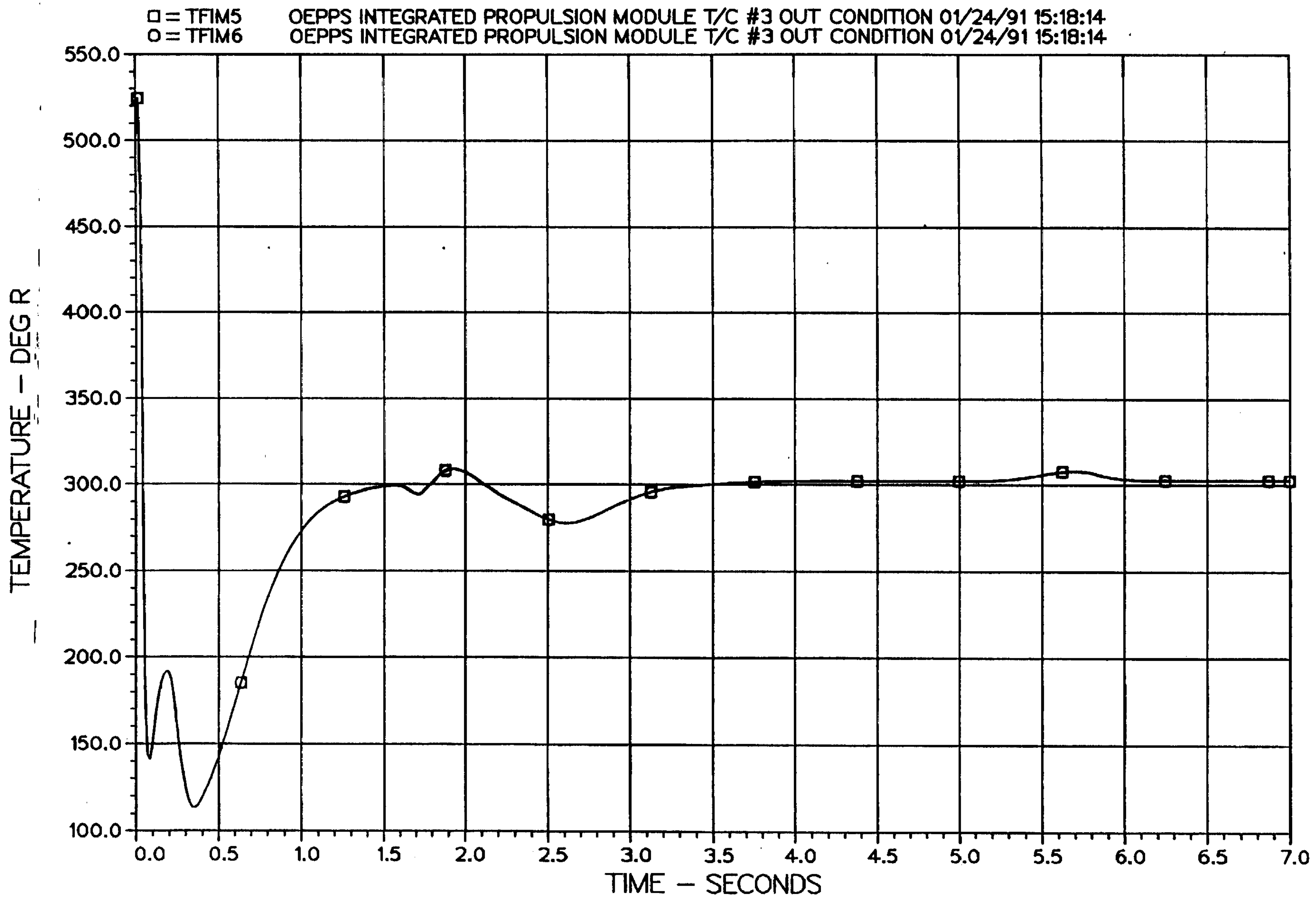


Figure G.12

HYDROGEN GAS FLOW FOR GG (3) SPIN

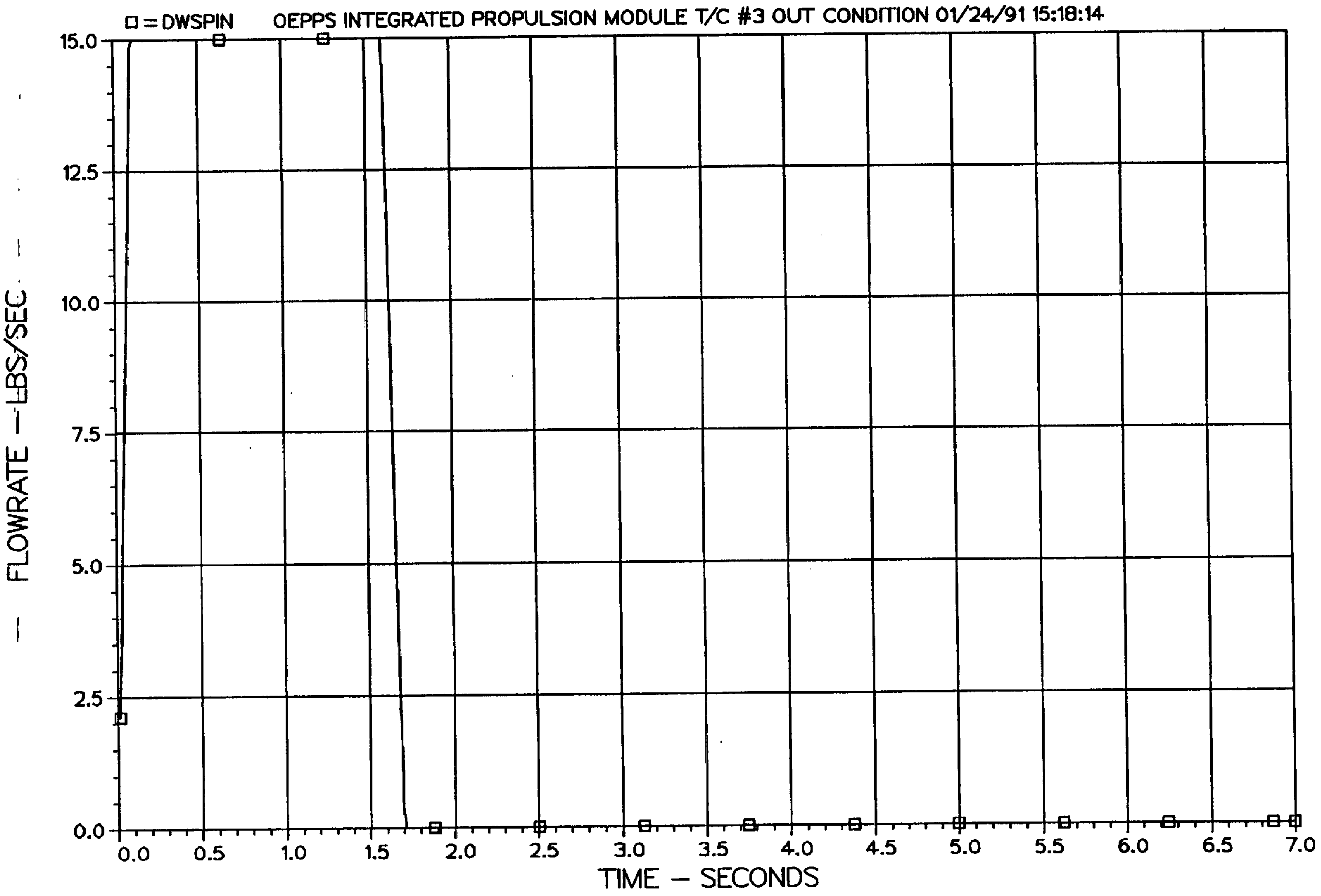


Figure G13

PLOT 21 13.50.54 FRI 1 FEB, 1991 JOB-r758335 , ISSCO DISSPLA 10.0

APPENDIX H

TRANSIENT ANALYTICAL RESULTS FOR THRUST CHAMBER #3 SHUTDOWN

FOR SYSTEM 4

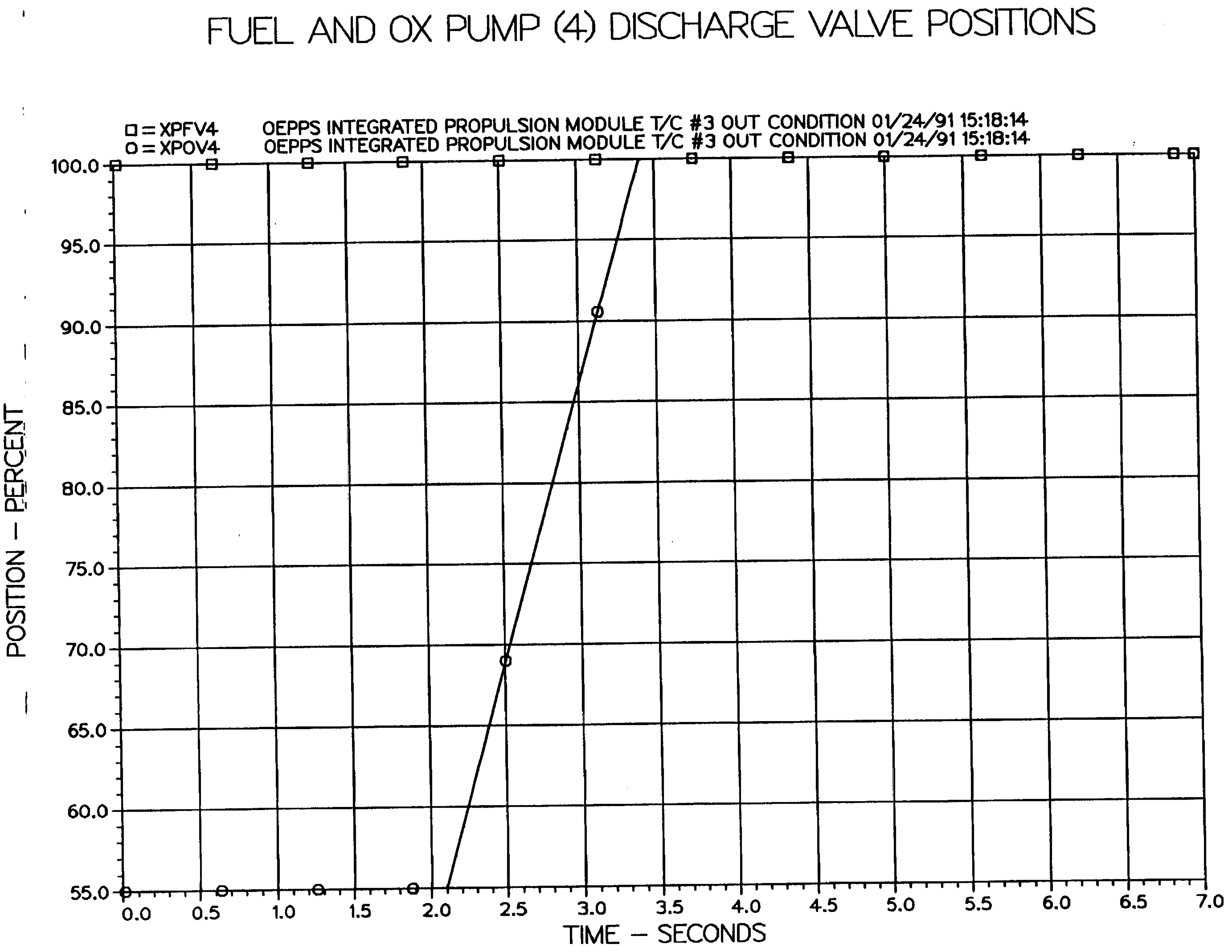


Figure H1

PLOT 2 10.12.02 MON 28 JAN, 1991 JOB-758335 , ISSCO DISSPLA 10.0

FUEL AND OX GAS GENERATOR (4) VALVE POSITIONS

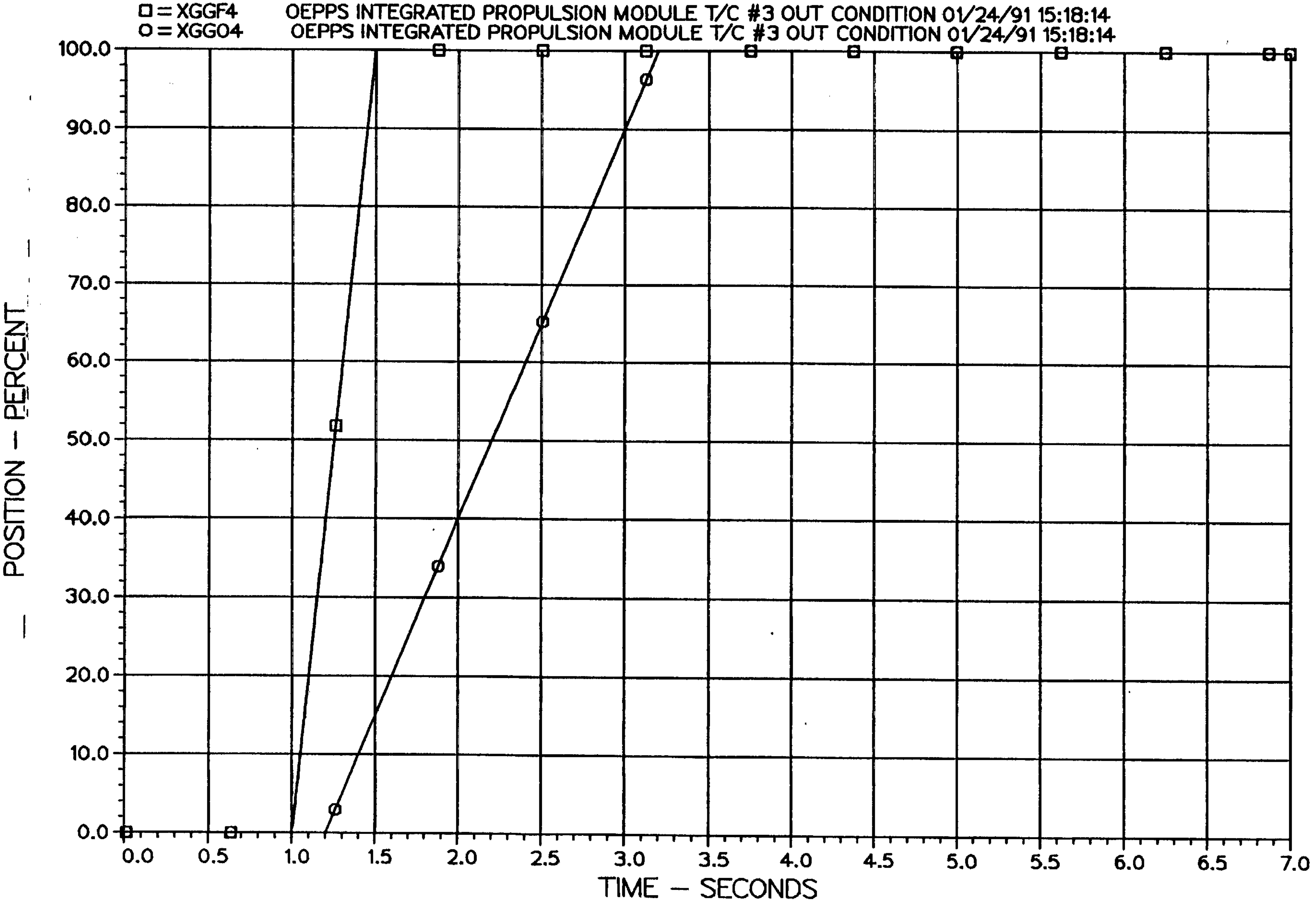


Figure H2

10.12.19 MON 28 JAN, 1991 JOB-758335 , ISSCO DISSPLA 10.0

OT 5

T/C (7,8) INLET FUEL VALVE POSITIONS

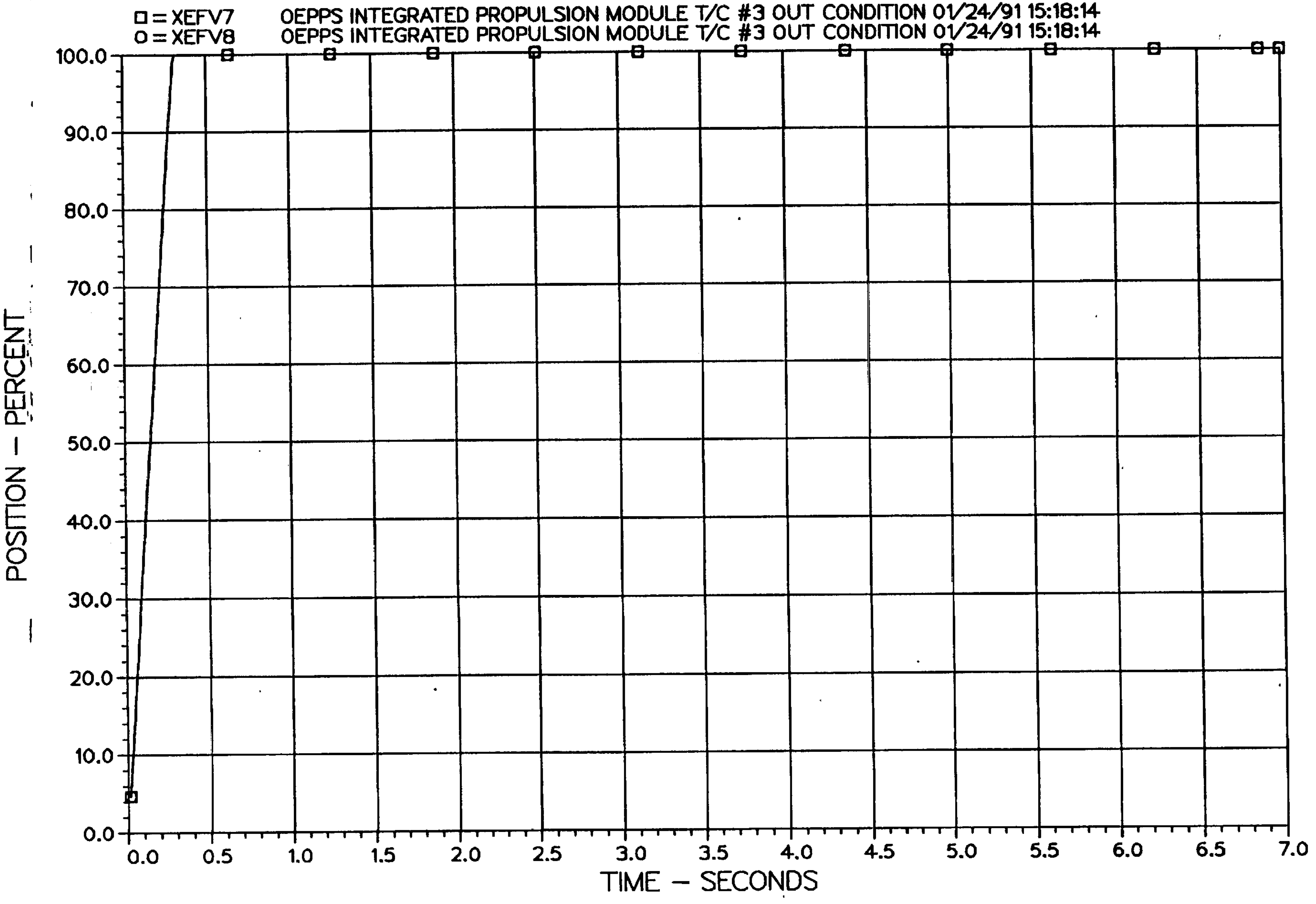


Figure H3

PLOT 3 10.12.07 MON 28 JAN, 1991 JOB-r758335 , ISSCO DISSPLA 10.0

T/C (7,8) INLET OX VALVE POSITIONS

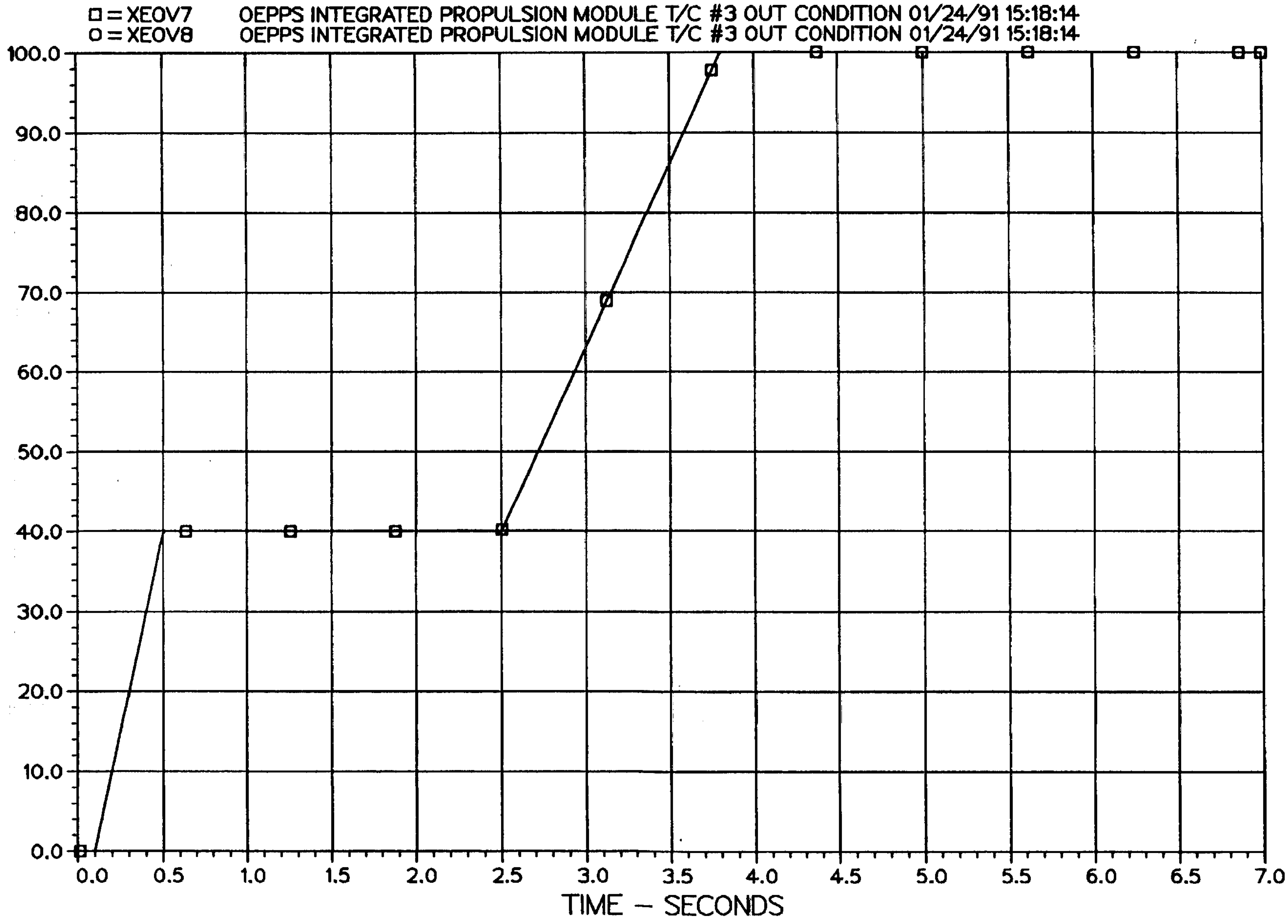


Figure H4

10.12.13 MON 28 JAN, 1991 JOB-758335 , ISSCO DISSPLA 10.0

OT 4

T/C (7,8) MAIN CHAMBER PRESSURES

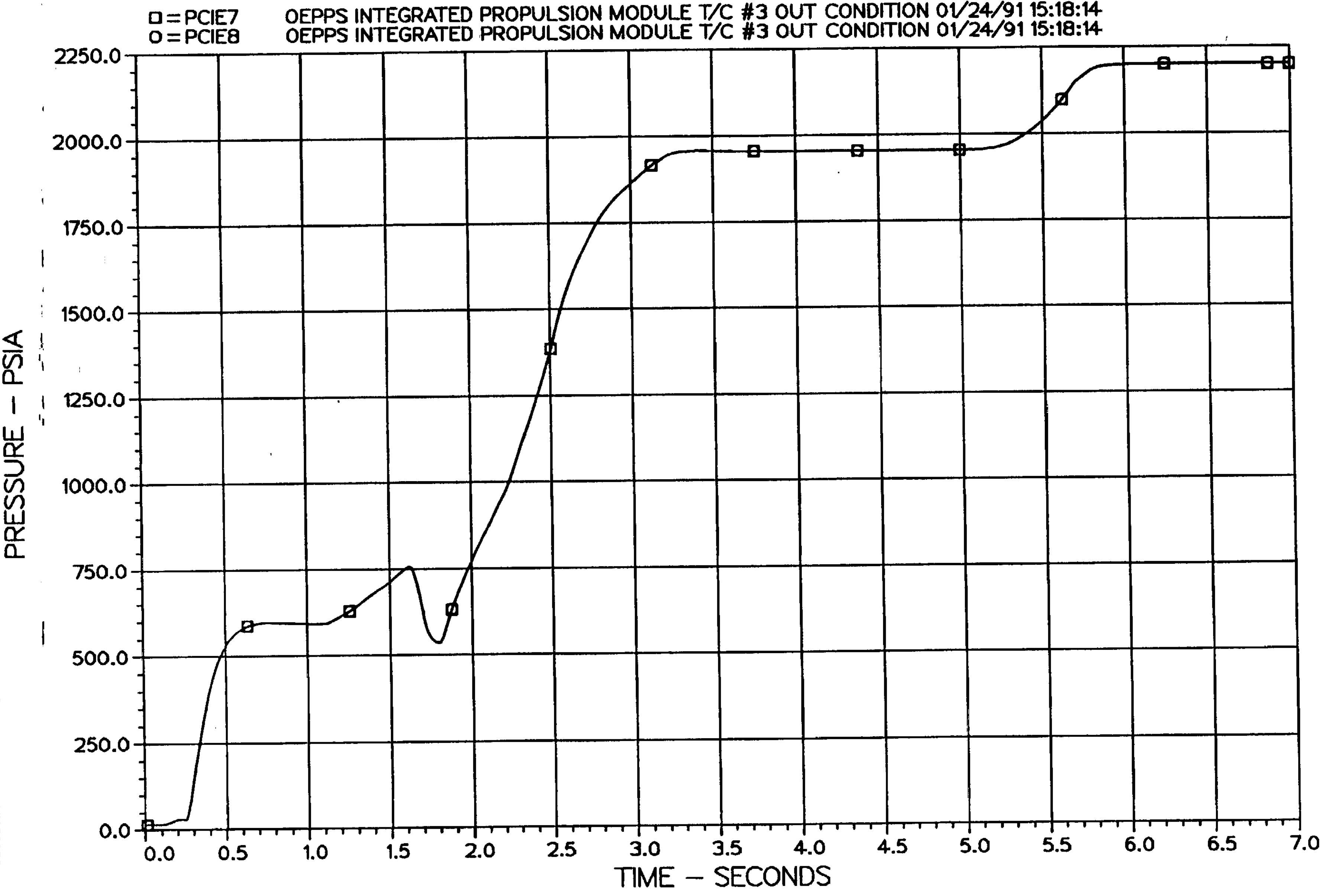


Figure H5

PLOT 6 10.12.24 MON 28 JAN, 1991 JOB-r758335 , ISSCO DISSPLA 10.0

GAS GENERATOR (4) CHAMBER PRESSURE

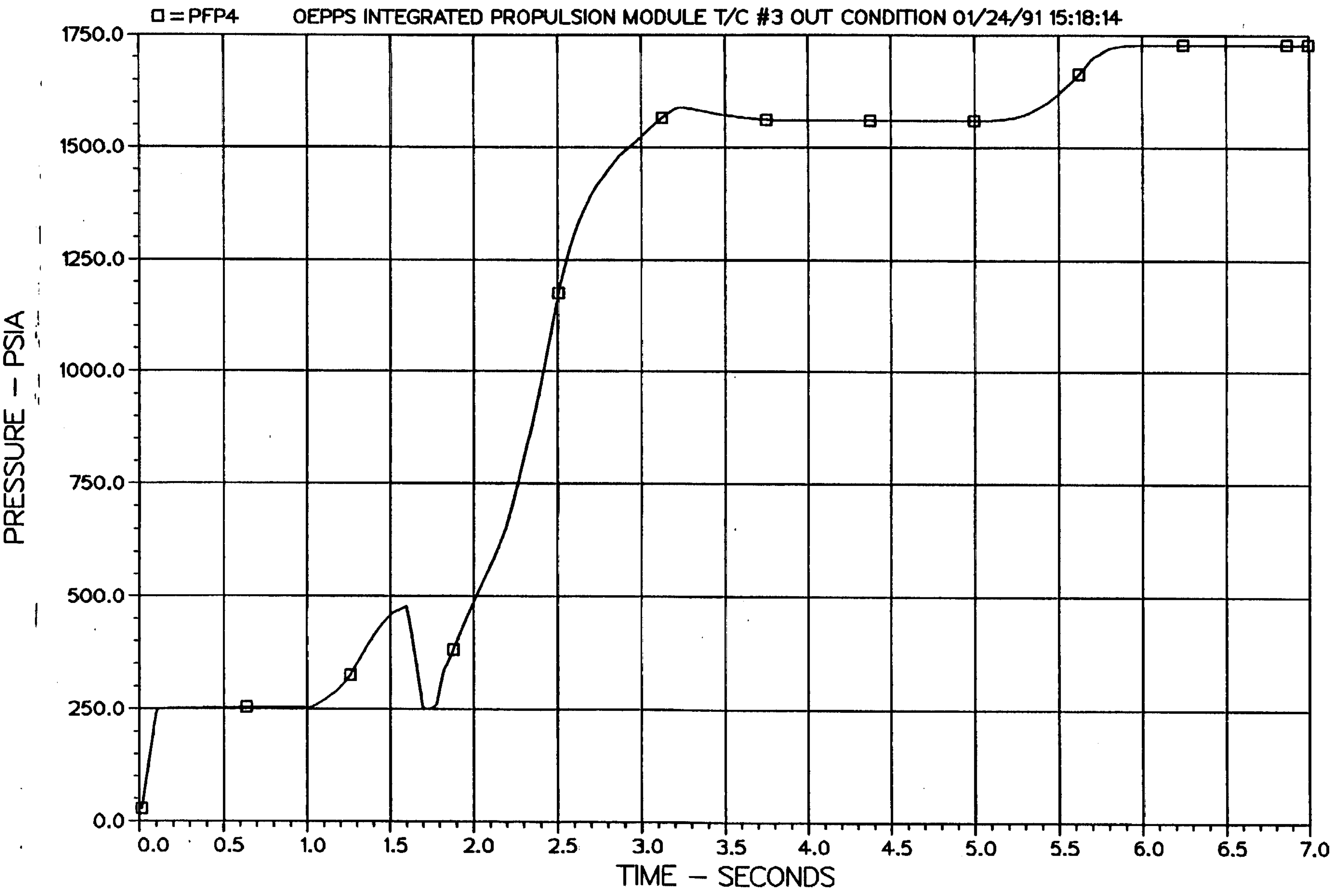


Figure H6

10.12.28 MON 28 JAN, 1991 JOB-758335 , ISSCO DISSPLA 10.0

OT 7

T/C (7,8) MIXTURE RATIOS

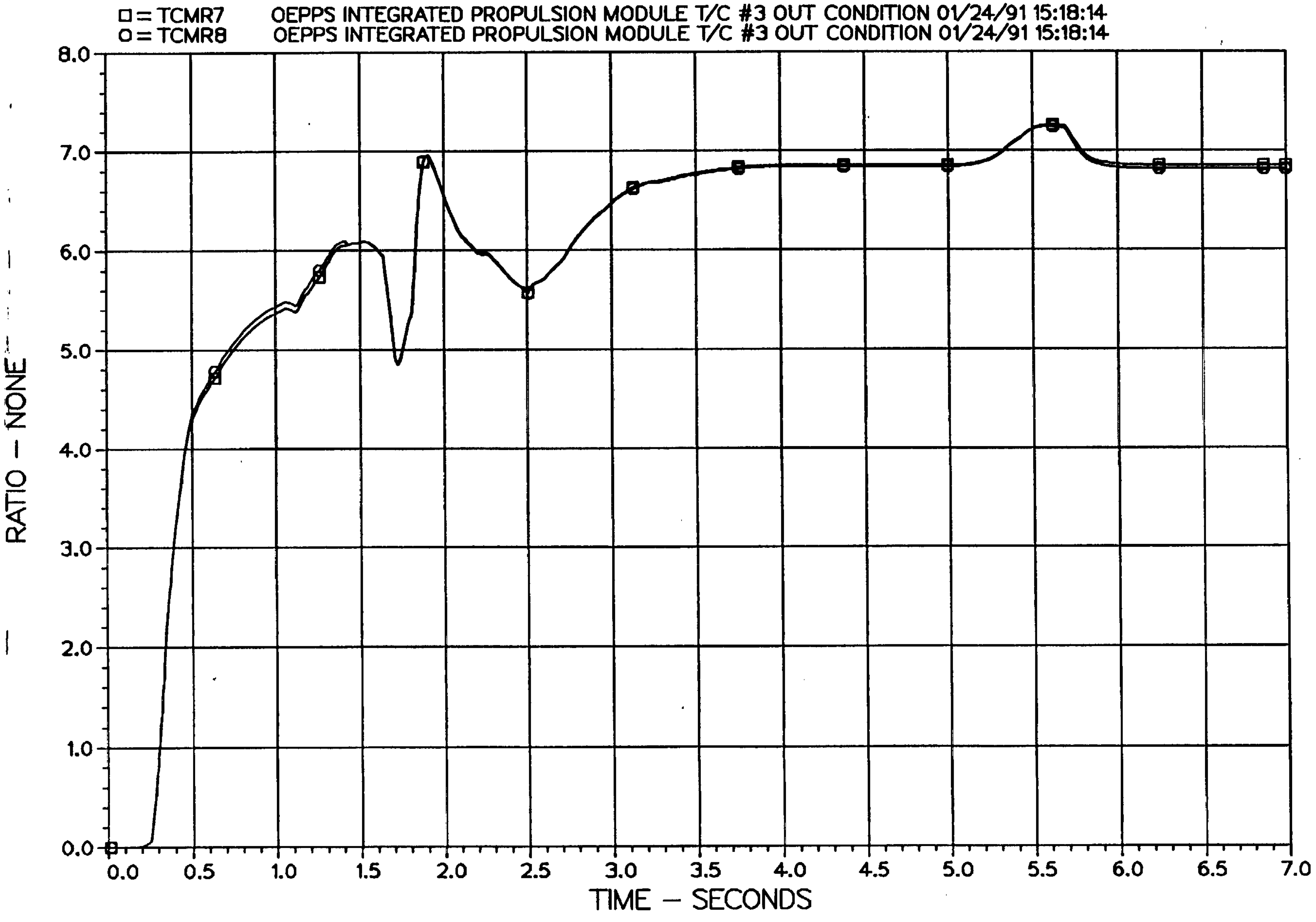


Figure H7

PLOT 8 10.12.33 MON 28 JAN, 1991 JOB-r758335 , ISSCO DISSPLA 10.0

GAS GENERATOR (4) MIXTURE RATIO

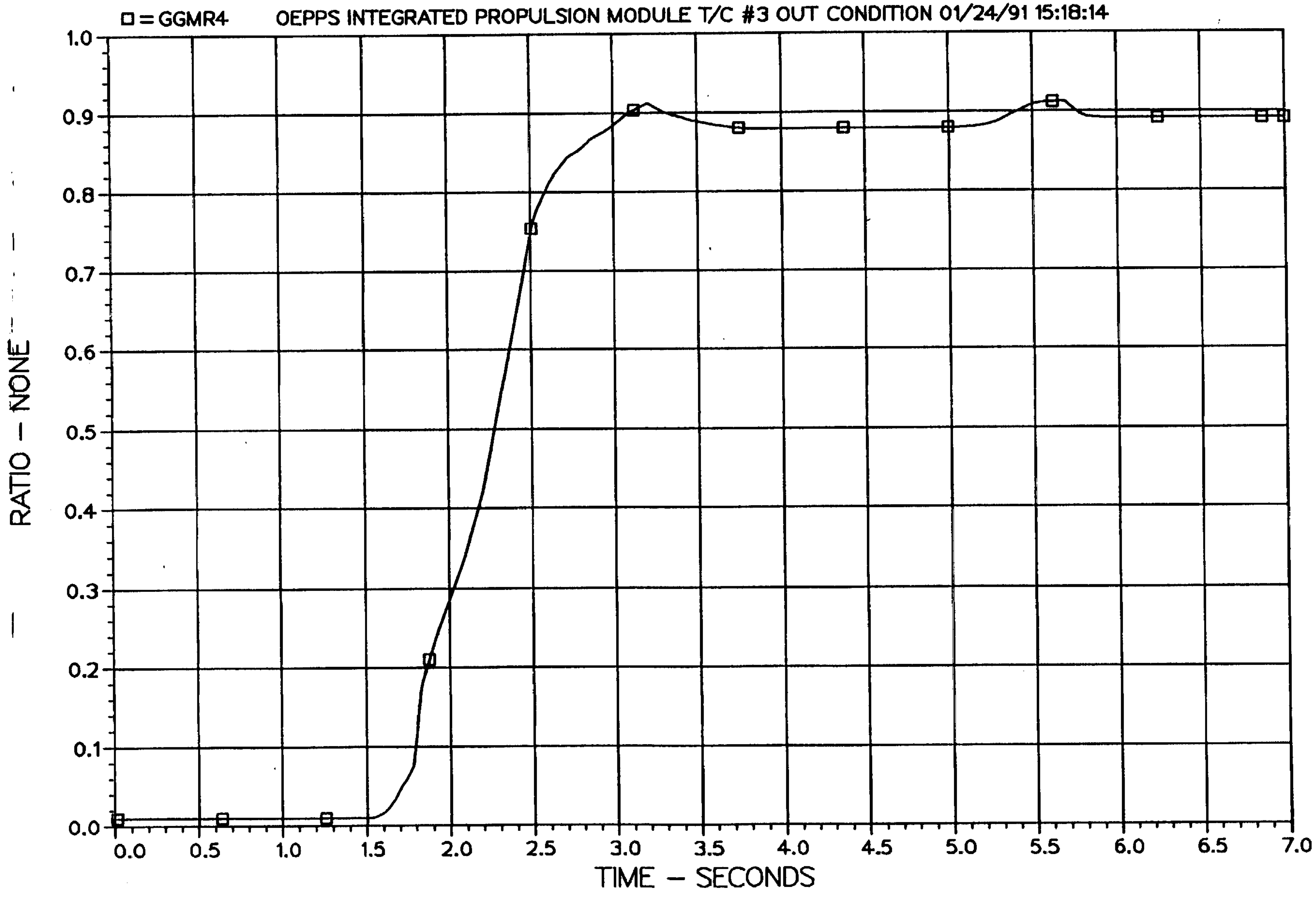


Figure H8.

OT 9 10.12.38 MON 28 JAN, 1991 JOB-r758335 , ISSCO DISSPLA 10.0

FUEL PUMP (4) SPEED

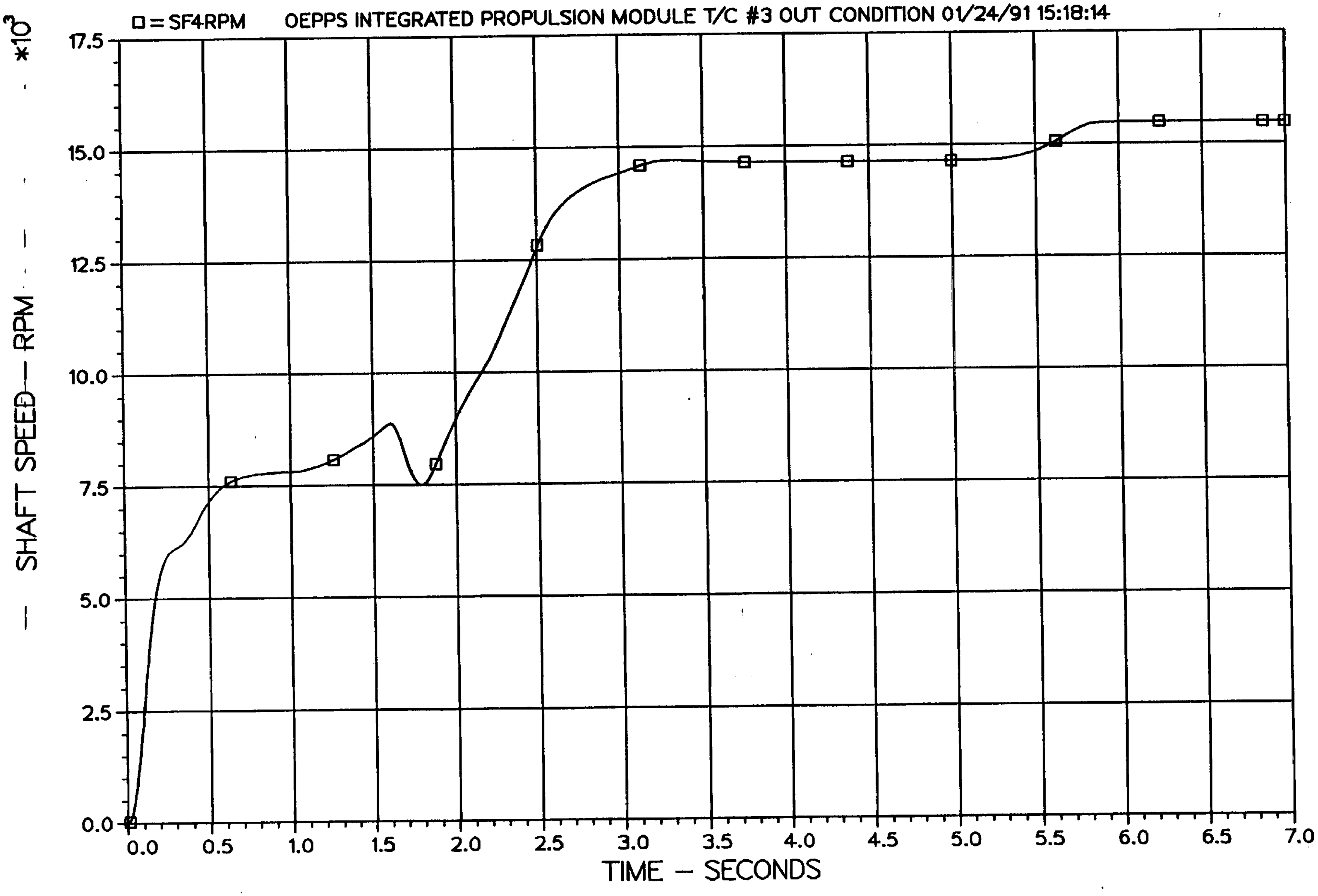


Figure H9

PLOT 10 10.12.46 MON 28 JAN, 1991 JOB-758335 , ISSCO DISSPLA 10.0

LOX PUMP (4) SPEED

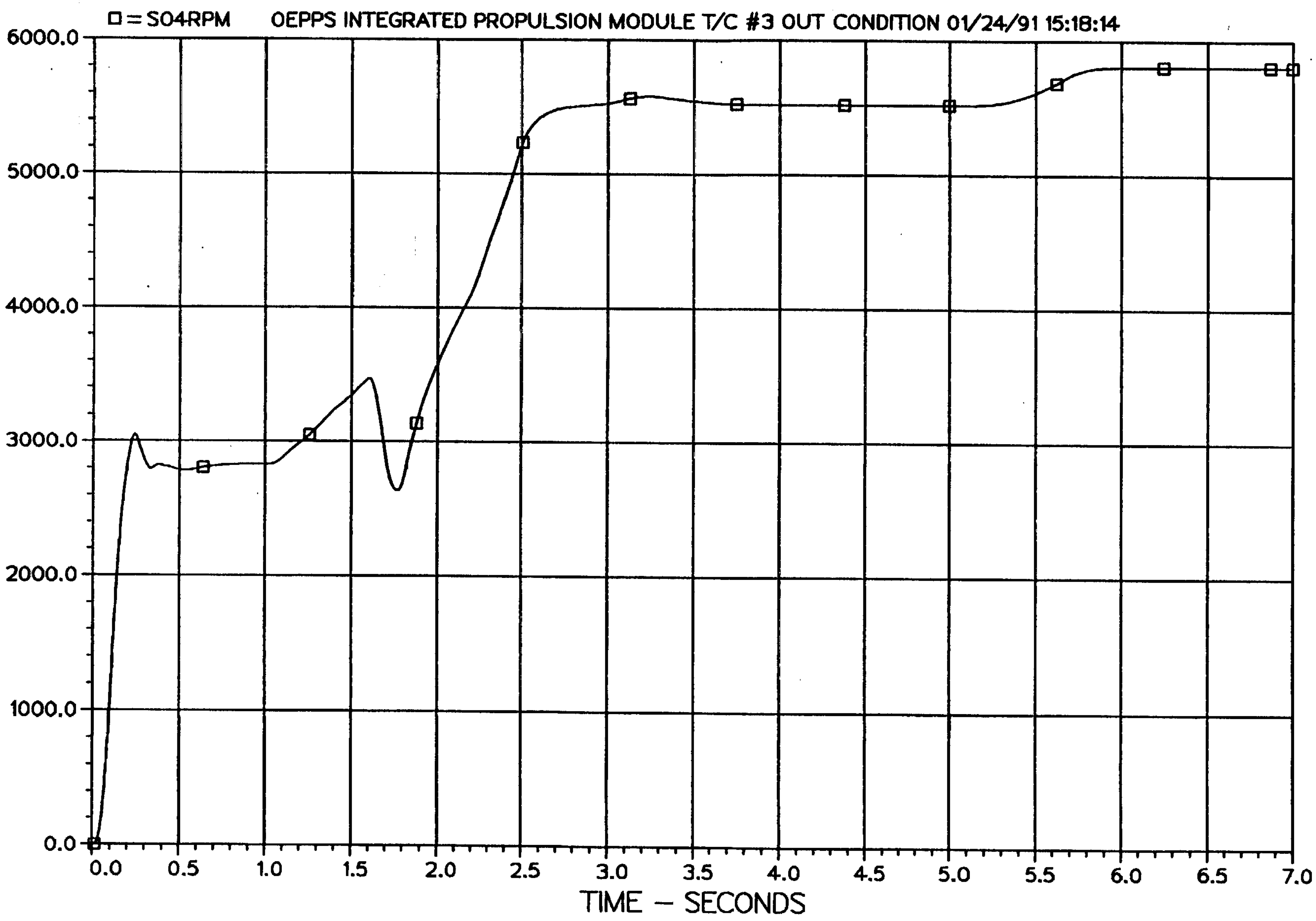


Figure 4.10

IT 11 10.12.53 MON 28 JAN, 1991 JOB-r758335 , ISSCO DISSPLA 10.0

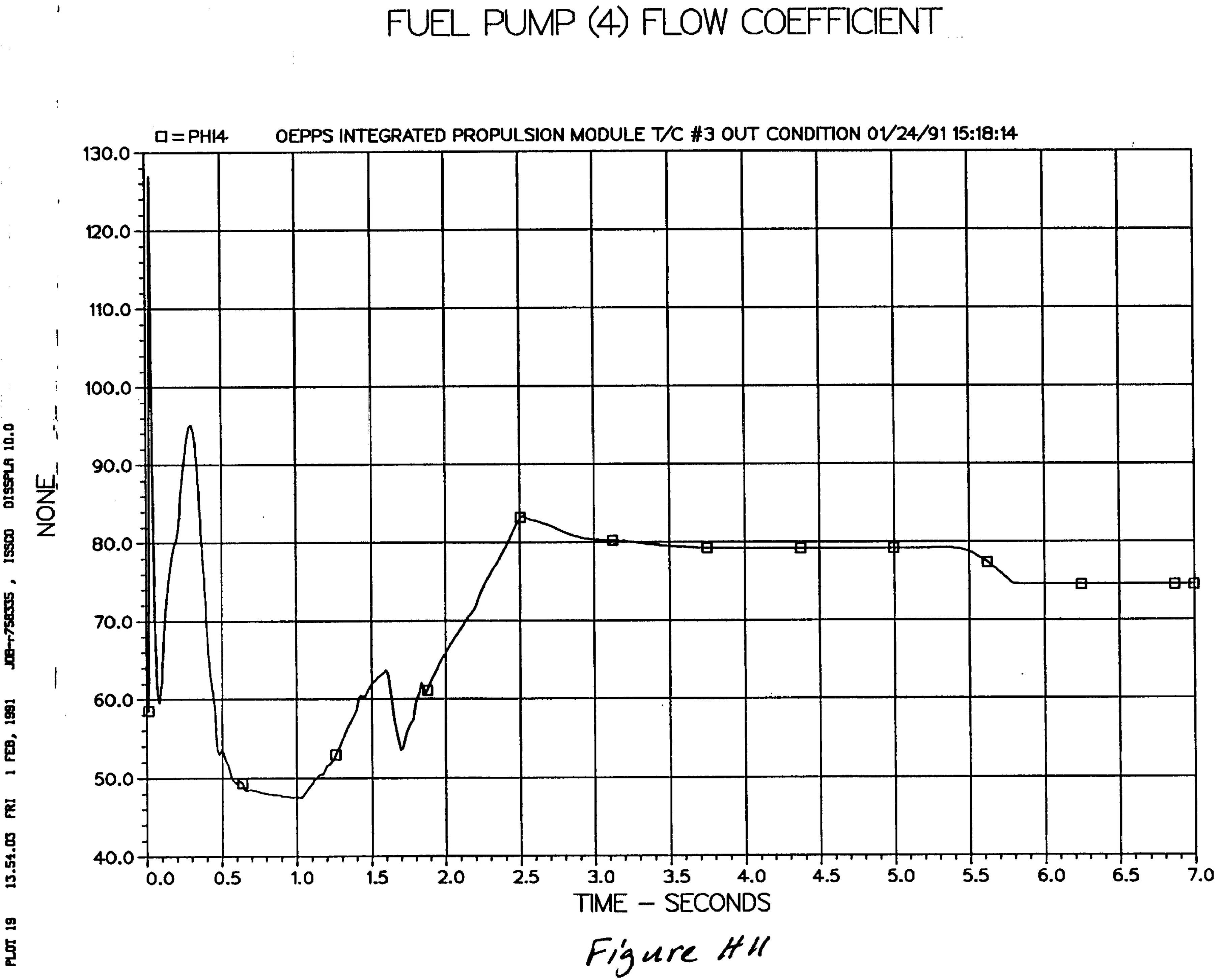
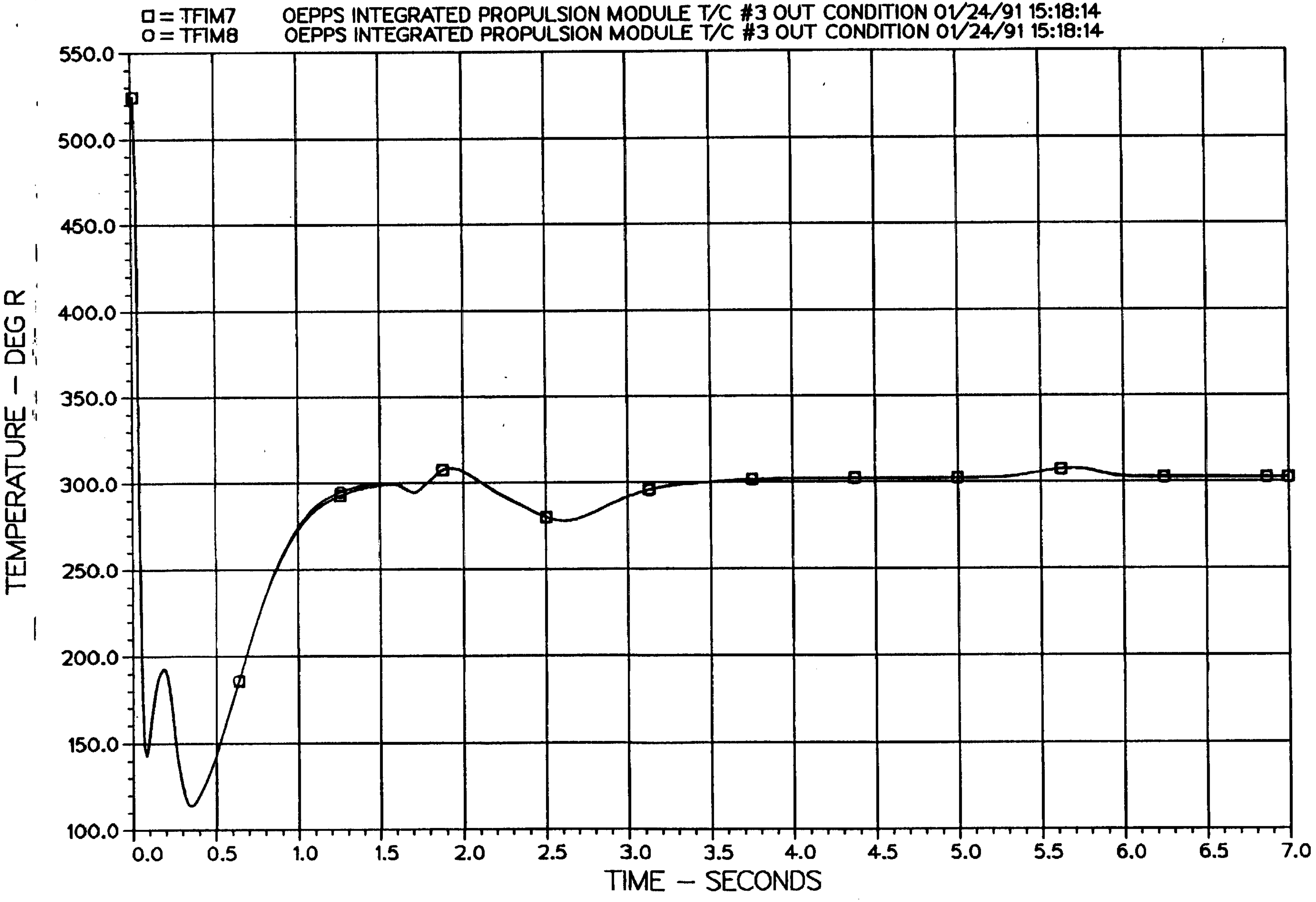

FUEL PUMP (4) FLOW COEFFICIENT
□ = PHI4
OEPPS INTEGRATED PROPULSION MODULE T/C #3 OUT CONDITION 01/24/91 15:18:14
130.0
120.0
110.0
100.0
90.0
80.0
70.0
60.0
50.0
40.0
NONE
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5
6.0
6.5
7.0
TIME — SECONDS
PLOT 19 13.54.03 FRI 1 FEB, 1991 JOB-+758335 , ISSCO DISSPLA 10.0

Figure H11

FUEL INJECTOR (7,8) TEMPERATURES



OT 20 13.54.09 FRI 1 FEB, 1991 JOB-r758335 , ISSCO DISSPLA 10.0

Figure #12

HYDROGEN GAS FLOW FOR GG (4) SPIN

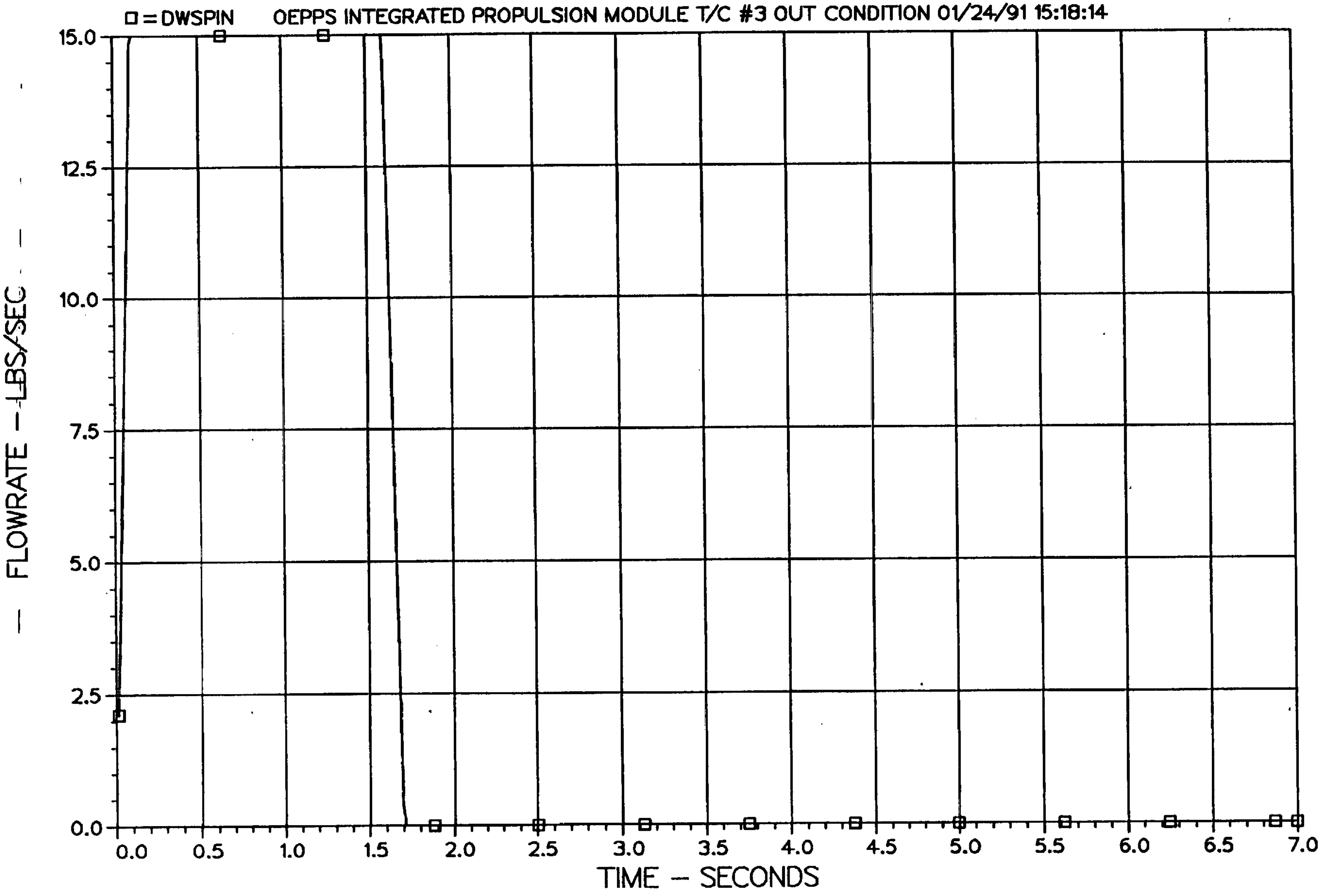


Figure H13

PLOT 21 13.54.13 FRI 1 FEB, 1991 JOB=758335 , ISSCO DISSPLA 10.0

Section 2

Internal Letter 2128-0037, "Operationally Efficient Propulsion System Study, Option 2, Transient Analysis Study: Turbopump Out and Combined Thrust Chamber/Turbopump Out Conditions," Victoria Kemp, dated March 5, 1992.

Internal Letter **Rockwell International**

Date: March 5, 1992

No: IL 2128-0037

TO: (Name, Organization, Internal Address)

Ron P. Pauckert
Rocketdyne-Plummer
D589, IB43
x4875

FROM: (Name, Organization, Internal Address, Phone)

Victoria R. Kemp
Rocketdyne-Plummer
D545-128, JB11
x5530

Subject:

Operationally Efficient Propulsion System Study, Option 2, Transient Analysis Study: Turbopump Out and Combined Thrust Chamber/Turbopump Out Conditions

References :

[1] Internal Letter 1128-0014, "Operationally Efficient Propulsion System Transient Analysis Study, Task 1.0", V. Kemp, 28 January 1991.

[2] Internal Letter EA90-011, "Operationally Efficient Propulsion System Study", W. Geniec, P. Chen, W. Bissell, C. Erickson to G.S. Wong, 22 March 1990.

[3} Notes: Additional steady state engine balance data, P. Chen, W. Bissell, 2 February 1990.

[4] Internal Letter 0128-0070, "System Dynamics Support to STEP GG Cycle (Helium Start) November 1989 Base Line Analysis", K. Danny Woo to Vernon Gregoire, 14 June 1990.

[5] Centrifugal and Axial Flow Pumps, Second Edition, A.J. Stepanoff, John Wiley & Sons, 1957, p.270.

[6] NBS Technical Note 617 - Thermophysical Properties of Parahydrogen, U.S. Department of Commerce, National Bureau of Standards, Issued April 1972.

[7] NBS Technical Note 384 - Thermophysical Properties of Oxygen, U.S. Department of Commerce, National Bureau of Standards, Issued July 1971.

Introduction

In support of the NASA/KSC program (contract no. NAS 10-11568, mod.no. 2), Operationally Efficient Propulsion System Study (OEPSS), Option 2, Task 1.0, an analysis of the transient behavior was performed for a single turbopump failure condition and for a combined thrust chamber/turbopump failure condition. A fluid-thermo dynamic digital transient model of the engine was used to perform the simulations and analyses. Work to study the transient behavior and to define a valve sequence for a nominal start and cutoff simulation, as well as for a single thrust chamber failure condition, was performed previously under Option 1. These results are documented in ref. 1. Simulations were carried out on the SUN workstation where the model currently resides. The FORTRAN code is compatible with SUN FORTRAN compiler requirements.

The integrated propulsion module incorporates eight STME (Space Transportation Main Engine) thrust chambers and four turbopumps, where each turbopump nominally feeds two thrust chambers (Figure 2). Each of the pumps and gas generators accommodates twice the flow of the STME pumps and gas generator. Under nominal operation, both the thrust chambers and turbopumps operate at throttled-down conditions. The eight (8) thrust chambers operate at 85% of their rated thrust capacity and the four (4) turbopumps operate at 90% of their rated speed. Use of torroidal propellant feed manifolds, common to the four turbopumps and eight thrust chambers, permits a failure out condition of either one chamber, one turbopump, or both a chamber and a turbopump. In the case of a component failure, the remaining components can be powered up to their design operating levels to compensate for the losses. During a turbopump failure, the three remaining fuel/LOX turbopump sets will operate at about 93% of their rated speed. During a combined thrust chamber/turbopump failure, the seven remaining chambers and the three remaining turbopump sets will operate at maximum (100%) rated thrust and speed capacities, respectively.

The focus of this analysis was to study the feasibility of the integrated engine system concept in regards to the transient behavior with a turbopump out as well as with a combined thrust chamber/turbopump out condition. The valve sequences used in the simulations during the start and during the shutdown of a thrust chamber were defined previously under the Option 1 study. A discussion of the nominal start/shutdown valve sequences and criteria for selection is provided in ref. 1.

Summary

In support of the OEPSS program, this report presents the results of transient analyses performed for a turbopump out condition and for a combined thrust chamber/turbopump out condition. The simulation results for the turbopump out condition are presented in Appendices A-D. The simulation results for the combined thrust chamber/turbopump out condition are presented in Appendices E-H. A directory to selected parameter profiles is provided on page 26.

The results of the analyses indicate the feasibility in throttling to and operating at configurations of 8/3, 7/4, and 7/3 chambers/turbopumps in the event of failure of a single thrust chamber, turbopump, or both. In order to shut down a failed thrust chamber, both the fuel and LOX valves supplying the chamber must be closed. The objective is to sequence the valves so as to maintain

acceptable mixture ratios in the remaining chambers as well as in the failed chamber, so that the potential for further damage to the failed chamber is avoided. The same valve sequences are used for both the shutdown of a single chamber and for the nominal shutdown of all eight chambers. This valve sequence maintains a fuel-rich environment in the single chamber during shutdown with only slight mixture ratio overshoots in the seven remaining chambers.

In order to shut down a failed turbopump, the gas generator (GG) valves must be closed to cut power to the failed pump. Consequently, power will also be cut to the complimentary fuel or LOX pump. The pump discharge valves must be closed to isolate both the fuel and LOX turbopumps from the system. Upon closing the GG valves, power is cut to the associated pumps resulting in decay of the pump speeds, discharge pressures, and flowrates. A back pressure on the pumps results due to the higher manifold pressures downstream which causes the propellant to flow back into the pumps. A check valve is used on the LOX side to prevent LOX from flowing back into the pump. On the fuel side, however, fuel is allowed to flow back into the pump to avoid boil-out. The fuel pump discharge valve is closed slowly to allow the available propellant to flow back into the fuel pump to facilitate slowing the pump down. This results in fuel pump speed reduction to about 30% of mainstage at the time the flow is reduced to zero. Boil-out should not be of concern under these conditions.

Nominal operation of the main chambers can be maintained by increasing the propellant supply to the three remaining GGs. The three remaining pump sets will thus be driven to higher operating speeds. A control mechanism is required on the GG valves to regulate the propellant flow in the event of failure of one of the turbopumps (see page 19).

The effects of the backflow on the fuel pump inlet ducts and fuel tank requires further investigation. The model would require a detailed description of the pump inlet ducts to predict the flow dynamics in this region. The potential for high pressures in the pump inlet ducts should be anticipated in the design.

Two additional simulations have been performed which are being documented in a separate internal letter (I.L. 2128-0041). These include (1) a simulation of a staggered gas spin start of the GGs where one GG lags in start behind the other three, and (2) simulations to study the sensitivity due to variations in pump performance characteristics between the four pump sets. Additional areas which should be focused on for subsequent transient analysis studies include:

- A detailed pump inlet duct design to evaluate the effects of backflow on the fuel pump inlet ducts and fuel tank for the turbopump out case
- Tank head start
- Component sensitivity studies

Method Of Analysis

Simulation of the integrated propulsion system was accomplished using a one-dimensional thermodynamic model which simulates the states of fluid parameters such as pressure, temperature, and flowrate for the propellants throughout the system, propellant mixture ratios for the GG chambers and thrust chambers, temperatures for the combustor and nozzle walls, pump speeds, and valve actuator positions. The system encompassed in the model includes the pump inlets to the thrust chambers. A partial system model fluid flow schematic, showing the basic flow configuration of one turbopump set, one gas generator, and one thrust chamber, is shown in Figure 3. The system may be envisioned as four sub-systems where each sub-system is comprised of a fuel and an oxidizer turbopump powered by a GG, eight valves, and two thrust chambers, interconnected by ducts and fuel/oxidizer torroidal manifolds. The eight valves consist of a pump discharge valve, a GG valve, and two thrust chamber inlet valves on each of the fuel and LOX sides. Reference will be made to each of these sub-systems as Systems 1, 2 , 3, and 4 where System 1 is comprised of GG 1 and thrust chambers (T/C) 1 and 2, System 2 is comprised of GG 2 and T/Cs 3 and 4, and so on. Each engine sub-system is configured as a gas generator cycle. A hydrogen spin is used on each of the four gas generators to obtain a simultaneous start of all GGs.

Various information was required as input data for the model. The valve characteristics depicting flow area versus position are shown in Figure 4. The same valve characteristics were used for the pump discharge valves, the GG valves, and the thrust chamber inlet valves. These are the same as those used in modelling the single STME GG engine design (ref. 4). The LOX and fuel pump performance maps, shown in Figures 5 through 8, are based on the pump characteristics documented in ref. 2. Generalized pump maps from ref. 5 were also used to expand the maps to encompass negative flow coefficients. The model was balanced to the engine balance design (ref. 2,3) at a thrust level of 497 Klb. Tables 1A-1D show the model mainstage conditions in addition to the engine balance design values for the 8/4, 8/3, 7/4, and 7/3 chamber/turbopump system configurations. The configuration geometry and the valve effective flow areas are presented in Tables 2 and 3, respectively.

Figure 1
8 - Engine Booster Propulsion Module

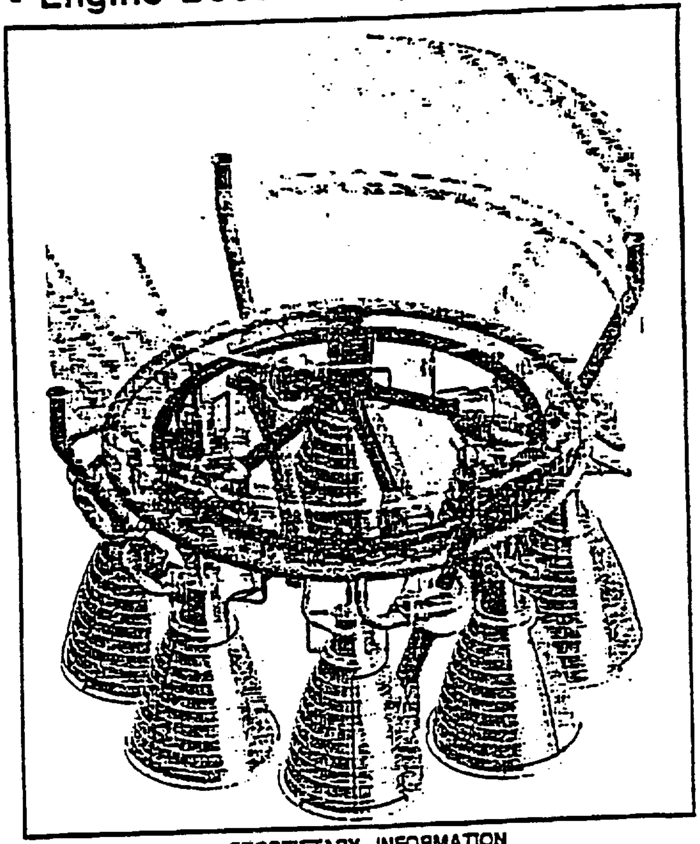


Figure 2
Integrated System Fluid Flow Schematic

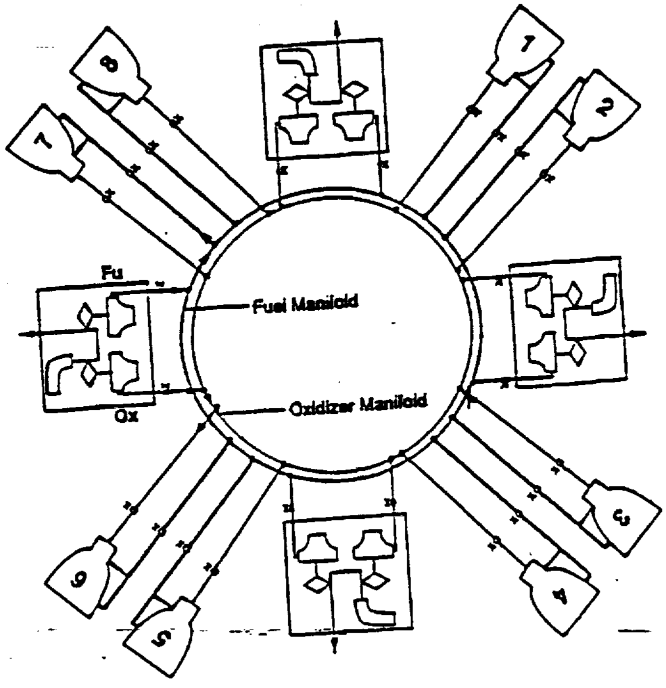
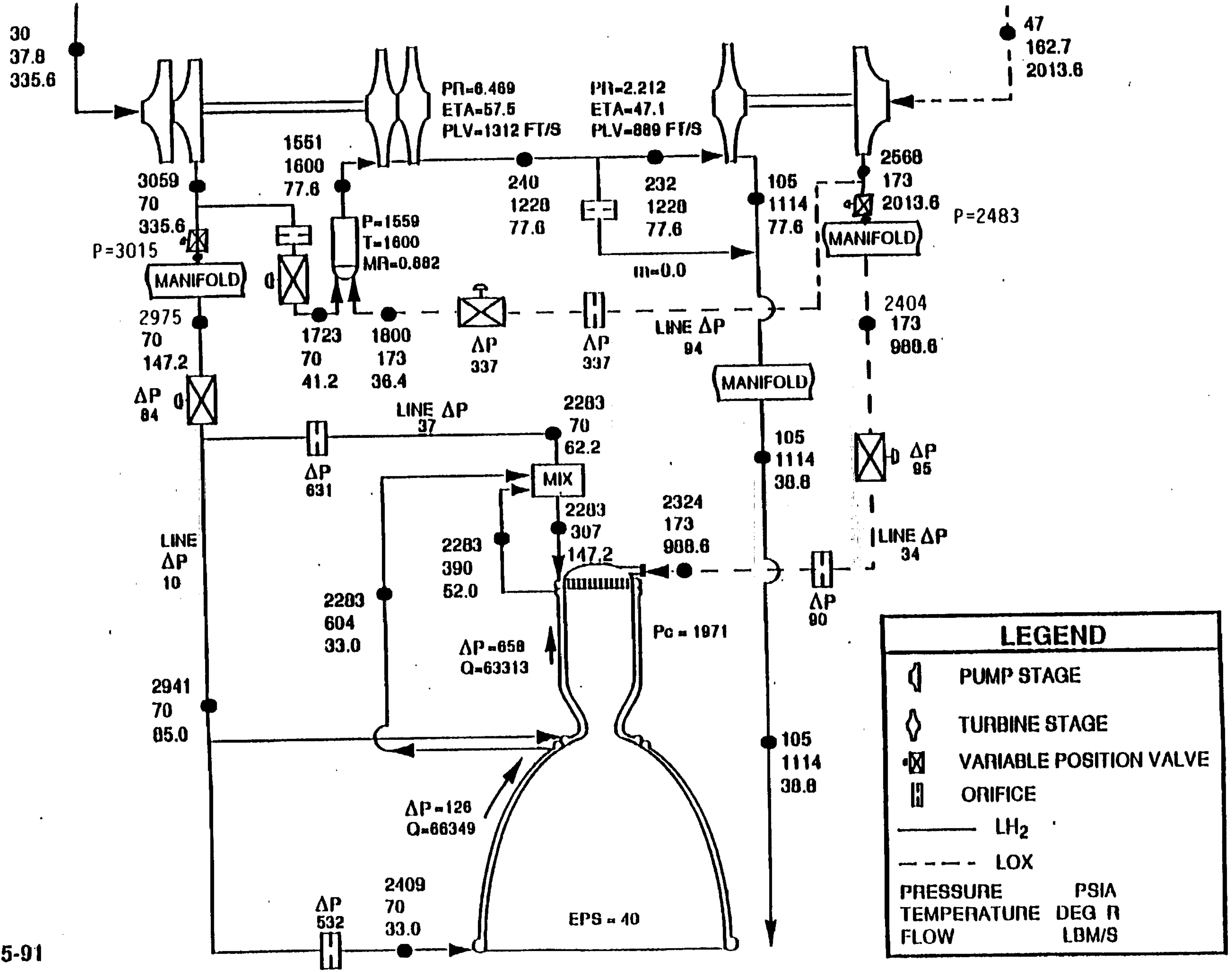


FIGURE 3 : STME THRUST CHAMBER FOR CLUSTER DESIGN
4 T/P + 8 T/C



2-5-91

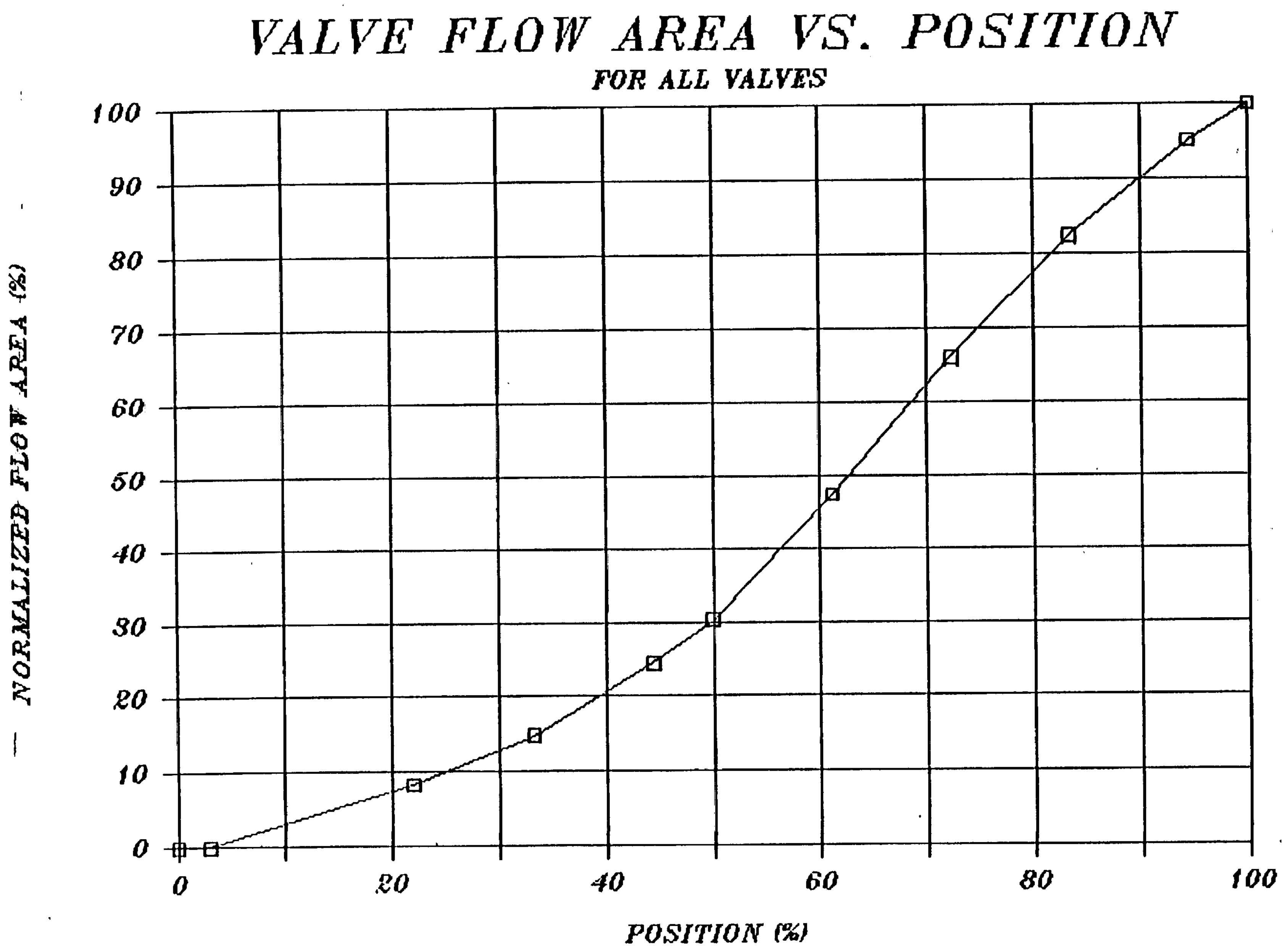

VALVE FLOW AREA VS. POSITION
FOR ALL VALVES
NORMALIZED FLOW AREA (%)
100
90
80
70
60
50
40
30
20
10
0
0
20
40
60
80
100
POSITION (%)

Figure 4

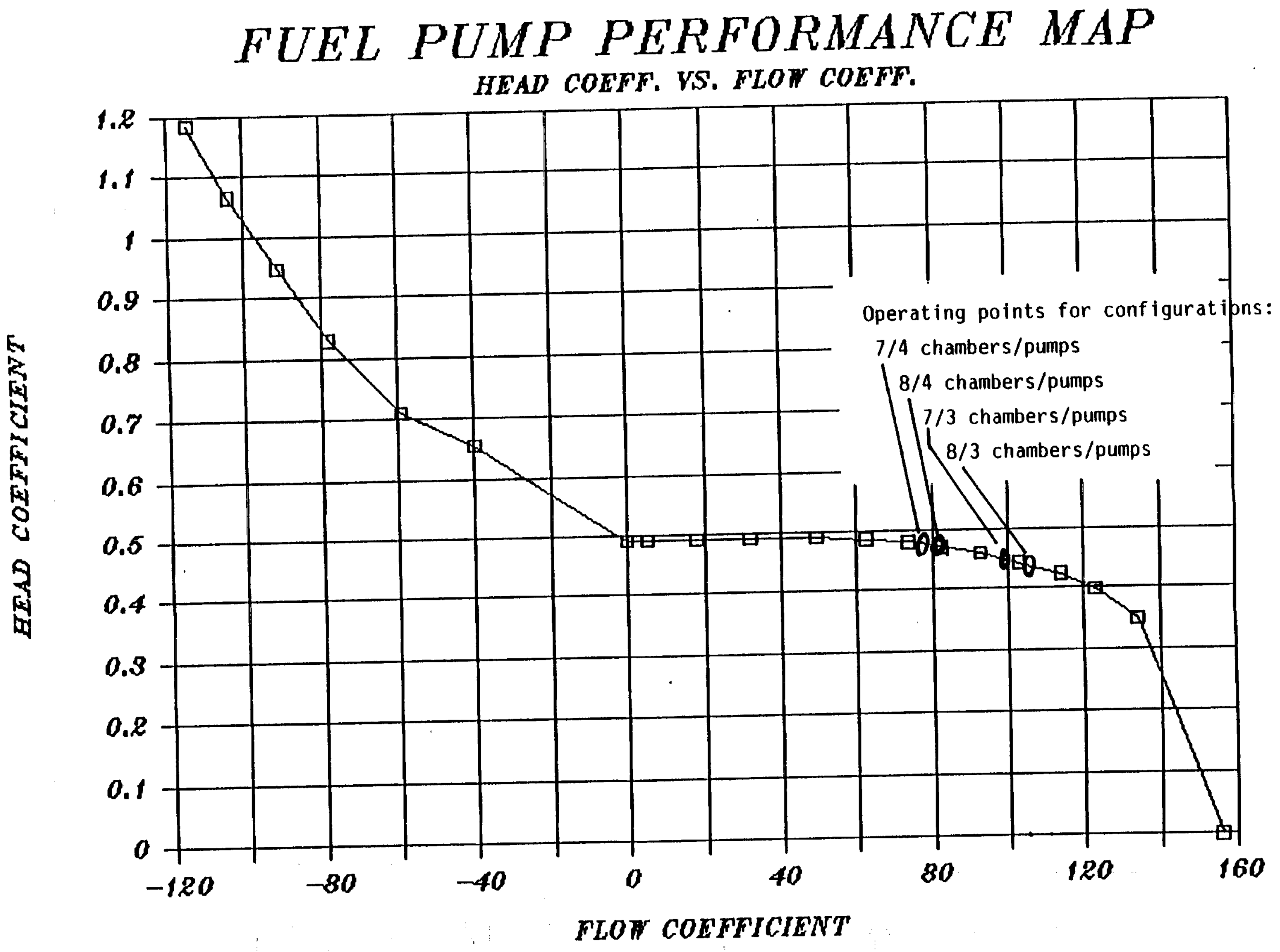

FUEL PUMP PERFORMANCE MAP
HEAD COEFF. VS. FLOW COEFF.
HEAD COEFFICIENT
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-120
-80
-40
0
40
80
120
160
FLOW COEFFICIENT
Operating points for configurations:
7/4 chambers/pumps
8/4 chambers/pumps
7/3 chambers/pumps
8/3 chambers/pumps

Figure 5

FUEL PUMP PERFORMANCE MAP

TORQUE COEFF. VS. FLOW COEFF.

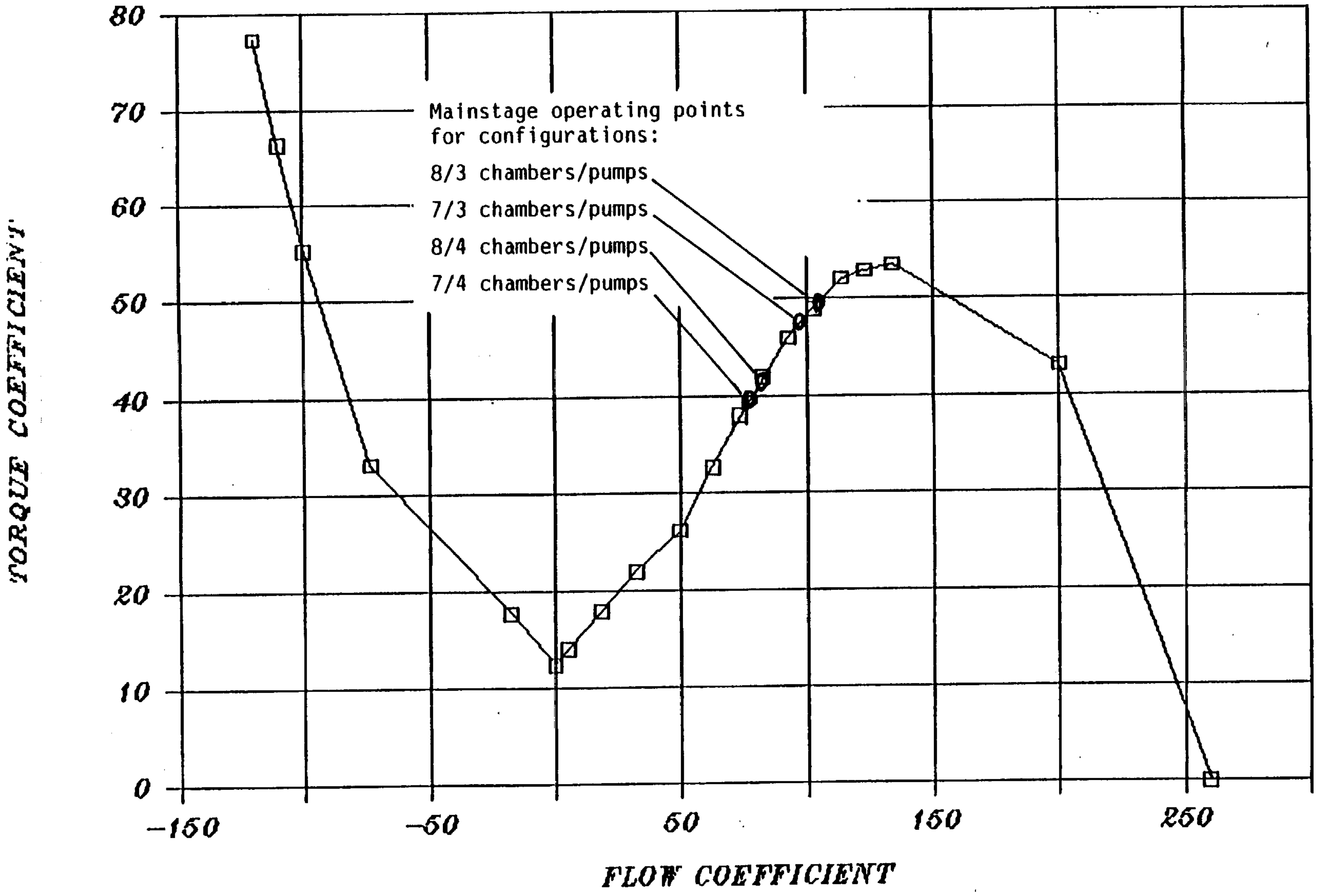


Figure 6

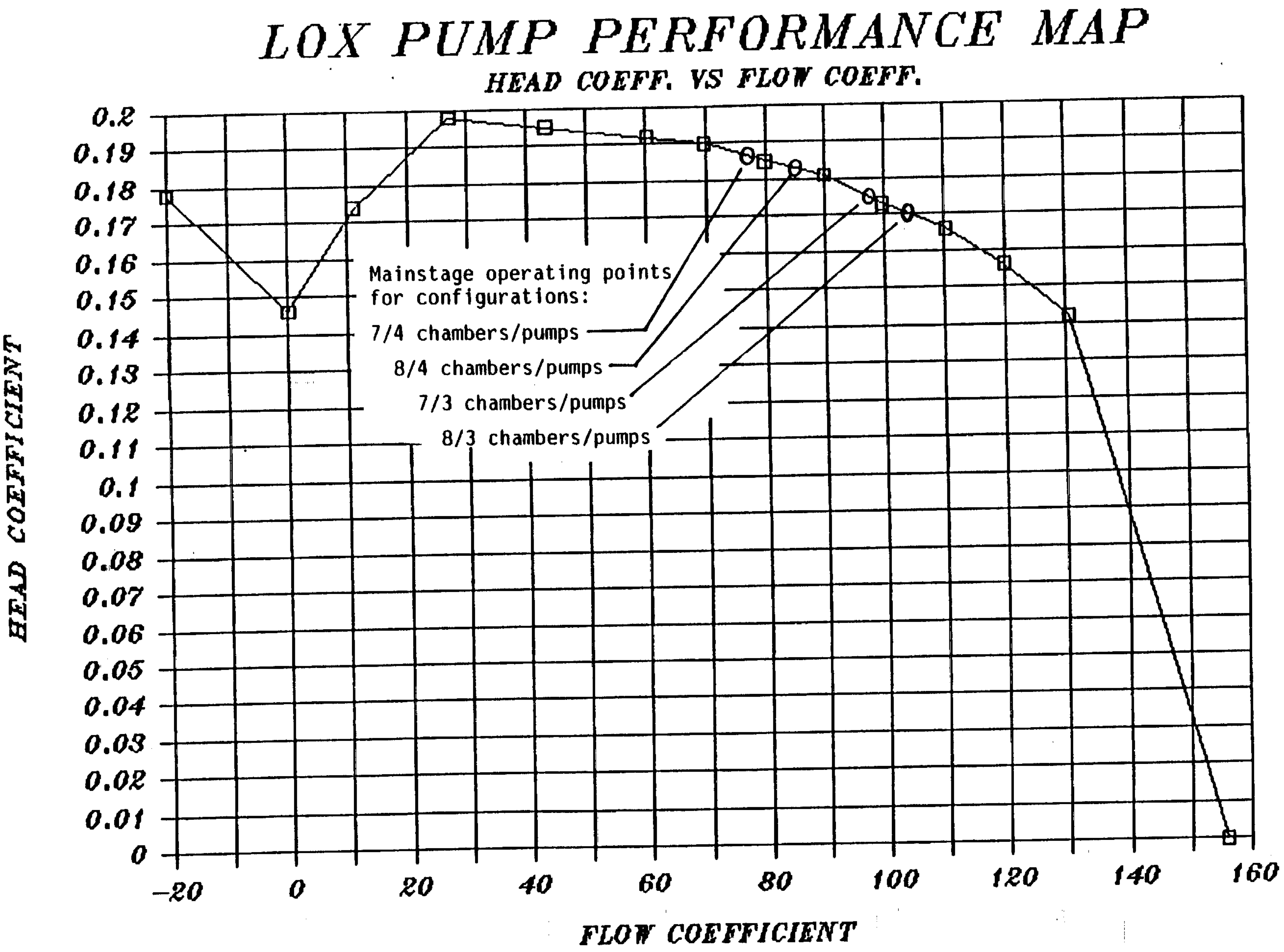

LOX PUMP PERFORMANCE MAP
HEAD COEFF. VS FLOW COEFF.
HEAD COEFFICIENT
0.2
0.19
0.18
0.17
0.16
0.15
0.14
0.13
0.12
0.11
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
-20
0
20
40
60
80
100
120
140
160
FLOW COEFFICIENT
Mainstage operating points
for configurations:
7/4 chambers/pumps
8/4 chambers/pumps
7/3 chambers/pumps
8/3 chambers/pumps

Figure 7

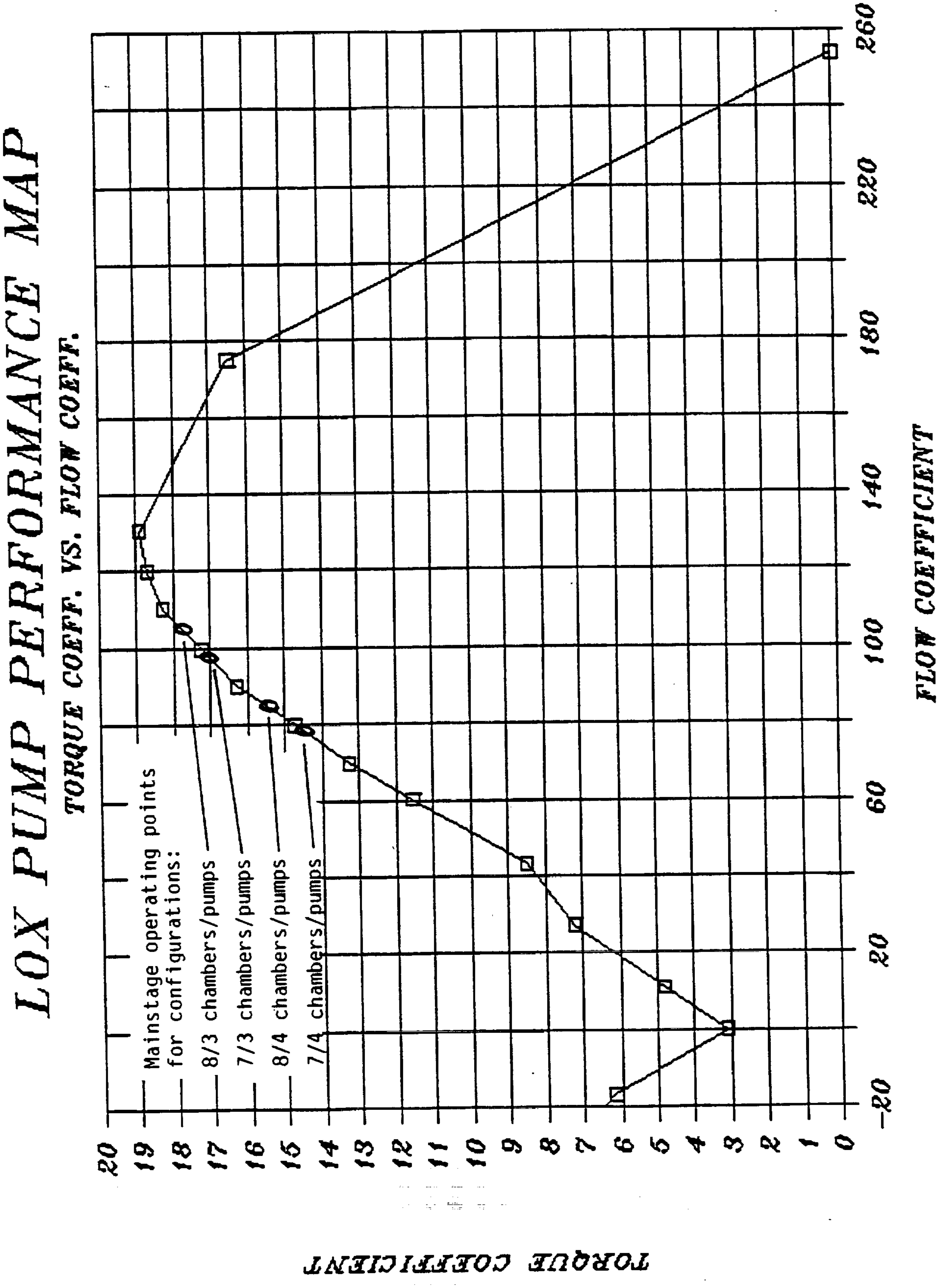

LOX PUMP PERFORMANCE MAP
TORQUE COEFF. VS. FLOW COEFF.
Mainstage operating points
for configurations:
8/3 chambers/pumps
7/3 chambers/pumps
8/4 chambers/pumps
7/4 chambers/pumps
FLOW COEFFICIENT
-20
20
60
100
140
180
220
260
TORQUE COEFFICIENT
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20

Figure 8

Table 1A
Steady State Engine Balance For The 8 Chamber/4 Turbopump Configuration

	Design Values	Model Results							
		T/P1		T/P2		T/P3		T/P4	
		T/C1	TC2	T/C3	T/C4	T/C5	T/C6	T/C7	T/C8
Thrust Chamber									
thrust (lb)	497000	425363	425360	425356	425363	425361	425358	425360	425360
pressure (psia)	1971	2013	2013	2013	2013	2013	2013	2013	2013
mixture ratio	6.701	6.66	6.66	6.66	6.66	6.66	6.66	6.66	6.66
fuel flowrate (lb/sec)	147	151	151	151	151	151	151	151	151
lox flowrate (lb/sec)	986	1008	1008	1008	1008	1008	1008	1008	1008
Fuel Pump									
speed (rpm)	14654	14826		14828		14826		14824	
torque (in-lb)	336295	350466		350781		350761		350743	
discharge pressure (psia)	3058	3117		3118		3117		3117	
flowrate (lb/sec)	336	346		347		347		346	
LOX Pump									
speed (rpm)	5521	5620		5620		5620		5620	
torque (in-lb)	274071	282640		282992		282838		282886	
discharge pressure (psia)	2568	2660		2660		2662		2658	
flowrate (lb/sec)	2014	2051		2054		2052		2053	
Gas Generator									
pressure (psia)	1559	1621		1621		1622		1621	
temperature (R)	1600	1556		1555		1556		1555	
mixture ratio	0.882	0.84		0.84		0.84		0.84	
fuel flowrate (lb/sec)	41.2	44		44		44		44	
lox flowrate (lb/sec)	36.4	37		37		37		37	
T/P - turbopump T/C - thrust chamber									

Table 1B
Steady State Engine Balance For The 8 Chamber/3 Turbopump Configuration

	Design Values	Model Results							
		T/P1 T/C1	TC2	T/P2 T/C3	T/C4	T/P3 T/C5	T/C6	T/P4 T/C7	T/C8
Thrust Chamber									
thrust (lb)	497000	410242	408874	404647	404643	408890	410236	410571	410578
pressure (psia)	1971	1953	1948	1930	1930	1948	1953	1954	1954
mixture ratio	---	6.52	6.48	6.53	6.53	6.48	6.52	6.53	6.53
fuel flowrate (lb/sec)	---	149	149	147	147	149	149	149	149
lox flowrate (lb/sec)	---	971	967	961	961	967	971	972	972
Fuel Pump									
speed (rpm)	~ 15142	15295		3342		15297		15299	
torque (in-lb)	---	442015		5411		442379		442929	
discharge pressure (psia)	---	3019		322		3090		3092	
flowrate (lb/sec)	---	454		~ 0		454		454	
LOX Pump									
speed (rpm)	~ 5705	5854		1594		5855		5860	
torque (in-lb)	---	350935		5000		351231		351472	
discharge pressure (psia)	---	2671		25		2671		2678	
flowrate (lb/sec)	---	2626		~ 0		2629		2626	
Gas Generator									
pressure (psia)	---	2072		14.7		2072		2076	
temperature (R)	---	1495		376		1495		1500	
mixture ratio	---	0.8		0.03		0.8		0.8	
fuel flowrate (lb/sec)	---	58.2		0		58.3		58.2	
lox flowrate (lb/sec)	---	46.7		0		46.7		46.8	
T/P - turbopump T/C - thrust chamber									

Table 1C
Steady State Engine Balance For The 7 Chamber/4 Turbopump Configuration

	Design Values	Model Results							
		T/P1 T/C1	TC2	T/P2 T/C3	T/C4	T/P3 T/C5	T/C6	T/P4 T/C7	T/C8
Thrust Chamber									
thrust (lb)	567781	486454	486858	0	486852	486460	486316	486296	486321
pressure (psia)	2250	2258	2260	14.7	2260	2258	2258	2258	2258
mixture ratio	---	6.64	6.65	0	6.65	6.64	6.63	6.63	6.63
fuel flowrate (lb/sec)	---	170	170	0	170	170	170	170	170
lox flowrate (lb/sec)	---	1128	1129	0	1129	1128	1128	1127	1127
Fuel Pump									
speed (rpm)	~ 15794	15629		15635		15629		15627	
torque (in-lb)	---	372490		372865		372657		372640	
discharge pressure (psia)	---	3533		3534		3532		3532	
flowrate (lb/sec)	---	345		346		345		345	
LOX Pump									
speed (rpm)	~ 5950	5945		5950		5944		5944	
torque (in-lb)	---	297328		297462		297435		297420	
discharge pressure (psia)	---	3013		3018		3011		3011	
flowrate (lb/sec)	---	2014		2013		2015		2015	
Gas Generator									
pressure (psia)	---	1774		1776		1774		1774	
temperature (R)	---	1560		1562		1560		1560	
mixture ratio	---	0.84		0.84		0.84		0.84	
fuel flowrate (lb/sec)	---	48.1		48.1		48.1		48.1	
lox flowrate (lb/sec)	---	40.4		40.4		40.4		40.4	
T/P - turbopump T/C - thrust chamber									

Table 1D
Steady State Engine Balance For The 7 Chamber/3 Turbopump Configuration

	Design Values	Model Results							
		T/P1 T/C1	TC2	T/P2 T/C3	T/C4	T/P3 T/C5	T/C6	T/P4 T/C7	T/C8
Thrust Chamber									
thrust (lb)	567781	471971	471684	0	468564	471292	471830	471292	471830
pressure (psia)	2250	2201	2200	14.7	2186	2198	2200	2198	2200
mixture ratio	6.773	6.51	6.5	0	6.66	6.49	6.51	6.49	6.51
fuel flowrate (lb/sec)	166.6	168	168	0	164	168	168	168	168
lox flowrate (lb/sec)	1128.4	1092	1091	0	1093	1090	1092	1090	1092
Fuel Pump									
speed (rpm)	16281	16059		2411		16058		16055	
torque (in-lb)	458285	474829		3755		475042		475437	
discharge pressure (psia)	3568	3508		20.4		3508		3508	
flowrate (lb/sec)	447.3	454		~0		455		454	
LOX Pump									
speed (rpm)	6209	6155		1543		6154		6156	
torque (in-lb)	377744	374485		7835		374687		374893	
discharge pressure (psia)	3053	3025		286		3022		3025	
flowrate (lb/sec)	2684	2598		~0		2601		2601	
Gas Generator									
pressure (psia)	2250	2293		14.7		2292		2294	
temperature (R)	1600	1506		343		1505		1506	
mixture ratio	0.878	0.8		0		0.8		0.8	
fuel flowrate (lb/sec)	59.5	64.2		0		64.2		64.2	
lox flowrate (lb/sec)	52.5	51.6		0		51.6		51.6	

T/P - turbopump
T/C - thrust chamber

Table 2

Configuration Geometry

Fuel Feed System:

Element	Length (in)	Diameter (in)	Volume (in**3)
pump inlet line	20	5	--
pump discharge valve inlet line	15	5	--
gas generator inlet line	15	1.5	--
ring manifold element inlet line	15	5	--
ring manifold element	93	8	--
thrust chamber valve inlet line	15	5	--
combustor cooling channels	100	5	8500
manifold	15	1.5	1500
injector	15	2	--

combustor cooling channels wall weight (lb):
ambient side 187
hot gas side 94

Oxidizer Feed System:

Element	Length (in)	Diameter (in)
pump discharge valve inlet line	15	5
gas generator inlet line	15	1.5
ring manifold element inlet line	107	5
ring manifold element	107	8
thrust chamber valve inlet line	15	5

Pumps, Turbines, Thrust Chamber:

fuel turbine inlet line volume (in**3)	1272
oxidizer turbine inlet line volume (in**3)	4000
oxidizer turbine discharge line volume (in**3)	1000
main combustion chamber volume (in**3)	12500
throat area (in**2)	132.5
area ratio	39:1
fuel pump inertia (lb-in-sec**2)	52.4
oxidizer pump inertia (lb-in-sec**2)	108.7

Table 3

Valve Flow Areas

Valves	Position at 497 klbf (%)	Fully Opened Effective Area (in**2)
Fuel Pump Discharge (4)	100	32.92
Oxidizer Pump Discharge (4)	100	38.70
Fuel Gas Generator (4)	100	0.92
Oxidizer Gas Generator (4)	100	0.24
Fuel Thrust Chamber Inlet (8)	100	17.80
Oxidizer Thrust Chamber Inlet (8)	100	19.59

Discussion and Results

Turbopump Out Condition

If one of the fuel or LOX turbopumps fails, the associated gas generator must be shut down which results in the loss of both the fuel and LOX turbopumps to the engine system. As one set of pumps is shut down, these pump discharge pressures begin to decay while the ring manifold pressures downstream are maintained at a relatively constant pressure due to the continued operation of the remaining pumps. The resulting back pressure on the pumps facilitates decay of the pump flow and eventually causes the propellant to flow back into the pumps. If the fuel pump flow decays too fast relative to the decay in fuel pump speed, boil-out in the pump will result.

For the simulation of one turbopump failure, a nominal start simulation was made and allowed to reach a nominal mainstage. The valve schedules for start are shown in Table 4. One of the fuel/LOX turbopump sets (set #2) was shut down at 4.0 seconds. The pumps were isolated from the system by closing the associated gas generator (GG) valves (set #2) and the pump discharge valves (set #2). The valve schedules for the pump out case are shown in Table 5. The fuel and LOX GG valves were closed in 0.3 and 0.1 seconds. These valves were closed quickly to cut the power supply to the pumps. The LOX valve was closed faster than the fuel valve to maintain a fuel-rich environment in the GG chamber during shutdown. In the earlier simulations made, the pump discharge valves were simulated as check valves. Since check valves close instantaneously for negative pressure differentials, the pump discharge valves closed at the instant the propellant flow was forced back in the direction of the pumps. The check valve on the LOX side will prevent LOX from flowing back into the LOX pump where it might leak through the turbine drain and mix with hot gas, with the probable result of a fire. Simulations with a check valve on the fuel side indicate that boil-out would result in the fuel pump, however. The fuel pump flow was reduced to nearly zero in 10 msec at which time the pump speed remained at about 86% of mainstage. Vaporization of the small fuel volume available would result in a case where the residual energy of the pump is so high. Boil-out should be avoided to prevent both damage to the pump as well as consequential damage to the surrounding hardware.

Due to the concern of boil-out in the fuel pump, subsequent simulations were made with a check valve on the LOX pump discharge only. The results are presented in Appendices A-D. The LOX pump discharge valve closed at the time the flow reversed directions, 0.2 seconds from the time power was cut to the pump by closing the GG valves (see Figure B14). The fuel pump discharge valve was closed in 0.7 seconds. This valve was closed slowly to allow the available propellant to flow back into the fuel pump to facilitate slowing the pump down. At the time the fuel pump flow was reduced to zero, the pump speed was about 30% of its mainstage operating speed (Figures B8,B9). Based on SSME test data, boil-out should not be of concern under these conditions.

A concern which was raised regarding backflow into the fuel pump is the potential for high pressures at the pump inlet duct. The propellant which flows back into the pump is warm and will be further heated due to energy imparted to it by the pump. As a result, the propellant density will decrease. If the density drops such that two-phase flow is induced, much higher pressures than normal will be produced. The pump inlet ducts will be required to withstand the resulting high pressures. The effect on the tank is also uncertain. A detailed description of the pump inlet ducts in the model is required to ascertain the effects of the backflow on the pump inlet duct and the fuel tank.

Upon shutting down one fuel/LOX turbopump set, the total system thrust was reduced to about 77% of nominal. In order to maintain operation of the chambers at nominal thrust, the propellant supply to the three remaining GGs was increased. The resulting higher GG output drove the three remaining pump sets at the higher level required to pump the same quantity of propellant as was nominally pumped with four pump sets. A control mechanism will be required on the GG valves to increase the GG supply line flow in the event of a pump failure. In the results of Appendix A-D the control mechanism was simulated with the fuel and LOX GG valve positions increased to 3 and 2.7 times the nominal flow areas, respectively, to maintain nominal operation of all eight chambers (Figures A2,C2,D2). Upon shutting down one pump set and throttling up the remaining three, the new mainstage operating level was reached in about 1 second. Slight variations resulted in the pressures between the eight chambers at the new mainstage (see Table 1B). These variations are due to resistance in the ducts and ring manifolds. The lowest pressures are found in the two chambers nearest to the pumps which were shut down. The average chamber pressure for the three turbopump configuration was about 1946 psia, about 3% lower than the nominal pressure for the four turbopump configuration. The three fuel/LOX turbopumps reached higher operating levels by 3.2% and 4.2%, respectively, compared to the nominal levels.

As the pump set was being shut down, a temporary decay in thrust for nearly one second as well as overshoots in the main chamber mixture ratios resulted. The thrust decay resulted in part due to the time required for the three fuel/LOX GG valves to attain their increased operating positions. The thrust decay can also attributed to the loss of fuel which was allowed to backflow into the fuel pump as it was being shut down. The mixture ratio overshoots are primarily due to the imbalance created by allowing backflow into the fuel pump and not into the LOX pump through the use of a check valve on the LOX side. The mixture ratios overshoot from a nominal 6.7 to about 7.5; these values are within acceptable limits.

Table 4

Valve Schedules For Hydrogen Spin-Assisted Start

Valve	Start/End (sec)	Rate (%/sec)	Final Position (%)
Fuel Pump Discharge (4)	0./0.	instantaneous	100.
LOX Pump Discharge (4)	0./0.	instantaneous	55.
	2.1/3.4	35.	100.
Fuel Gas Generator (4)	0./1.0	0.	0.
	1.0/1.5	200.	100.
LOX Gas Generator (4)	0./1.2	0.	0.
	1.2/3.2	50.	100.
Fuel Thrust Chamber Inlet (8)	0./0.3	333.	100.
LOX Thrust Chamber Inlet (8)	0./0.1	0.	0.
	0.1/0.5	100.	40.
	0.5/2.5	0.	40.
	2.5/3.8	46.	100.

Table 5

Valve Schedules For Turbopump #2 Out Condition At 4.0 seconds

Valve	Start/End (sec)	Rate (%/sec)	Initial/Final Position(%)
Fuel Pump Discharge (# 1,3,4)	no change	---	100./100.
Fuel Pump Discharge (# 2)	4.0/4.7	143.	100./0.
LOX Pump Discharge (# 1,3,4)	no change	---	100./100.
LOX Pump Discharge (# 2)	4.0/4.2 (check valve)	---	100./0.
Fuel Gas Generator (# 1,3,4)	4.0/4.1	2000.	100./300.
Fuel Gas Generator (# 2)	4.0/4.3	333.	100./0.
LOX Gas Generator (# 1,3,4)	4.0/4.3	567.	100./270.
LOX Gas Generator (# 2)	4.0/4.1	1000.	100./0.
Fuel Thrust Chamber Inlet (# 1-8)	no change	---	100./100.
LOX Thrust Chamber Inlet (# 1-8)	no change	---	100./100.

Combined Thrust Chamber/Turbopump Out Condition

The simulation results of the scenario in which both a thrust chamber and a turbopump fail are presented in Appendices E-H. A nominal start simulation was made; mainstage was reached in about 3.5 seconds. When a thrust chamber fails, both the fuel and LOX valves supplying the failed thrust chamber must be closed. The propellant flow which would nominally supply this thrust chamber is thus diverted via the ring manifolds to the other seven chambers. When a turbopump fails, the pump must be shut down and isolated from the system by closing the pump discharge valves and the GG valves, as mentioned in the last section.

In the simulation, shutting down main chamber #3 was initiated at 4.0 seconds by closing the chamber inlet valves. The fuel and LOX valves were closed in 0.8 seconds and 0.7 seconds, respectively, as shown in Table 6A. This valve sequence, which ensures a fuel-rich environment in the chamber during shutdown, is also used for the nominal shutdown of all eight chambers. When a chamber is shut down, the objective is to maintain acceptable mixture ratios in the remaining chambers as well as in the failed chamber, so that the potential for further damage to the failed chamber is avoided. Figures F4 and F5 show the main chamber (#3) pressure and mixture ratio decay due to shutdown of this chamber. The operating level of the pumps and remaining chambers increased as a result, as shown in the profiles of Appendices E-H. The engine balance for the 7 chamber/4 turbopump system is shown in Table 1C. The pressures in the seven remaining chambers increased from 2013 psia to 2258 psia, about 12%. Slightly higher pressures were achieved in the two chambers adjacent to that being shut down. These chambers were affected slightly more by the diverted flow due to the closer proximity (less resistance). Fuel and LOX pump speeds of about 15,630 rpm and 5,945 rpm, respectively, were achieved. These represent increases of 5.4% and 5.8% from the nominal operating speeds of 14,826 rpm and 5,620 rpm, for the fuel and LOX pumps, respectively. Slight mixture ratio overshoots from the design of 6.7 to about 7.2 in the seven remaining chambers, and slight GG mixture ratio overshoots resulted.

Shutdown of the fuel/LOX turbopump #2 was initiated at 6.0 seconds by closing the GG valves and the pump discharge valves. The same sequences described in the last section for the turbopump out case were used and are summarized in Table 6B. The fuel and LOX GG valves were closed in 0.3 and 0.1 seconds, respectively. The fuel pump discharge valve was closed slowly in 0.7 seconds. This schedule allowed the fuel to backflow into the pump to facilitate in slowing the pump down. The LOX pump discharge valve was simulated as a check valve and closed at the time the flow reversed directions. The LOX valve closed about 0.2 seconds from the time power was cut to the pump by closing the GG valves. The three remaining fuel/LOX GG valve positions were increased by 300% and 270%, respectively, to power up the turbopumps. As the pump set was being shut down, slight mixture ratio overshoots in the seven main chambers from about 6.64 to 7.6 resulted which are within acceptable limits. As was mentioned earlier, these overshoots are due to the loss of some fuel from the system as a result of backflow into the fuel pump as it was shut down. A temporary decay in thrust resulted due to both the lag time for the GG valves to further open and to the loss of some fuel from the chambers.

The engine balance for the 7 chamber/3 turbopump configuration is shown in Table 1D. The average pressure in the seven remaining chambers was about 2198 psia, about 9% higher than the 8/4 (chamber/pump) configuration. The fuel and LOX pump speeds for the three remaining pump sets were about 16,057 rpm and 6,155 rpm, 8.3% and 9.5% higher than the 8/4 configuration.

Tables 6A,6B
Valve Schedules For Combined Thrust Chamber - Turbopump Out Condition

Table 6A - Position Changes For Thrust Chamber #3 Out at 4.0 seconds

Valve	Start/End (sec)	Rate (%/sec)	Initial/Final (%)
Fuel Pump Discharge (# 1-4)	no change	---	100./100.
LOX Pump Discharge(# 1-4)	no change	---	100./100.
Fuel Gas Generator (# 1-4)	no change	---	100./100.
LOX Gas Generator (# 1-4)	no change	---	100./100.
Fuel Thrust Chamber Inlet (# 1,2,4-8)	no change	---	100./100.
Fuel Thrust Chamber (# 3)	4.0/4.8	125.	100./0.
LOX Thrust Chamber Inlet (# 1,2,4-8)	no change	---	100./100.
LOX Thrust Chamber Inlet (# 3)	4.0/4.7	143.	100./0.

Table 6B - Position Changes For Turbopump #2 Out at 6.0 seconds

Valve	Start/End (sec)	Rate (%/sec)	Initial/Final (%)
Fuel Pump Discharge (# 1,3,4)	no change	---	100./100.
Fuel Pump Discharge (# 2)	6.0/6.7	143.	100./0.
LOX Pump Discharge (# 1,3,4)	no change	---	100./100.
LOX Pump Discharge (# 2)	6.0/6.2 (check valve)	---	100./0.
Fuel Gas Generator (# 1,3,4)	6.0/6.1	2000.	100./300.
Fuel Gas Generator (# 2)	6.0/6.3	333.	100./0.
LOX Gas Generator (# 1,3,4)	6.0/6.3	567.	100./270.
LOX Gas Generator (# 2)	6.0/6.1	1000.	100./0.
Fuel Thrust Chamber Inlet (# 1-8)	no change	---	100./100.
LOX Thrust Chamber Inlet (# 1-8)	no change	---	100./100.

Conclusions/Recommendations

The results of the foregoing analyses indicate the feasibility in throttling to and operating at configurations of 8/3, 7/4, and 7/3 chambers/turbopumps in the event of failure of a single thrust chamber, turbopump, or both. Upon shutting down a thrust chamber, slight mixture ratio overshoots from 6.7 to 7.2 in the seven remaining chambers, and slight GG mixture ratio overshoots result. As a turbopump set is shut down and the remaining three are throttled to higher operating levels, a temporary decay in thrust results. Mixture ratio overshoots in the main chambers from about 6.7 to 7.5 also result which are within acceptable limits.

The effects on the pump inlet duct and tank due to the backflow when shutting down a fuel pump require further investigation. The model requires the addition of a detailed description of the pump inlet ducts to predict these effects. Further, since NASA has defined a tank head start for the NLS (National Launch System) vehicle engines, a tank head start should be simulated as an alternative to the gas spin start.

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APPENDICES A THROUGH H
TRANSIENT ANALYTICAL RESULTS

Transient Analytical Results:
Turbopump Out Condition and Combined Thrust Chamber/Turbopump Out Condition

Turbopump out condition, systems 1-4, appendices A-D, respectively;
Combined thrust chamber/turbopump out condition, systems 1-4, appendices E-H, respectively.

Figures	Description
A1-H1	Fuel and Oxidizer Pump Discharge Valve Positions
A2-H2	Fuel and Oxidizer GG Valve Positions
A3-H3	Thrust Chamber Inlet Fuel and Oxidizer Valve Positions
A4-H4	Main Chamber Pressure
A5-H5	Main Chamber Mixture Ratio
A6-H6	GG Chamber Pressure
A7-H7	GG Mixture Ratio
A8-H8	Fuel Pump Speed
A9-H9	Fuel Pump Flowrate
A10-H10	Fuel Pump Discharge Valve Flowrate
A11-H11	Fuel Pump Discharge Pressure
A12-H12	Oxidizer Pump Speed
A13-H13	Oxidizer Pump Flowrate
A14-H14	Oxidizer Pump Discharge Valve Flowrate
A15-H15	Oxidizer Pump Discharge Pressure
A16-H16	GG Chamber Temperature
A17-H17	Oxidizer Turbine Inlet Temperature
A18-H18	Oxidizer Turbine Discharge Temperature
A19-H19	Fuel Injector Inlet Temperature
A20-H20	Hydrogen Gas Flow For GG Spin-Assisted Start

APPENDIX A

TURBOPUMP OUT CONDITION RESULTS

FOR SYSTEM 1

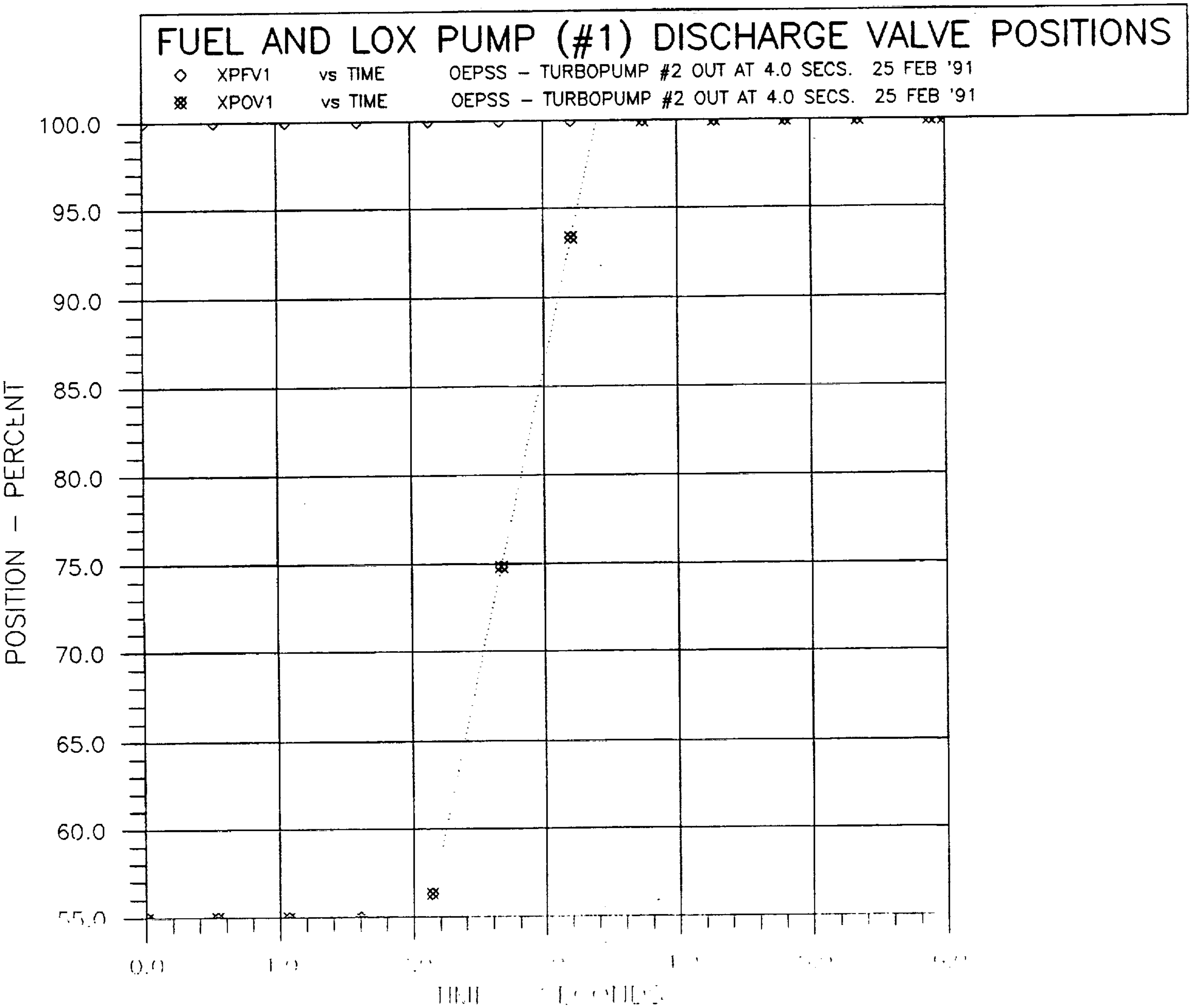

FUEL AND LOX PUMP (#1) DISCHARGE VALVE POSITIONS
◇ XPFV1 vs TIME OEPSS - TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
⊗ XPOV1 vs TIME OEPSS - TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
100.0
95.0
90.0
85.0
80.0
75.0
70.0
65.0
60.0
55.0
POSITION - PERCENT
0.0
1.0
TIME - SECONDS

Figure A1

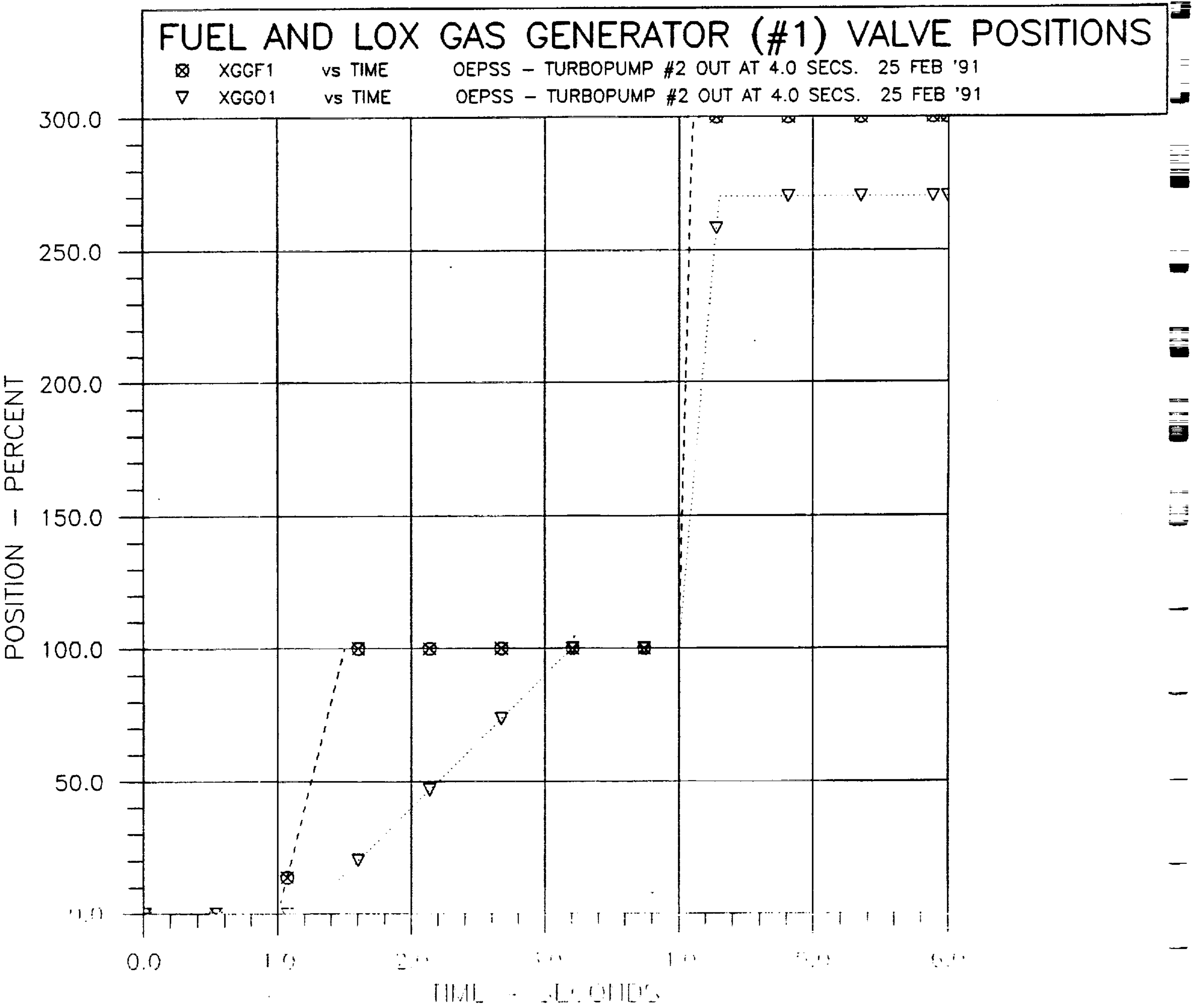
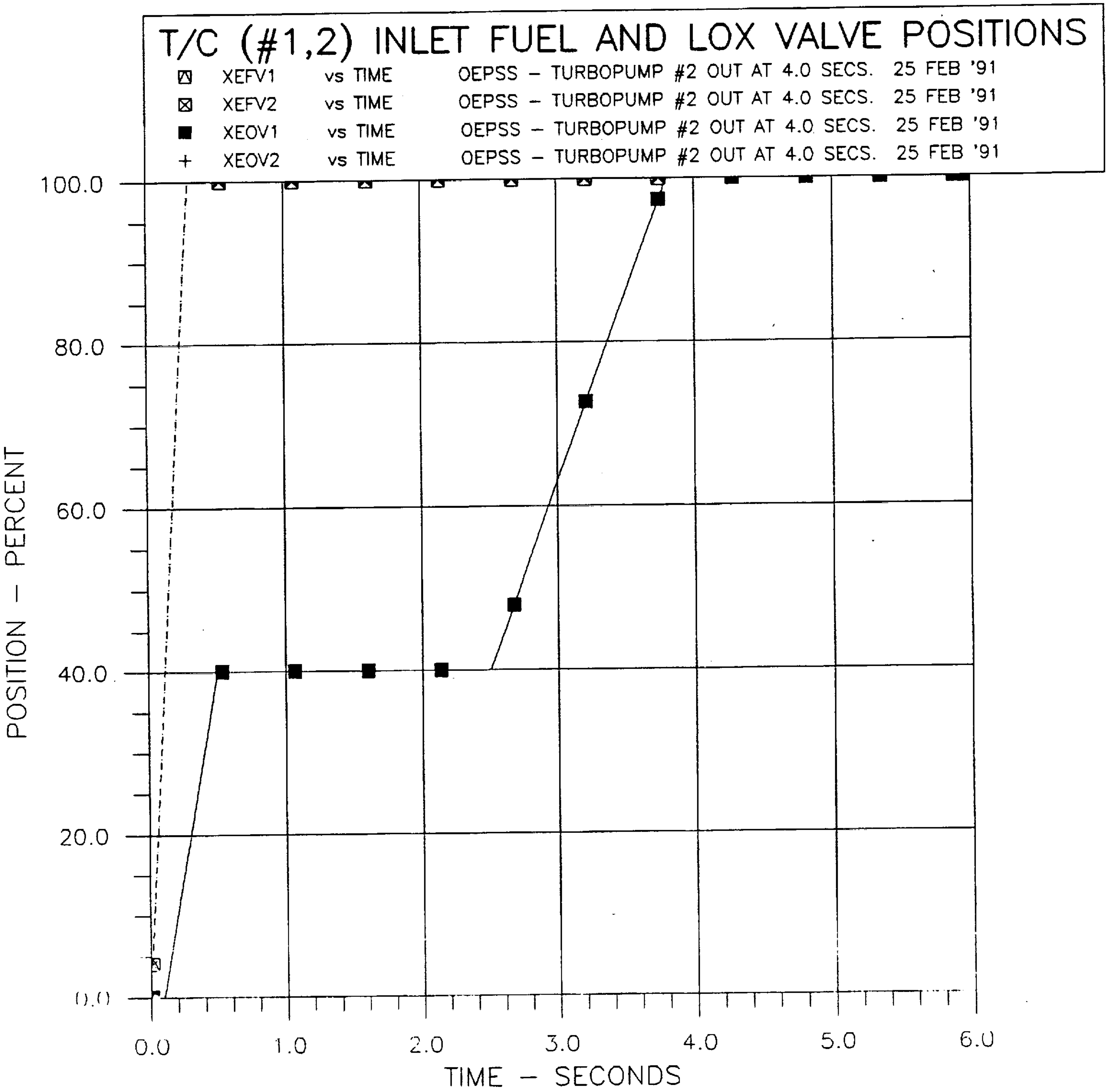

FUEL AND LOX GAS GENERATOR (#1) VALVE POSITIONS
⊠ XGGF1 vs TIME OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
▽ XGGO1 vs TIME OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
300.0
250.0
200.0
150.0
100.0
50.0
0.0
POSITION – PERCENT
0.0
1.0
2.0
3.0
4.0
5.0
6.0
TIME – SECONDS

Figure A2



T/C (#1,2) INLET FUEL AND LOX VALVE POSITIONS
XEFV1 vs TIME OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
XEFV2 vs TIME OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
XEOV1 vs TIME OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
XEOV2 vs TIME OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
100.0
80.0
60.0
40.0
20.0
0.0
POSITION – PERCENT
0.0
1.0
2.0
3.0
4.0
5.0
6.0
TIME – SECONDS

Figure A3

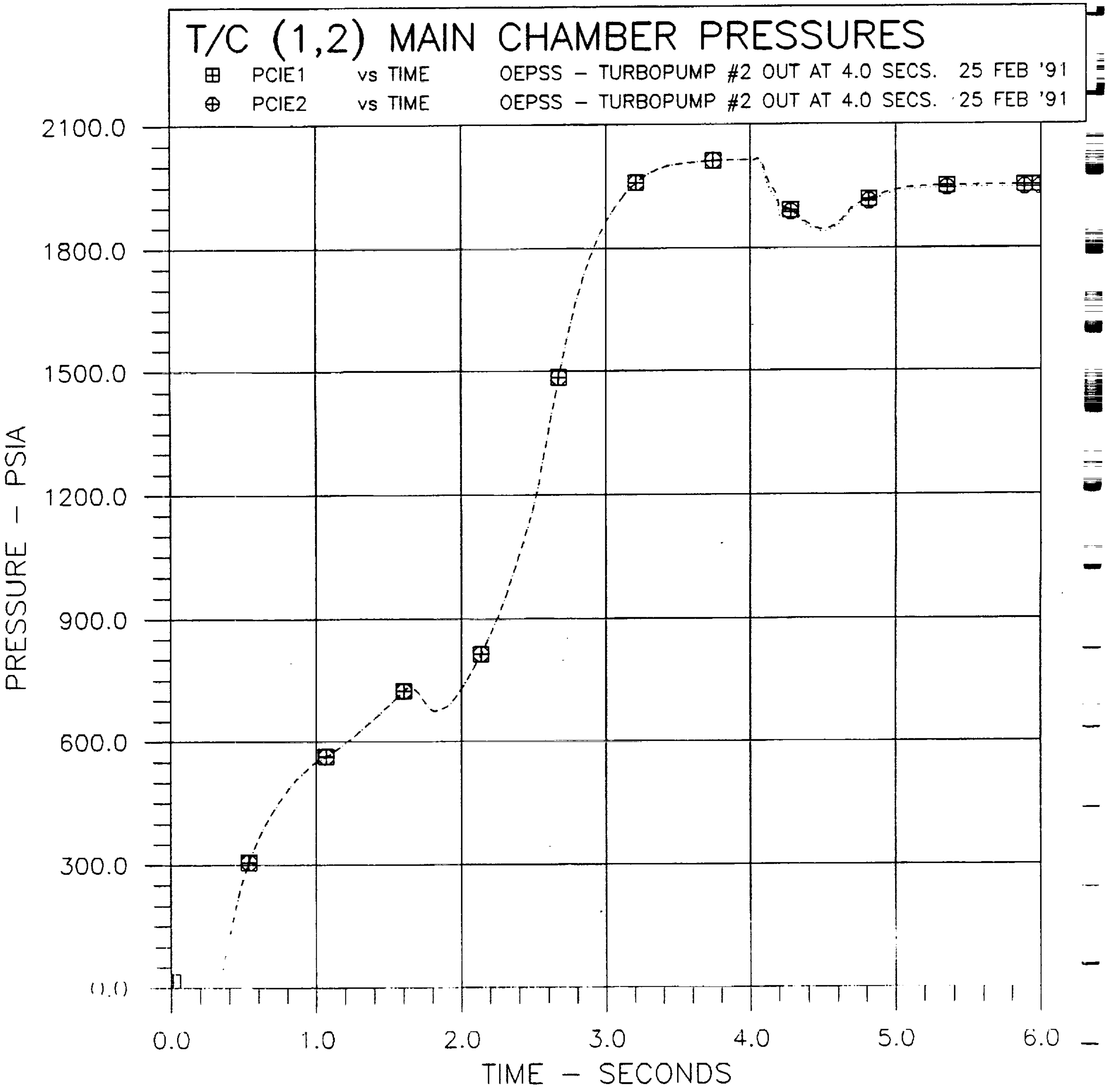

T/C (1,2) MAIN CHAMBER PRESSURES
⊞ PCIE1 vs TIME OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
⊕ PCIE2 vs TIME OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
2100.0
1800.0
1500.0
1200.0
900.0
600.0
300.0
0.0
PRESSURE – PSIA
0.0
1.0
2.0
3.0
4.0
5.0
6.0
TIME – SECONDS

Figure A4

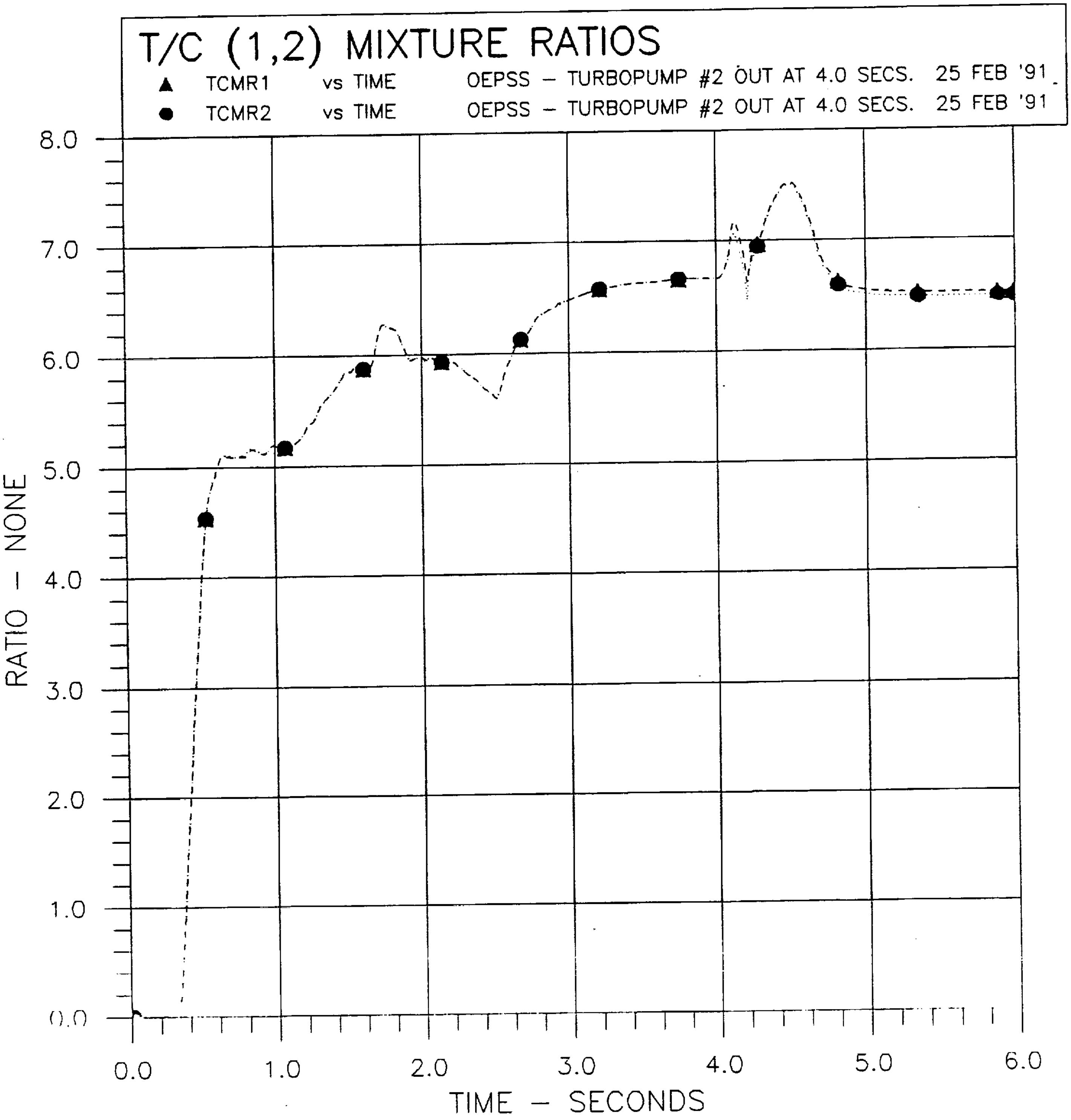

T/C (1,2) MIXTURE RATIOS
▲ TCMR1 vs TIME OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
● TCMR2 vs TIME OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
RATIO – NONE
0.0
1.0
2.0
3.0
4.0
5.0
6.0
TIME – SECONDS

Figure A5

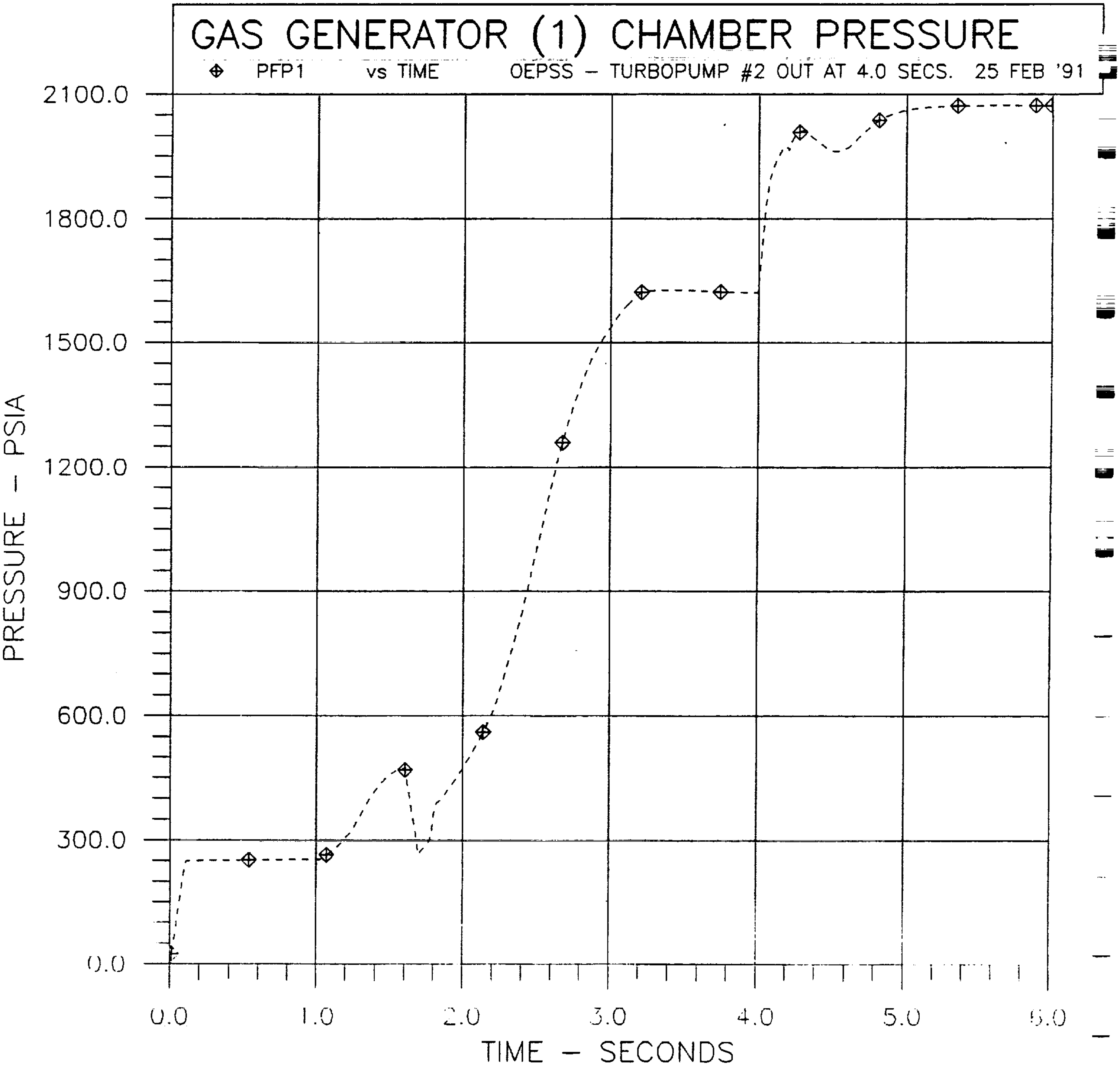

GAS GENERATOR (1) CHAMBER PRESSURE
⊕ PFP1 vs TIME OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
PRESSURE – PSIA
2100.0
1800.0
1500.0
1200.0
900.0
600.0
300.0
0.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
TIME – SECONDS

Figure A6

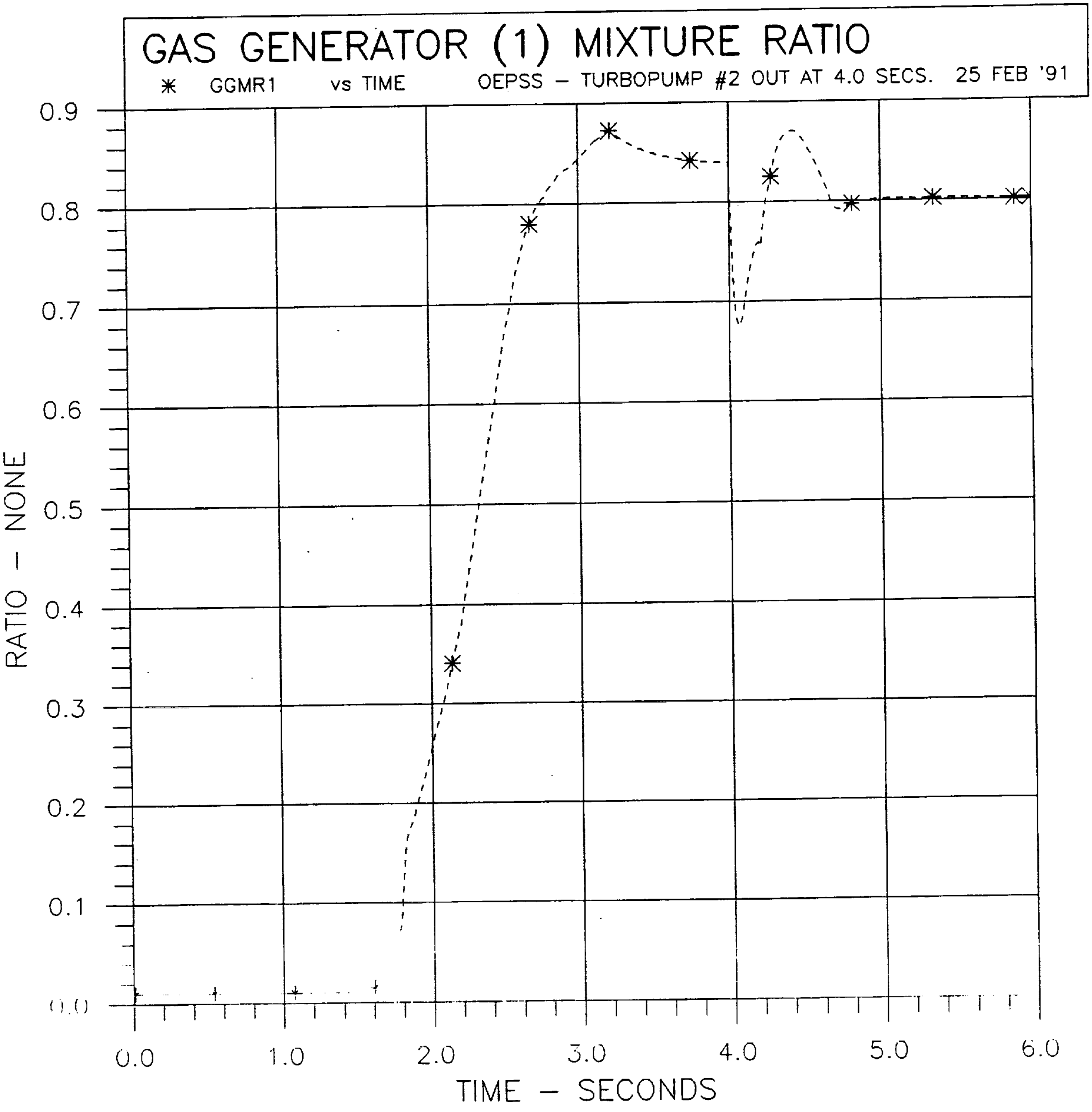

GAS GENERATOR (1) MIXTURE RATIO
✳ GGMR1 vs TIME
OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
RATIO – NONE
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
TIME – SECONDS

Figure A7

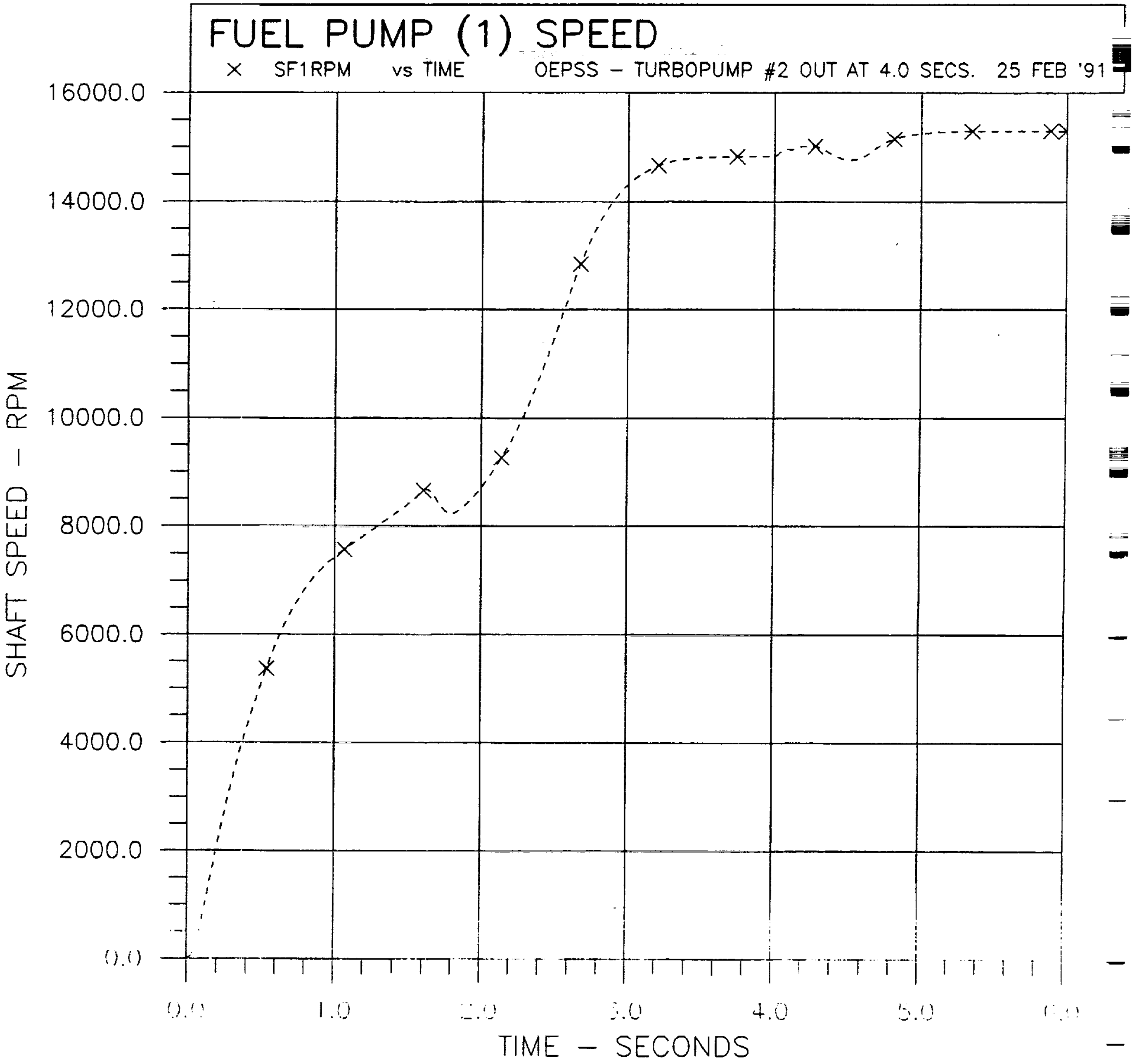

FUEL PUMP (1) SPEED
× SF1RPM vs TIME
OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
SHAFT SPEED – RPM
16000.0
14000.0
12000.0
10000.0
8000.0
6000.0
4000.0
2000.0
0.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
TIME – SECONDS

Figure A8

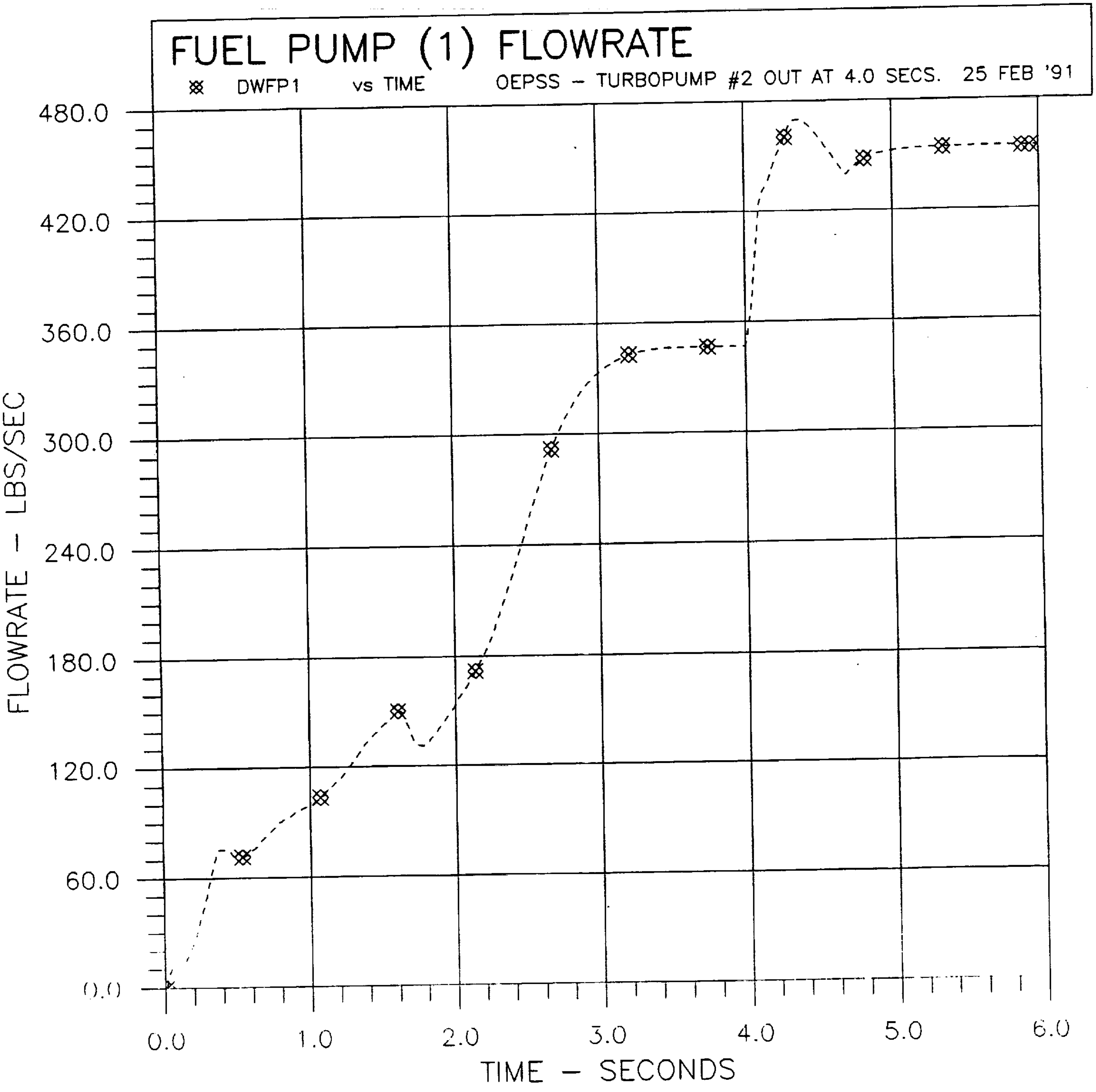

FUEL PUMP (1) FLOWRATE
⊗ DWFP1 vs TIME
OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
FLOWRATE – LBS/SEC
480.0
420.0
360.0
300.0
240.0
180.0
120.0
60.0
0.0
TIME – SECONDS
0.0
1.0
2.0
3.0
4.0
5.0
6.0

Figure A9

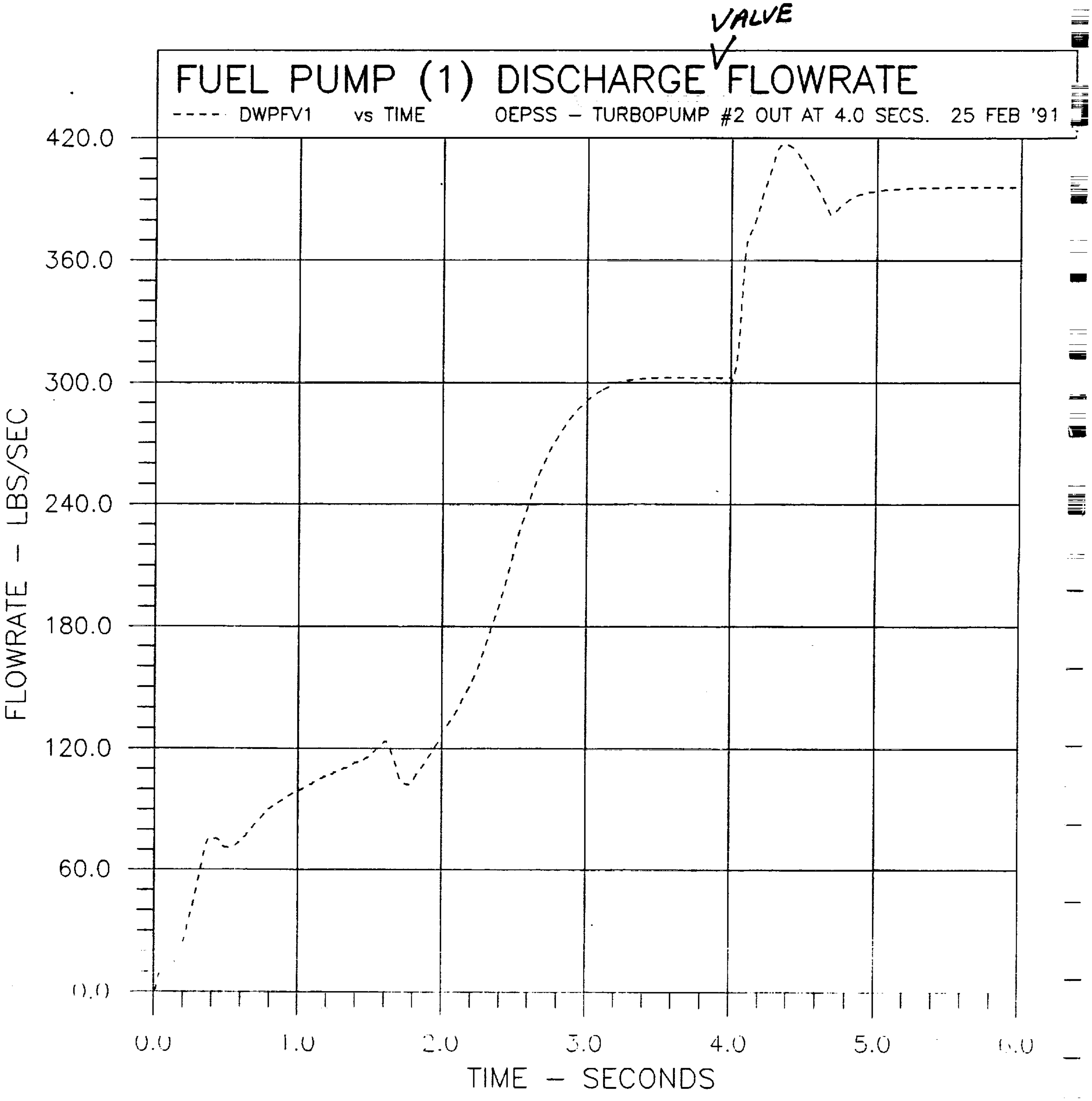
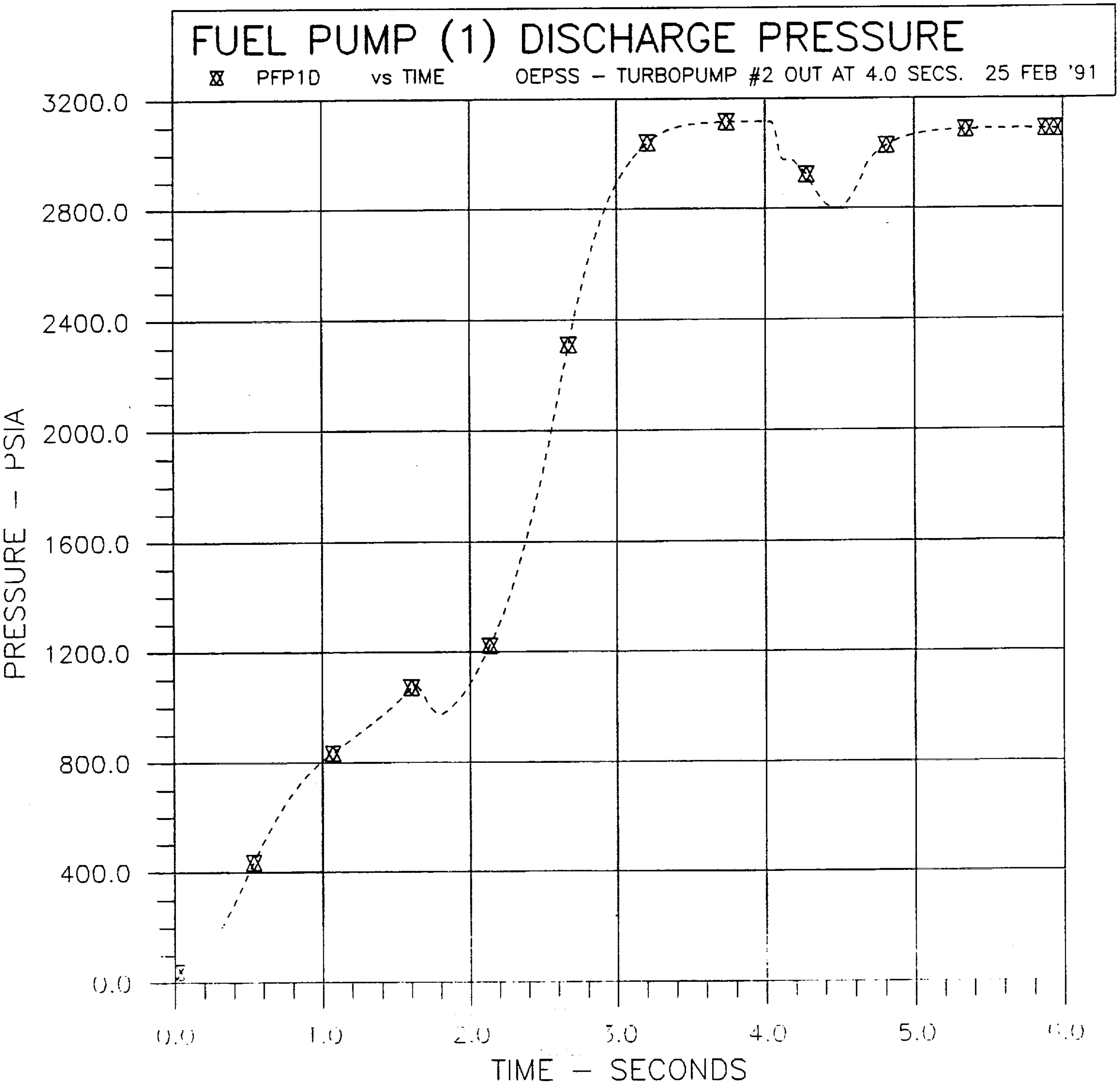

VALVE
FUEL PUMP (1) DISCHARGE FLOWRATE
---- DWPFV1 vs TIME
OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
420.0
360.0
300.0
240.0
180.0
120.0
60.0
0.0
FLOWRATE – LBS/SEC
0.0
1.0
2.0
3.0
4.0
5.0
6.0
TIME – SECONDS

Figure A10



FUEL PUMP (1) DISCHARGE PRESSURE
PFP1D vs TIME
OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
3200.0
2800.0
2400.0
2000.0
1600.0
1200.0
800.0
400.0
0.0
PRESSURE – PSIA
0.0
1.0
2.0
3.0
4.0
5.0
6.0
TIME – SECONDS

Figure A11

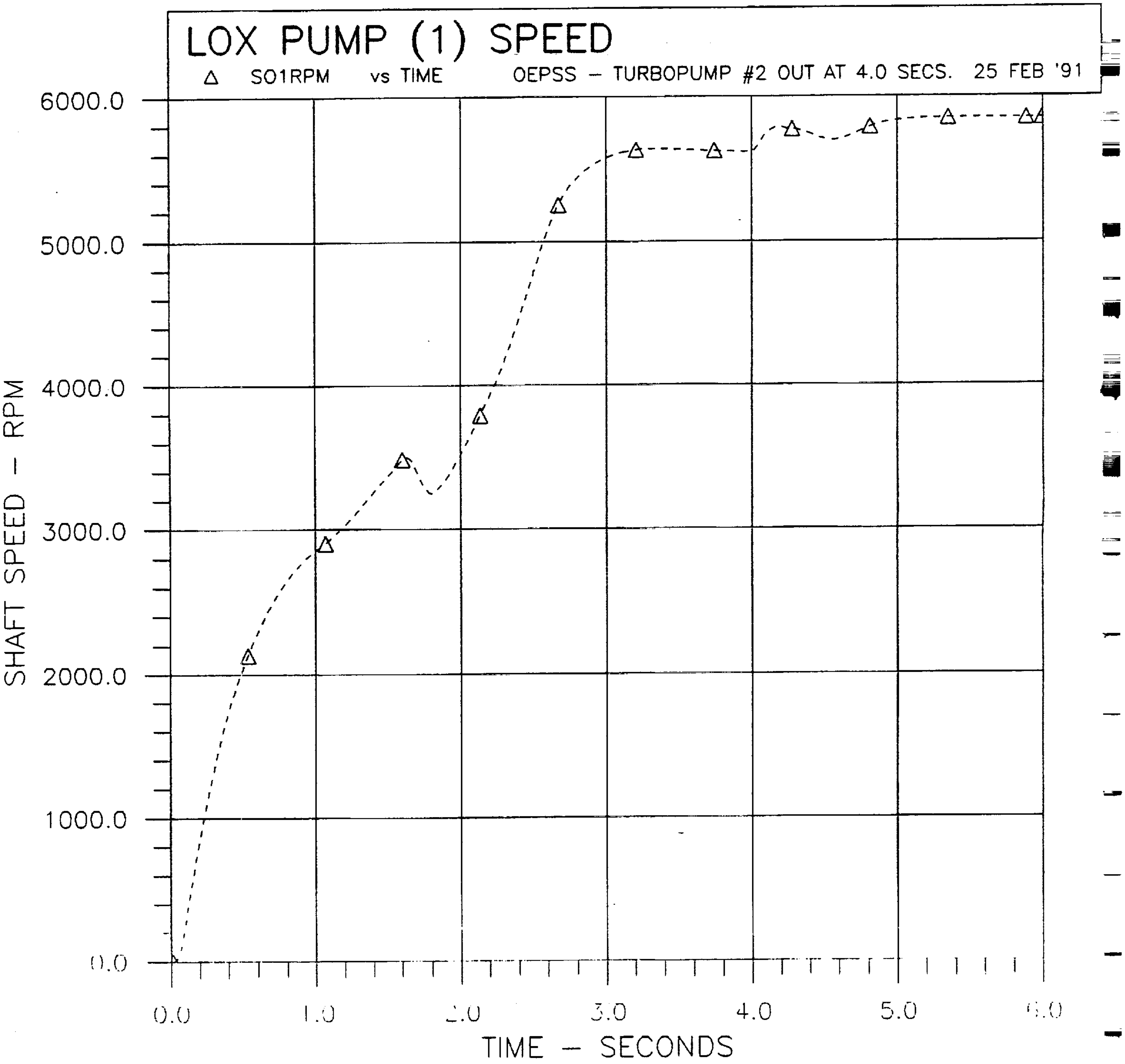

LOX PUMP (1) SPEED
△ SO1RPM vs TIME
OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
SHAFT SPEED – RPM
6000.0
5000.0
4000.0
3000.0
2000.0
1000.0
0.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
TIME – SECONDS

Figure A12

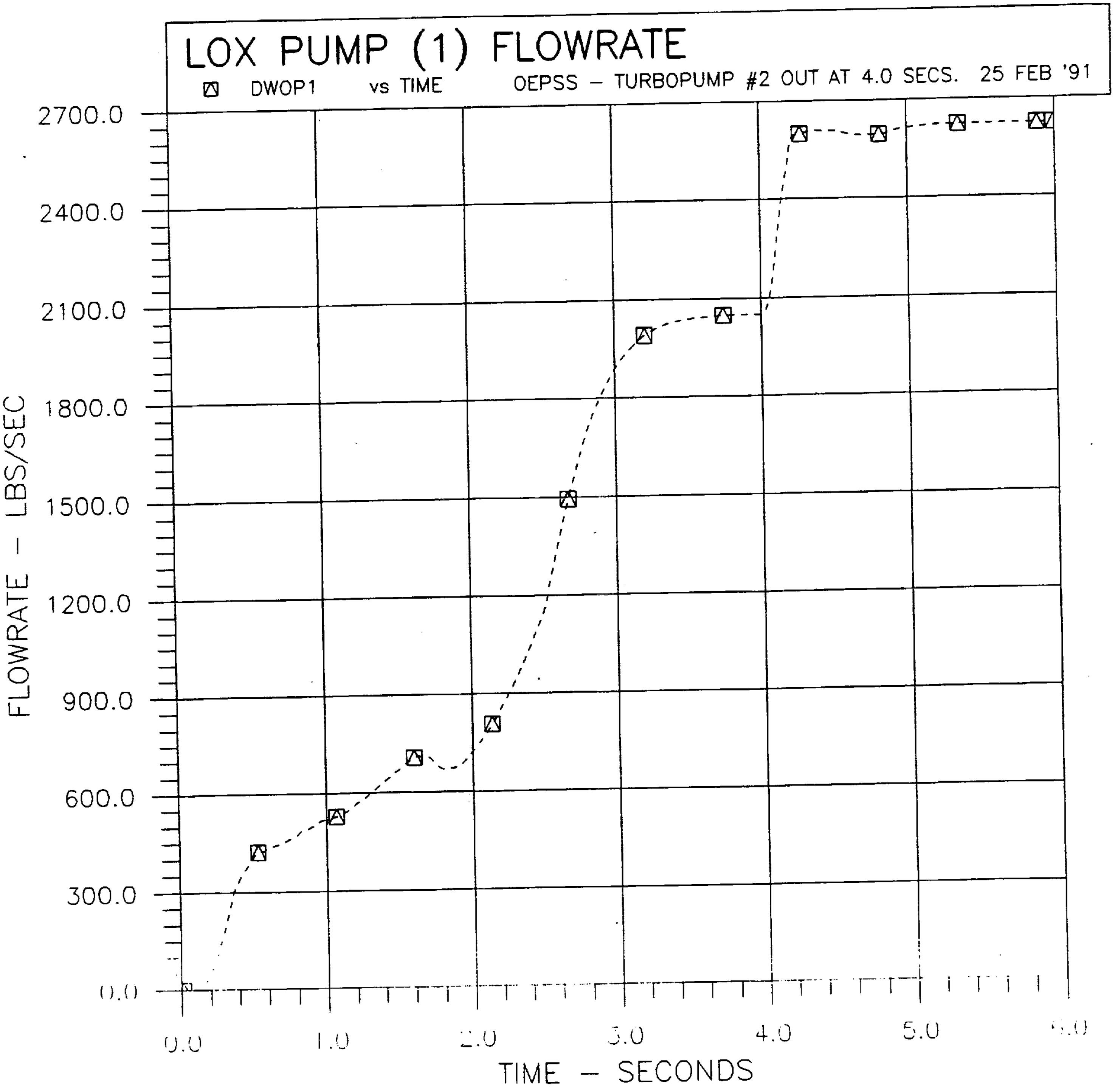

LOX PUMP (1) FLOWRATE
DWOP1 vs TIME
OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
FLOWRATE – LBS/SEC
2700.0
2400.0
2100.0
1800.0
1500.0
1200.0
900.0
600.0
300.0
0.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
TIME – SECONDS

Figure A13

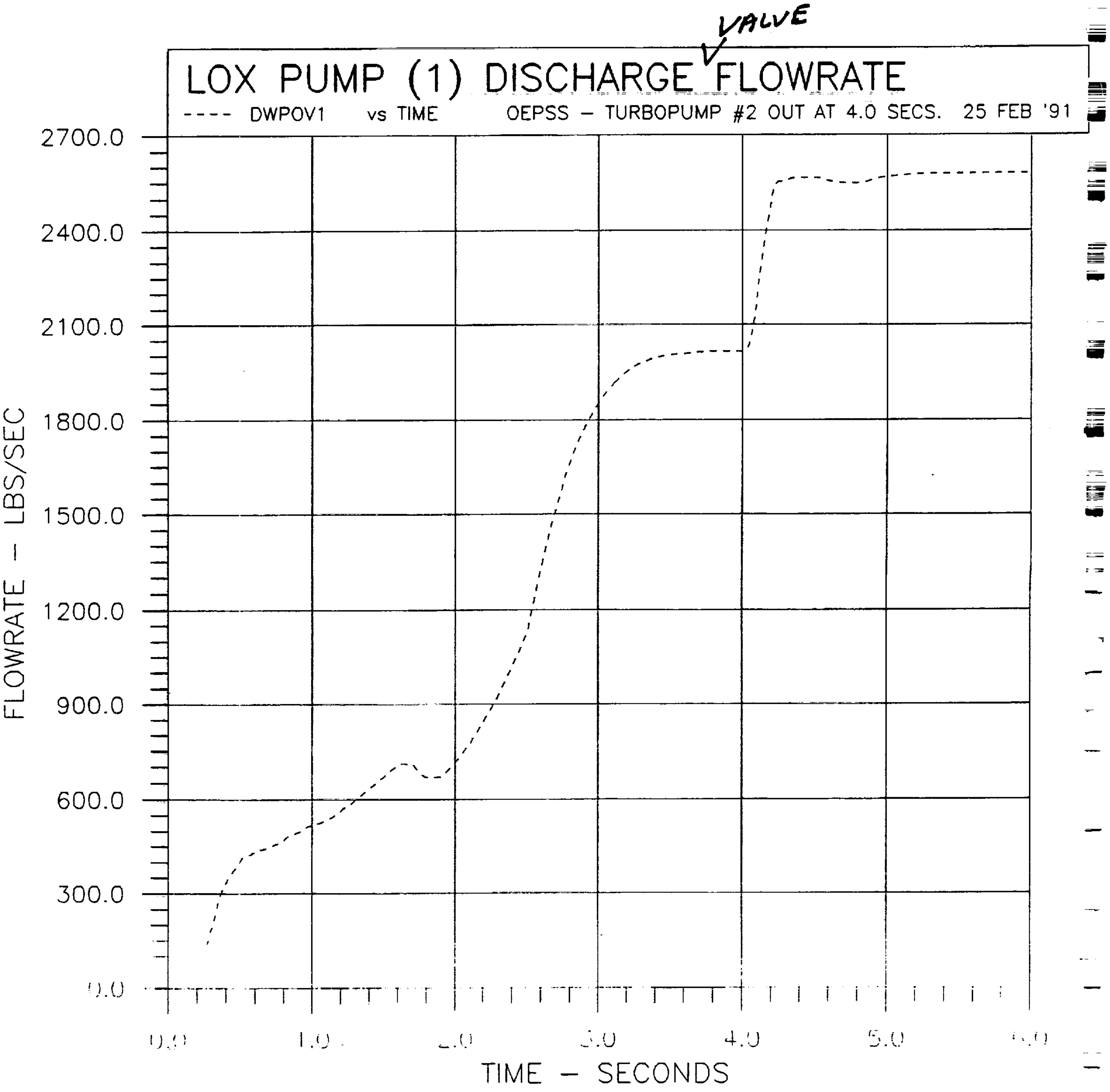

LOX PUMP (1) DISCHARGE VALVE FLOWRATE
---- DWPOV1 vs TIME
OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
FLOWRATE – LBS/SEC
2700.0
2400.0
2100.0
1800.0
1500.0
1200.0
900.0
600.0
300.0
0.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
TIME – SECONDS

Figure A14

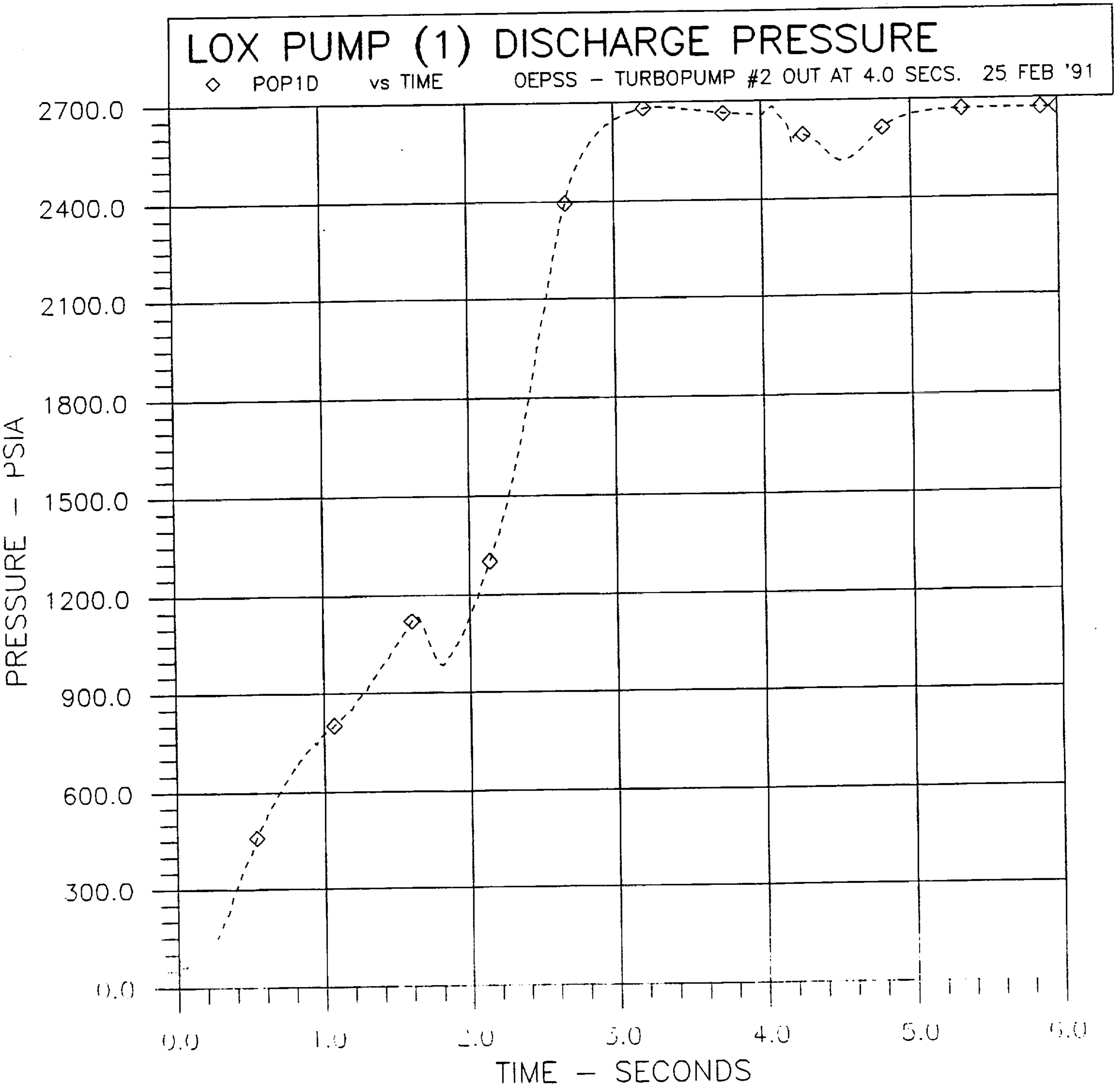
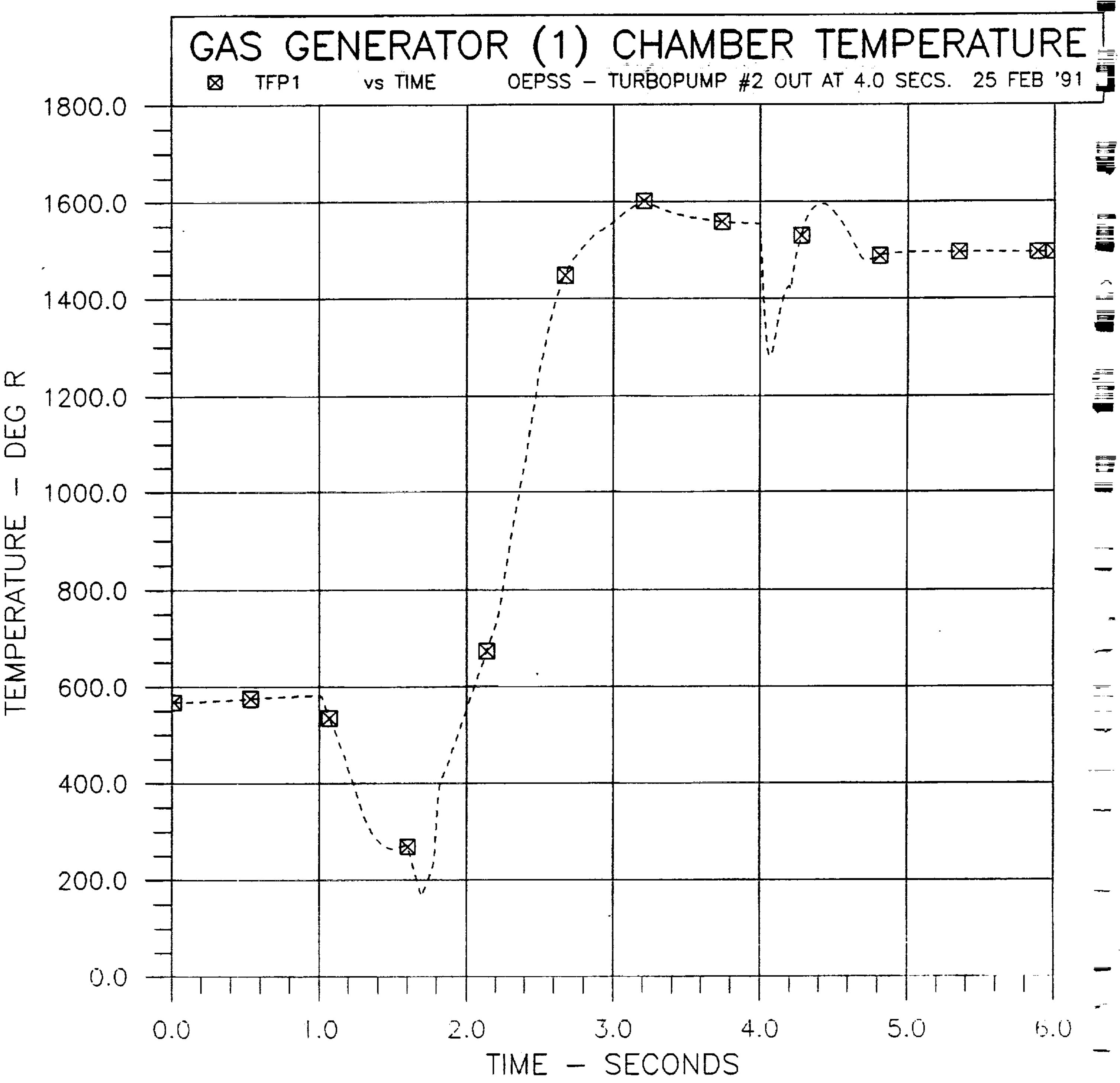

LOX PUMP (1) DISCHARGE PRESSURE
◇ POP1D vs TIME
OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
PRESSURE – PSIA
2700.0
2400.0
2100.0
1800.0
1500.0
1200.0
900.0
600.0
300.0
0.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
TIME – SECONDS

Figure A15



GAS GENERATOR (1) CHAMBER TEMPERATURE
☒ TFP1 vs TIME OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
TEMPERATURE – DEG R
1800.0
1600.0
1400.0
1200.0
1000.0
800.0
600.0
400.0
200.0
0.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
TIME – SECONDS

Figure A16

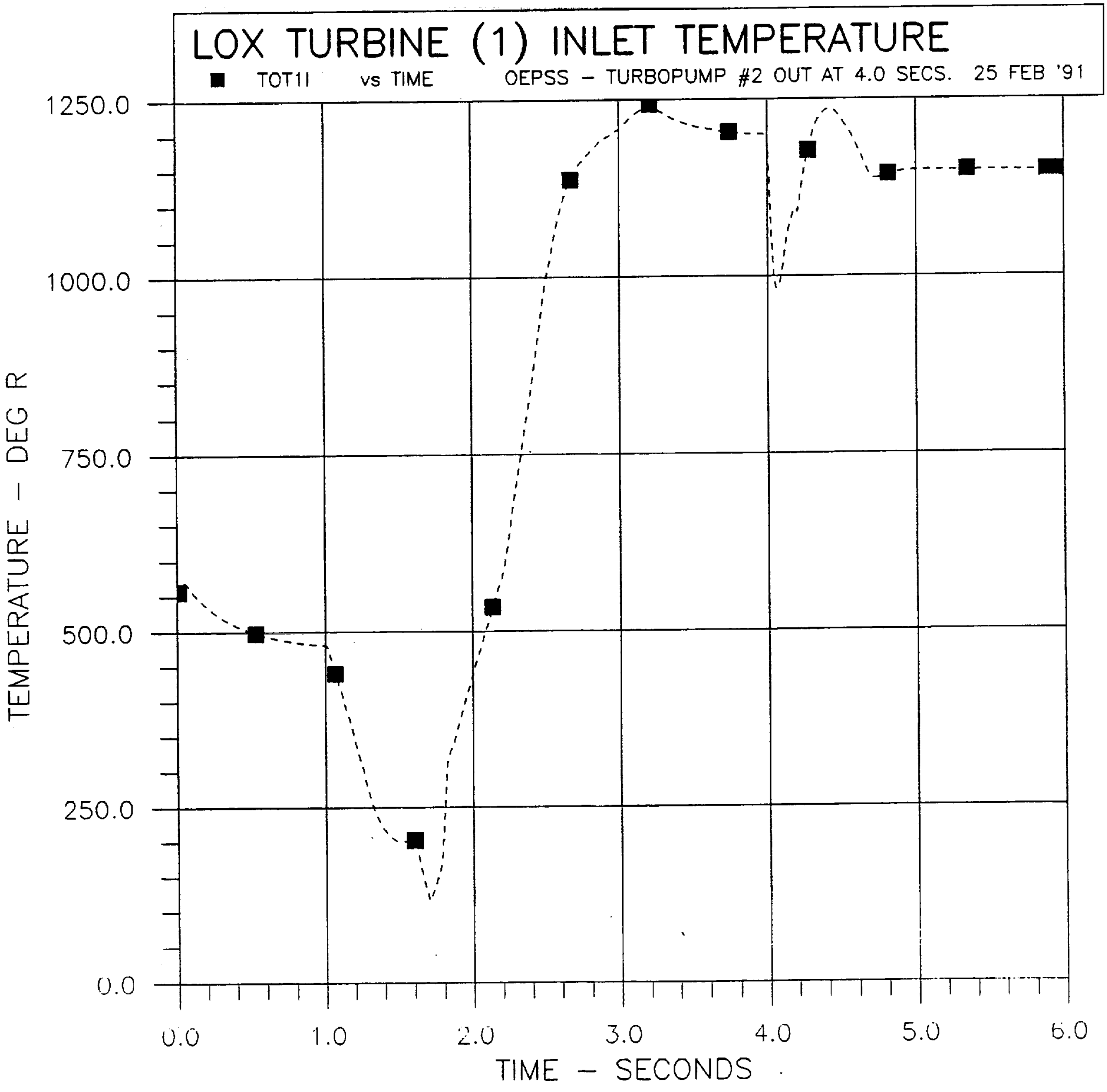

LOX TURBINE (1) INLET TEMPERATURE
■ TOT11 vs TIME
OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
TEMPERATURE – DEG R
1250.0
1000.0
750.0
500.0
250.0
0.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
TIME – SECONDS

Figure A17

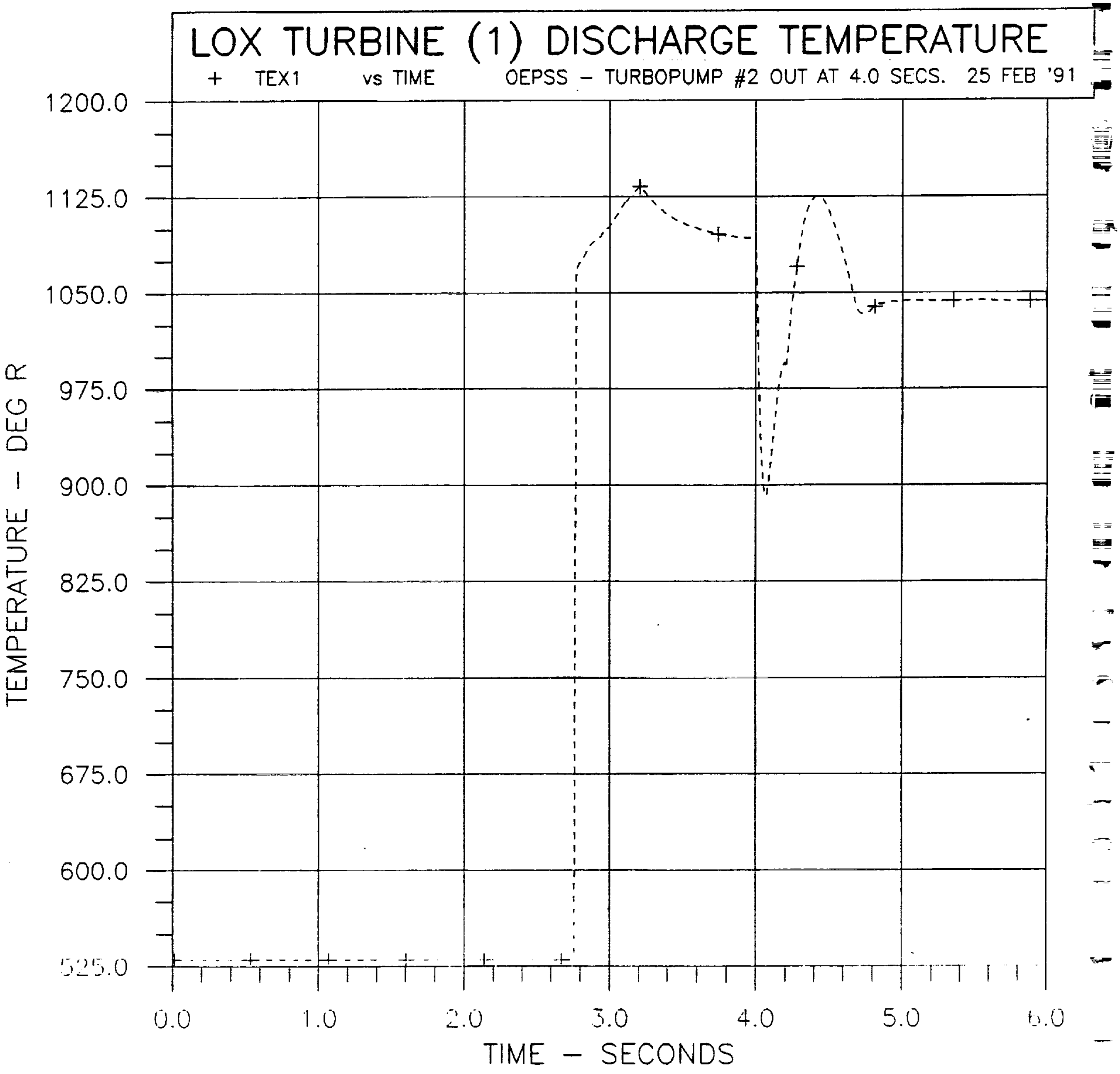

LOX TURBINE (1) DISCHARGE TEMPERATURE
+ TEX1 vs TIME OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
TEMPERATURE – DEG R
1200.0
1125.0
1050.0
975.0
900.0
825.0
750.0
675.0
600.0
525.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
TIME – SECONDS

Figure A18

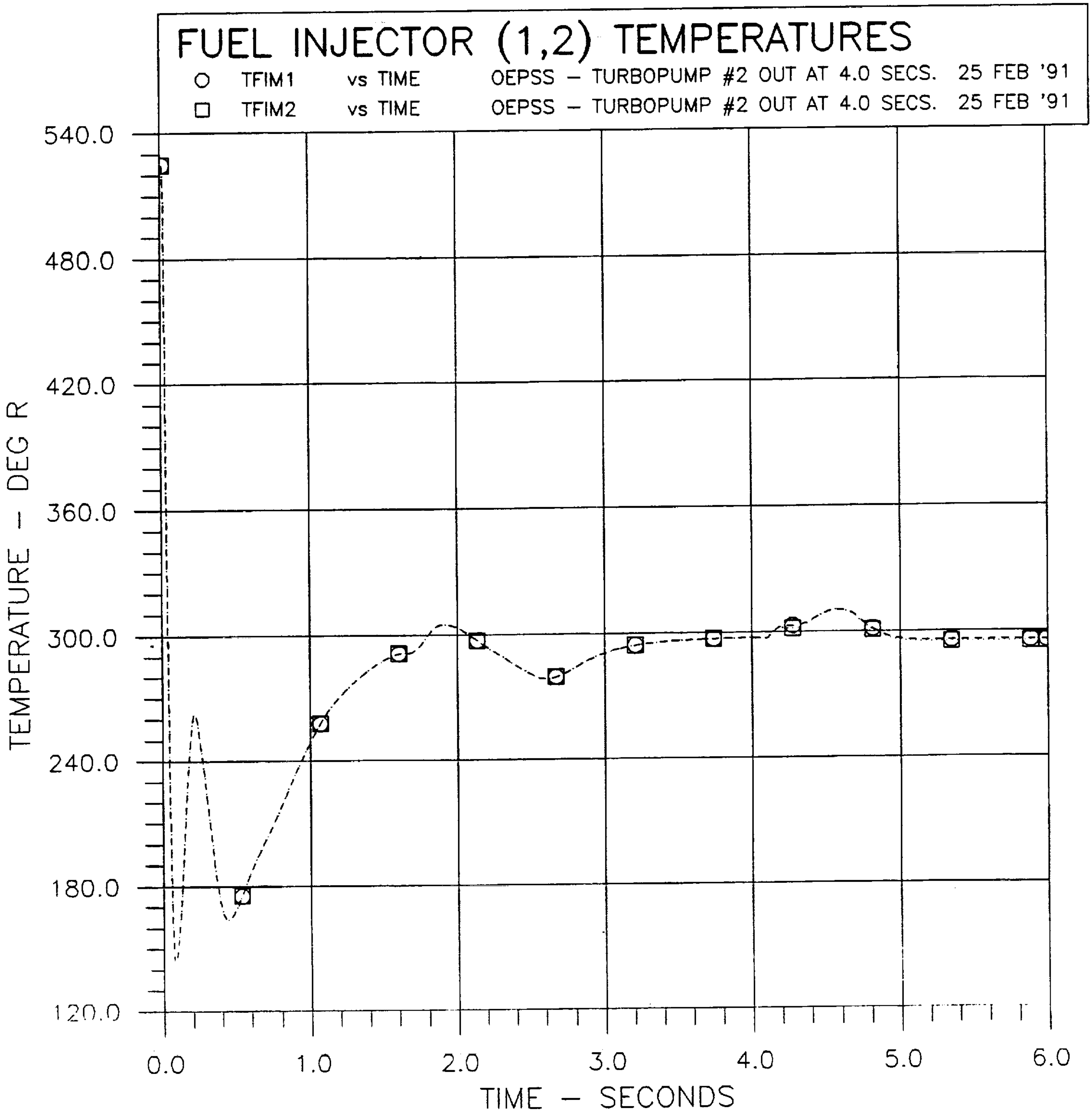

FUEL INJECTOR (1,2) TEMPERATURES
○ TFIM1 vs TIME OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
□ TFIM2 vs TIME OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
TEMPERATURE – DEG R
540.0
480.0
420.0
360.0
300.0
240.0
180.0
120.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
TIME – SECONDS

Figure A19

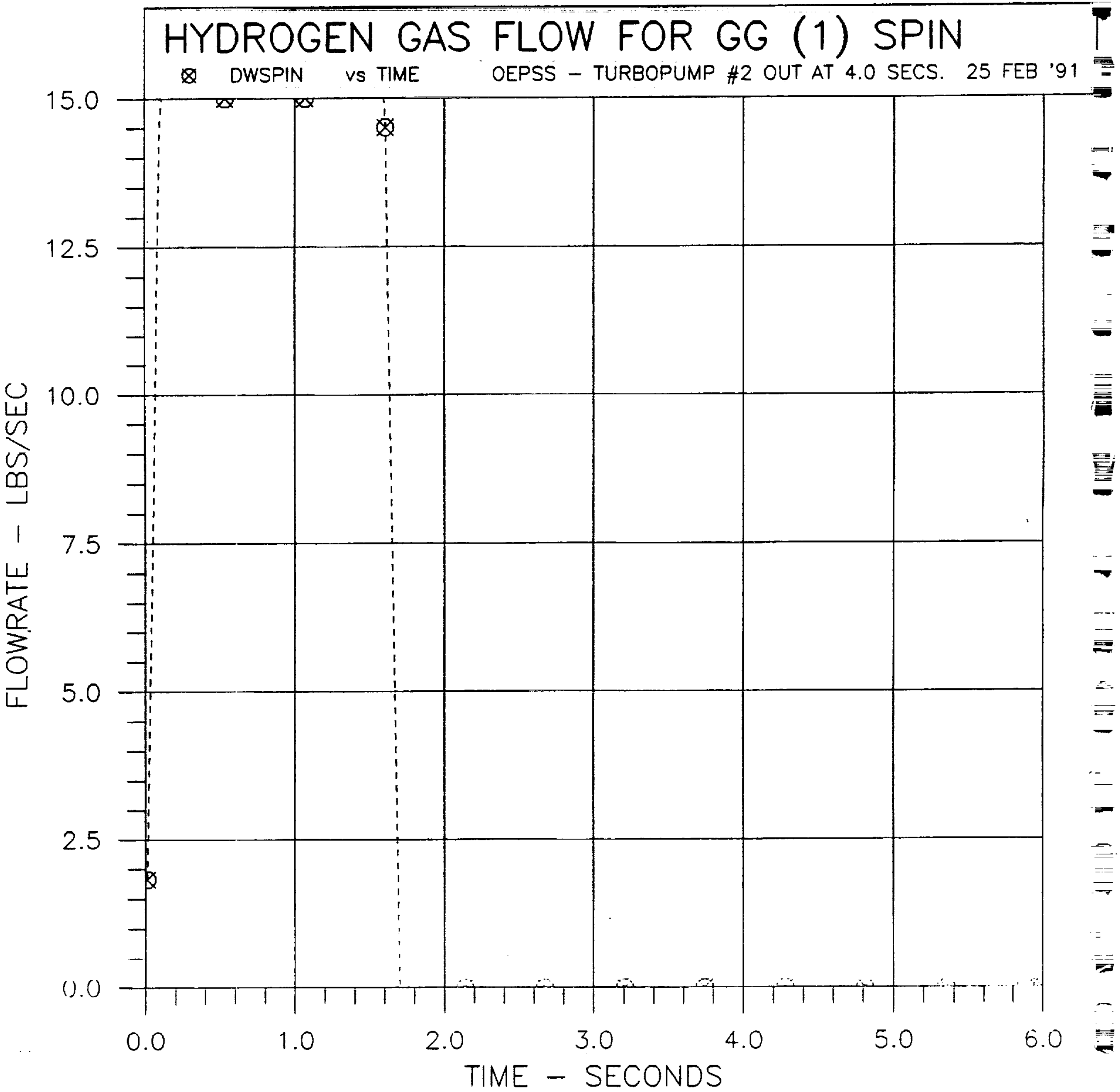

HYDROGEN GAS FLOW FOR GG (1) SPIN
⊗ DWSPIN vs TIME
OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
FLOWRATE – LBS/SEC
15.0
12.5
10.0
7.5
5.0
2.5
0.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
TIME – SECONDS

Figure A20

APPENDIX B

TURBOPUMP OUT CONDITION RESULTS FOR SYSTEM 2

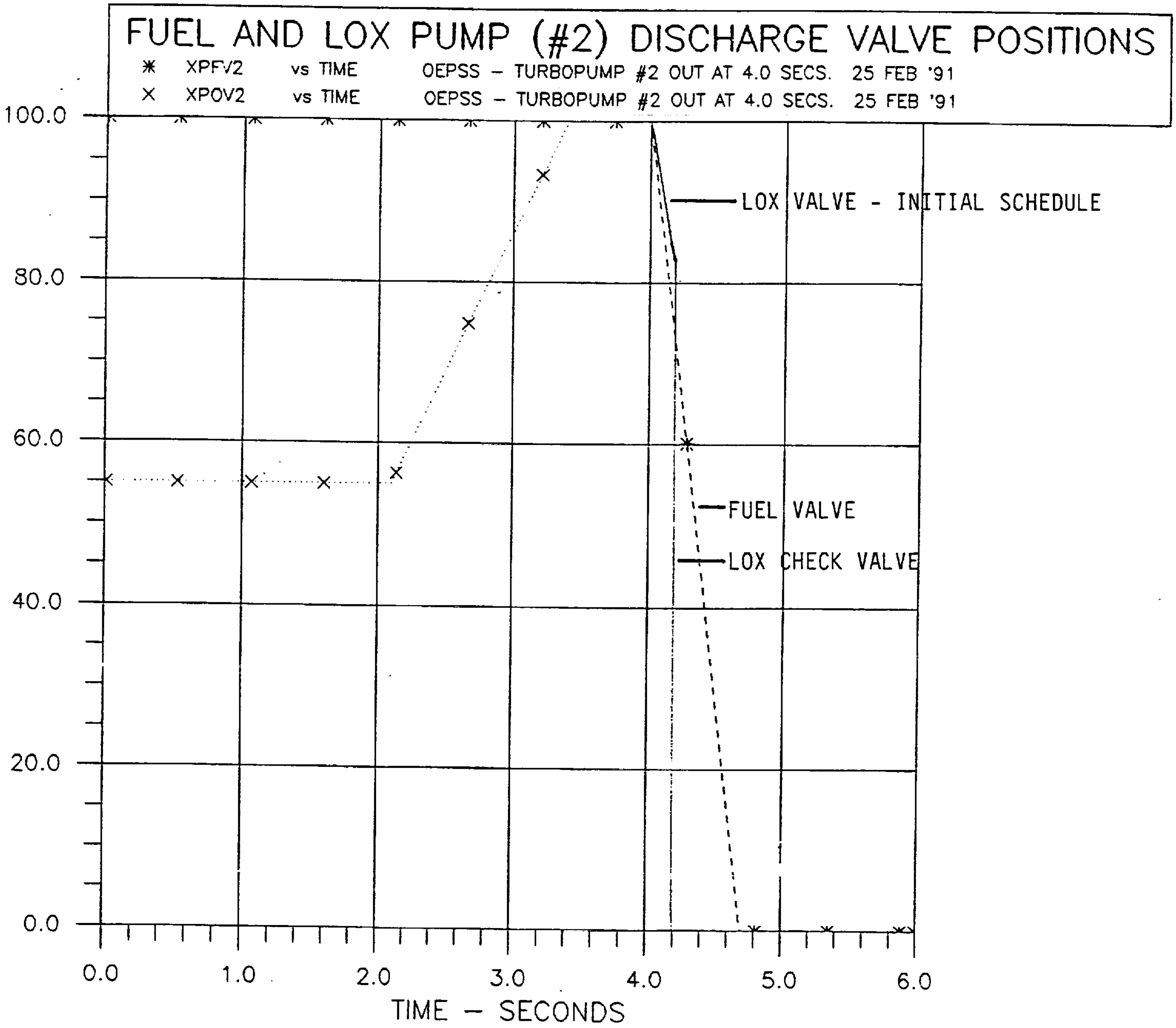

FUEL AND LOX PUMP (#2) DISCHARGE VALVE POSITIONS
✳ XPFV2 vs TIME OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
× XPOV2 vs TIME OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
100.0
80.0
60.0
40.0
20.0
0.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
TIME – SECONDS
LOX VALVE - INITIAL SCHEDULE
FUEL VALVE
LOX CHECK VALVE

Figure B1

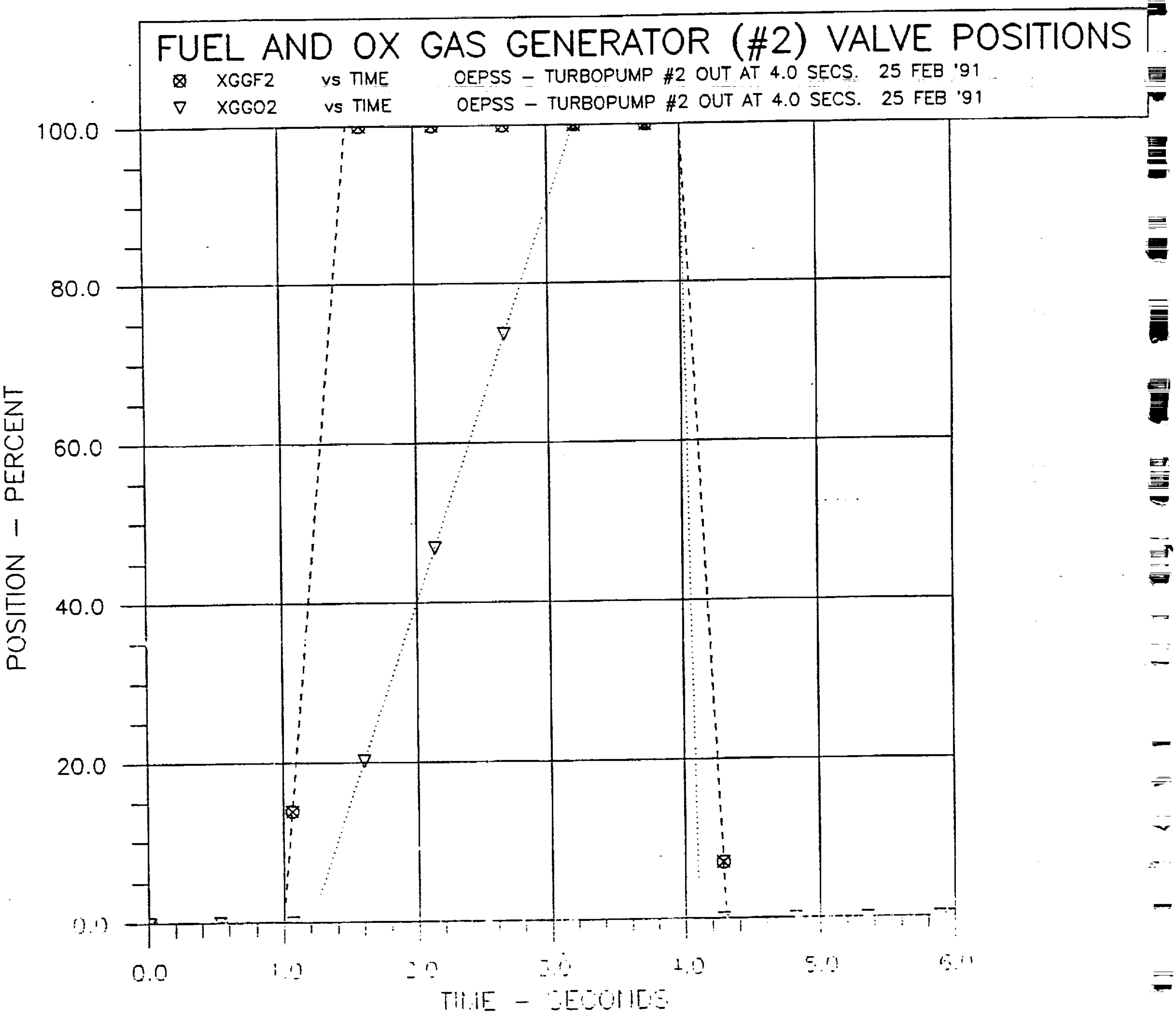

FUEL AND OX GAS GENERATOR (#2) VALVE POSITIONS
⊠ XGGF2 vs TIME OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
▽ XGGO2 vs TIME OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
100.0
80.0
60.0
40.0
20.0
0.0
POSITION – PERCENT
0.0
1.0
2.0
3.0
4.0
5.0
6.0
TIME – SECONDS

Figure B2

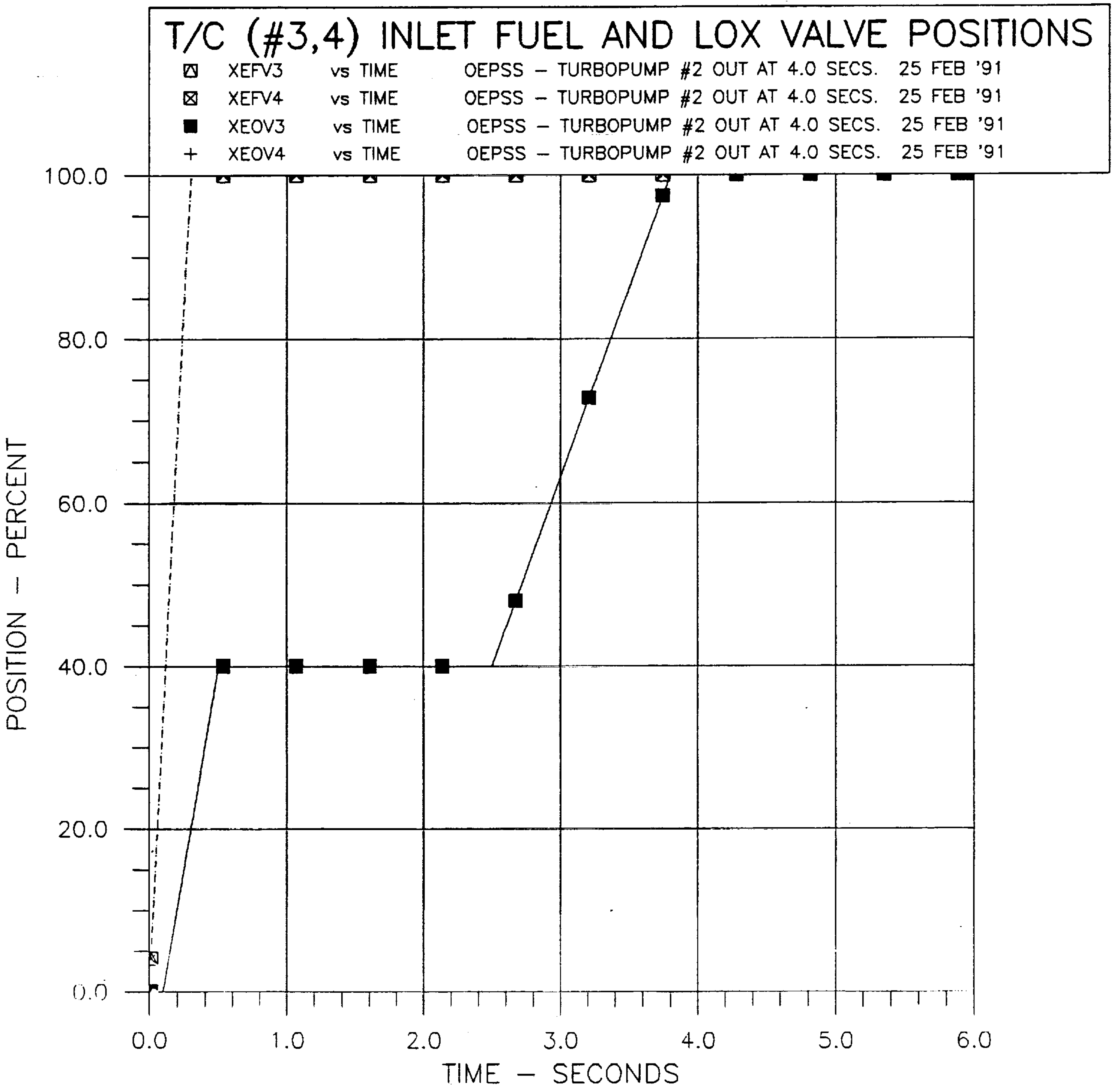

T/C (#3,4) INLET FUEL AND LOX VALVE POSITIONS
XEFV3 vs TIME OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
XEFV4 vs TIME OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
XEOV3 vs TIME OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
XEOV4 vs TIME OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
POSITION – PERCENT
100.0
80.0
60.0
40.0
20.0
0.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
TIME – SECONDS

Figure B3

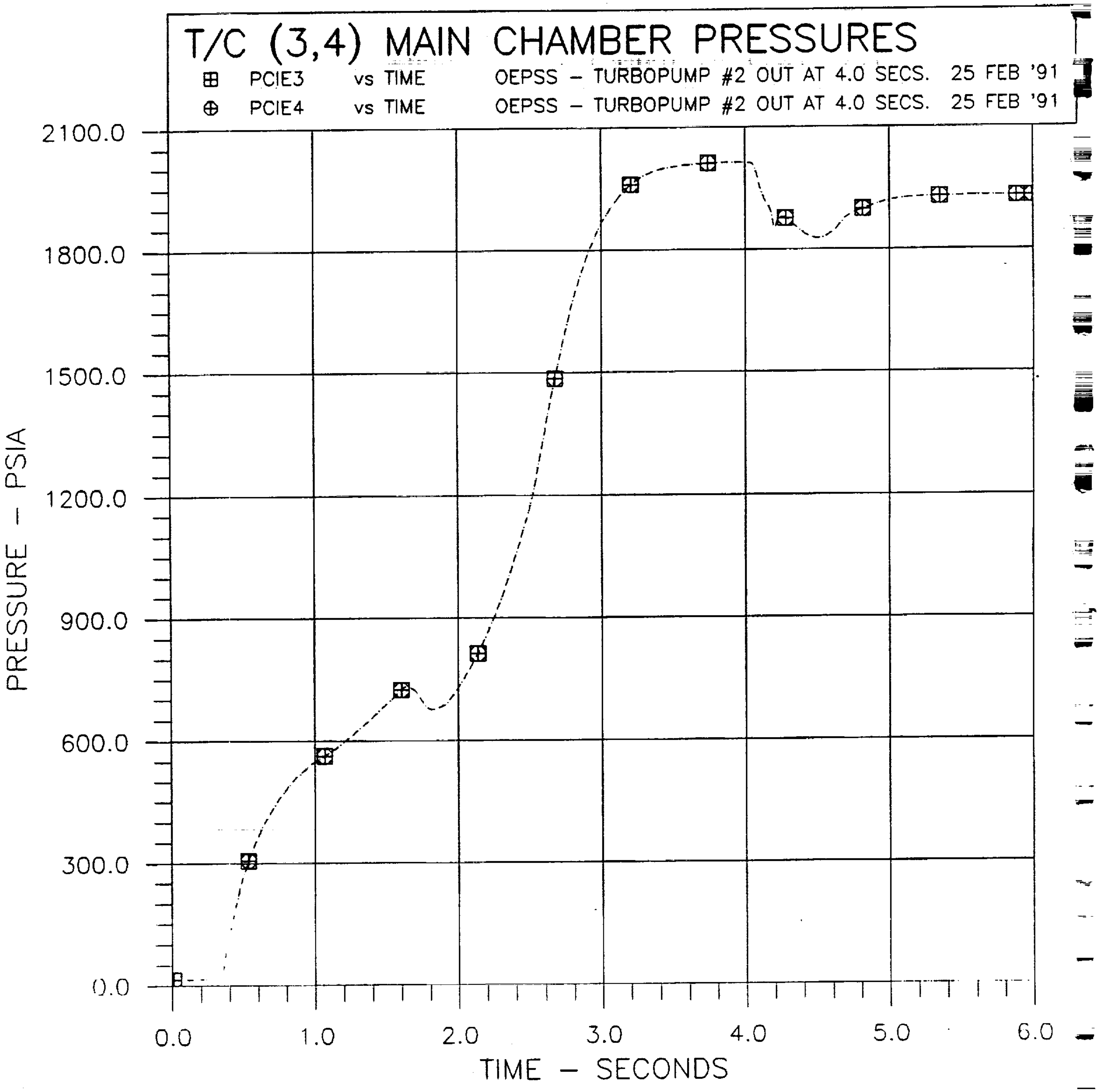

T/C (3,4) MAIN CHAMBER PRESSURES
⊞ PCIE3 vs TIME OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
⊕ PCIE4 vs TIME OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
2100.0
1800.0
1500.0
1200.0
900.0
600.0
300.0
0.0
PRESSURE – PSIA
0.0
1.0
2.0
3.0
4.0
5.0
6.0
TIME – SECONDS

Figure B4

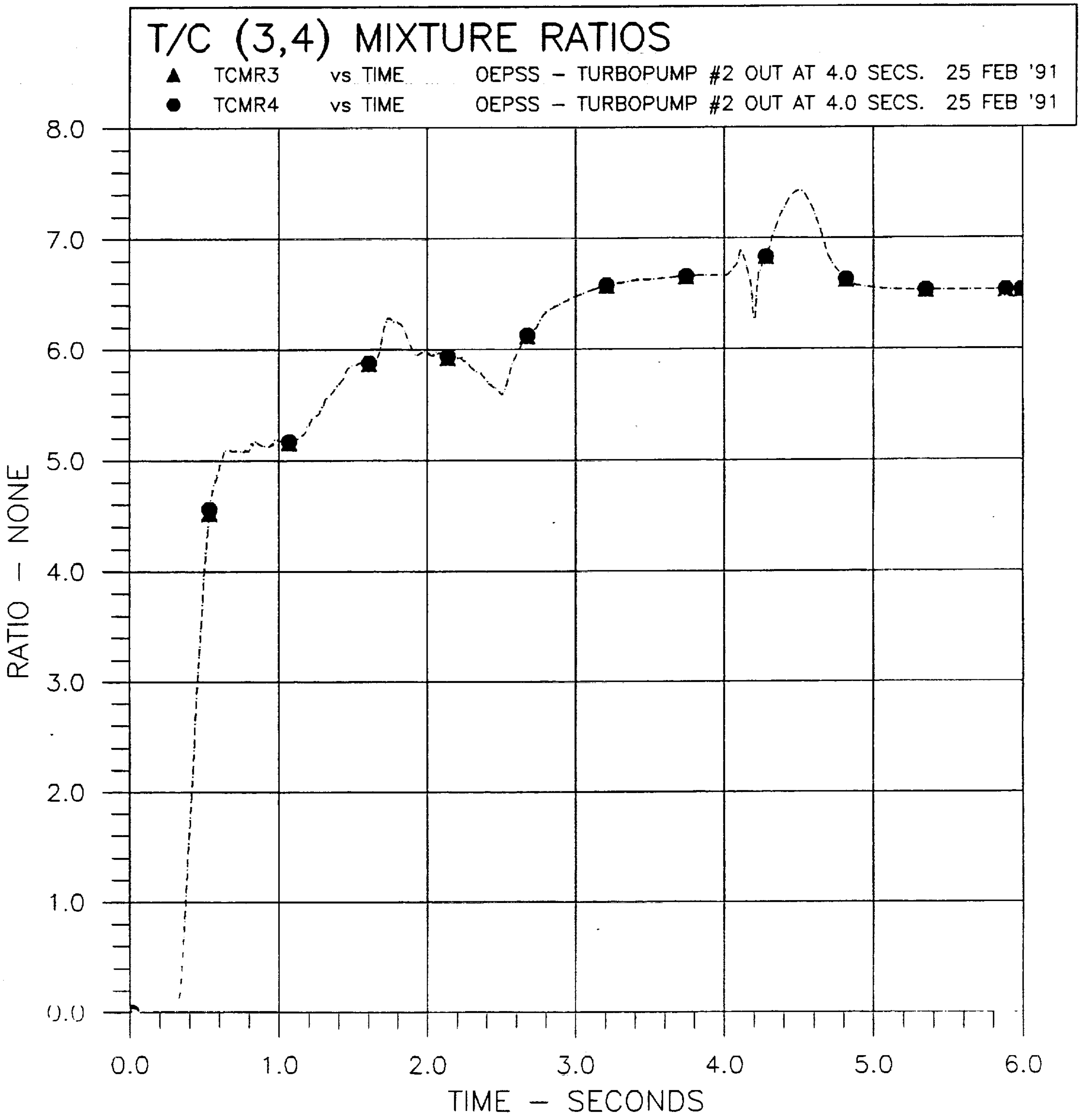

T/C (3,4) MIXTURE RATIOS
▲ TCMR3 vs TIME OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
● TCMR4 vs TIME OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
RATIO – NONE
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
TIME – SECONDS

Figure B5

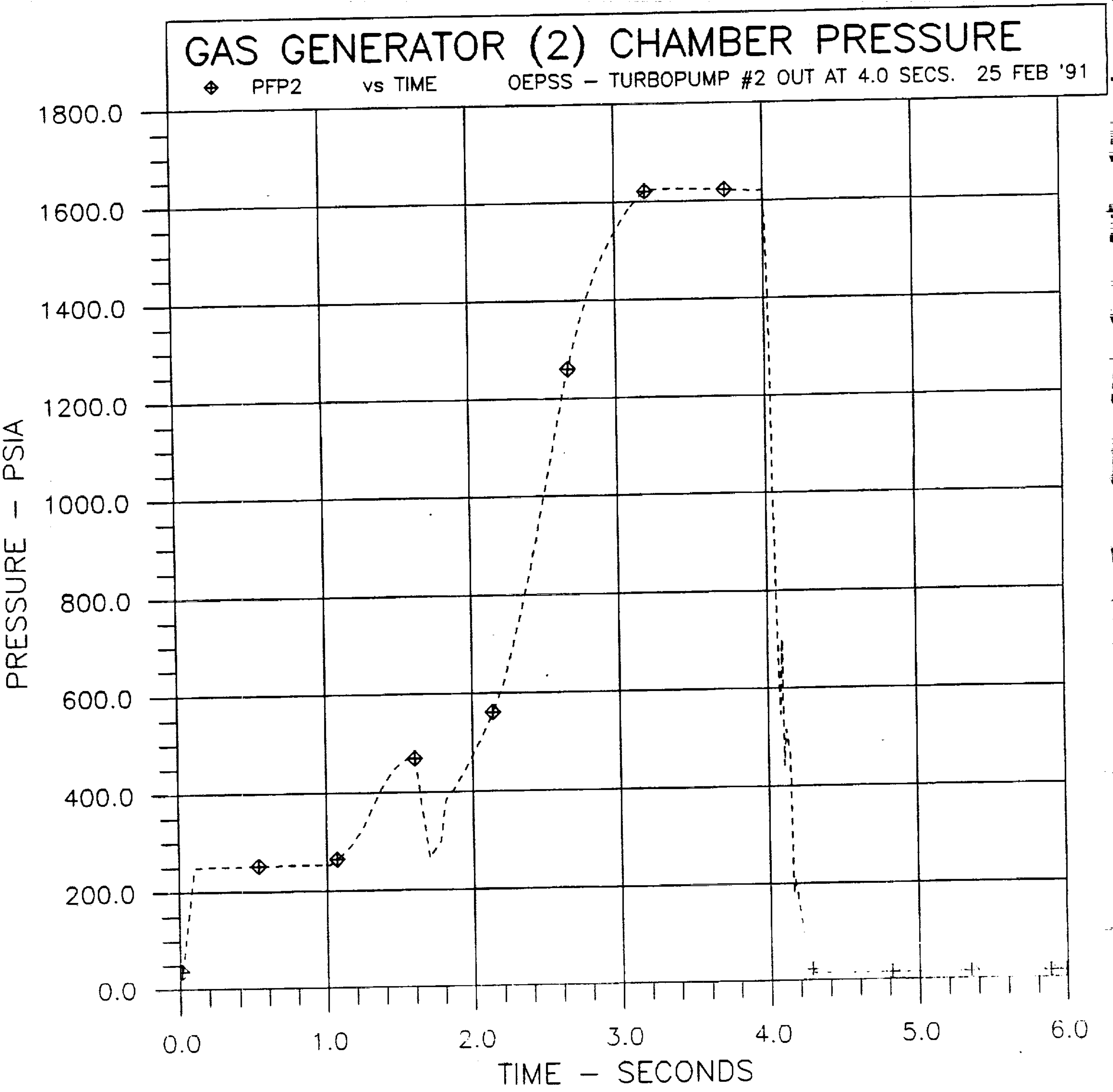

GAS GENERATOR (2) CHAMBER PRESSURE
◆ PFP2 vs TIME
OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
PRESSURE – PSIA
1800.0
1600.0
1400.0
1200.0
1000.0
800.0
600.0
400.0
200.0
0.0
TIME – SECONDS
0.0
1.0
2.0
3.0
4.0
5.0
6.0

Figure B6

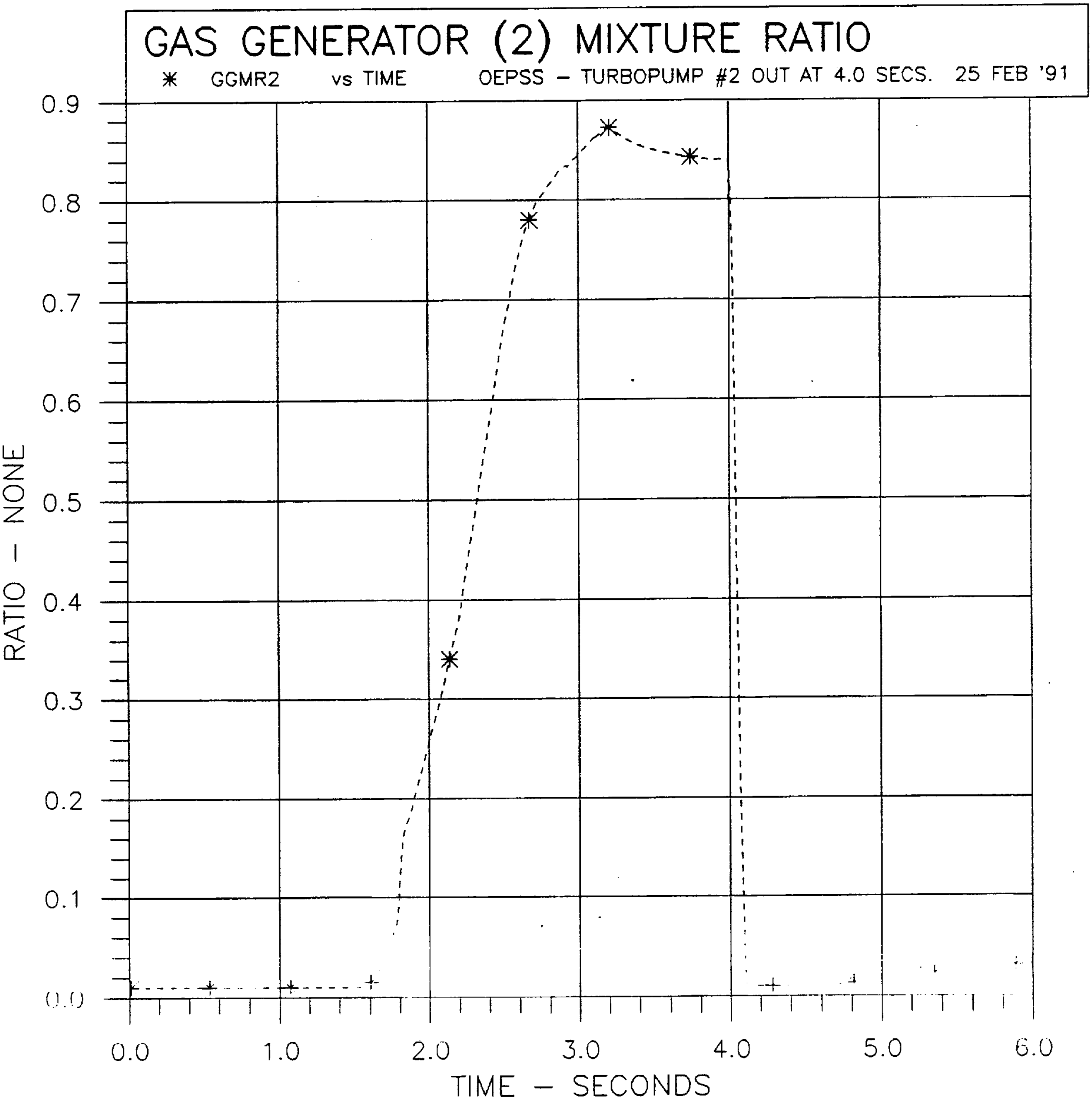

GAS GENERATOR (2) MIXTURE RATIO
✳ GGMR2 vs TIME OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
RATIO – NONE
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
TIME – SECONDS
0.0
1.0
2.0
3.0
4.0
5.0
6.0

Figure B7

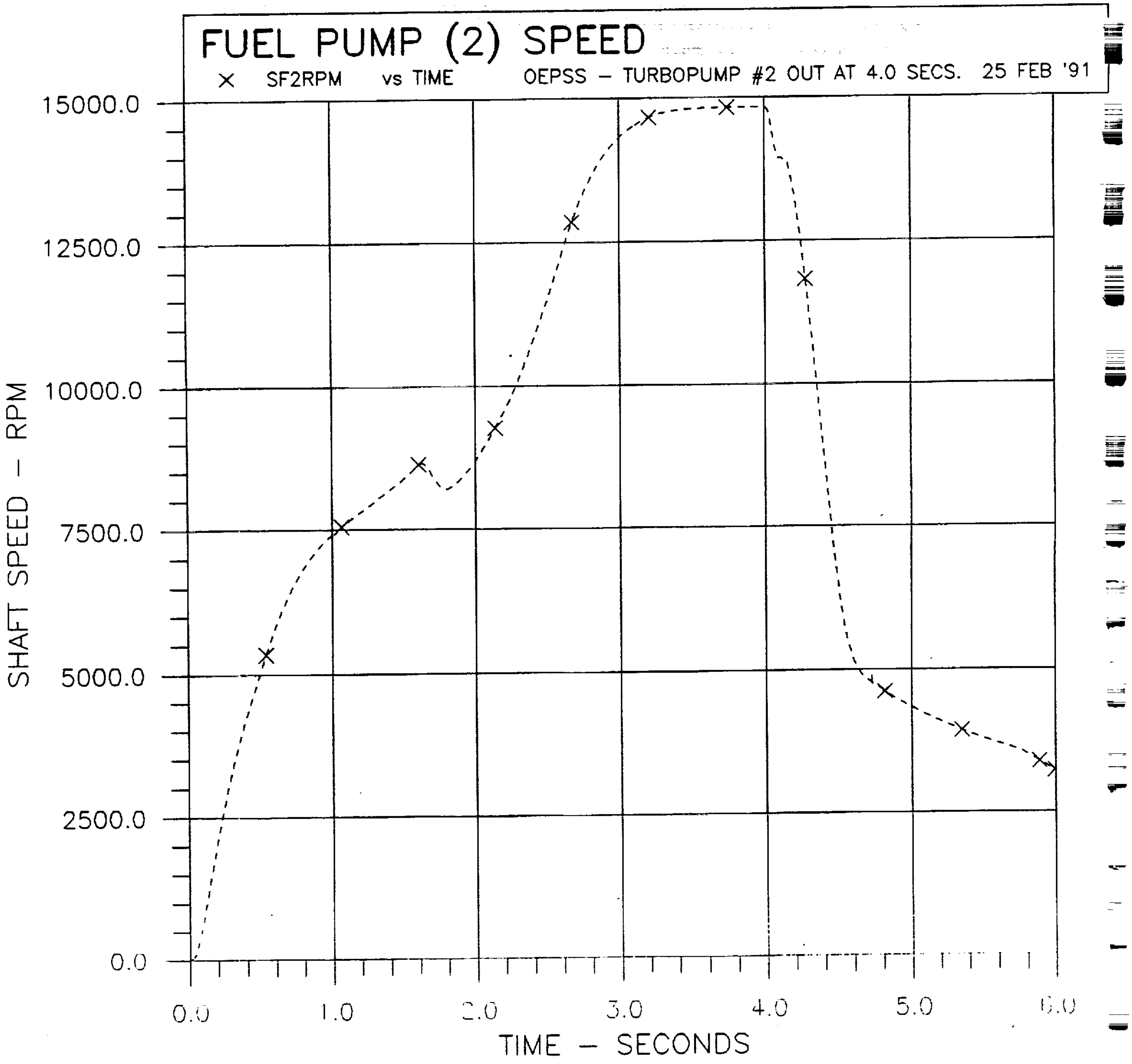
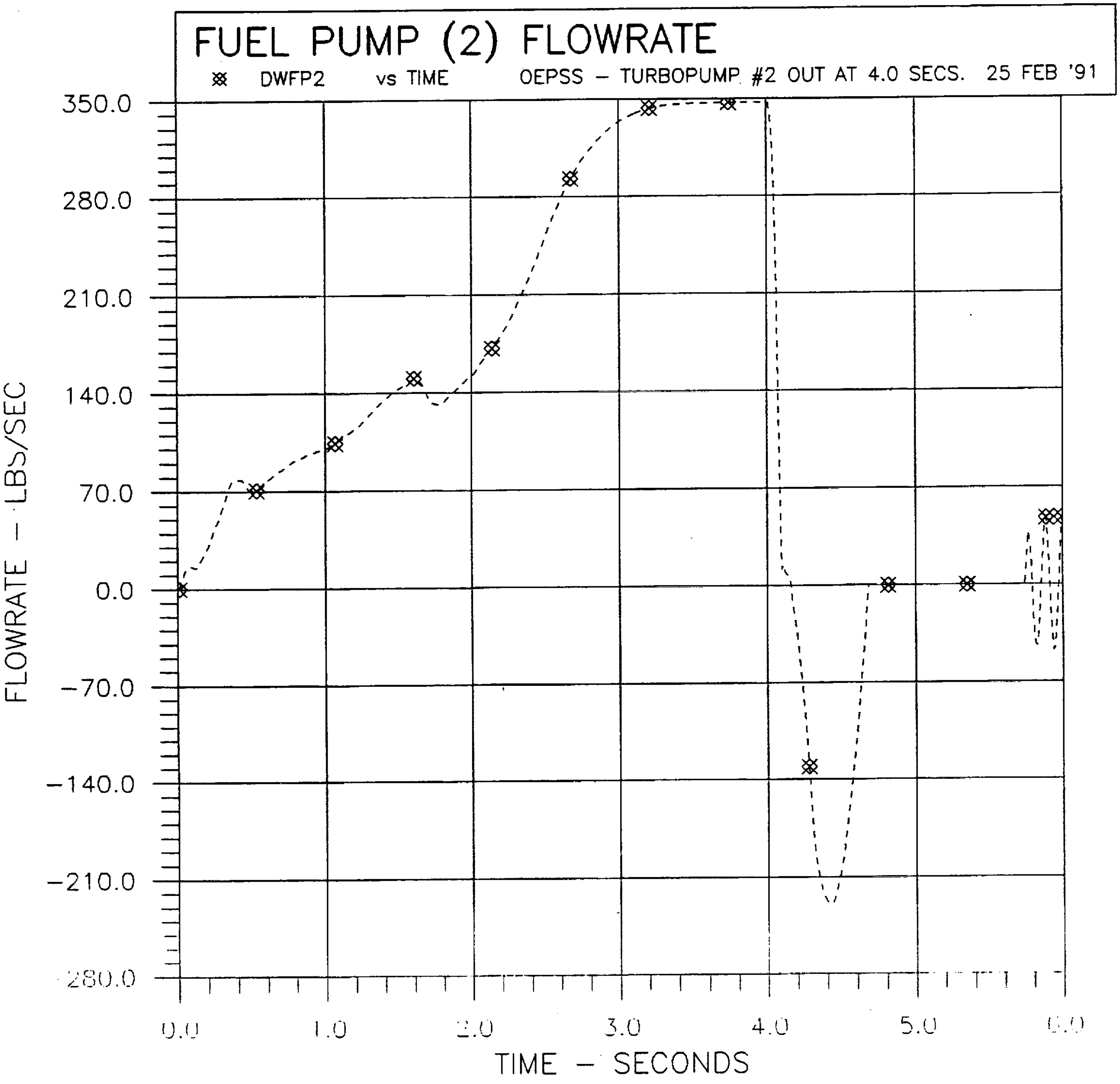

FUEL PUMP (2) SPEED
× SF2RPM vs TIME OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
SHAFT SPEED – RPM
15000.0
12500.0
10000.0
7500.0
5000.0
2500.0
0.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
TIME – SECONDS

Figure B8



FUEL PUMP (2) FLOWRATE
DWFP2 vs TIME
OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
350.0
280.0
210.0
140.0
70.0
0.0
−70.0
−140.0
−210.0
−280.0
FLOWRATE – LBS/SEC
0.0
1.0
2.0
3.0
4.0
5.0
6.0
TIME – SECONDS

Figure B9

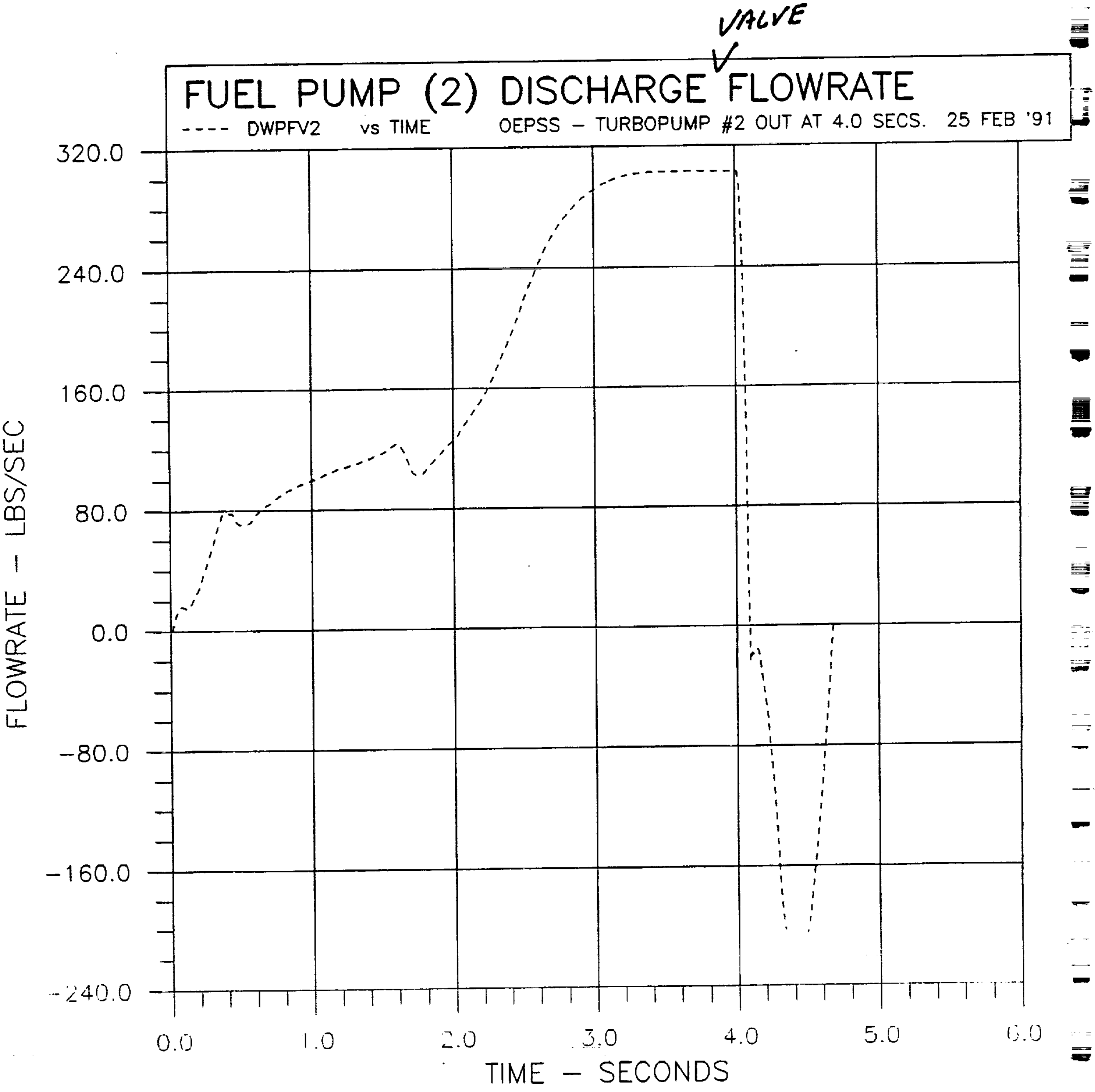

VALVE
FUEL PUMP (2) DISCHARGE FLOWRATE
---- DWPFV2 vs TIME
OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
FLOWRATE – LBS/SEC
320.0
240.0
160.0
80.0
0.0
-80.0
-160.0
-240.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
TIME – SECONDS

Figure B10

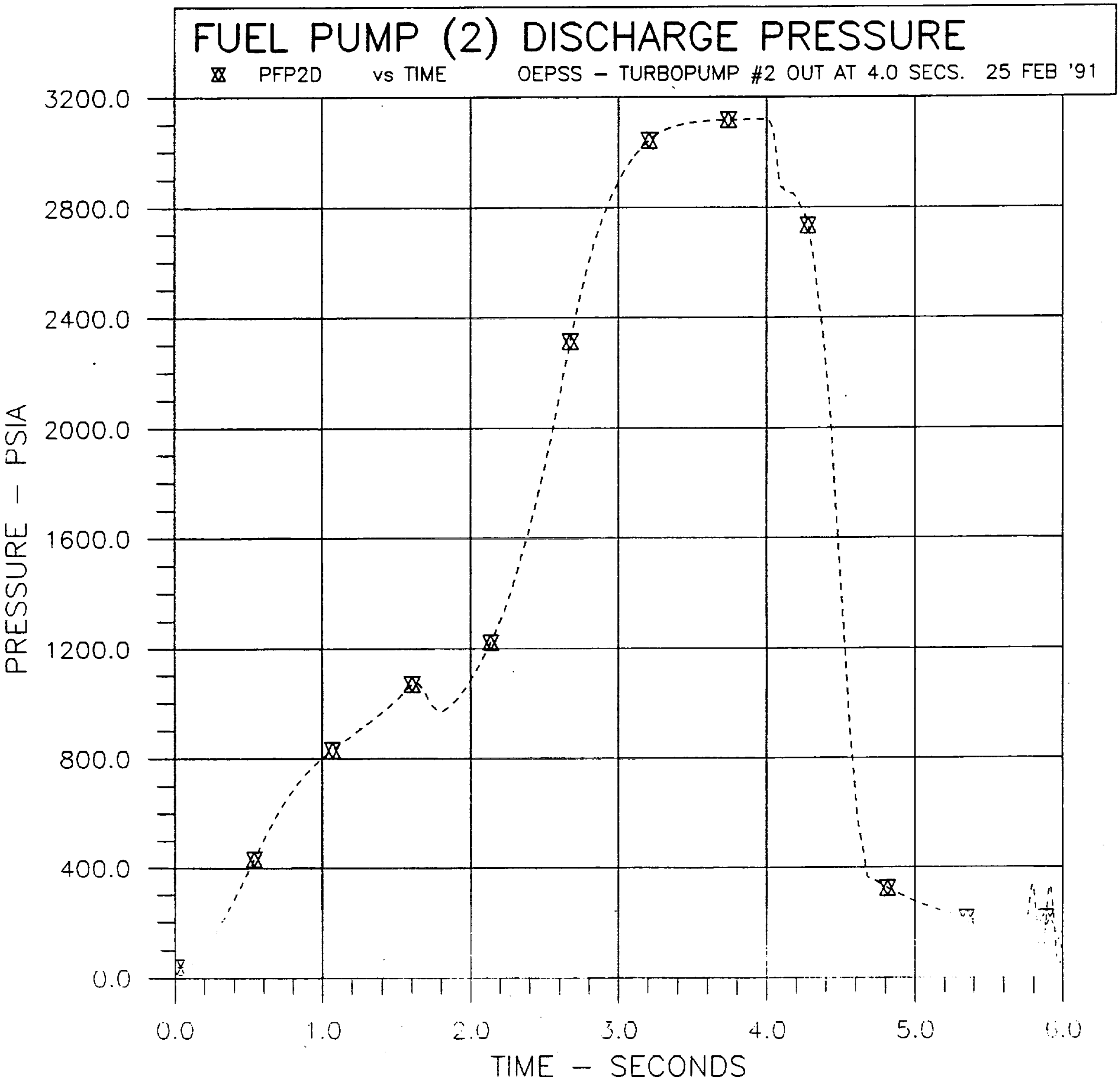
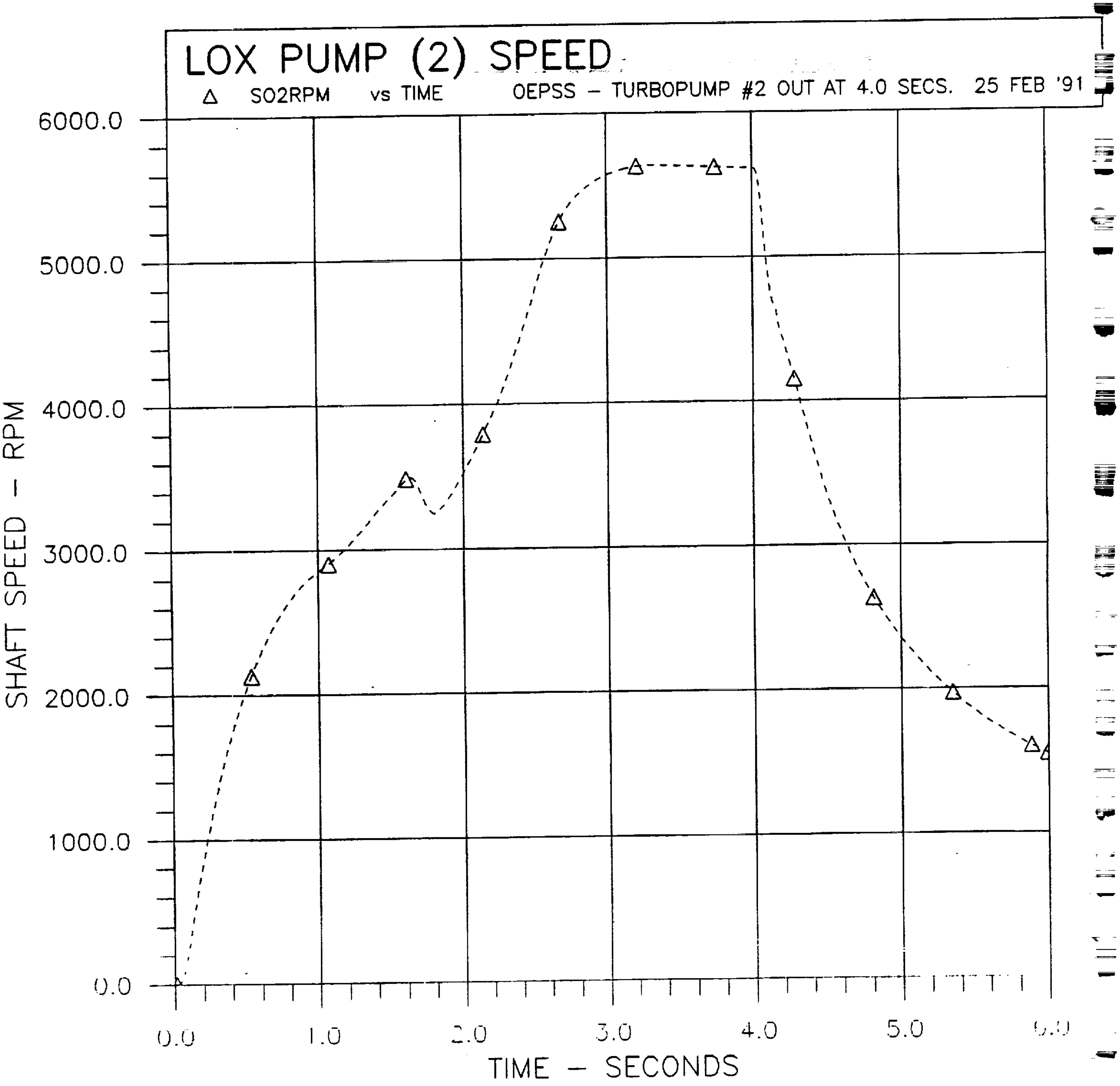

FUEL PUMP (2) DISCHARGE PRESSURE
⧖ PFP2D vs TIME OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
PRESSURE – PSIA
3200.0
2800.0
2400.0
2000.0
1600.0
1200.0
800.0
400.0
0.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
TIME – SECONDS

Figure B11



LOX PUMP (2) SPEED
△ SO2RPM vs TIME
OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
6000.0
5000.0
4000.0
3000.0
2000.0
1000.0
0.0
SHAFT SPEED – RPM
0.0
1.0
2.0
3.0
4.0
5.0
6.0
TIME – SECONDS

Figure B12

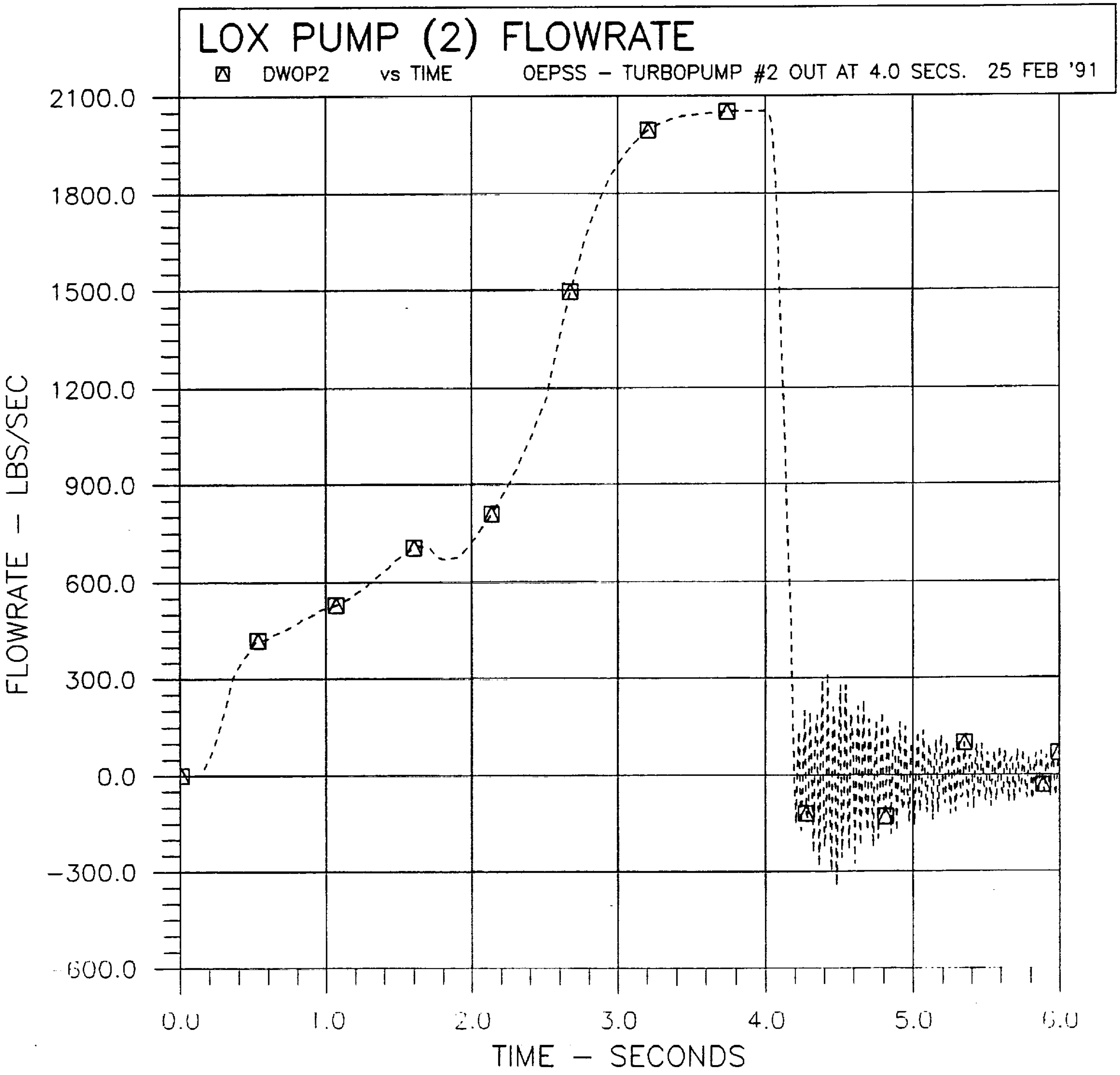

LOX PUMP (2) FLOWRATE
DWOP2 vs TIME
OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
2100.0
1800.0
1500.0
1200.0
900.0
600.0
300.0
0.0
-300.0
-600.0
FLOWRATE – LBS/SEC
0.0
1.0
2.0
3.0
4.0
5.0
6.0
TIME – SECONDS

Figure B13

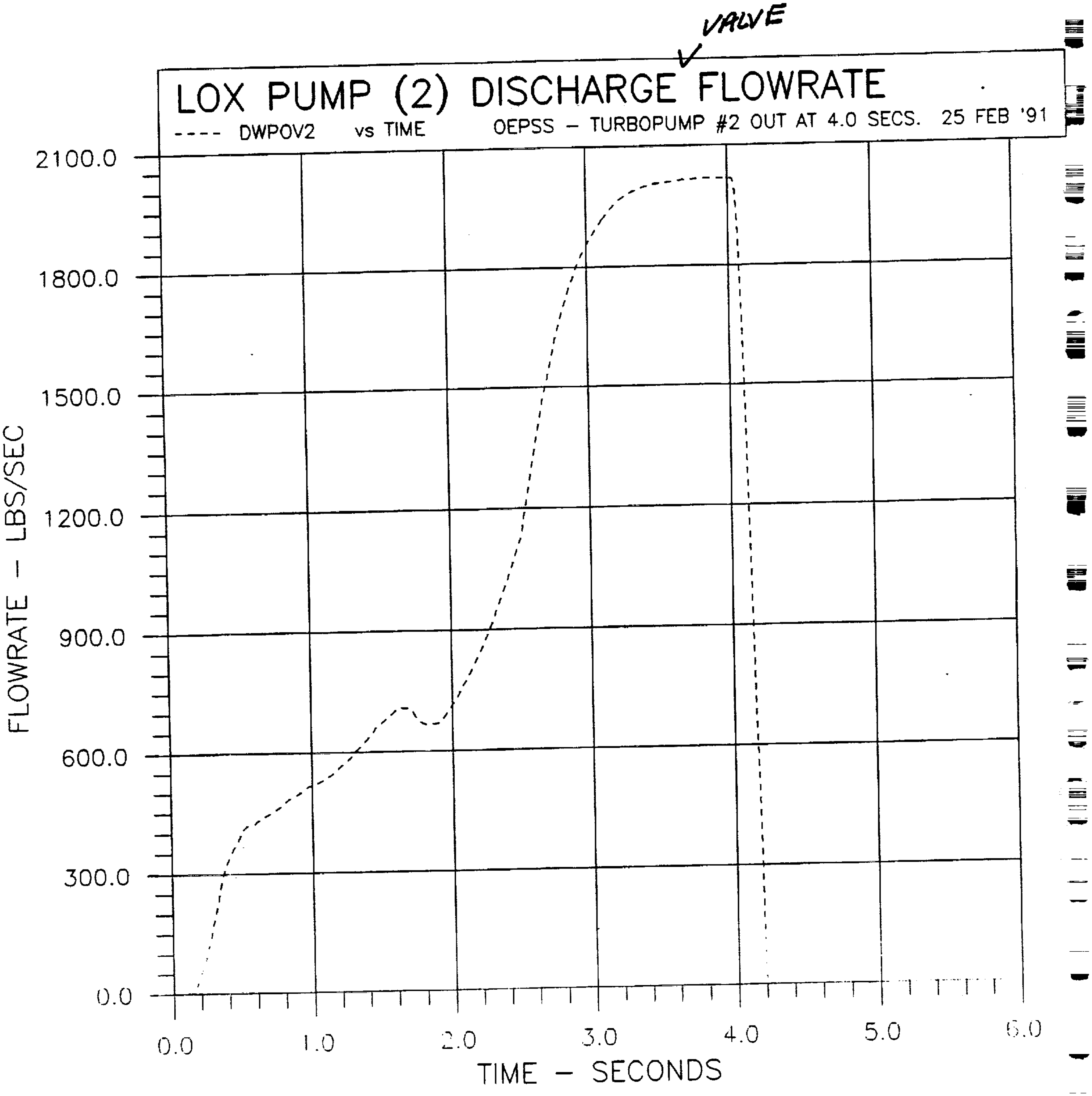

VALVE
LOX PUMP (2) DISCHARGE FLOWRATE
---- DWPOV2 vs TIME
OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
FLOWRATE – LBS/SEC
0.0
300.0
600.0
900.0
1200.0
1500.0
1800.0
2100.0
TIME – SECONDS
0.0
1.0
2.0
3.0
4.0
5.0
6.0

Figure B14

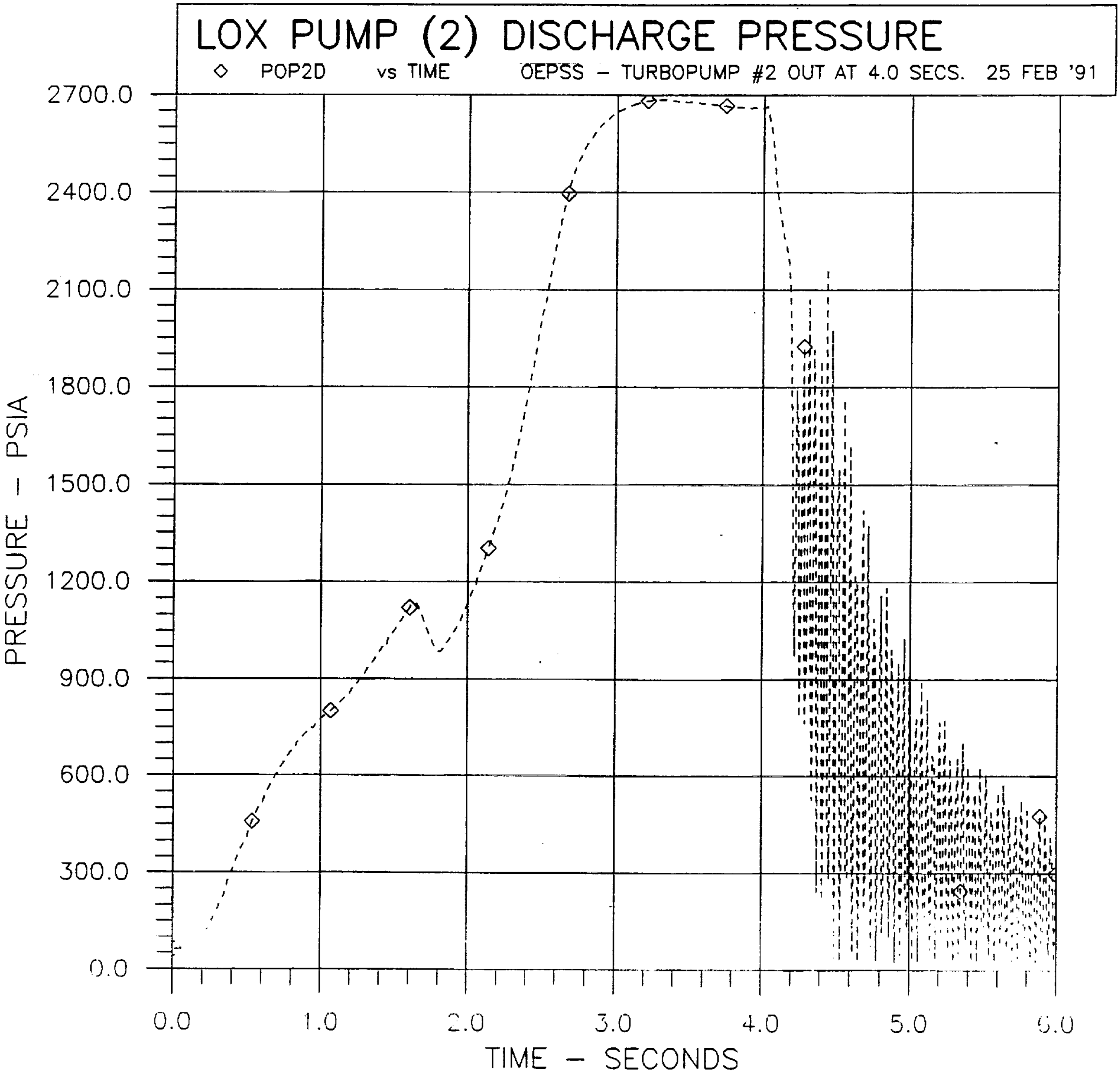

LOX PUMP (2) DISCHARGE PRESSURE
◇ POP2D vs TIME
OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
PRESSURE – PSIA
2700.0
2400.0
2100.0
1800.0
1500.0
1200.0
900.0
600.0
300.0
0.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
TIME – SECONDS

Figure B15

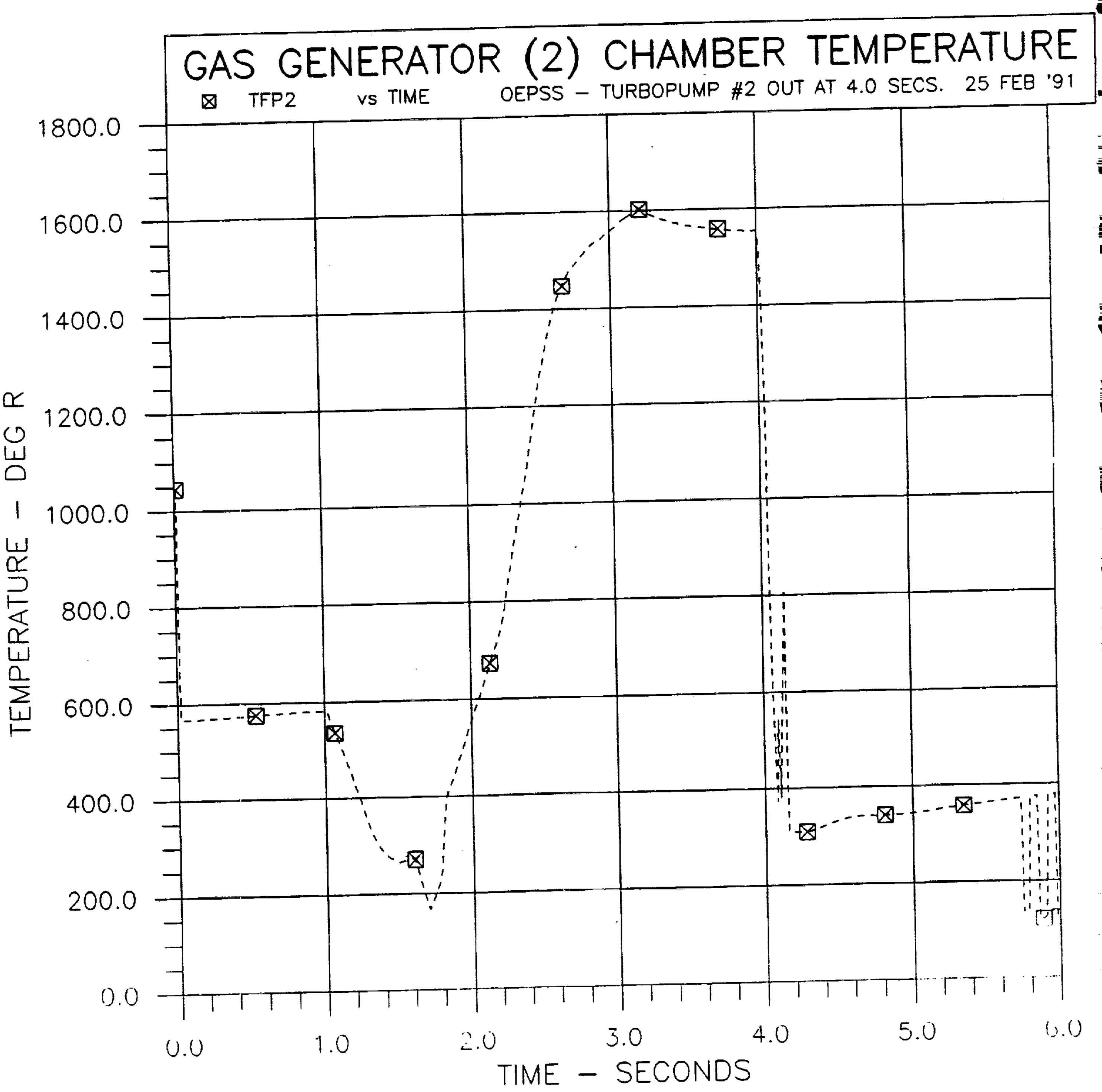

GAS GENERATOR (2) CHAMBER TEMPERATURE
⊠ TFP2 vs TIME
OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
TEMPERATURE – DEG R
1800.0
1600.0
1400.0
1200.0
1000.0
800.0
600.0
400.0
200.0
0.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
TIME – SECONDS

Figure B16

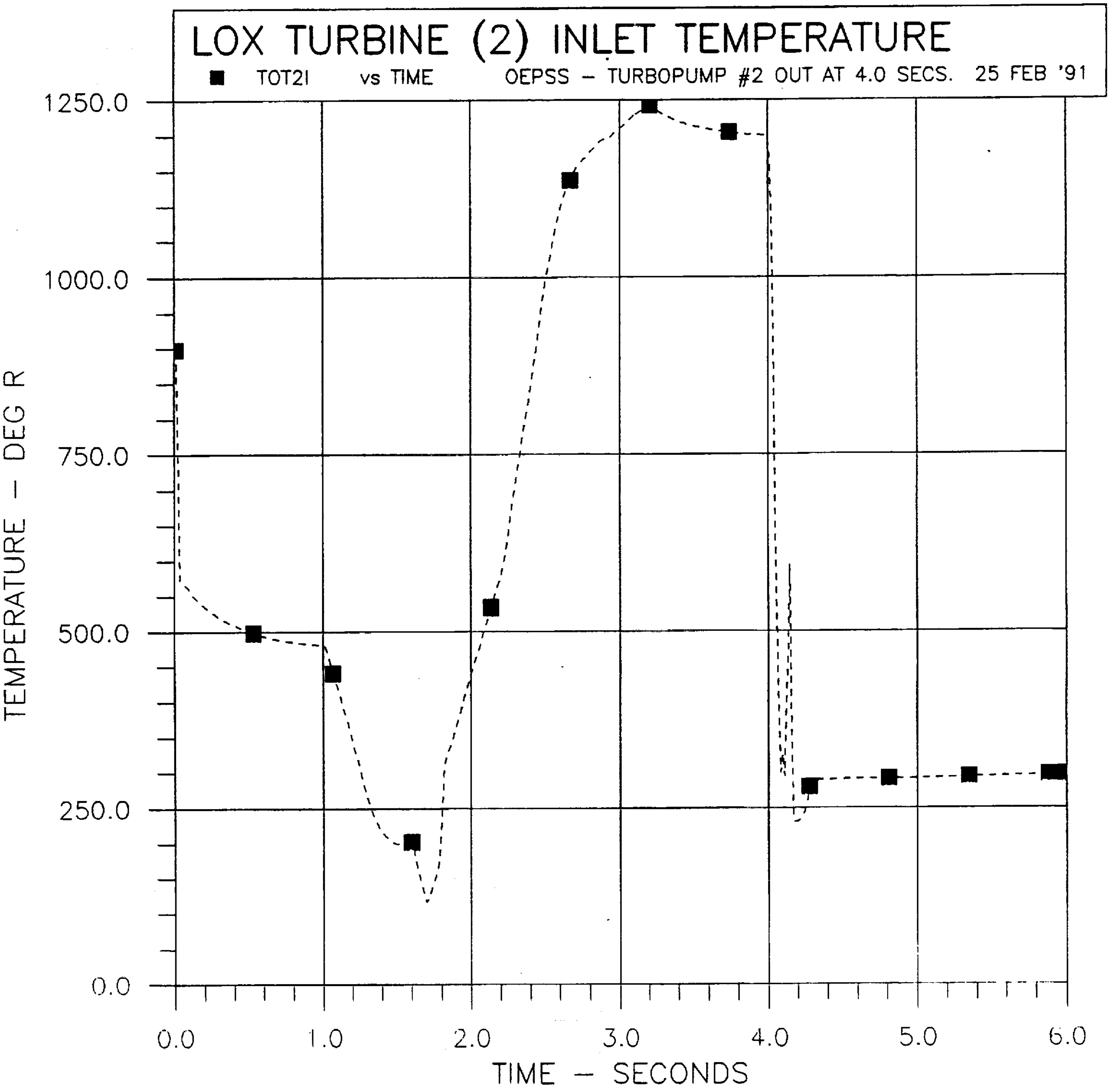

LOX TURBINE (2) INLET TEMPERATURE
■ TOT2I vs TIME
OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
TEMPERATURE – DEG R
1250.0
1000.0
750.0
500.0
250.0
0.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
TIME – SECONDS

Figure B17

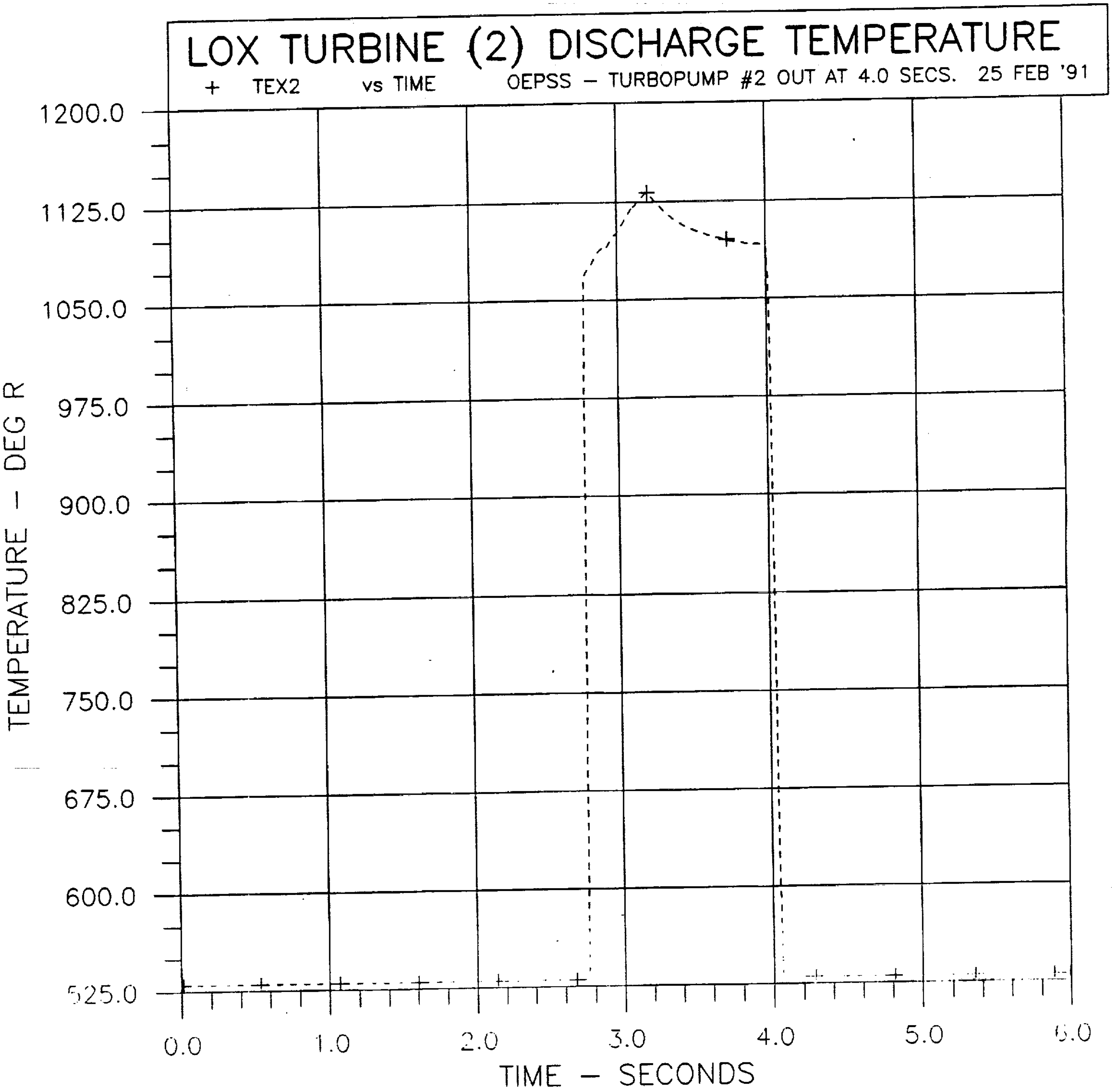

LOX TURBINE (2) DISCHARGE TEMPERATURE
+ TEX2 vs TIME
OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
TEMPERATURE – DEG R
1200.0
1125.0
1050.0
975.0
900.0
825.0
750.0
675.0
600.0
525.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
TIME – SECONDS

Figure B18

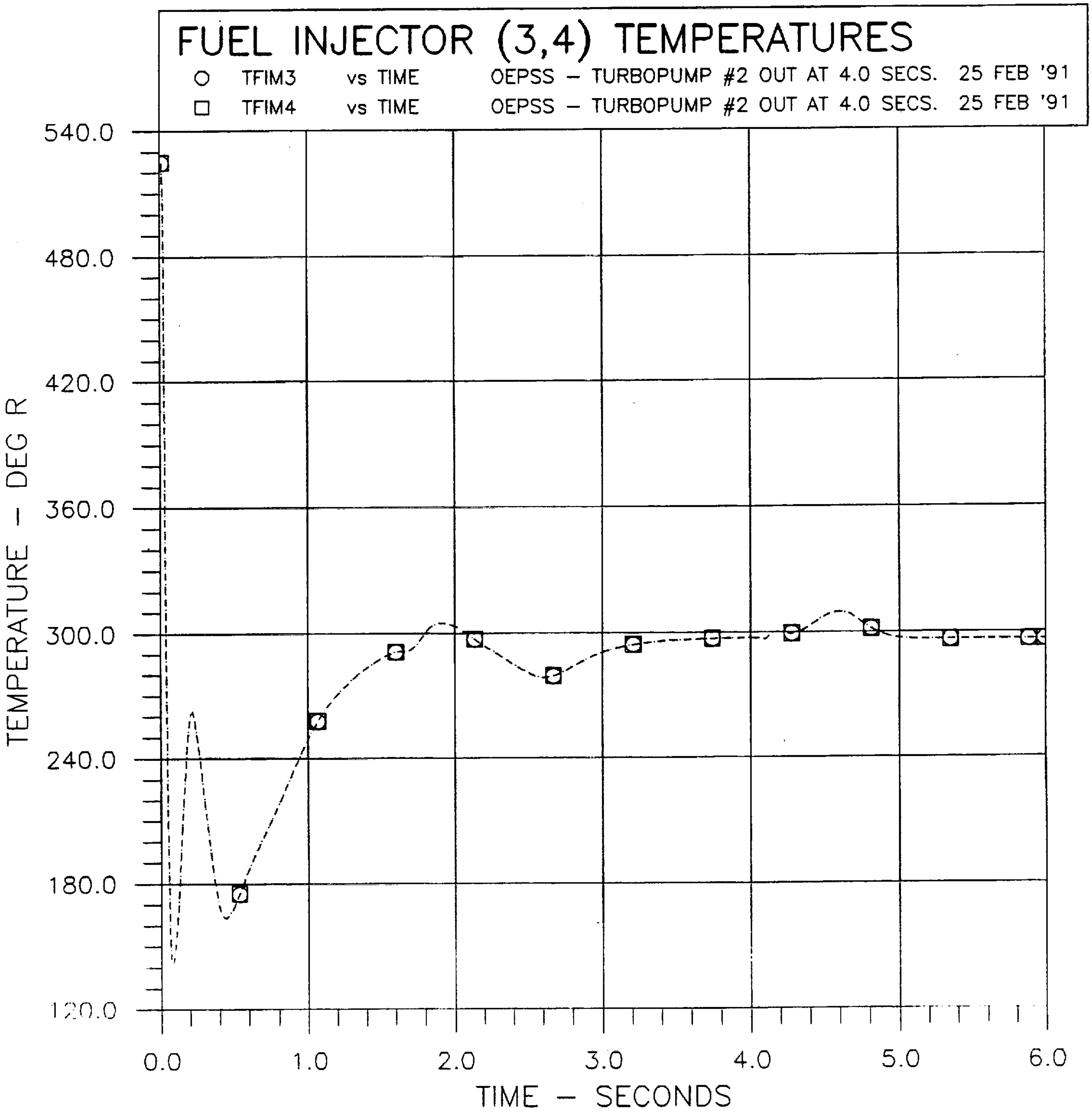

FUEL INJECTOR (3,4) TEMPERATURES
○ TFIM3 vs TIME OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
□ TFIM4 vs TIME OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
540.0
480.0
420.0
360.0
300.0
240.0
180.0
120.0
TEMPERATURE – DEG R
0.0
1.0
2.0
3.0
4.0
5.0
6.0
TIME – SECONDS

Figure B19

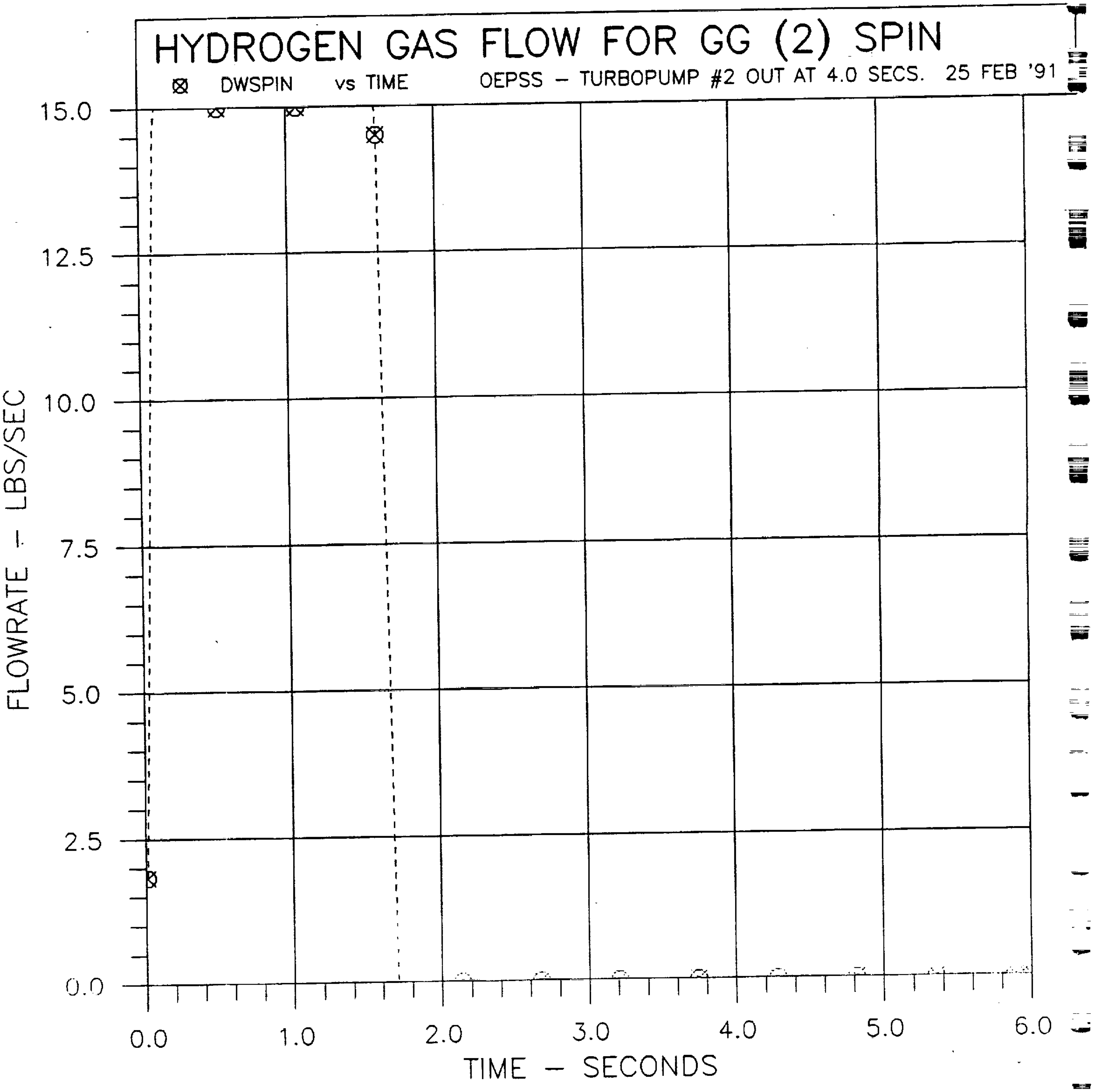

HYDROGEN GAS FLOW FOR GG (2) SPIN
⊗ DWSPIN vs TIME
OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
FLOWRATE – LBS/SEC
15.0
12.5
10.0
7.5
5.0
2.5
0.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
TIME – SECONDS

Figure B20

APPENDIX C

TURBOPUMP OUT CONDITION RESULTS FOR SYSTEM 3

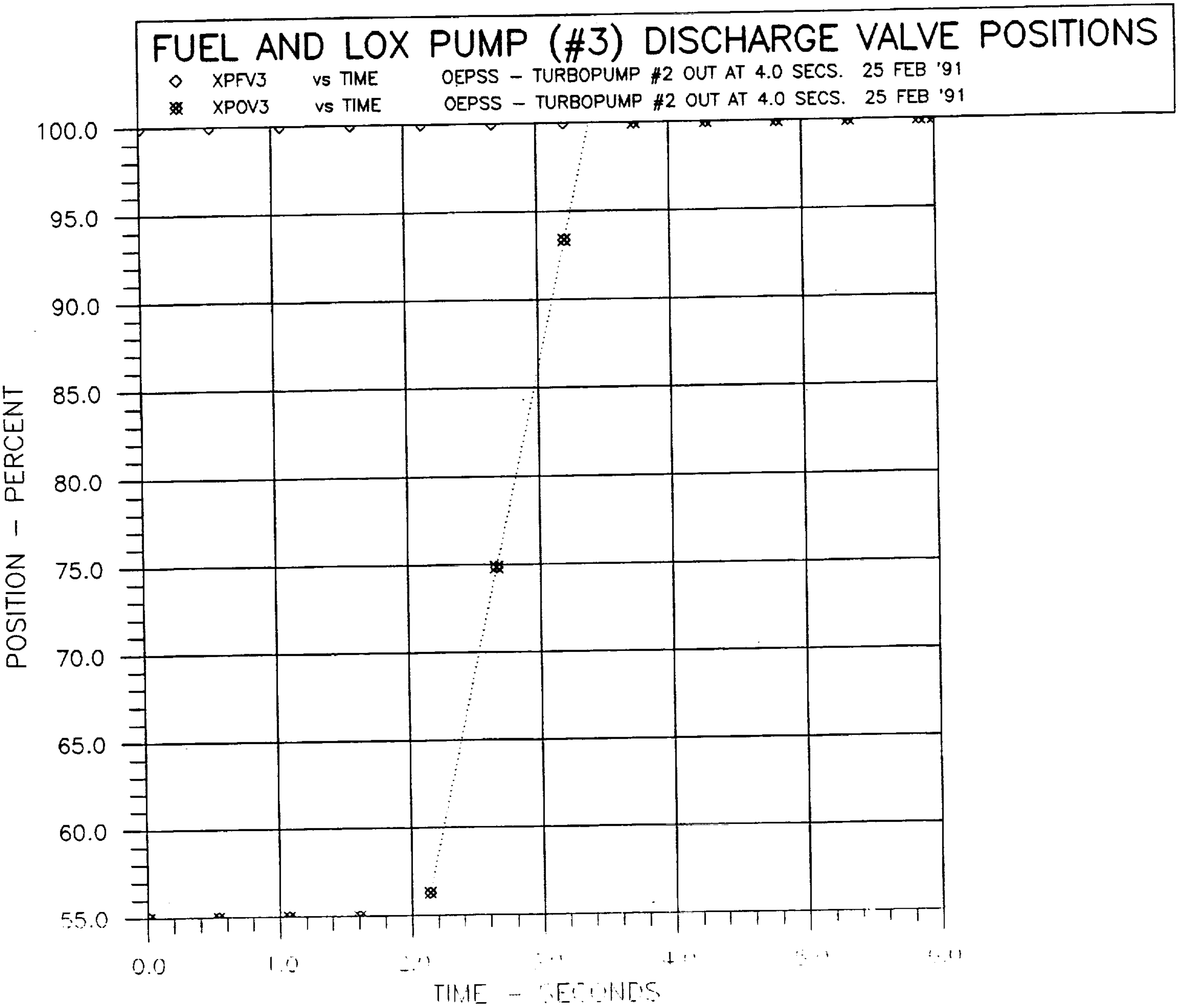

FUEL AND LOX PUMP (#3) DISCHARGE VALVE POSITIONS
◇ XPFV3 vs TIME OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
⊗ XPOV3 vs TIME OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
100.0
95.0
90.0
85.0
80.0
75.0
70.0
65.0
60.0
55.0
POSITION – PERCENT
0.0
1.0
2.0
3.0
4.0
5.0
6.0
TIME – SECONDS

Figure C1

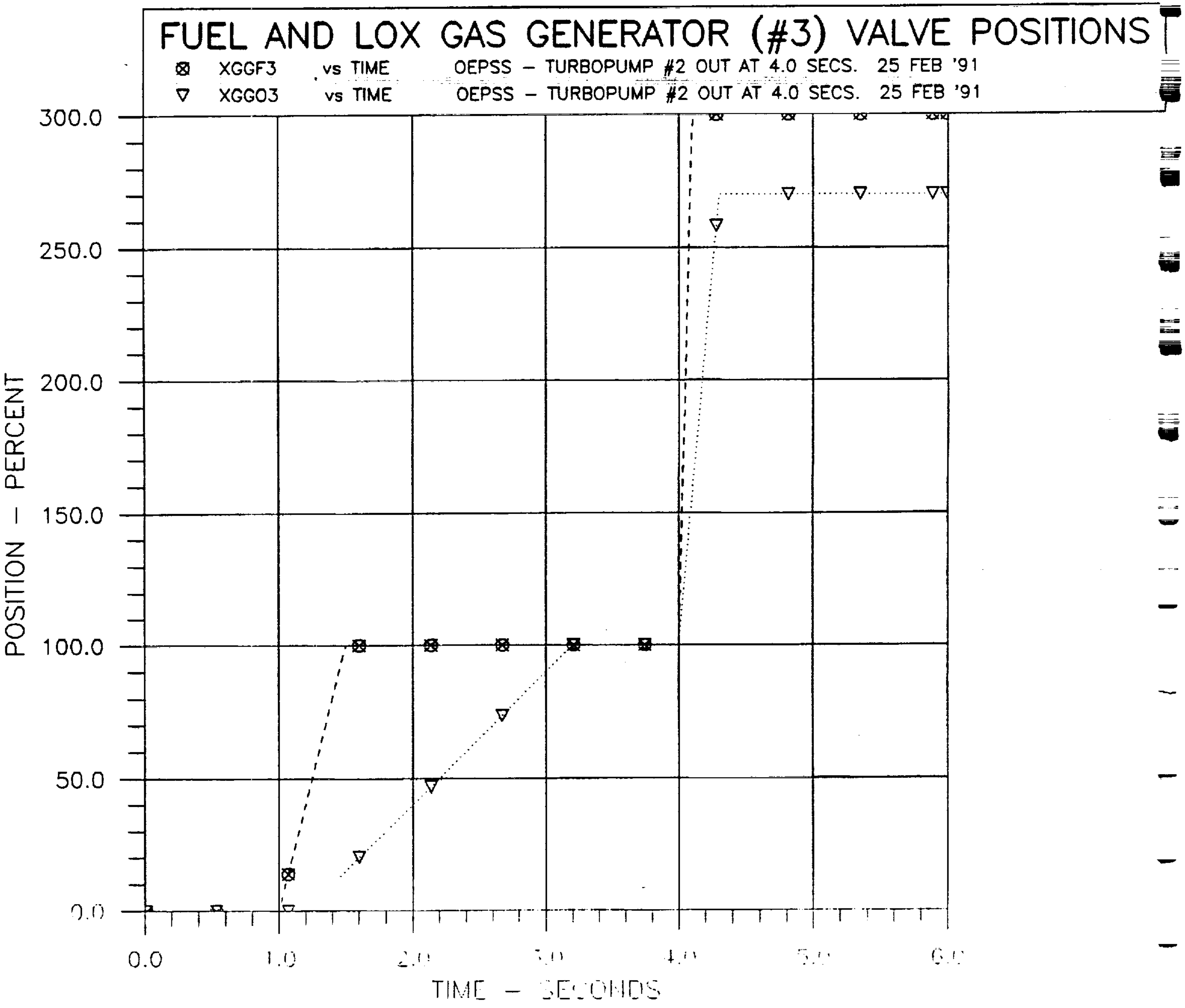

FUEL AND LOX GAS GENERATOR (#3) VALVE POSITIONS
⊠ XGGF3 vs TIME OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
▽ XGGO3 vs TIME OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
POSITION – PERCENT
300.0
250.0
200.0
150.0
100.0
50.0
0.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
TIME – SECONDS

Figure C2

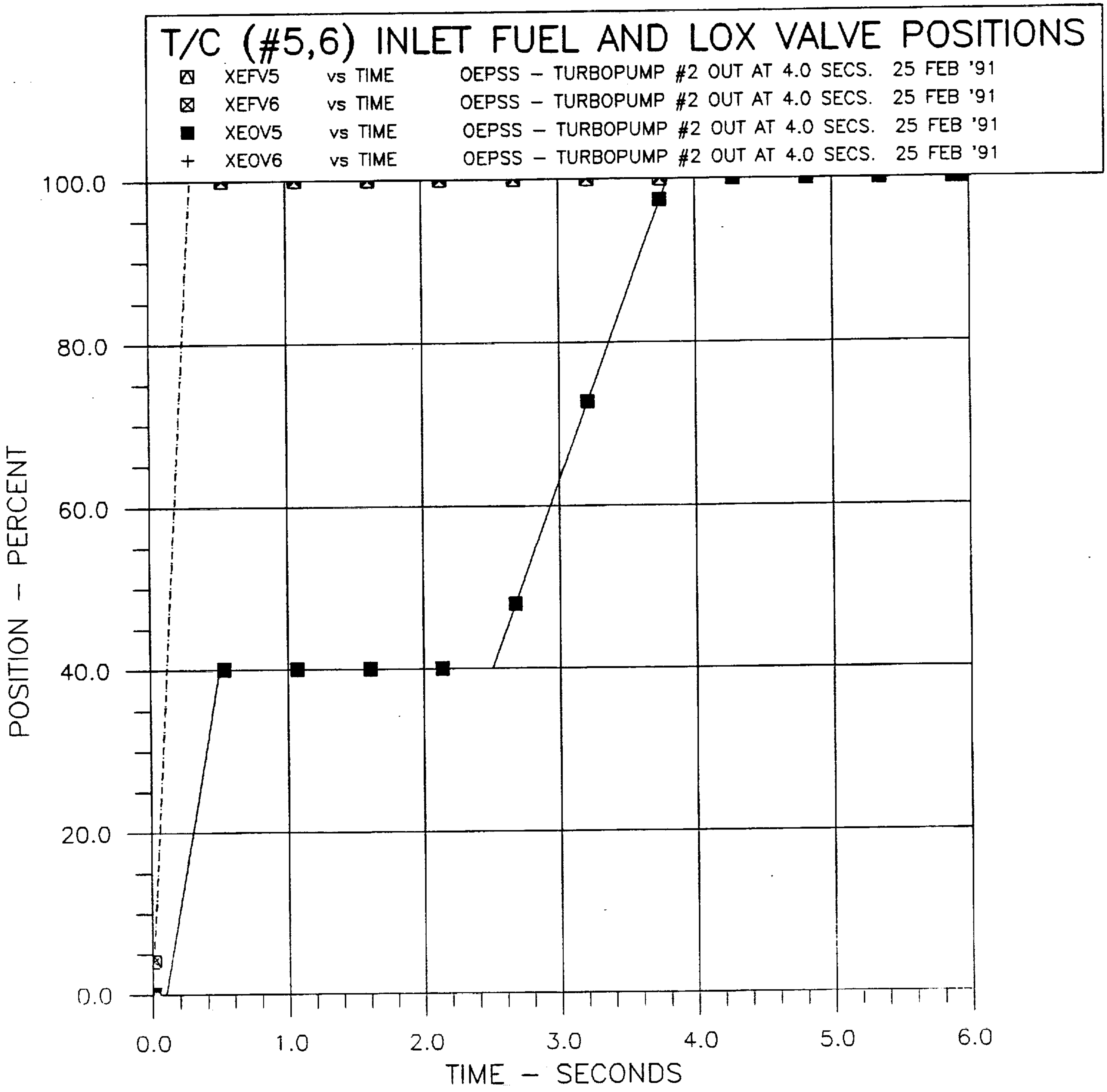

T/C (#5,6) INLET FUEL AND LOX VALVE POSITIONS
XEFV5 vs TIME OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
XEFV6 vs TIME OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
XEOV5 vs TIME OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
+ XEOV6 vs TIME OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
100.0
80.0
60.0
40.0
20.0
0.0
POSITION – PERCENT
0.0
1.0
2.0
3.0
4.0
5.0
6.0
TIME – SECONDS

Figure C3

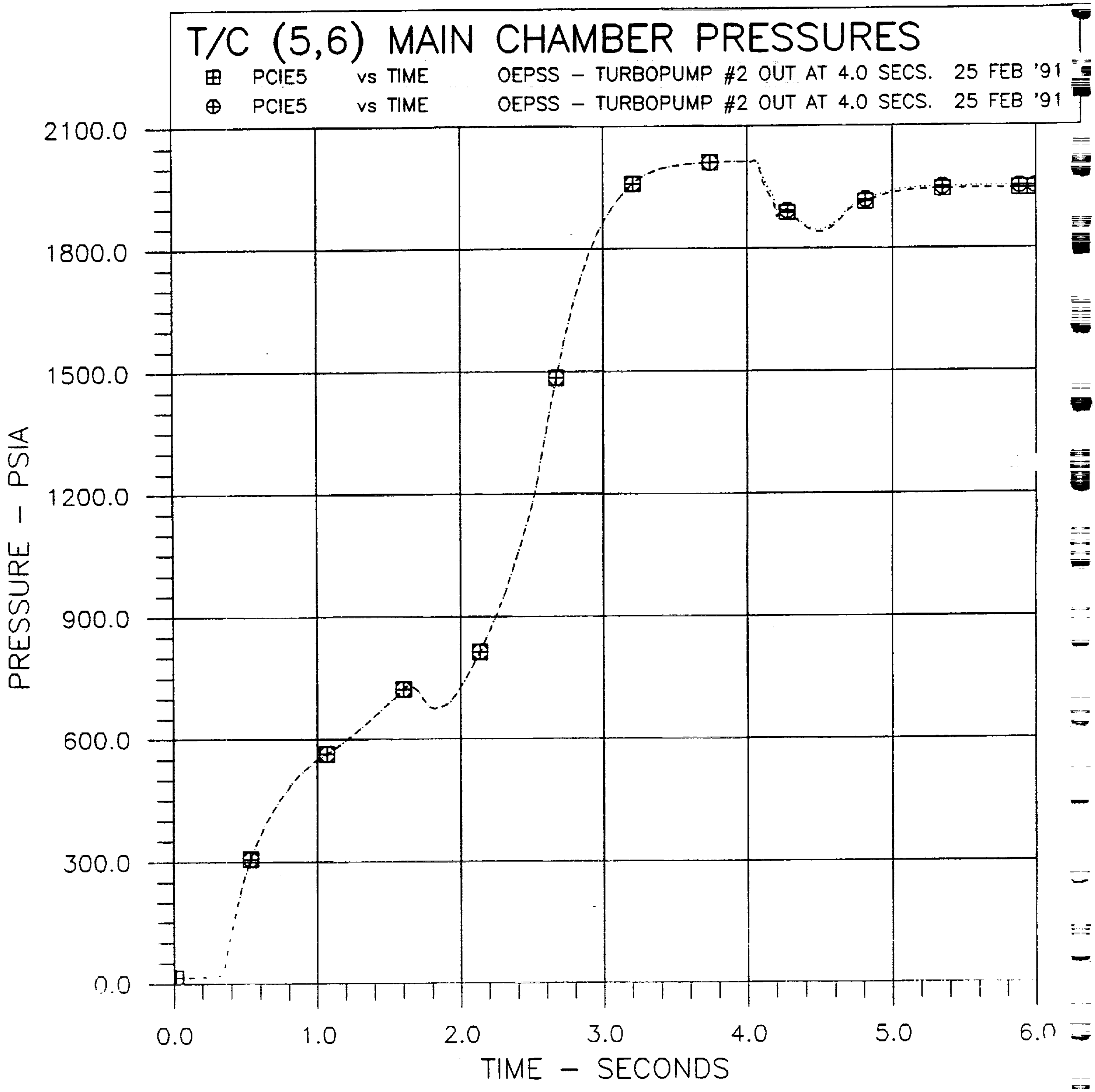

T/C (5,6) MAIN CHAMBER PRESSURES
⊞ PCIE5 vs TIME OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
⊕ PCIE5 vs TIME OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
PRESSURE – PSIA
2100.0
1800.0
1500.0
1200.0
900.0
600.0
300.0
0.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
TIME – SECONDS

Figure C4

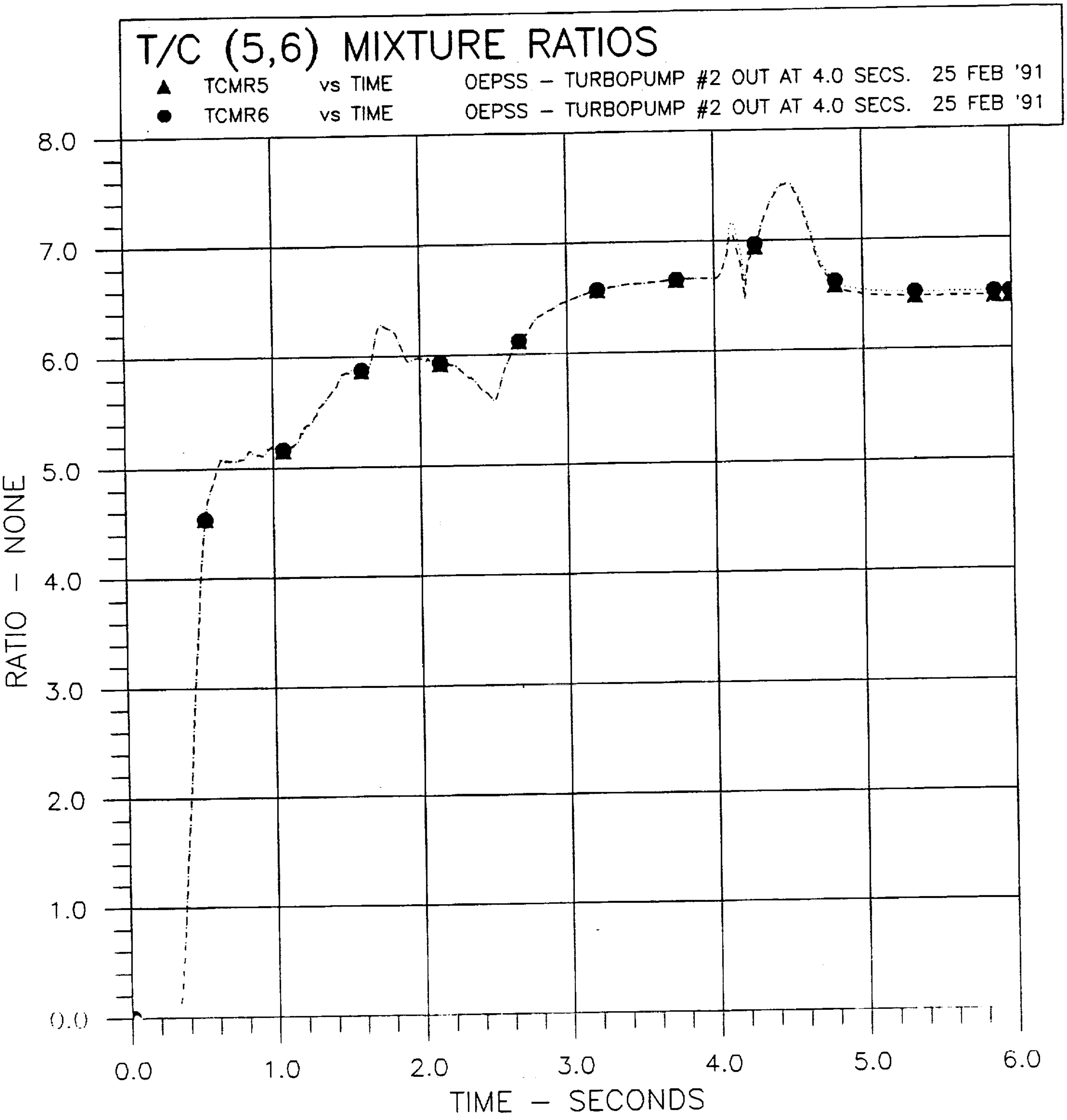
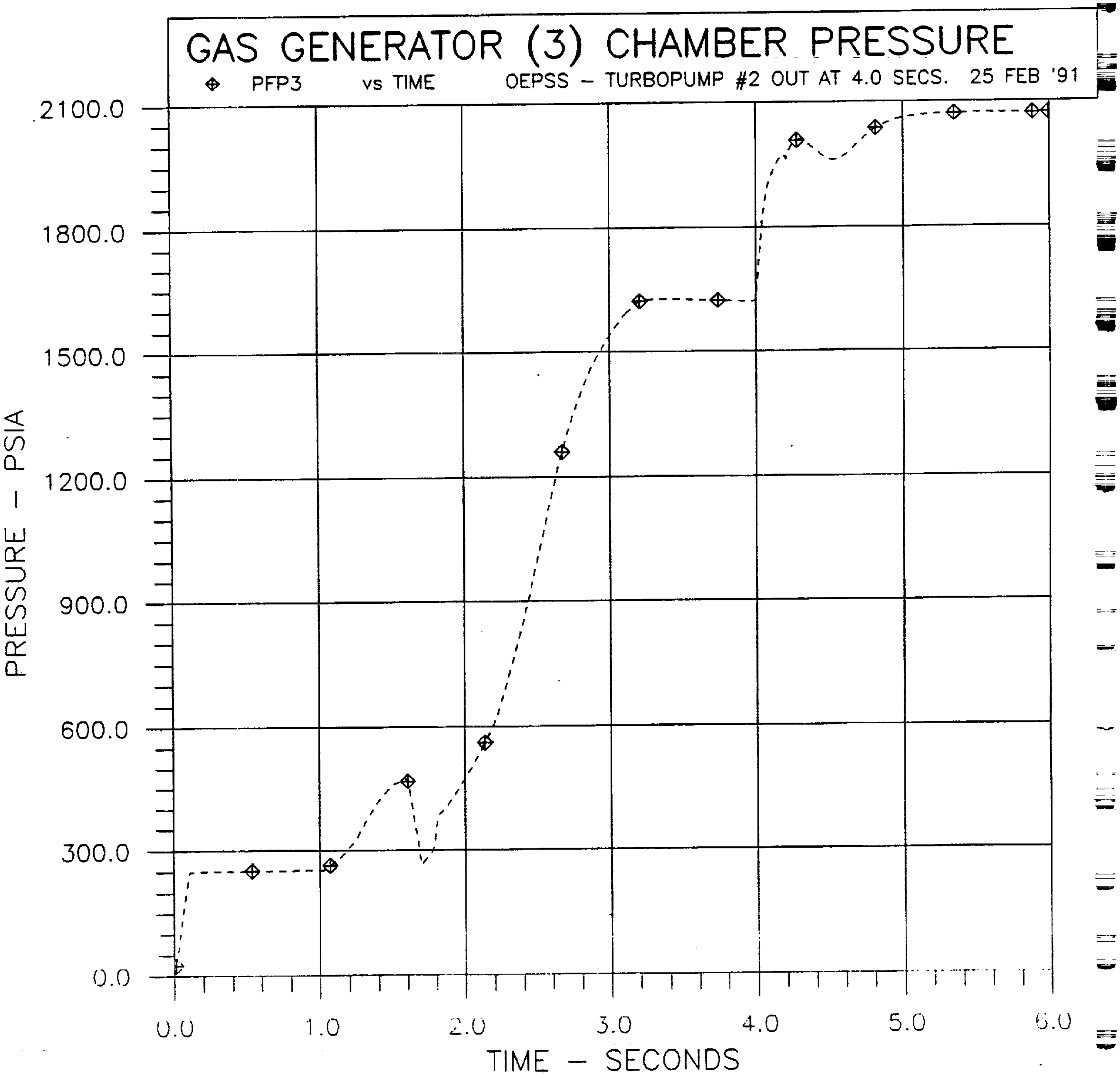

T/C (5,6) MIXTURE RATIOS
▲ TCMR5 vs TIME OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
● TCMR6 vs TIME OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
RATIO – NONE
0.0
1.0
2.0
3.0
4.0
5.0
6.0
TIME – SECONDS

Figure C5



GAS GENERATOR (3) CHAMBER PRESSURE
⊕ PFP3 vs TIME OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
PRESSURE – PSIA
0.0
300.0
600.0
900.0
1200.0
1500.0
1800.0
2100.0
TIME – SECONDS
0.0
1.0
2.0
3.0
4.0
5.0
6.0

Figure C6

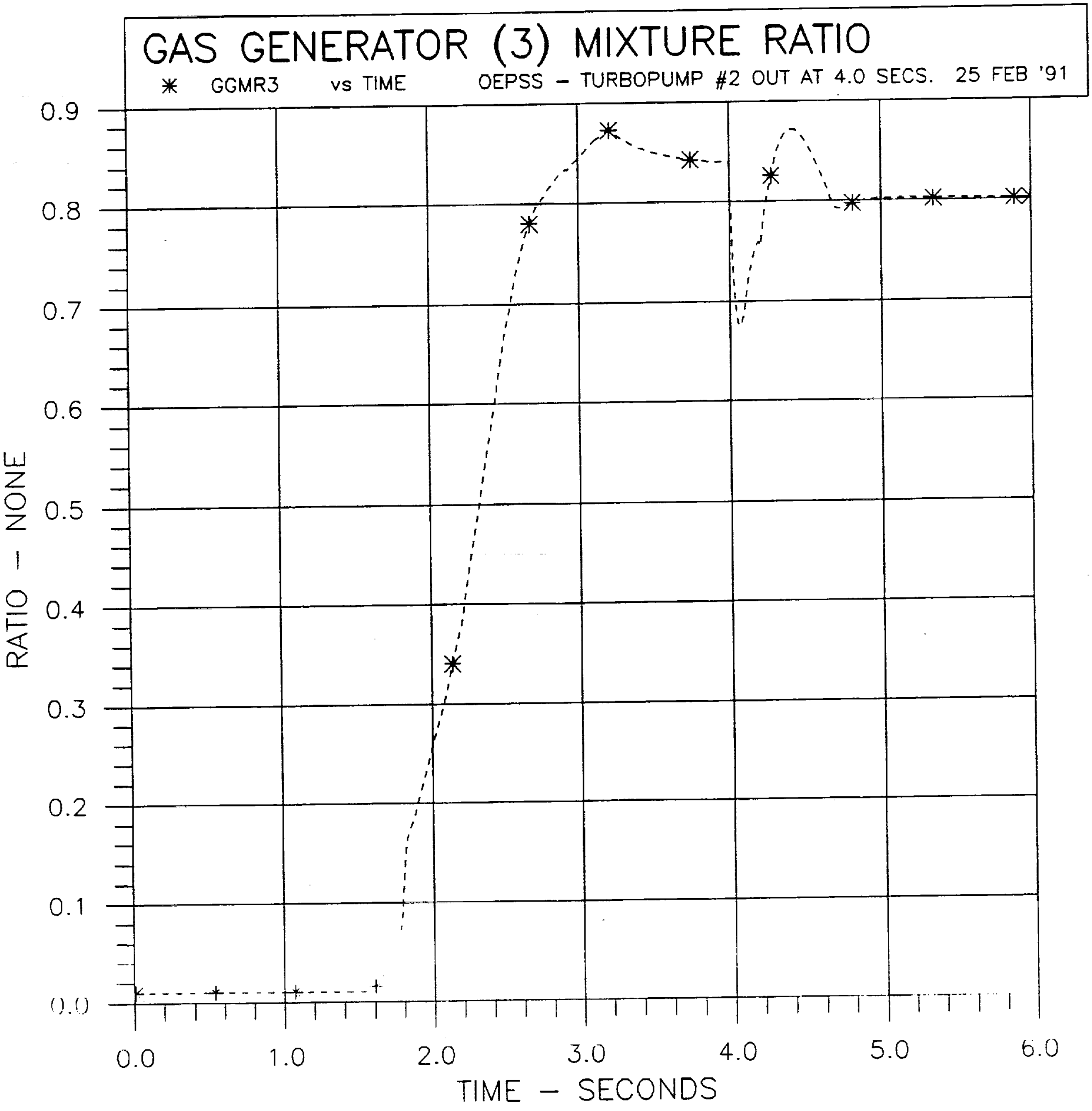

GAS GENERATOR (3) MIXTURE RATIO
✳ GGMR3 vs TIME
OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
RATIO – NONE
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
TIME – SECONDS

Figure C7

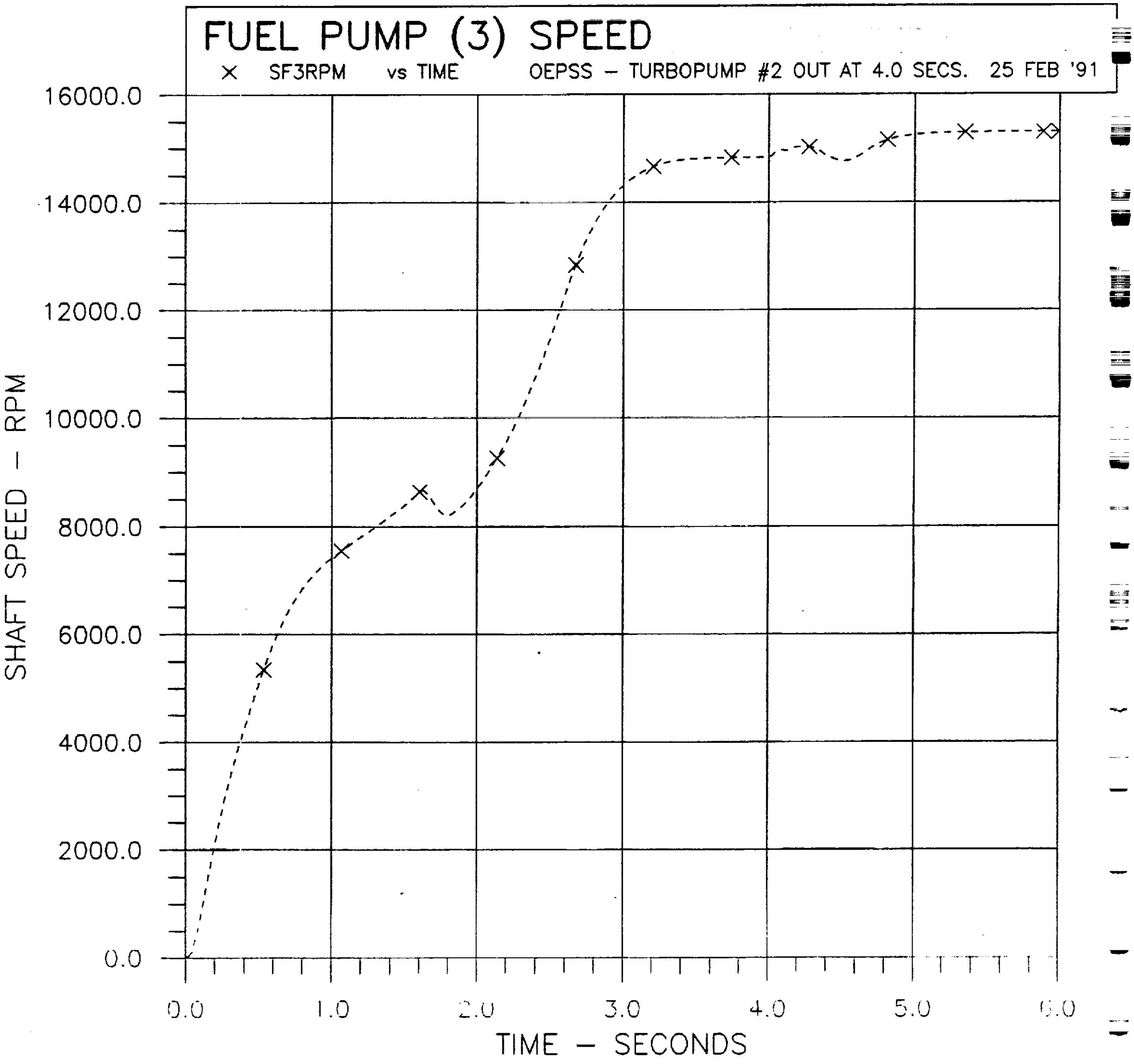

FUEL PUMP (3) SPEED
× SF3RPM vs TIME
OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
SHAFT SPEED – RPM
16000.0
14000.0
12000.0
10000.0
8000.0
6000.0
4000.0
2000.0
0.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
TIME – SECONDS

Figure C8

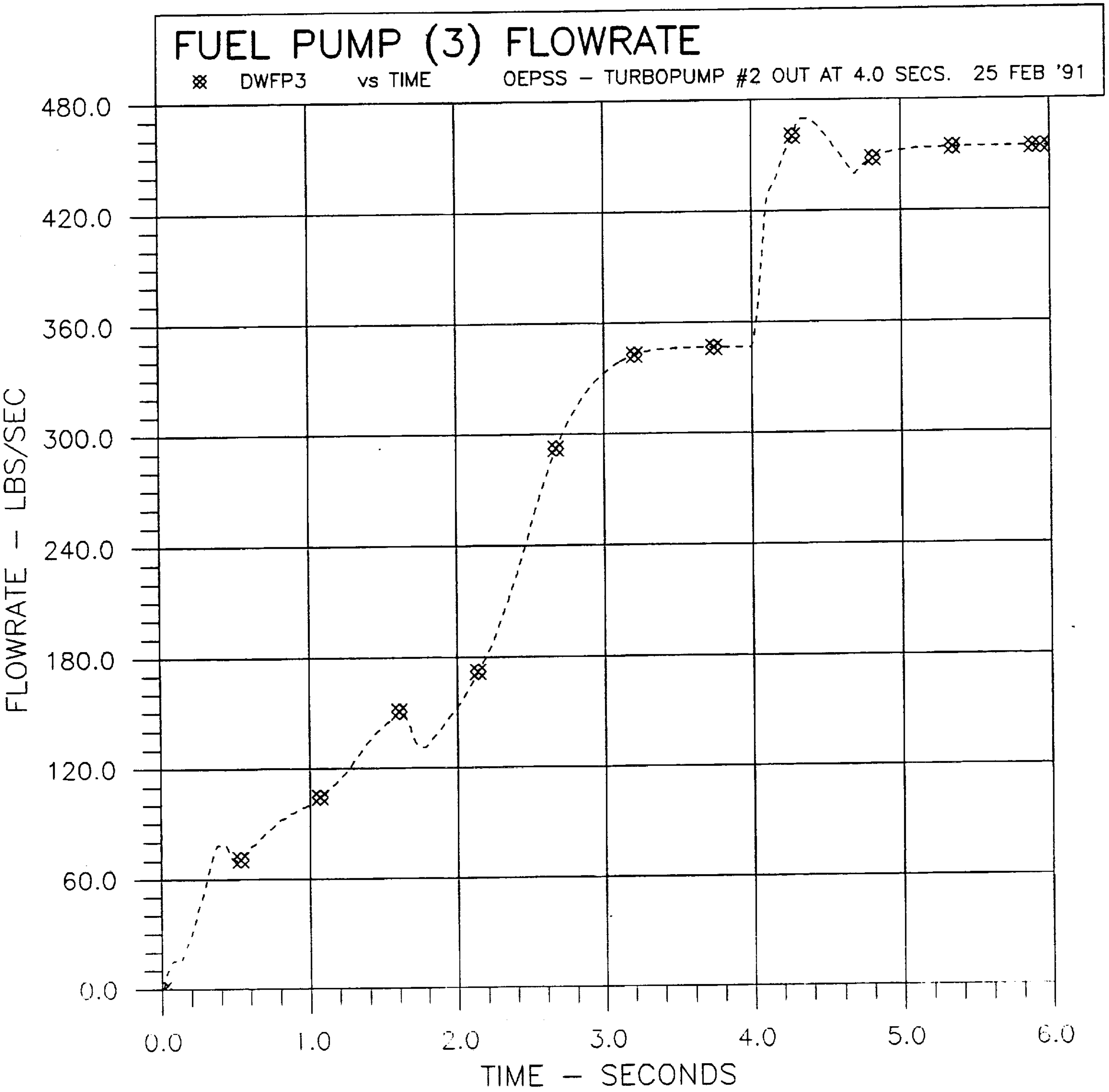
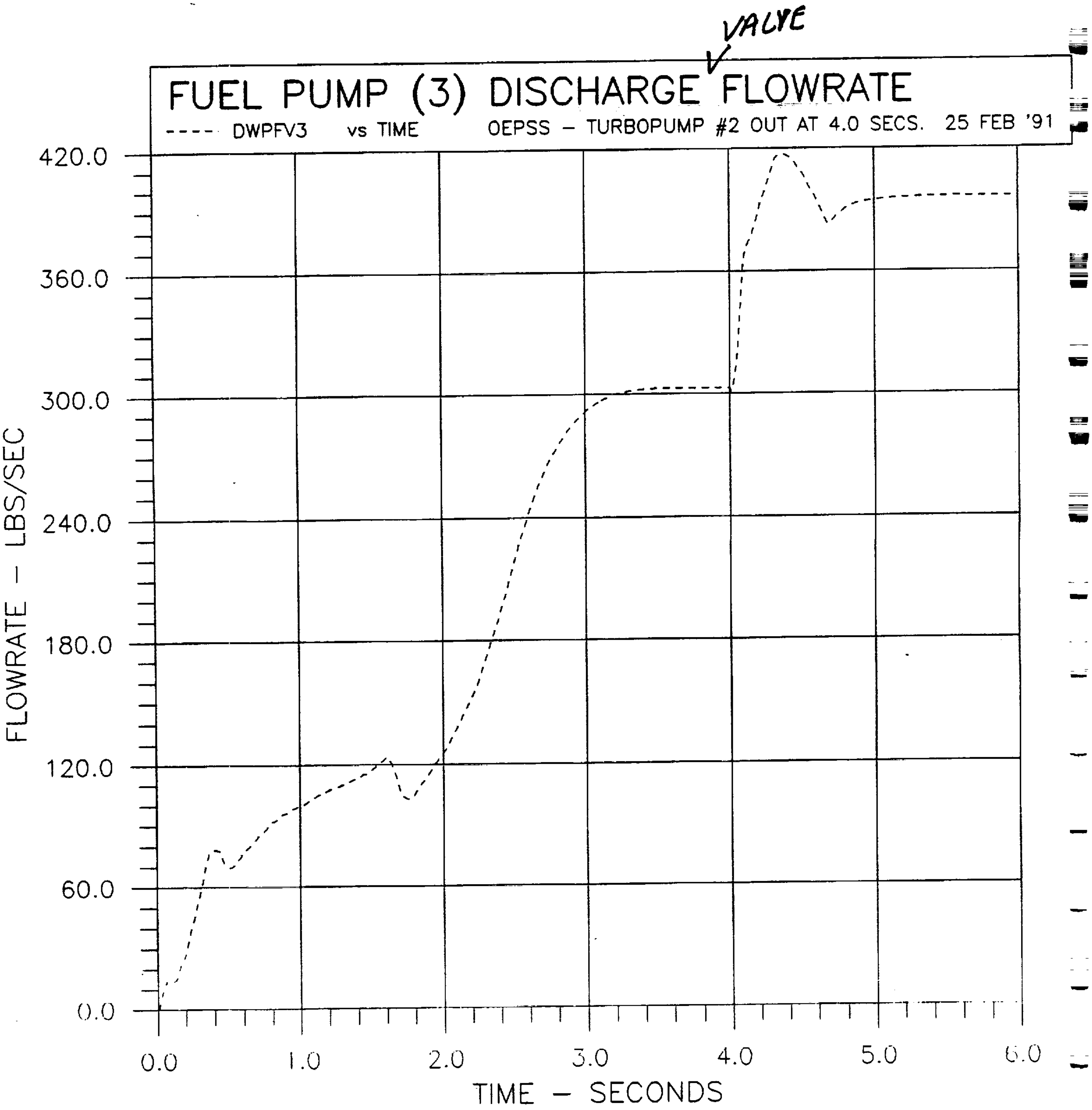

FUEL PUMP (3) FLOWRATE
⊗ DWFP3 vs TIME
OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
FLOWRATE – LBS/SEC
480.0
420.0
360.0
300.0
240.0
180.0
120.0
60.0
0.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
TIME – SECONDS

Figure C9



VALVE
FUEL PUMP (3) DISCHARGE FLOWRATE
---- DWPFV3 vs TIME
OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
420.0
360.0
300.0
240.0
180.0
120.0
60.0
0.0
FLOWRATE – LBS/SEC
0.0
1.0
2.0
3.0
4.0
5.0
6.0
TIME – SECONDS

Figure C10

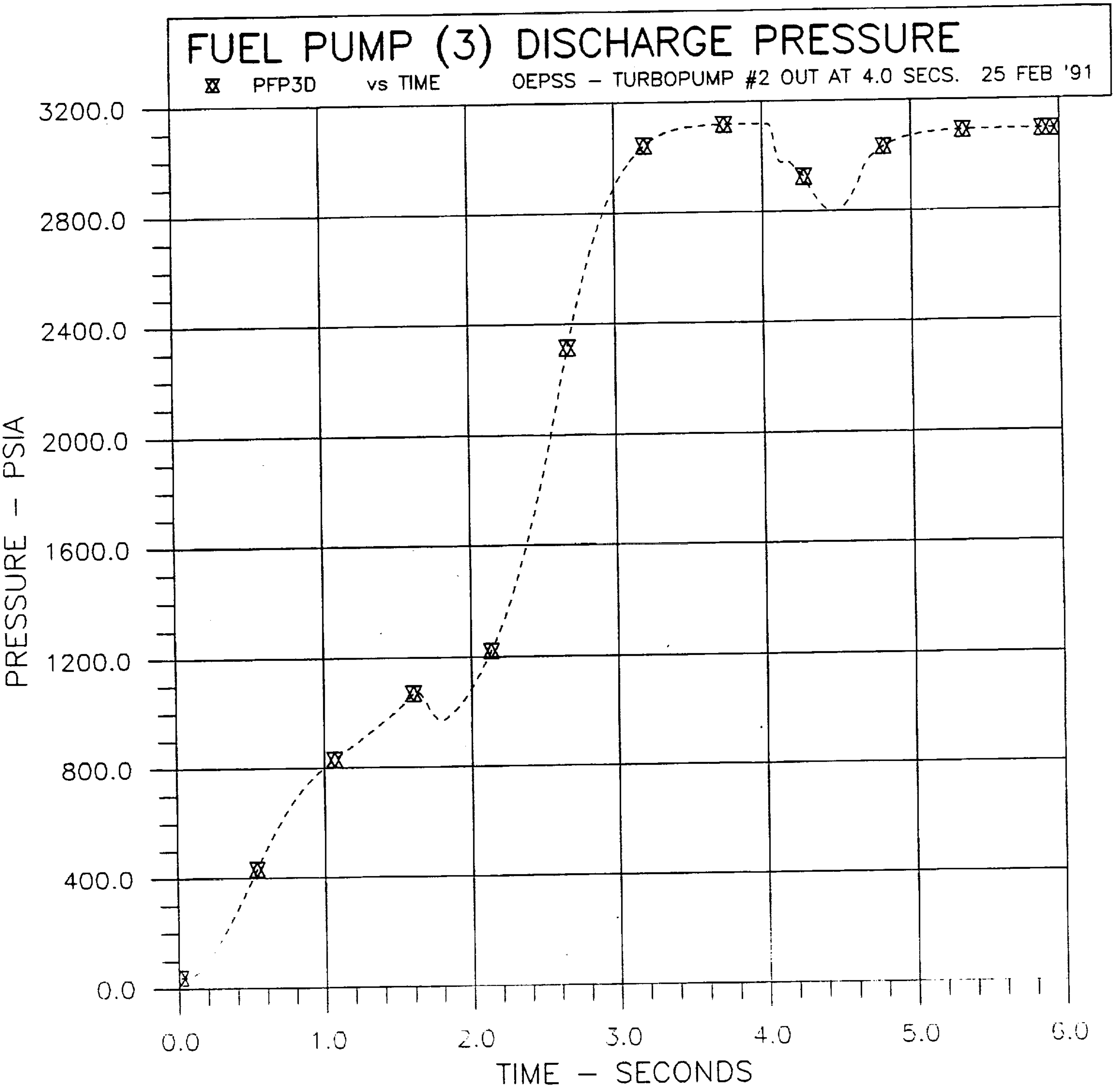

FUEL PUMP (3) DISCHARGE PRESSURE
PFP3D vs TIME
OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
PRESSURE – PSIA
3200.0
2800.0
2400.0
2000.0
1600.0
1200.0
800.0
400.0
0.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
TIME – SECONDS

Figure C11

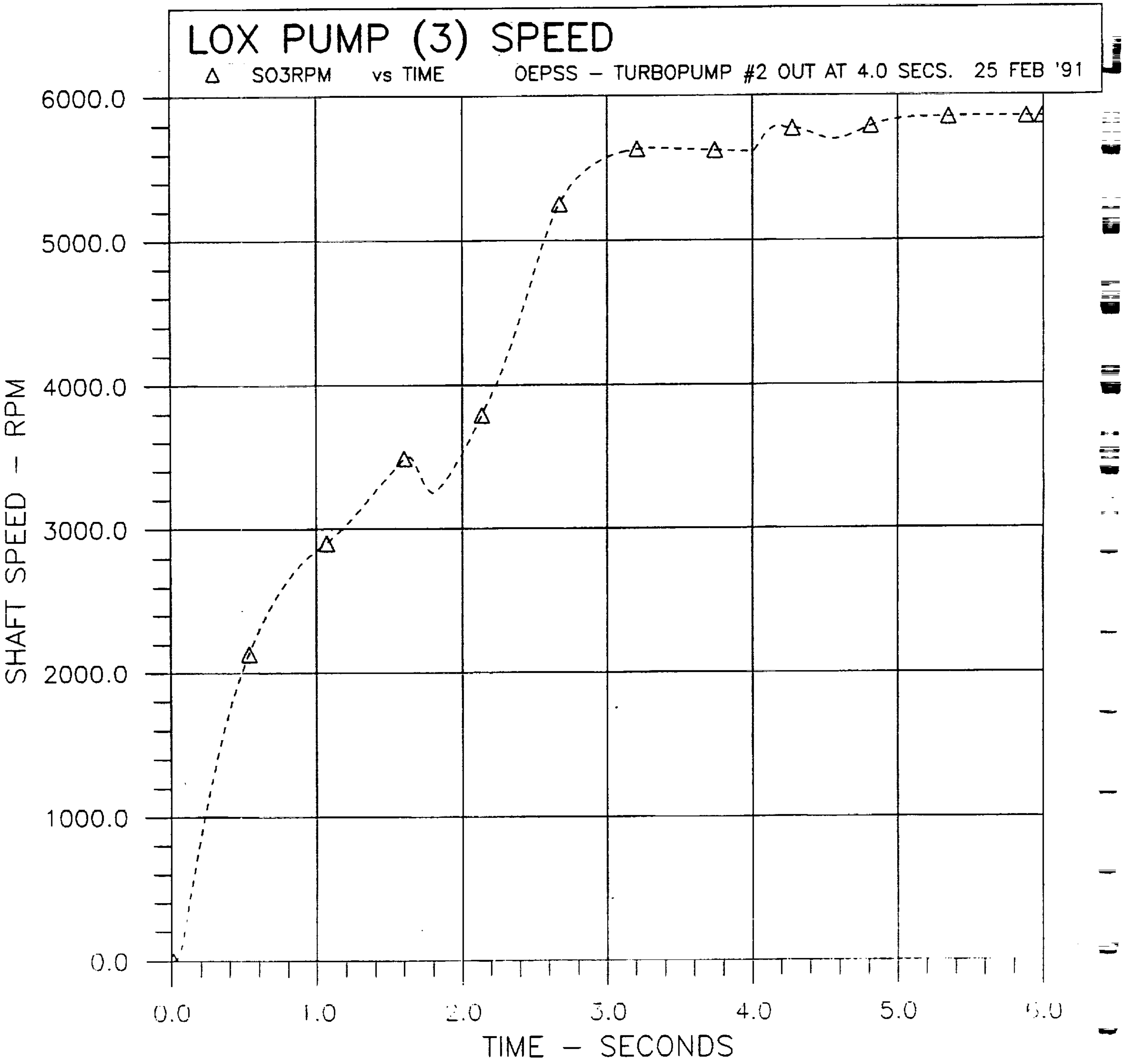

LOX PUMP (3) SPEED
△ SO3RPM vs TIME
OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
SHAFT SPEED – RPM
6000.0
5000.0
4000.0
3000.0
2000.0
1000.0
0.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
TIME – SECONDS

Figure C12

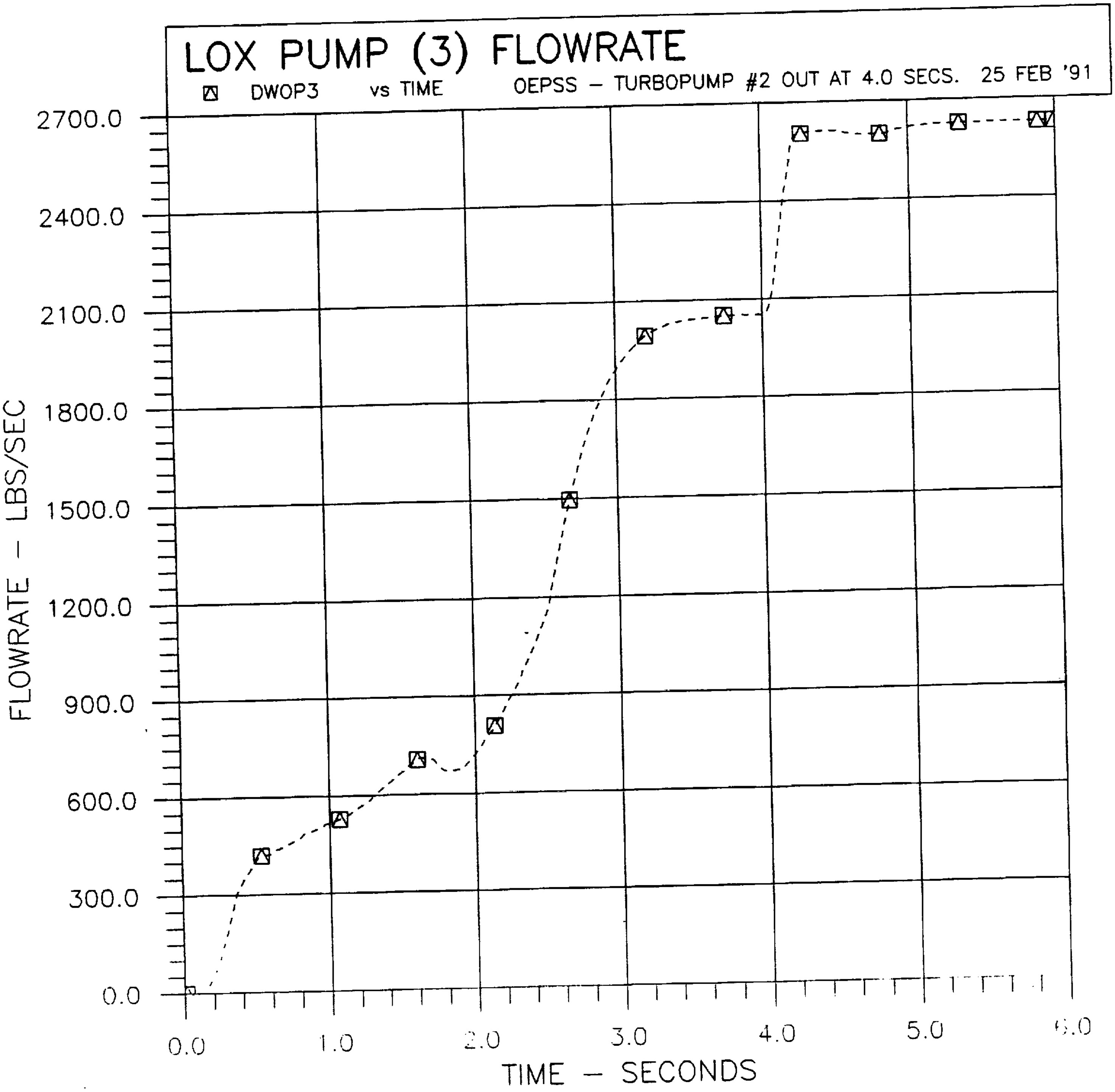

LOX PUMP (3) FLOWRATE
⊠ DWOP3 vs TIME
OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
FLOWRATE – LBS/SEC
2700.0
2400.0
2100.0
1800.0
1500.0
1200.0
900.0
600.0
300.0
0.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
TIME – SECONDS

Figure C13

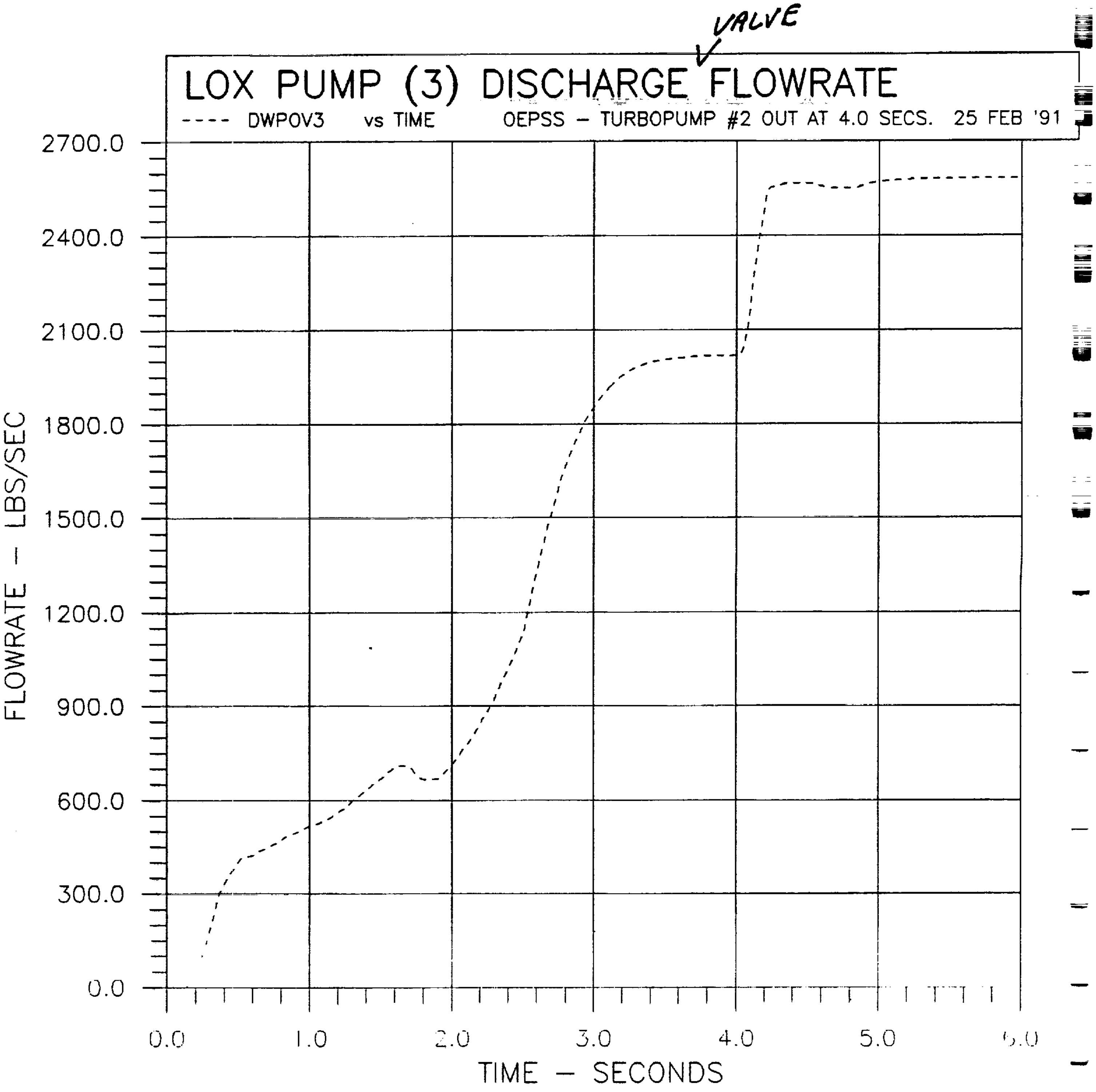

VALVE
LOX PUMP (3) DISCHARGE FLOWRATE
---- DWPOV3 vs TIME
OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
FLOWRATE – LBS/SEC
2700.0
2400.0
2100.0
1800.0
1500.0
1200.0
900.0
600.0
300.0
0.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
TIME – SECONDS

Figure C14

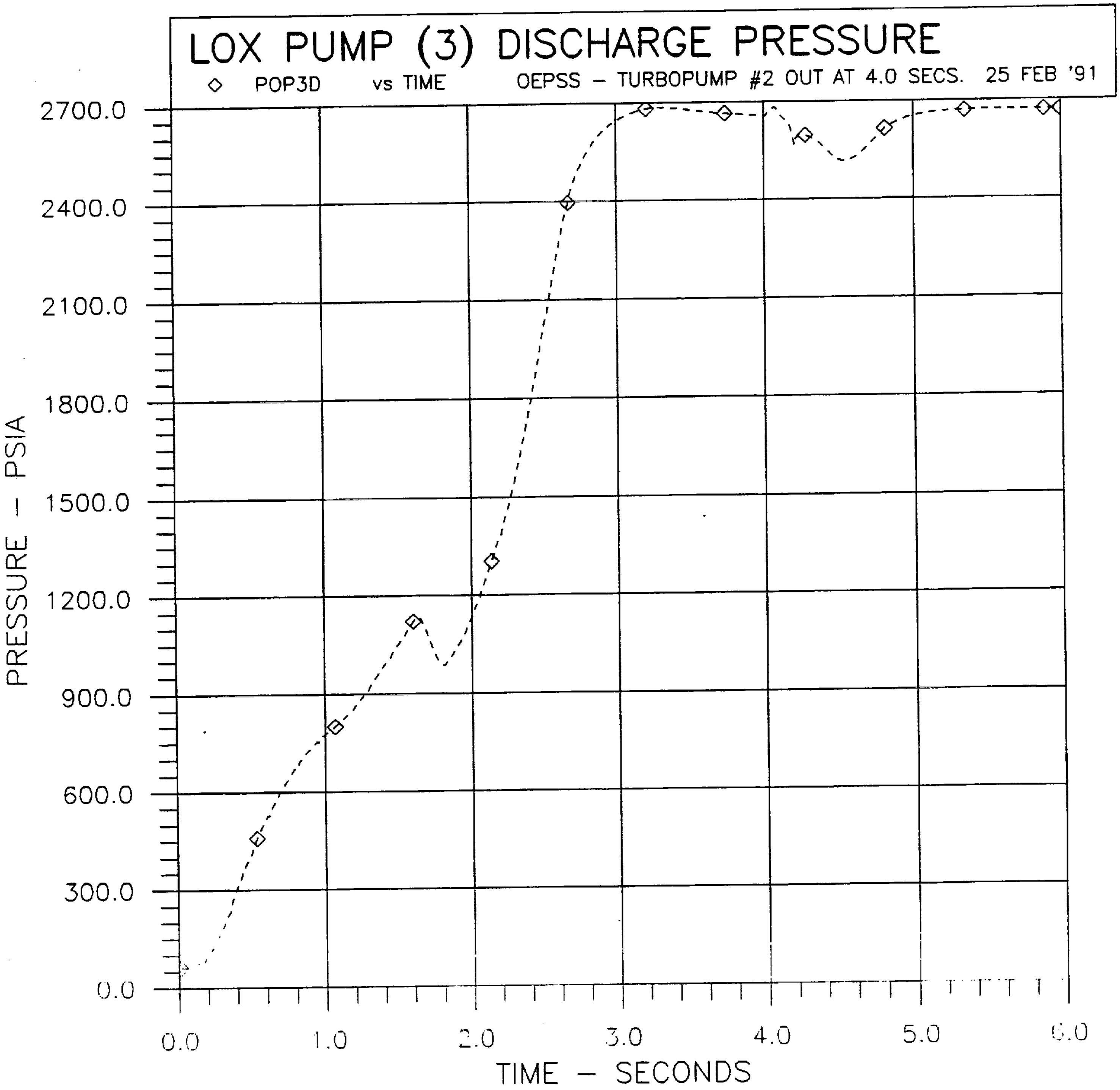

LOX PUMP (3) DISCHARGE PRESSURE
◇ POP3D vs TIME OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
2700.0
2400.0
2100.0
1800.0
1500.0
1200.0
900.0
600.0
300.0
0.0
PRESSURE – PSIA
0.0
1.0
2.0
3.0
4.0
5.0
6.0
TIME – SECONDS

Figure C15

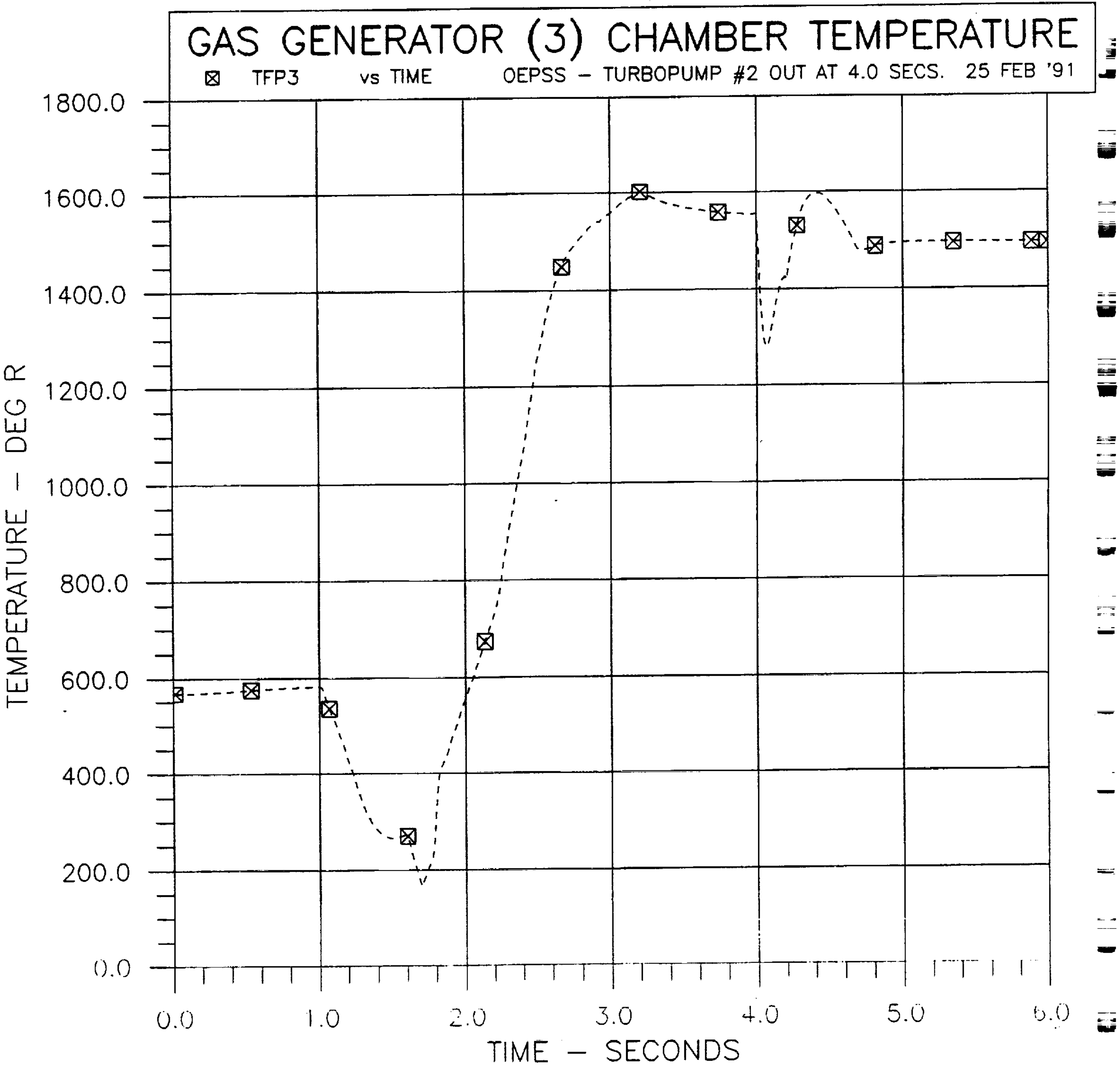

GAS GENERATOR (3) CHAMBER TEMPERATURE
☒ TFP3 vs TIME
OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
TEMPERATURE – DEG R
1800.0
1600.0
1400.0
1200.0
1000.0
800.0
600.0
400.0
200.0
0.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
TIME – SECONDS

Figure C16

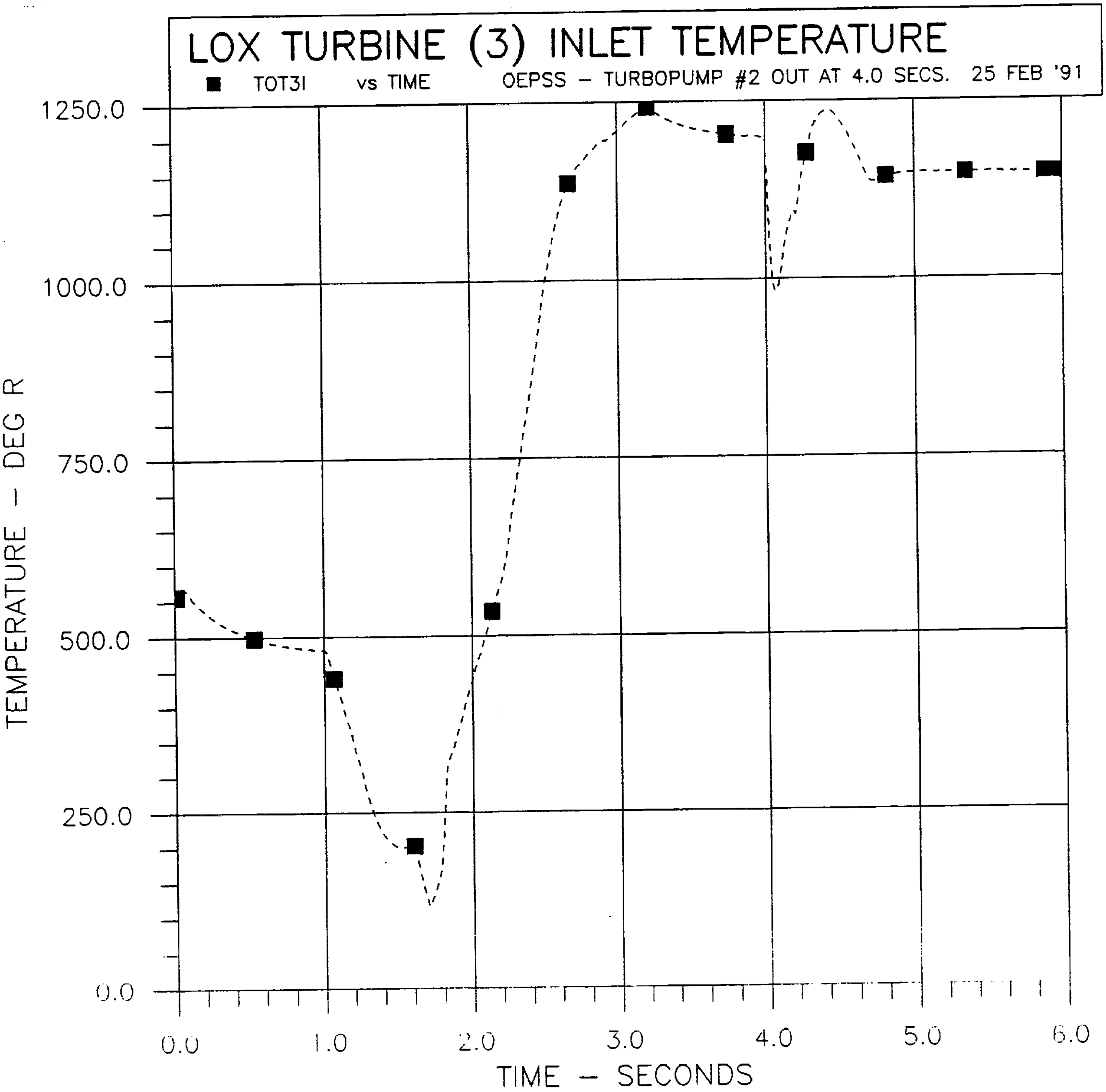
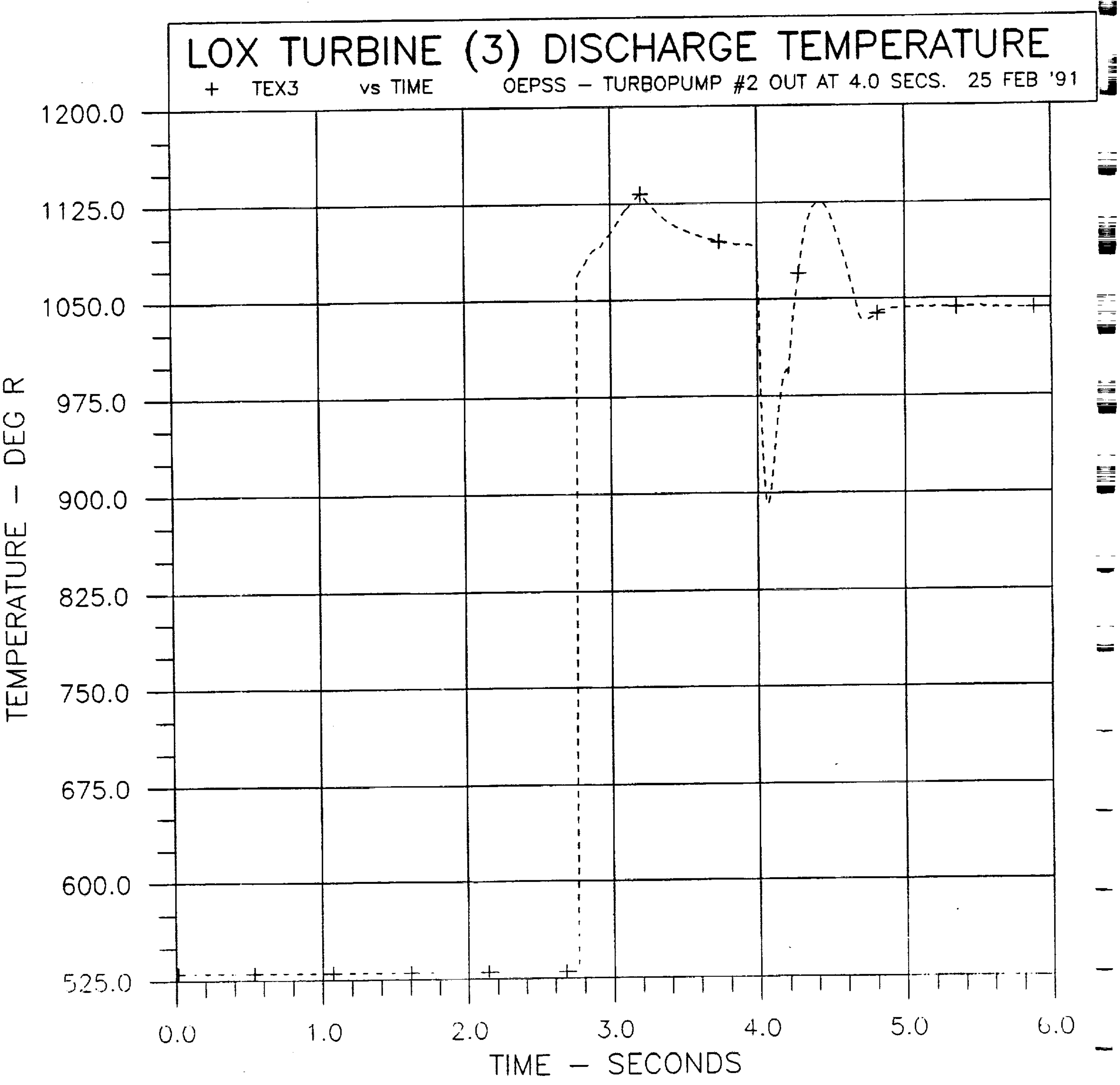

LOX TURBINE (3) INLET TEMPERATURE
■ TOT3I vs TIME OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
1250.0
1000.0
750.0
500.0
250.0
0.0
TEMPERATURE – DEG R
0.0
1.0
2.0
3.0
4.0
5.0
6.0
TIME – SECONDS

Figure C17



LOX TURBINE (3) DISCHARGE TEMPERATURE
+ TEX3 vs TIME
OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
1200.0
1125.0
1050.0
975.0
900.0
825.0
750.0
675.0
600.0
525.0
TEMPERATURE – DEG R
0.0
1.0
2.0
3.0
4.0
5.0
6.0
TIME – SECONDS

Figure C18

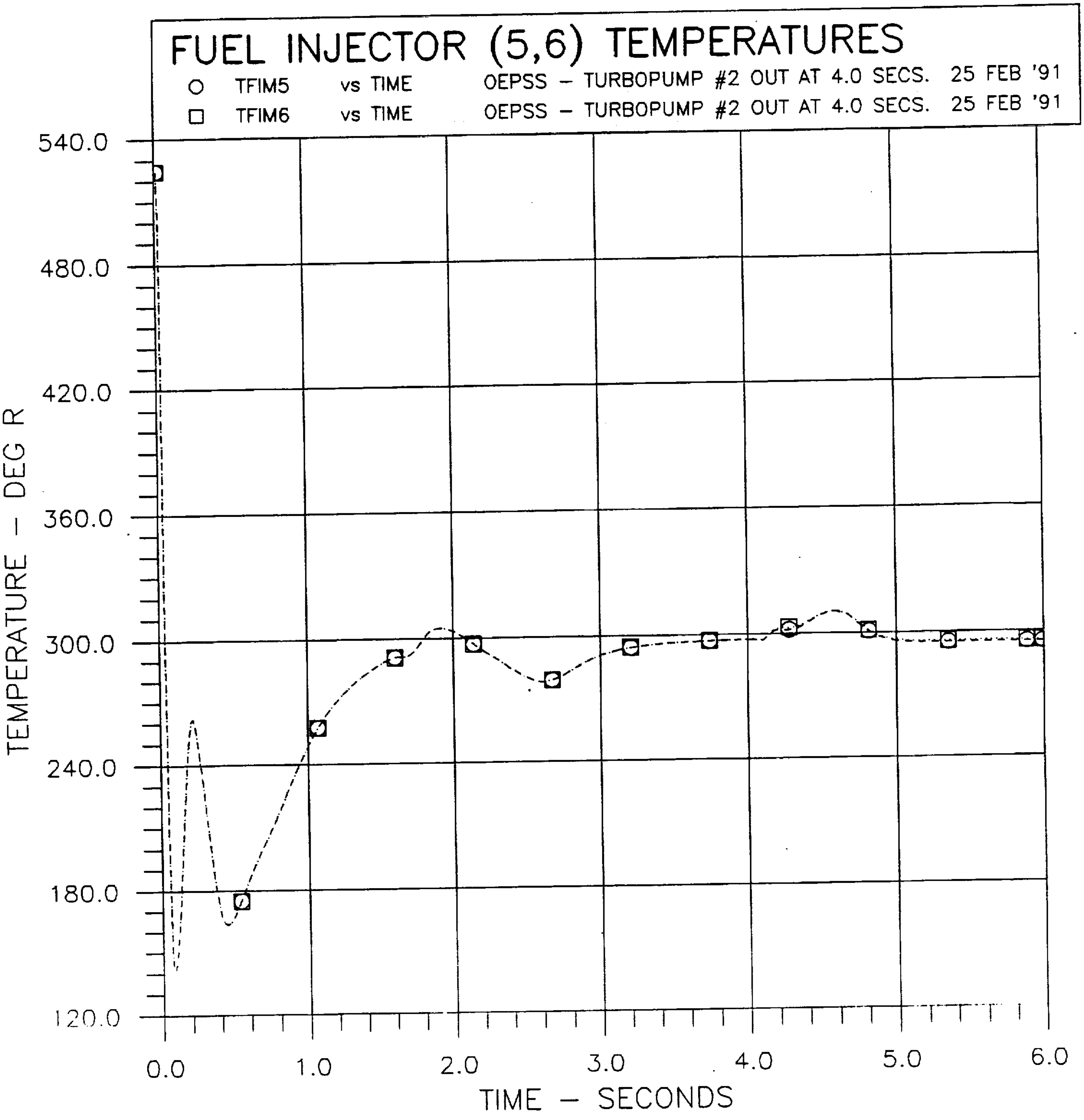

FUEL INJECTOR (5,6) TEMPERATURES
○ TFIM5 vs TIME OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
□ TFIM6 vs TIME OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
540.0
480.0
420.0
360.0
300.0
240.0
180.0
120.0
TEMPERATURE – DEG R
0.0
1.0
2.0
3.0
4.0
5.0
6.0
TIME – SECONDS

Figure C19

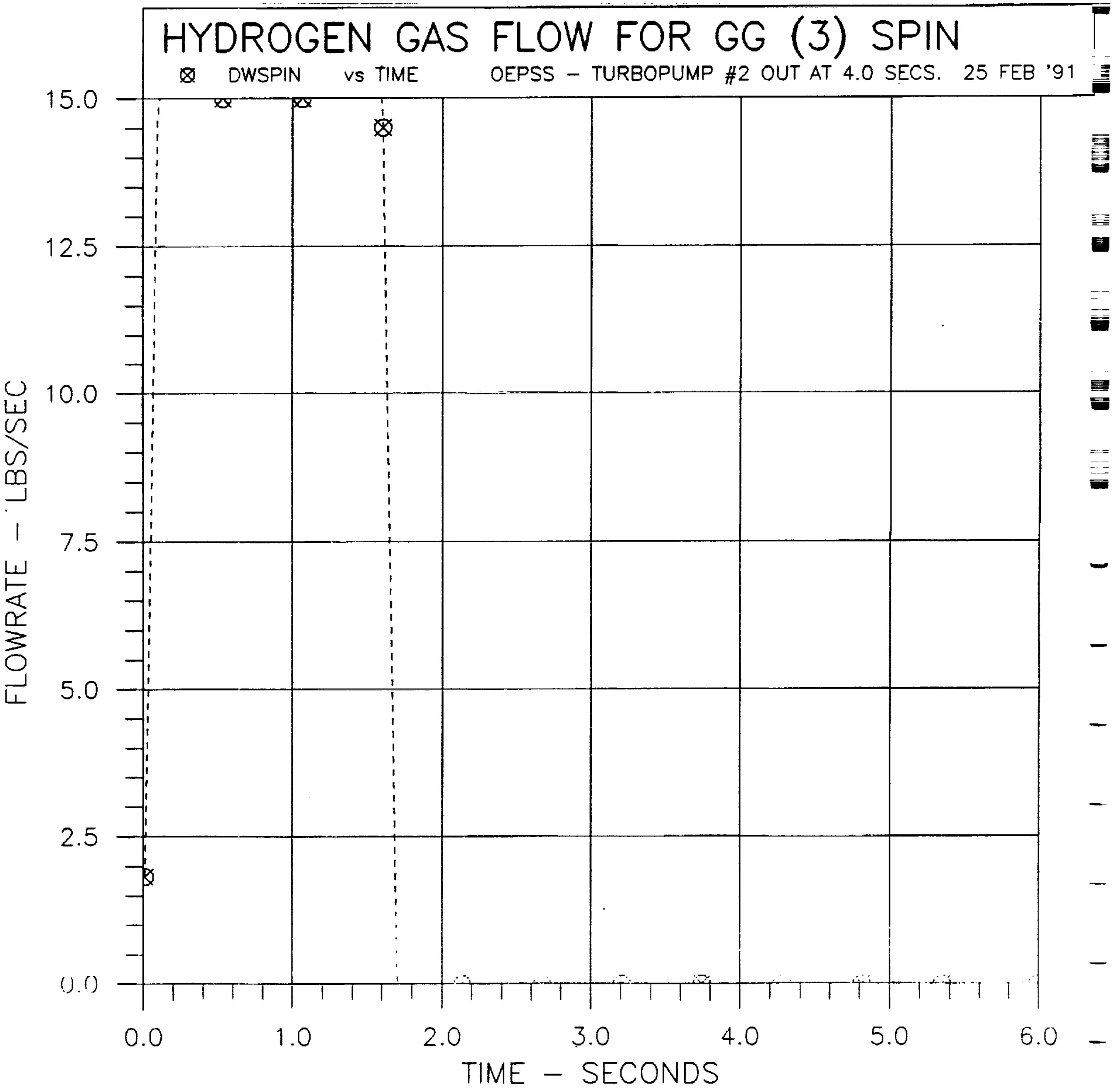

HYDROGEN GAS FLOW FOR GG (3) SPIN
⊗ DWSPIN vs TIME
OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
FLOWRATE – LBS/SEC
15.0
12.5
10.0
7.5
5.0
2.5
0.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
TIME – SECONDS

Figure C20

APPENDIX D

TURBOPUMP OUT CONDITION RESULTS

FOR SYSTEM 4

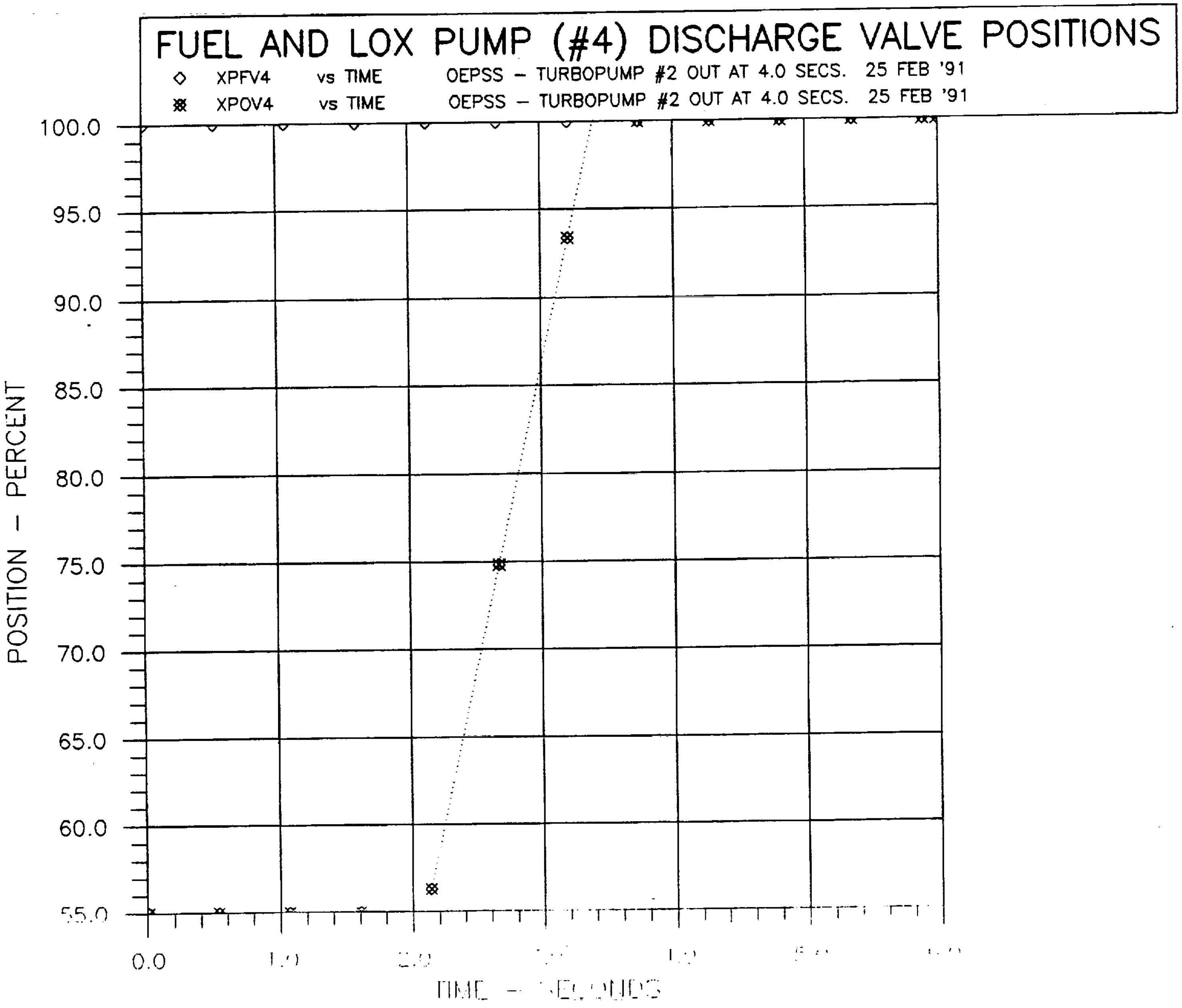

FUEL AND LOX PUMP (#4) DISCHARGE VALVE POSITIONS
◇ XPFV4 vs TIME OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
⊗ XPOV4 vs TIME OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
100.0
95.0
90.0
85.0
80.0
75.0
70.0
65.0
60.0
55.0
POSITION – PERCENT
0.0
1.0
2.0
3.0
4.0
5.0
6.0
TIME – SECONDS

Figure D1

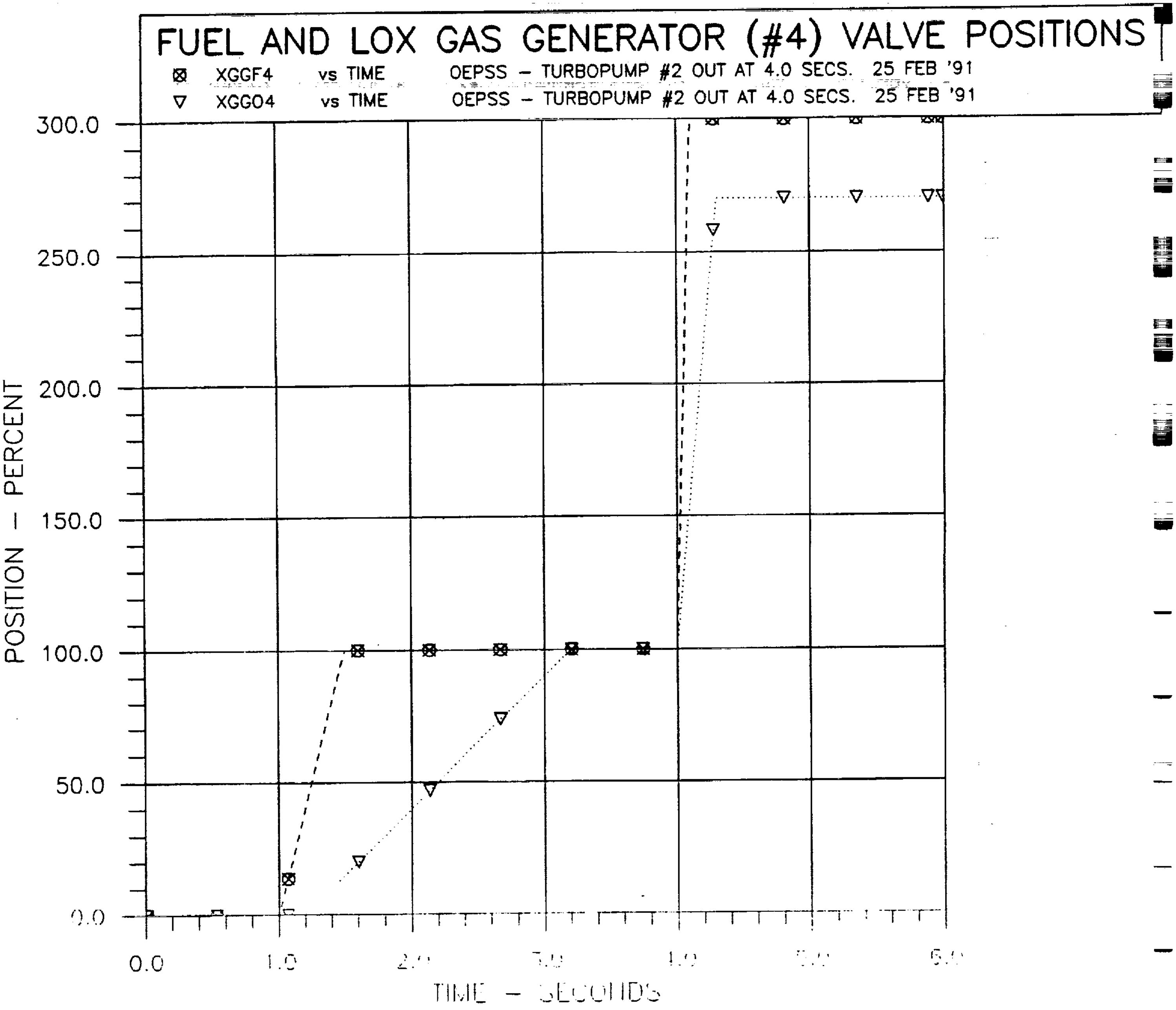

FUEL AND LOX GAS GENERATOR (#4) VALVE POSITIONS
⊠ XGGF4 vs TIME OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
▽ XGGO4 vs TIME OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
300.0
250.0
200.0
150.0
100.0
50.0
0.0
POSITION – PERCENT
0.0
1.0
2.0
3.0
4.0
5.0
6.0
TIME – SECONDS

Figure D2

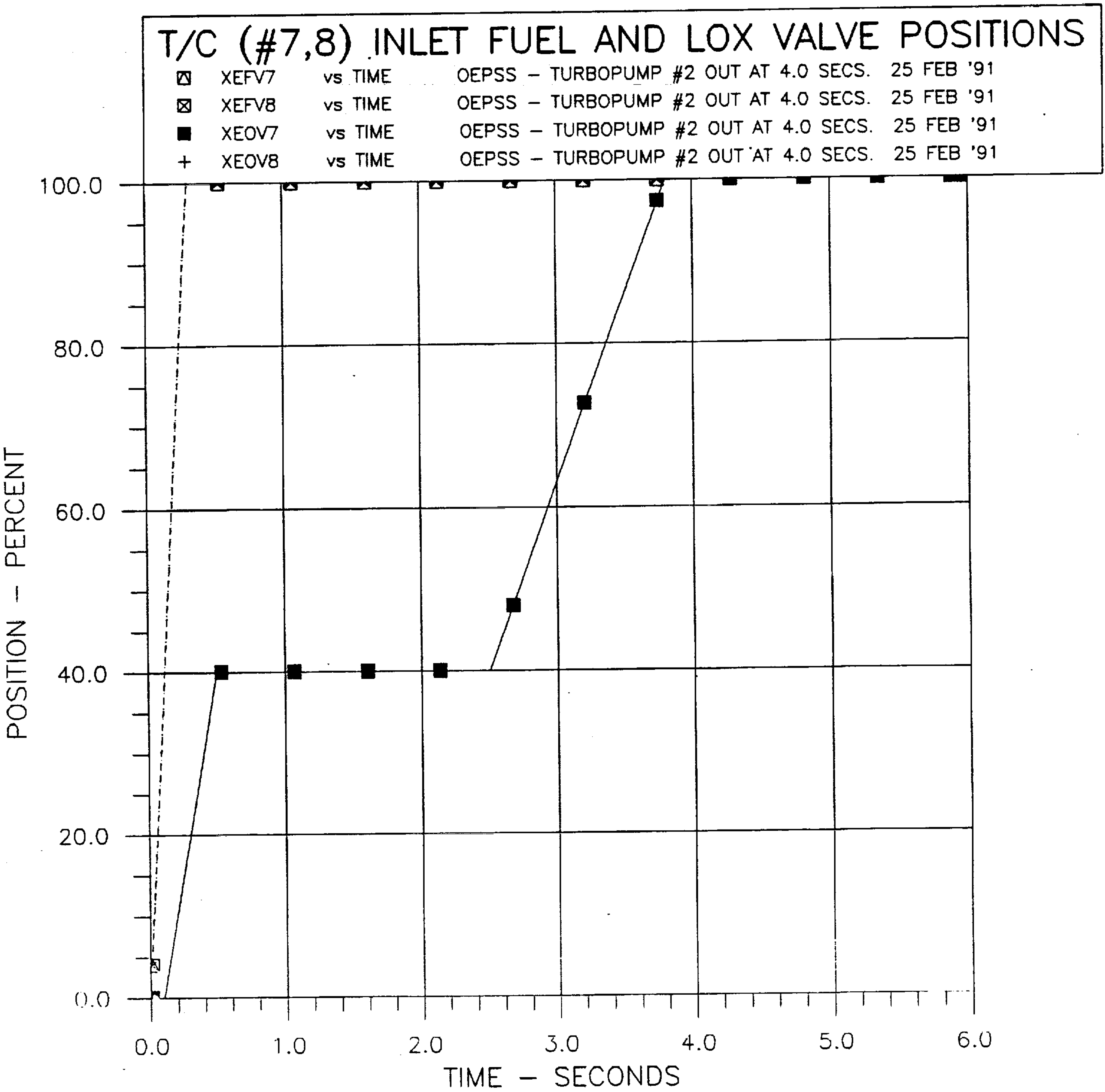

T/C (#7,8) INLET FUEL AND LOX VALVE POSITIONS
XEFV7 vs TIME OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
XEFV8 vs TIME OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
XEOV7 vs TIME OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
XEOV8 vs TIME OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
100.0
80.0
60.0
40.0
20.0
0.0
POSITION – PERCENT
0.0
1.0
2.0
3.0
4.0
5.0
6.0
TIME – SECONDS

Figure D3

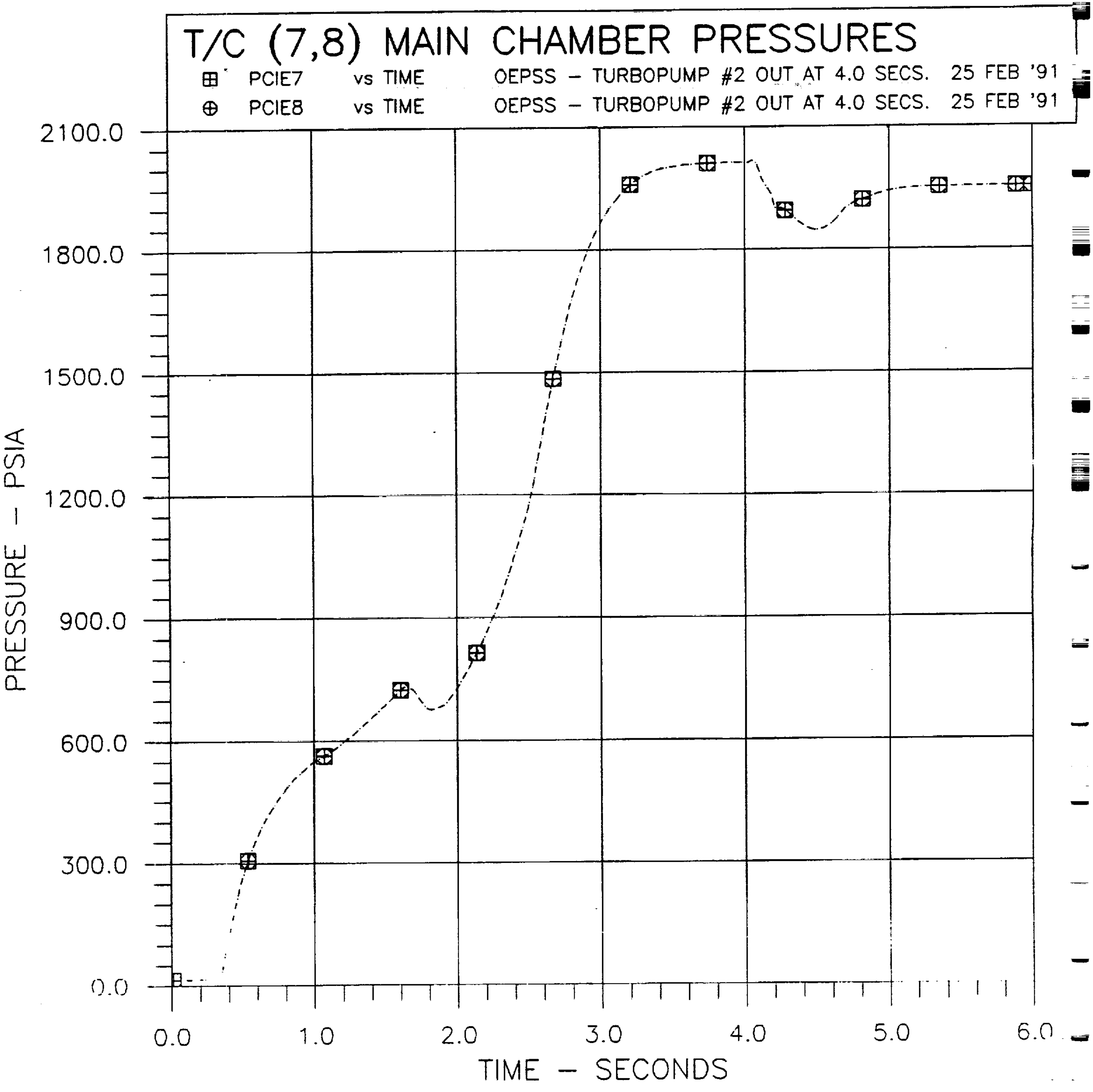

T/C (7,8) MAIN CHAMBER PRESSURES
⊞ PCIE7 vs TIME OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
⊕ PCIE8 vs TIME OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
2100.0
1800.0
1500.0
1200.0
900.0
600.0
300.0
0.0
PRESSURE – PSIA
0.0
1.0
2.0
3.0
4.0
5.0
6.0
TIME – SECONDS

Figure D4

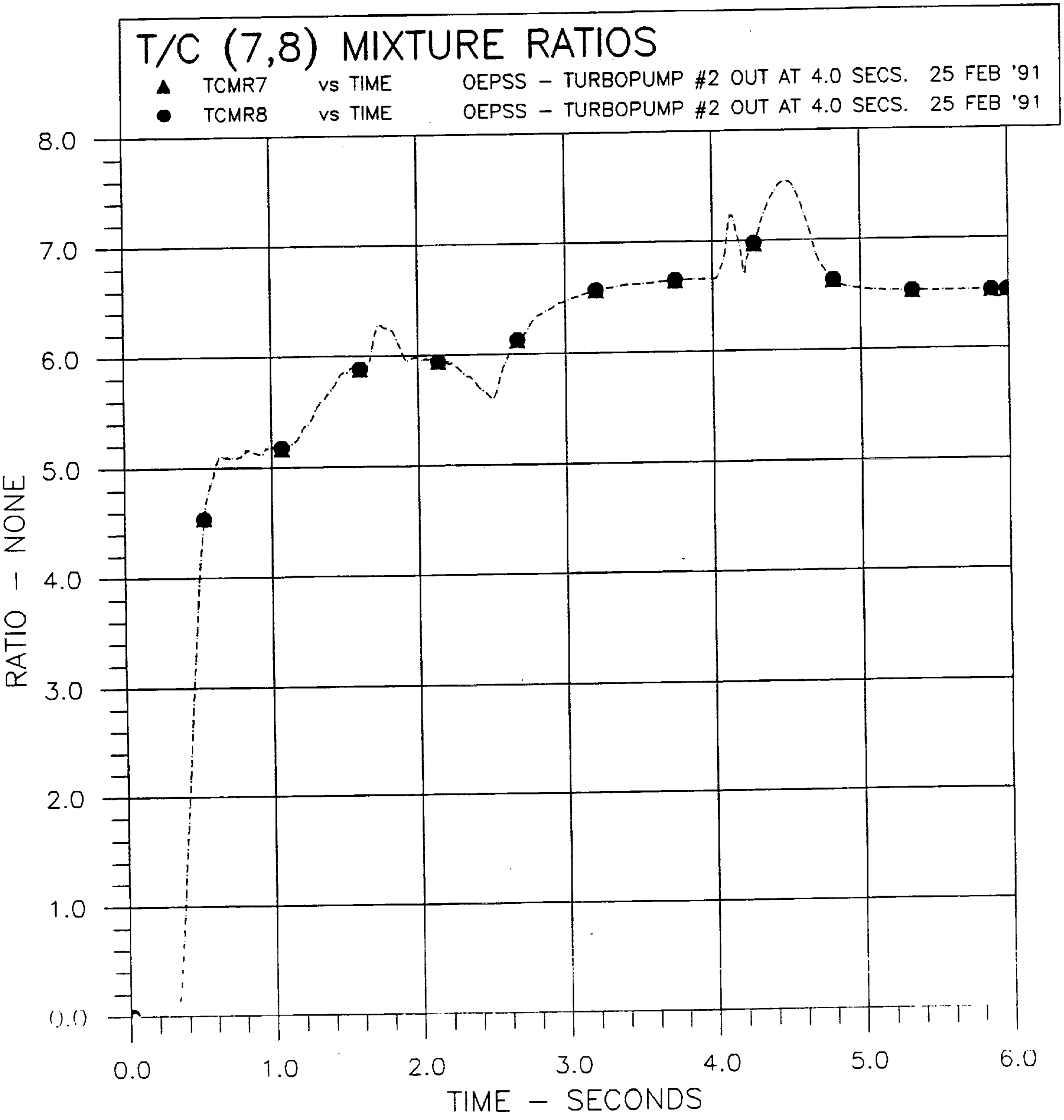

T/C (7,8) MIXTURE RATIOS
▲ TCMR7 vs TIME OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
● TCMR8 vs TIME OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
RATIO – NONE
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
TIME – SECONDS

Figure D5

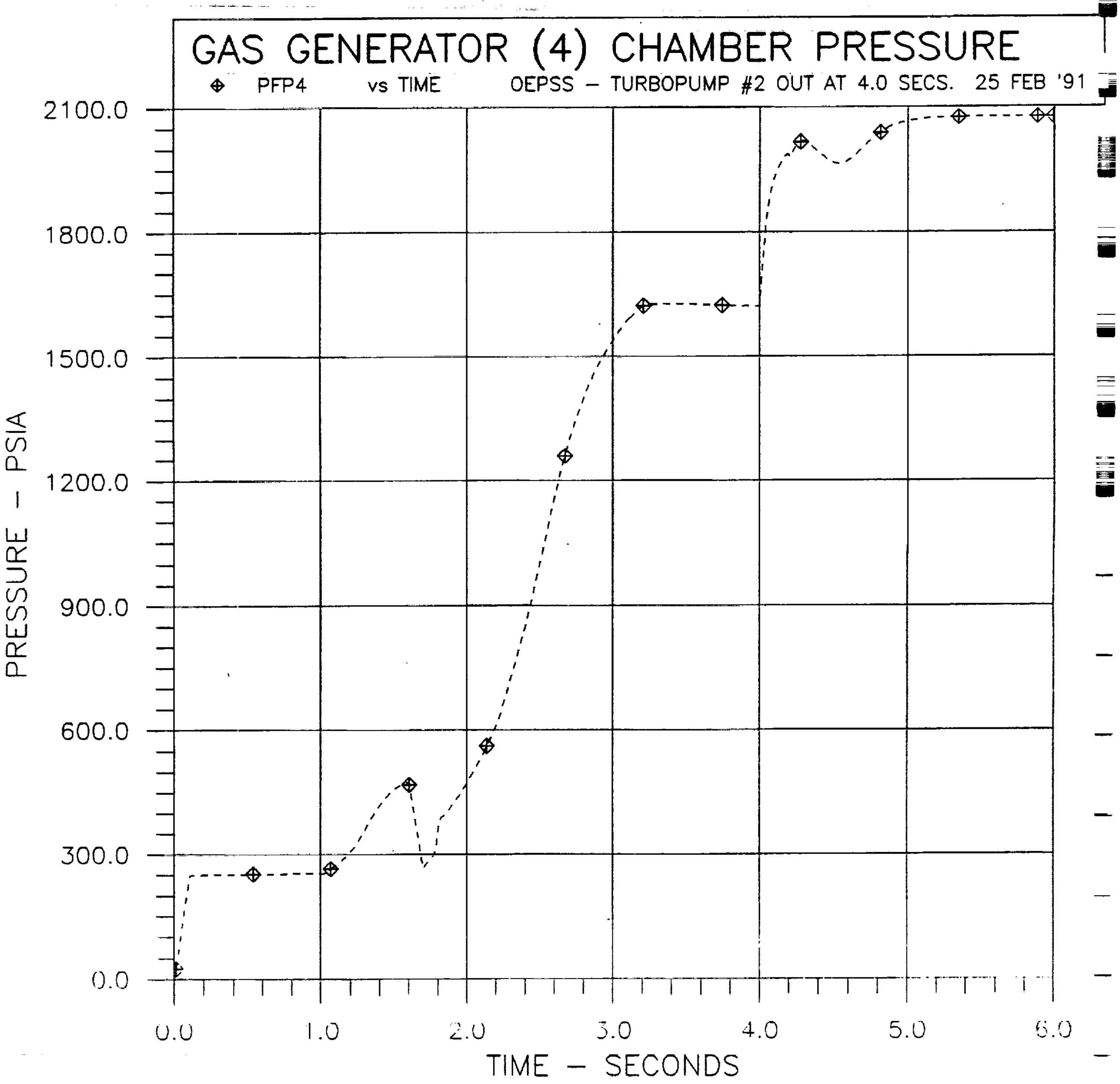

GAS GENERATOR (4) CHAMBER PRESSURE
⊕ PFP4 vs TIME OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
PRESSURE – PSIA
2100.0
1800.0
1500.0
1200.0
900.0
600.0
300.0
0.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
TIME – SECONDS

Figure D6

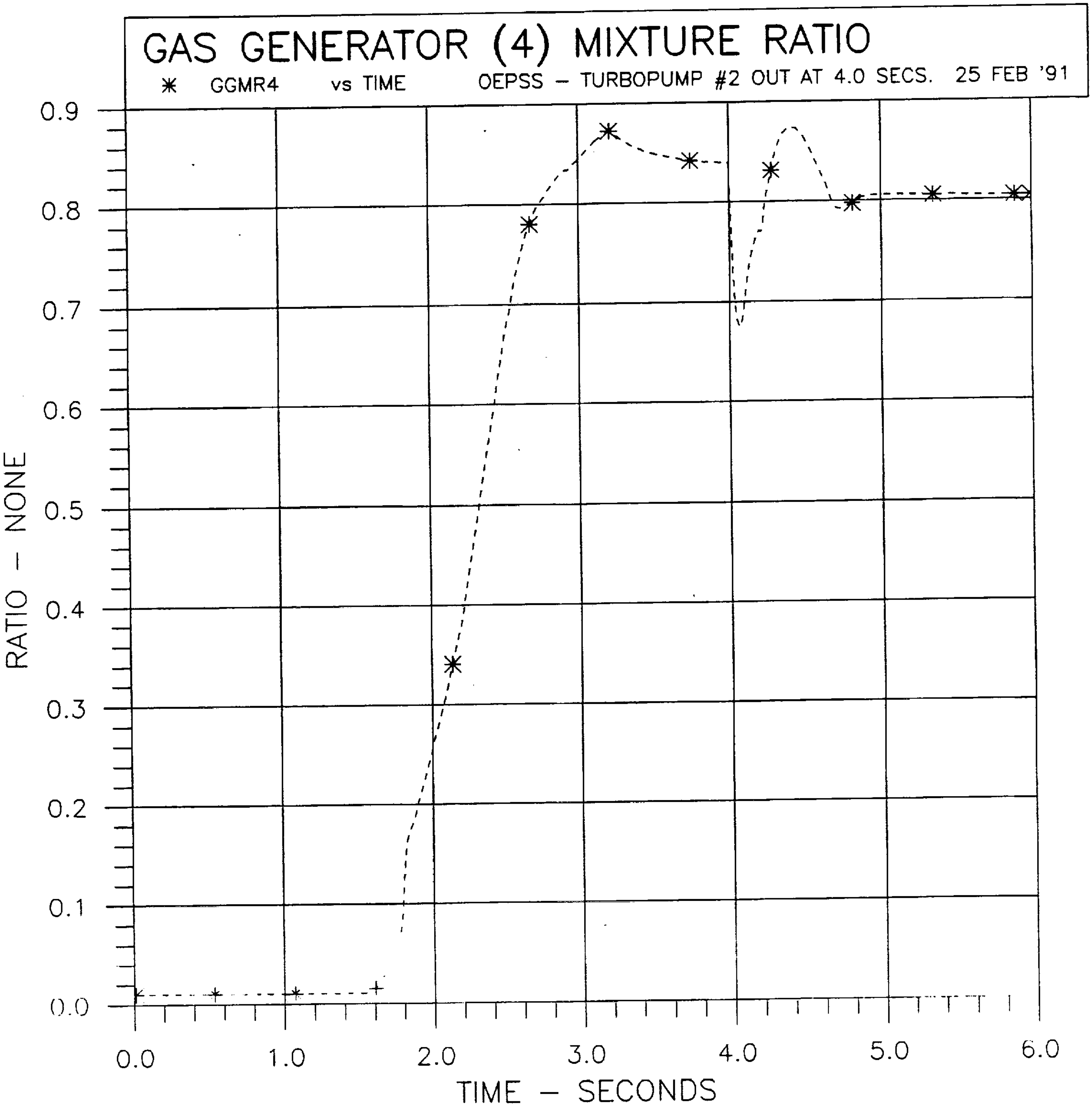

GAS GENERATOR (4) MIXTURE RATIO
✳ GGMR4 vs TIME OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
RATIO – NONE
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
TIME – SECONDS
0.0
1.0
2.0
3.0
4.0
5.0
6.0

Figure D7

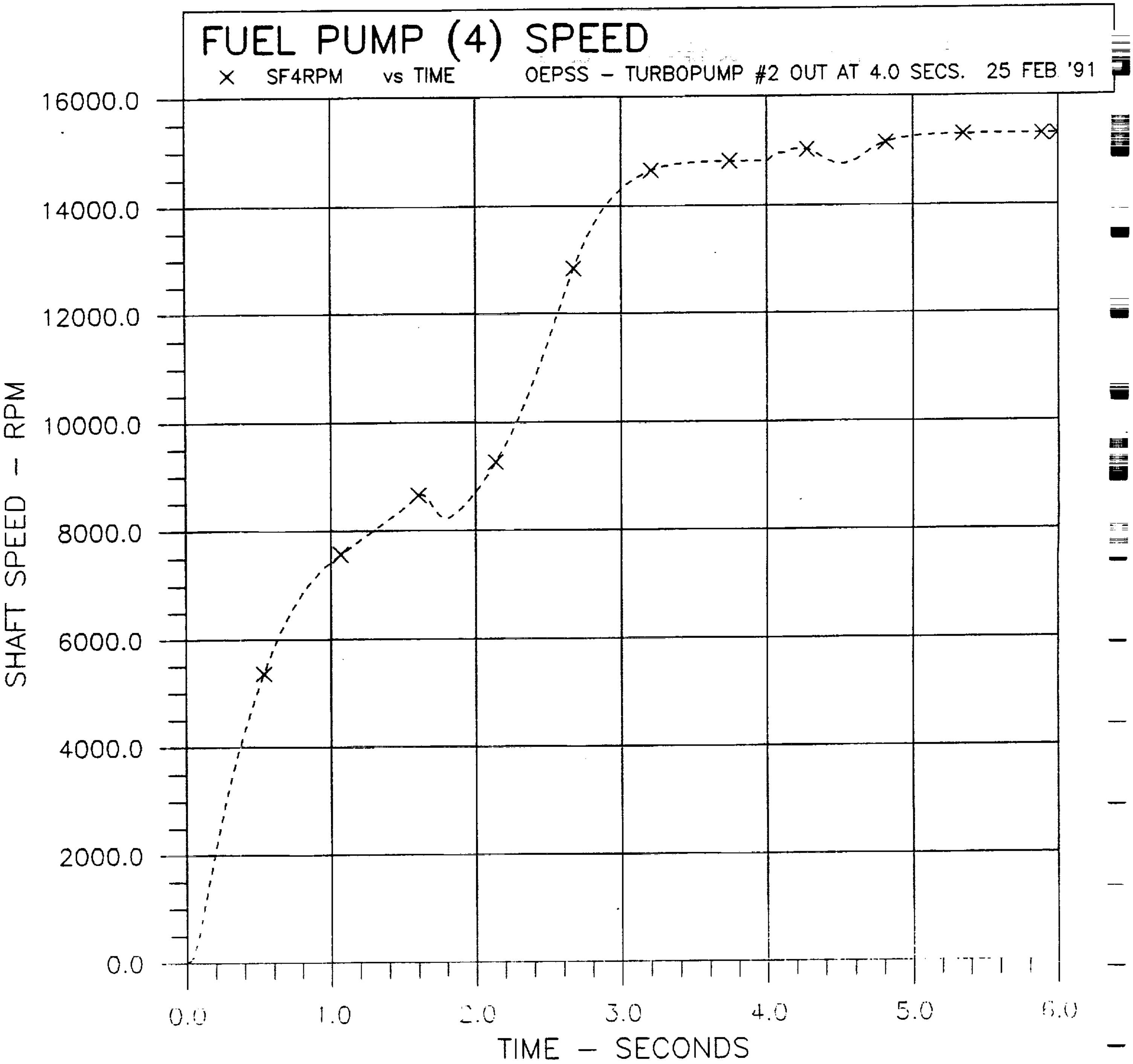

FUEL PUMP (4) SPEED
× SF4RPM vs TIME
OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
SHAFT SPEED – RPM
16000.0
14000.0
12000.0
10000.0
8000.0
6000.0
4000.0
2000.0
0.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
TIME – SECONDS

Figure D8

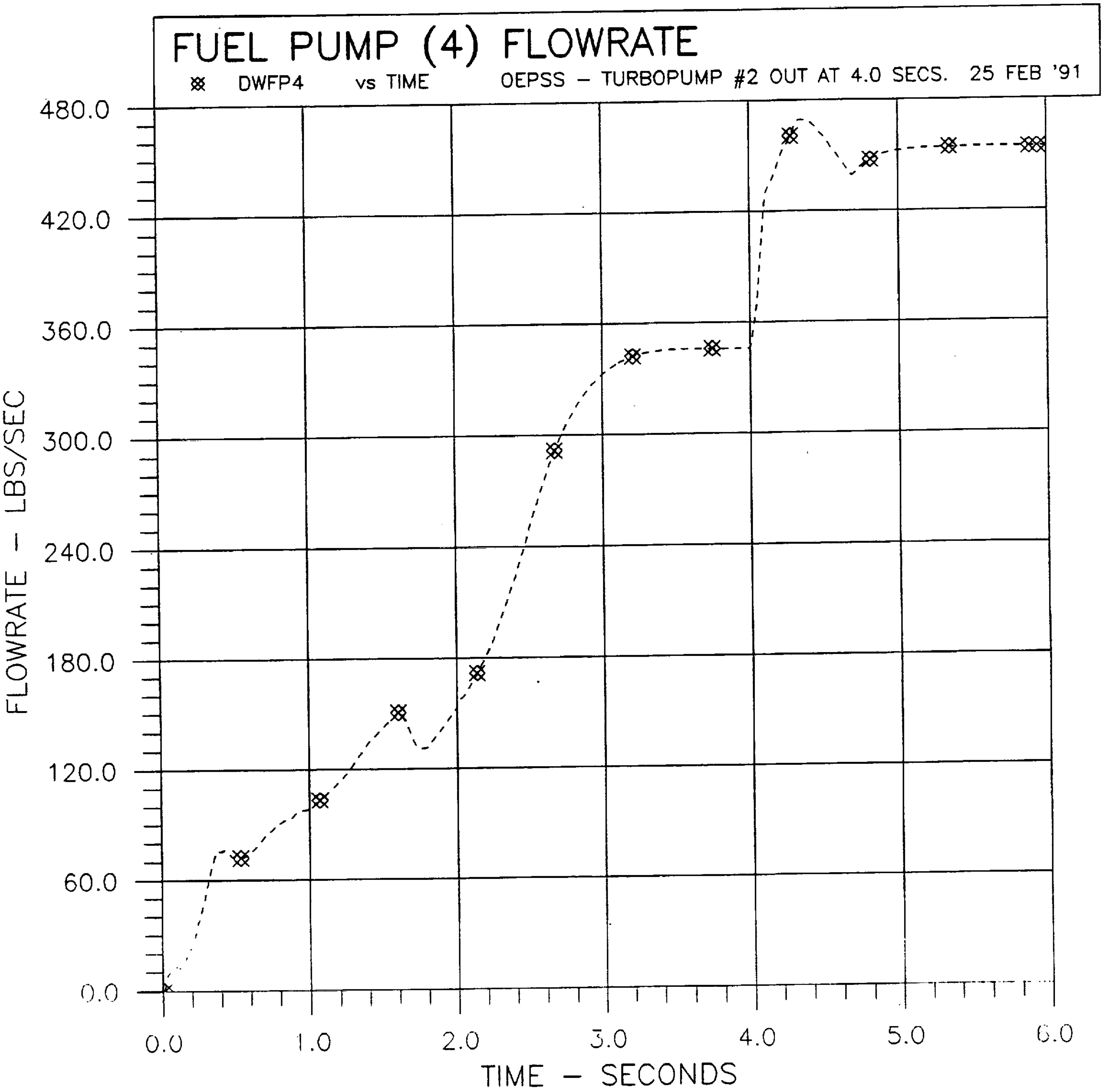

FUEL PUMP (4) FLOWRATE
DWFP4 vs TIME
OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
FLOWRATE – LBS/SEC
480.0
420.0
360.0
300.0
240.0
180.0
120.0
60.0
0.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
TIME – SECONDS

Figure D9

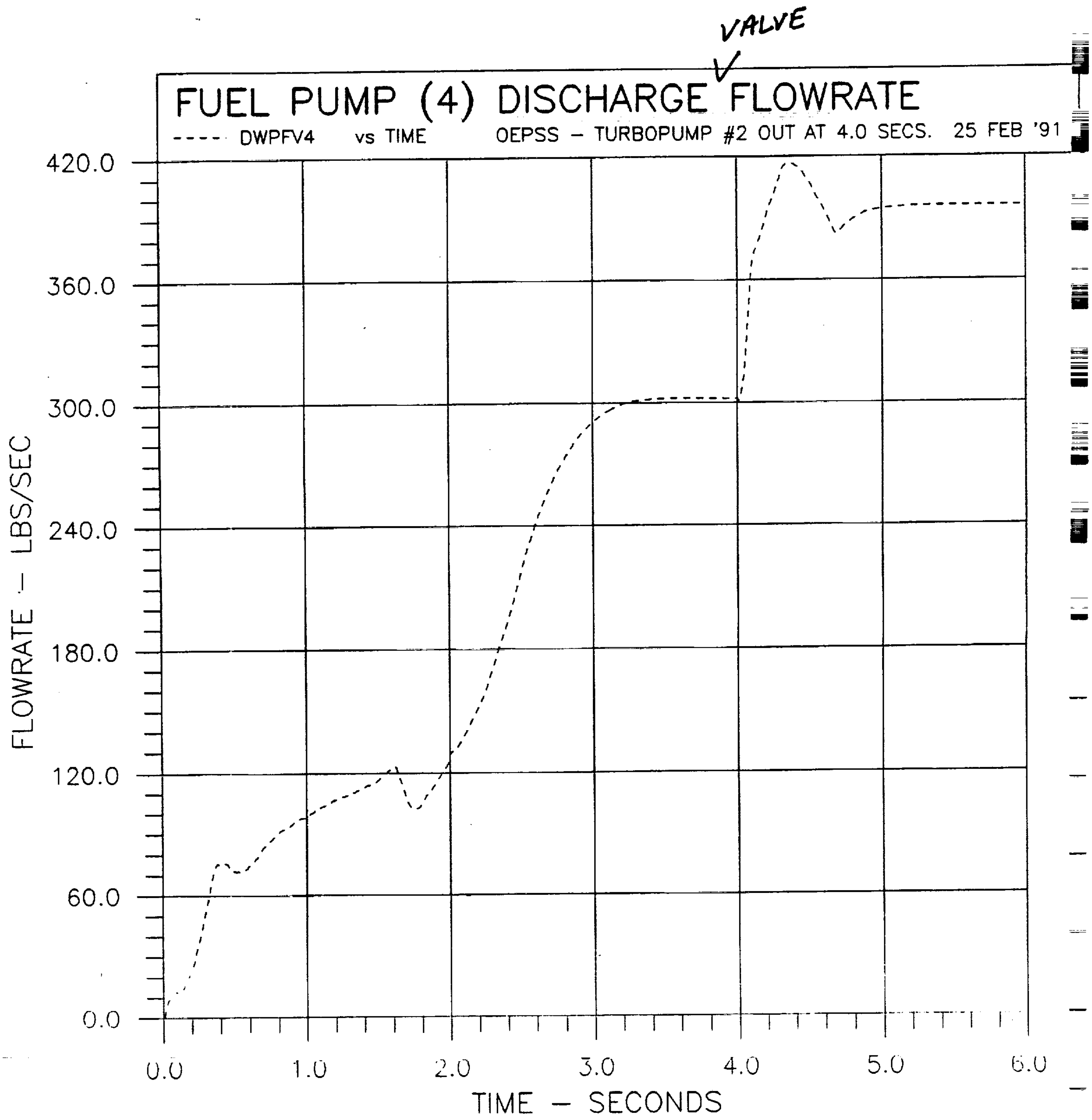

VALVE
FUEL PUMP (4) DISCHARGE FLOWRATE
---- DWPFV4 vs TIME
OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
FLOWRATE – LBS/SEC
420.0
360.0
300.0
240.0
180.0
120.0
60.0
0.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
TIME – SECONDS

Figure D10

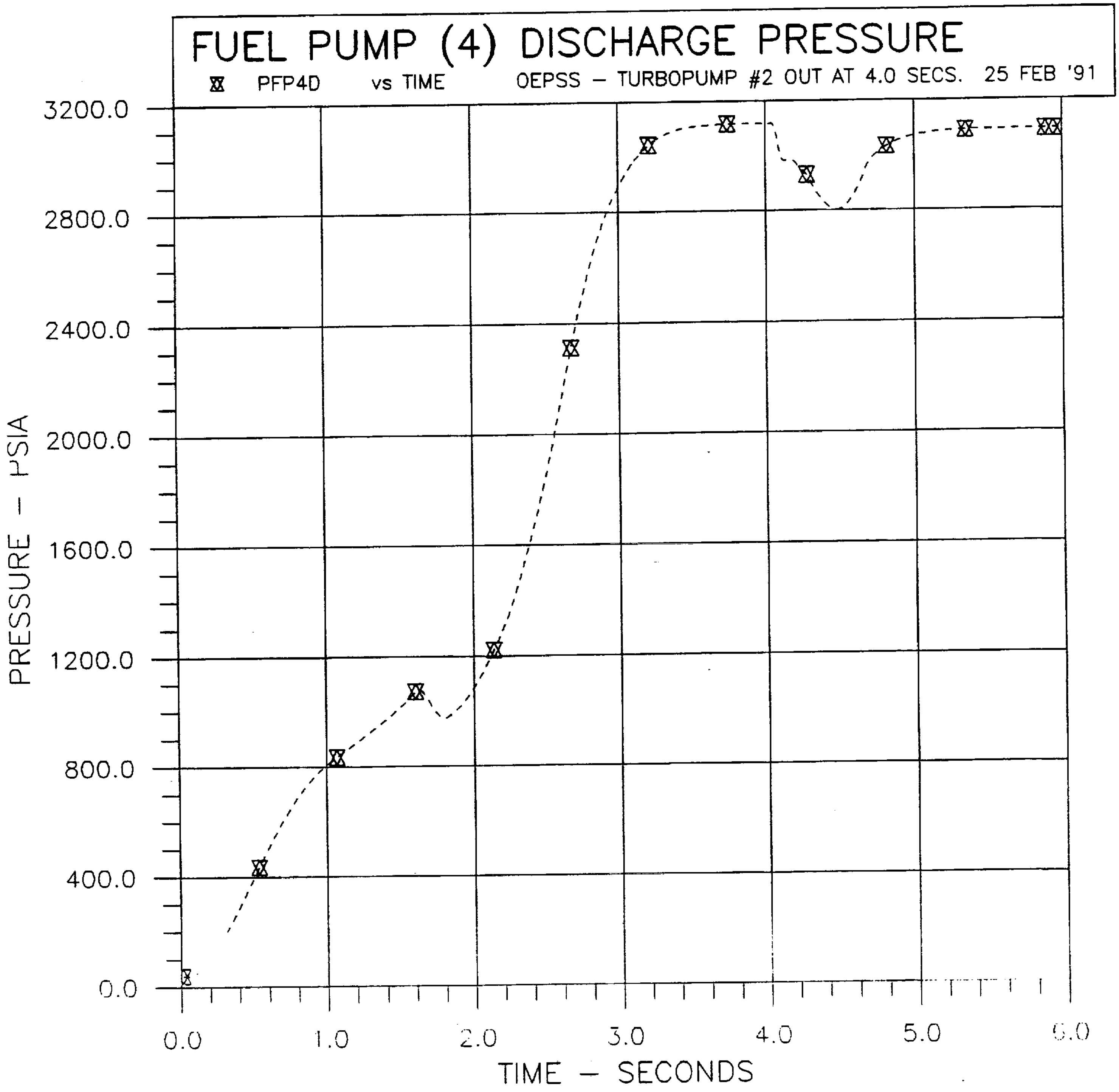
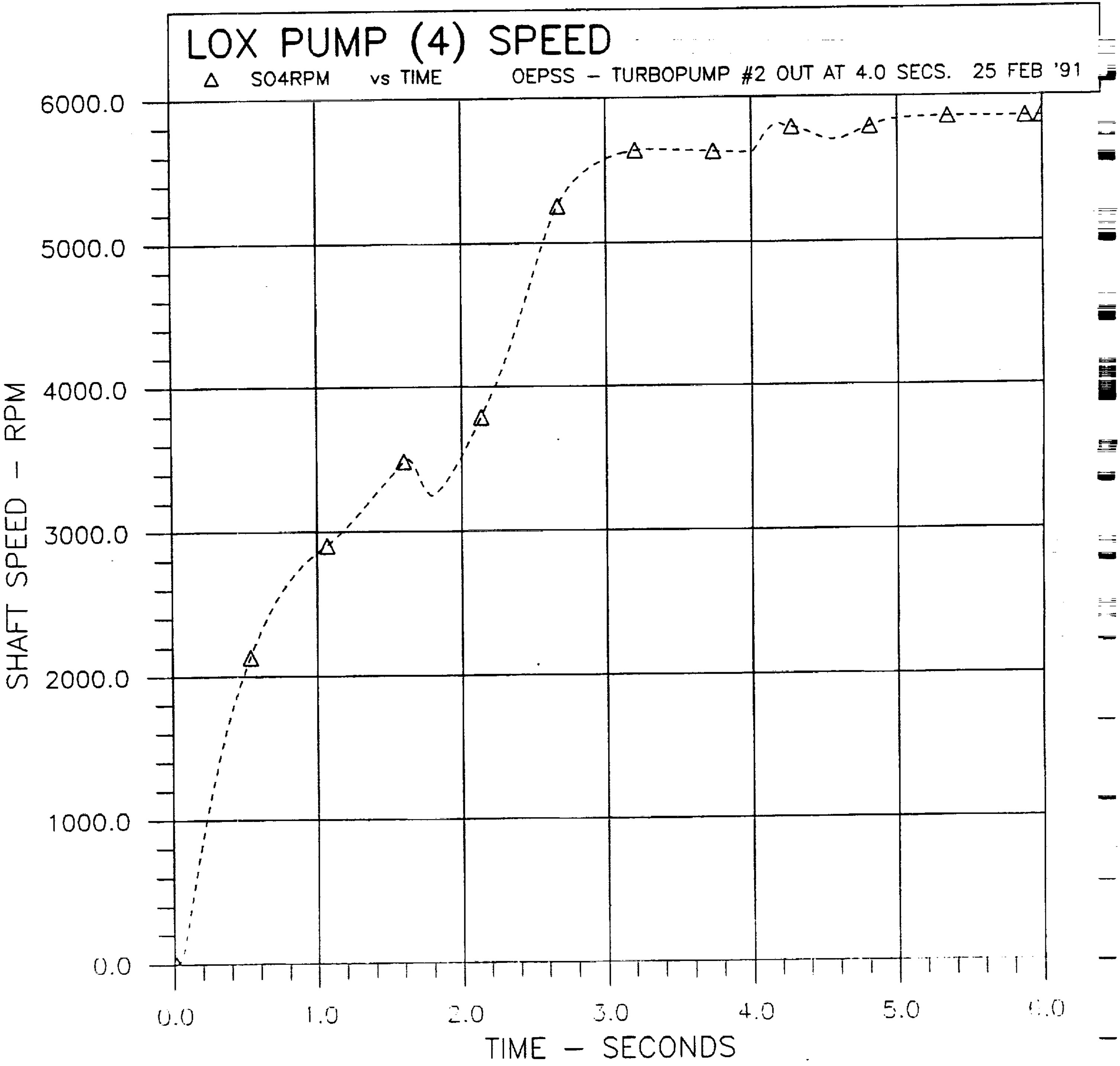
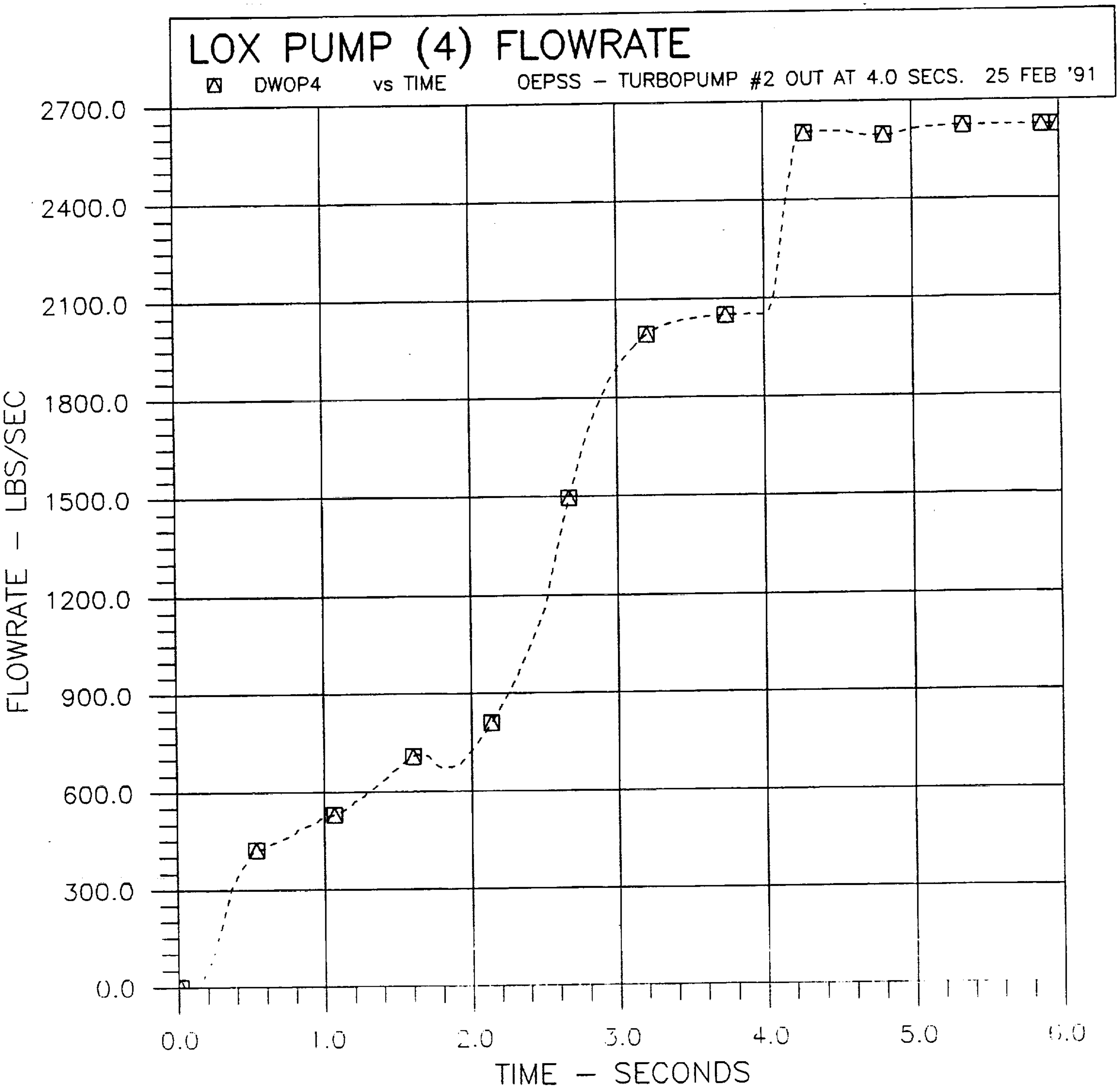

FUEL PUMP (4) DISCHARGE PRESSURE
PFP4D vs TIME
OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
PRESSURE – PSIA
3200.0
2800.0
2400.0
2000.0
1600.0
1200.0
800.0
400.0
0.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
TIME – SECONDS

Figure D11

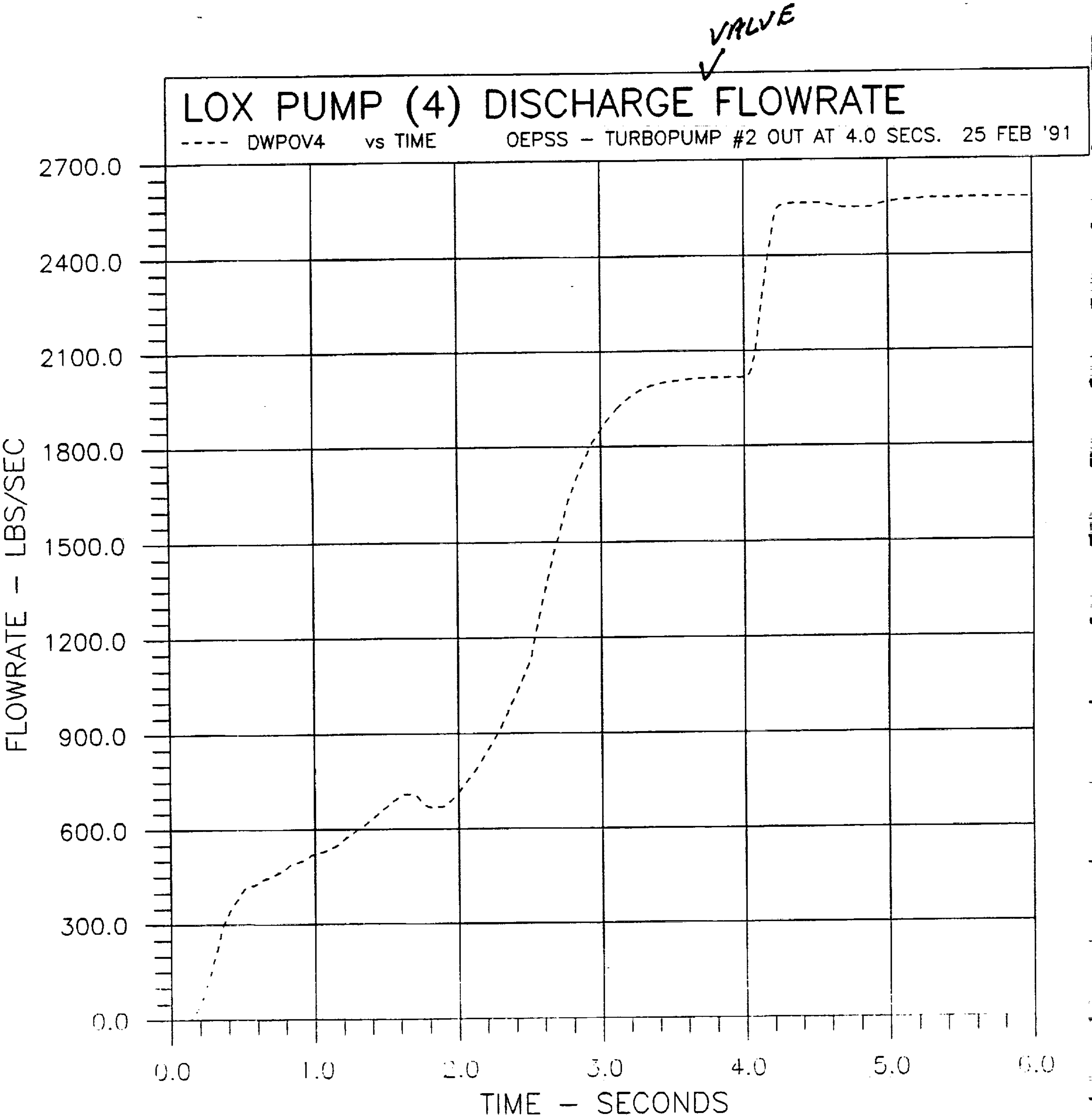

LOX PUMP (4) SPEED
△ S04RPM vs TIME
OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
SHAFT SPEED – RPM
6000.0
5000.0
4000.0
3000.0
2000.0
1000.0
0.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
TIME – SECONDS

~~Figure~~ D12



LOX PUMP (4) FLOWRATE
DWOP4 vs TIME
OEPSS - TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
FLOWRATE - LBS/SEC
2700.0
2400.0
2100.0
1800.0
1500.0
1200.0
900.0
600.0
300.0
0.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
TIME - SECONDS

Figure D13


VALVE
LOX PUMP (4) DISCHARGE FLOWRATE
---- DWPOV4 vs TIME
OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
FLOWRATE – LBS/SEC
2700.0
2400.0
2100.0
1800.0
1500.0
1200.0
900.0
600.0
300.0
0.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
TIME – SECONDS

~~Figure~~ D14

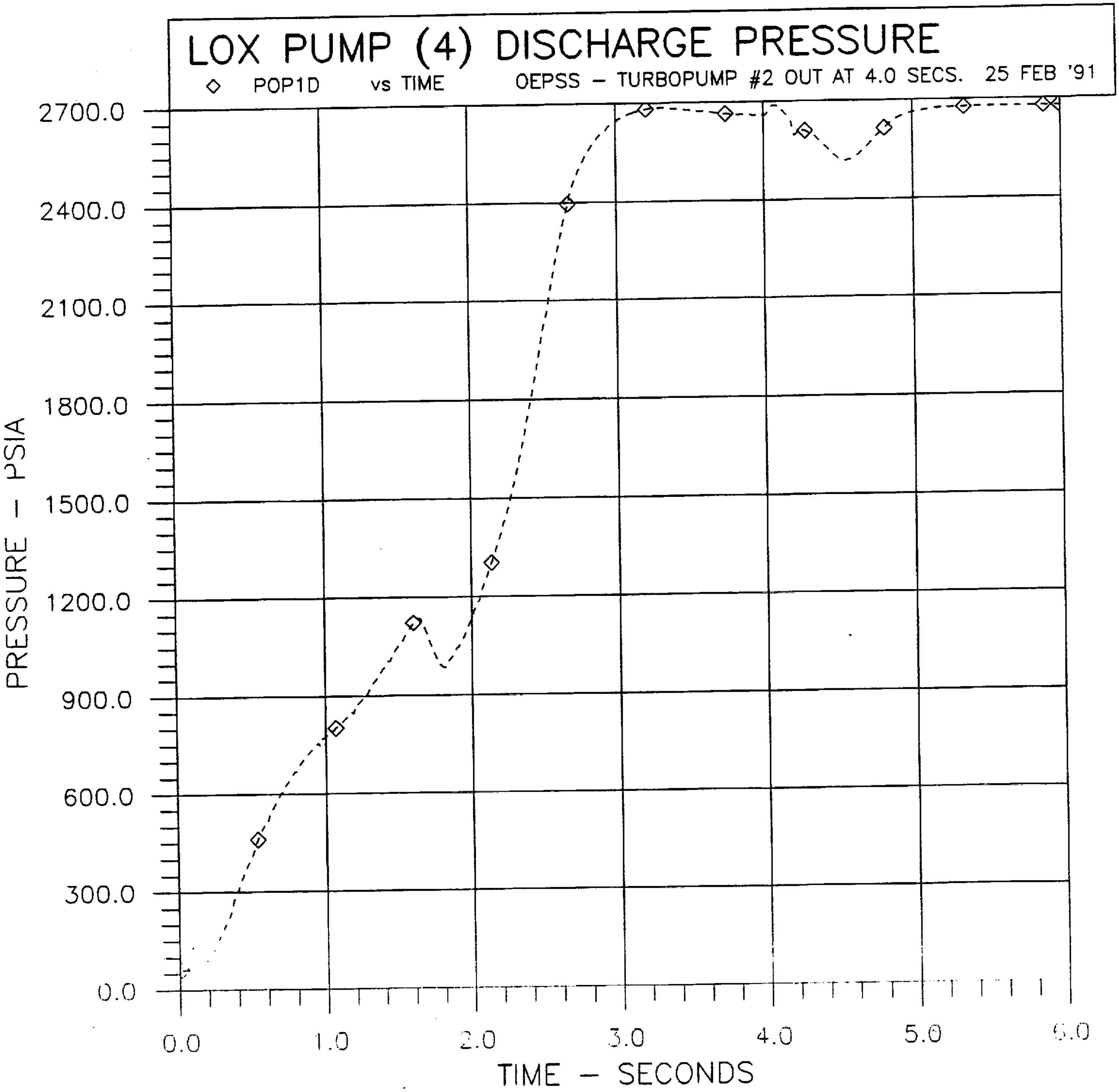

LOX PUMP (4) DISCHARGE PRESSURE
◇ POP1D vs TIME
OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
2700.0
2400.0
2100.0
1800.0
1500.0
1200.0
900.0
600.0
300.0
0.0
PRESSURE – PSIA
0.0
1.0
2.0
3.0
4.0
5.0
6.0
TIME – SECONDS

Figure D15

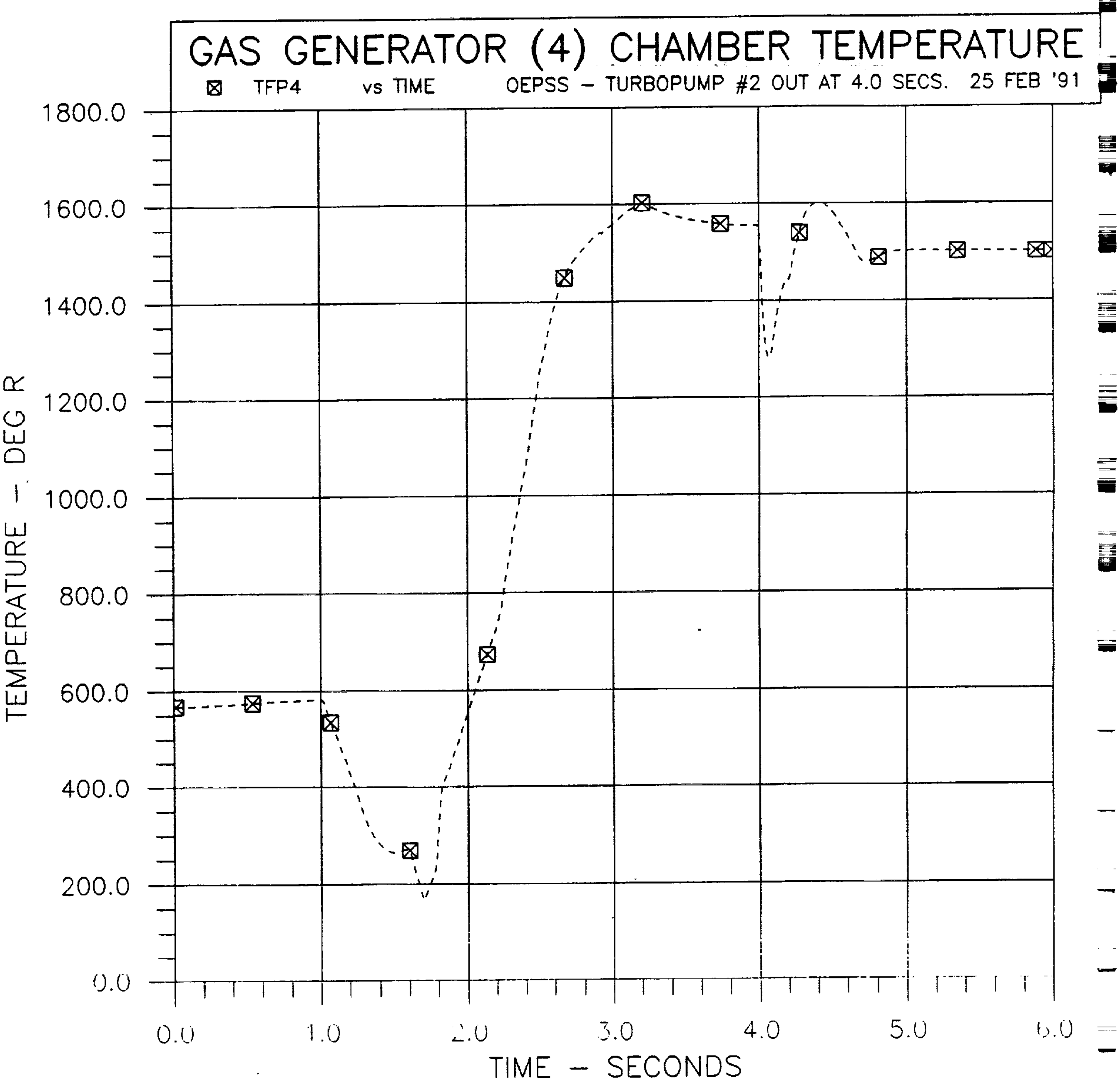

GAS GENERATOR (4) CHAMBER TEMPERATURE
☒ TFP4 vs TIME OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
TEMPERATURE – DEG R
1800.0
1600.0
1400.0
1200.0
1000.0
800.0
600.0
400.0
200.0
0.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
TIME – SECONDS

Figure D16

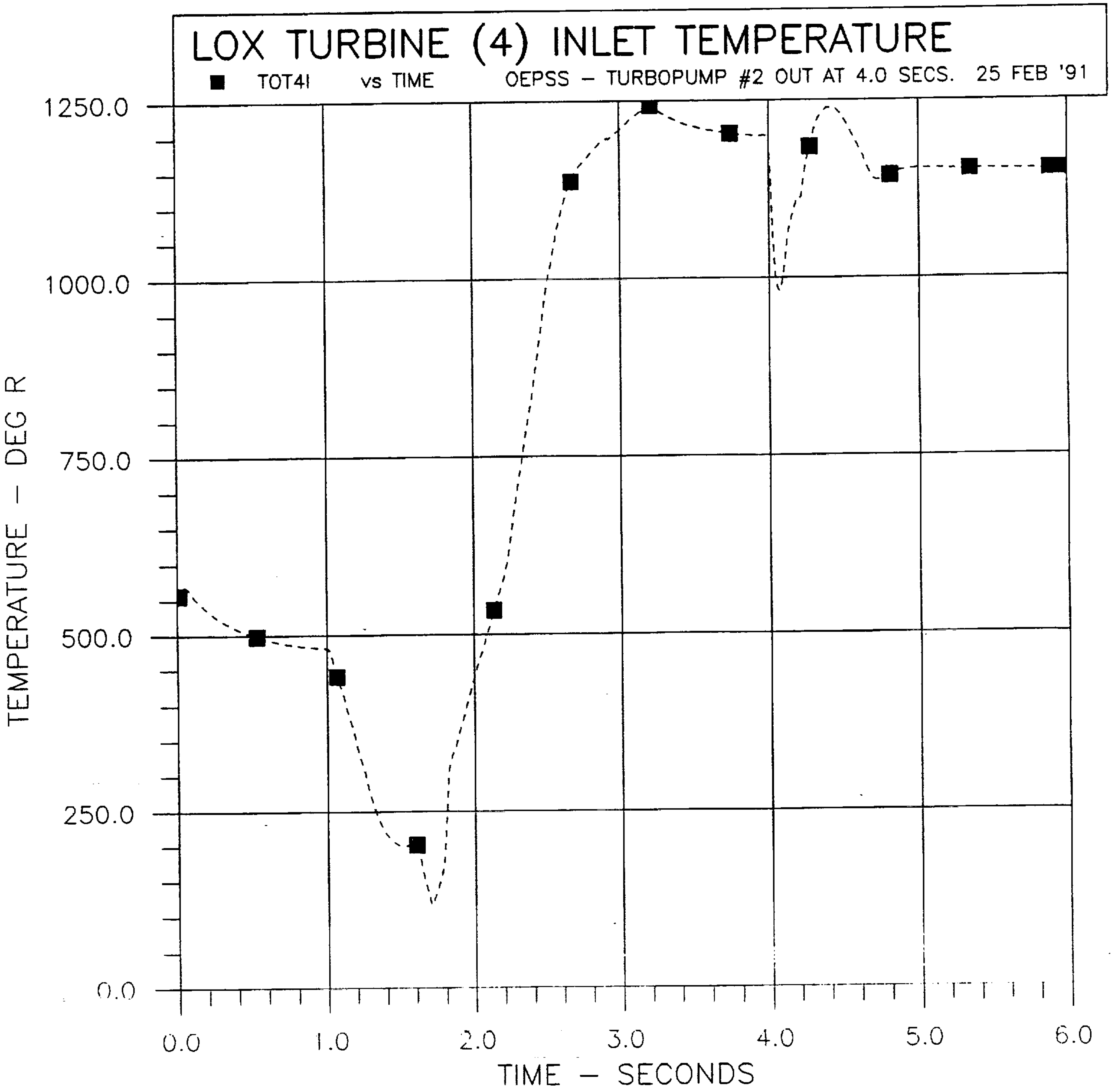
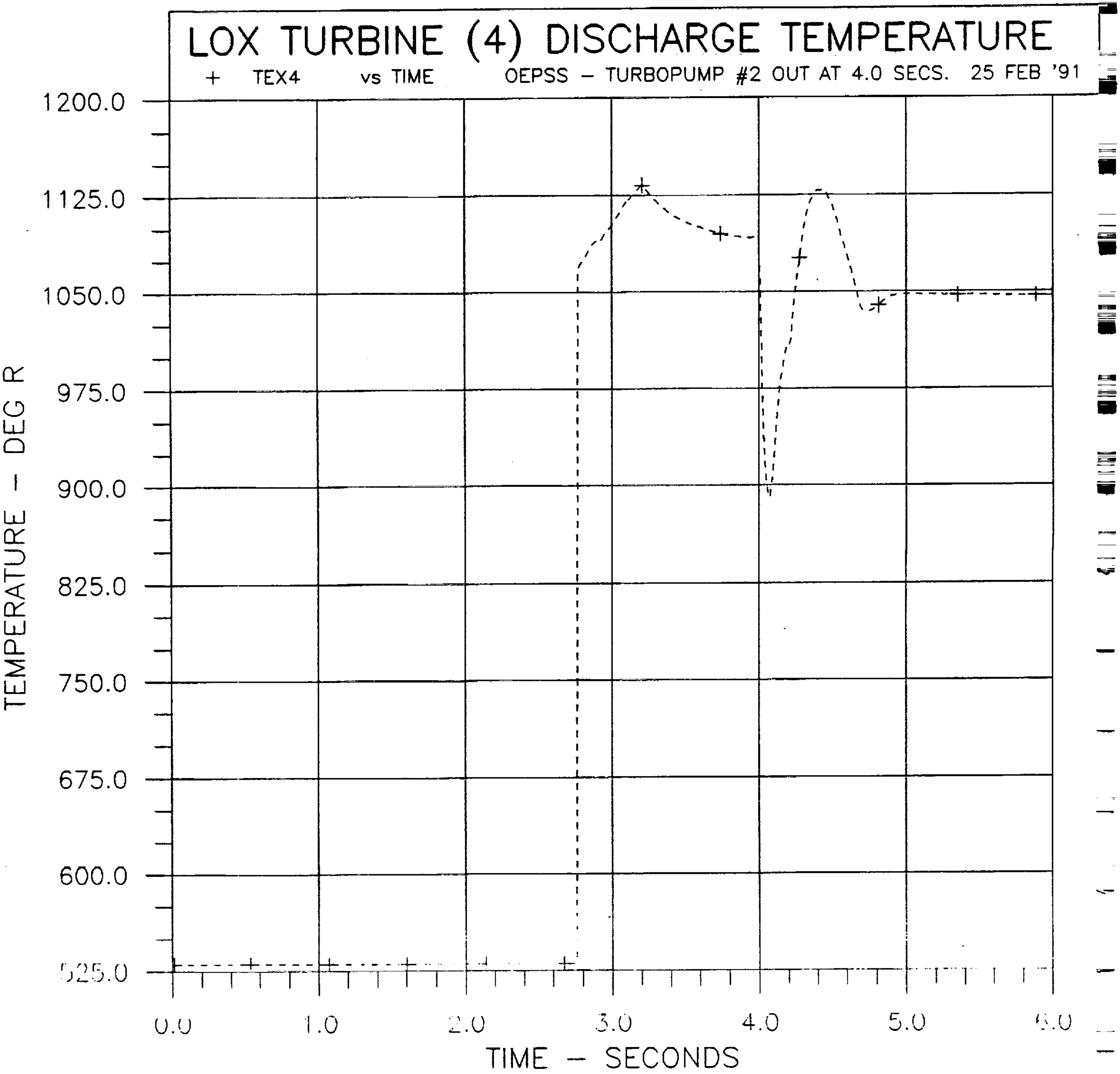

LOX TURBINE (4) INLET TEMPERATURE
■ TOT4I vs TIME OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
TEMPERATURE – DEG R
1250.0
1000.0
750.0
500.0
250.0
0.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
TIME – SECONDS

Figure D17


LOX TURBINE (4) DISCHARGE TEMPERATURE
+ TEX4 vs TIME OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
1200.0
1125.0
1050.0
975.0
900.0
825.0
750.0
675.0
600.0
525.0
TEMPERATURE – DEG R
0.0
1.0
2.0
3.0
4.0
5.0
6.0
TIME – SECONDS

~~Figure~~ D18

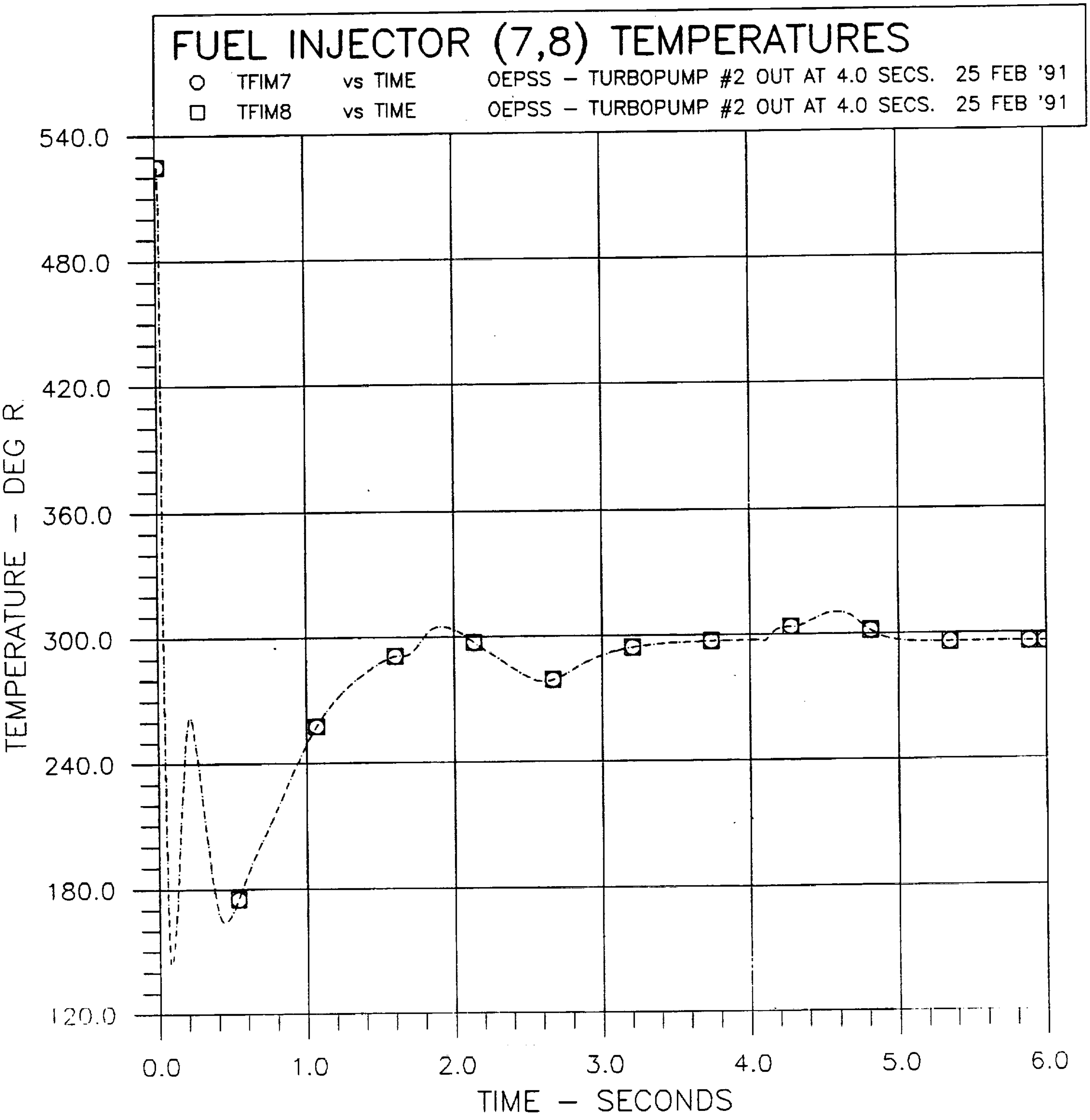
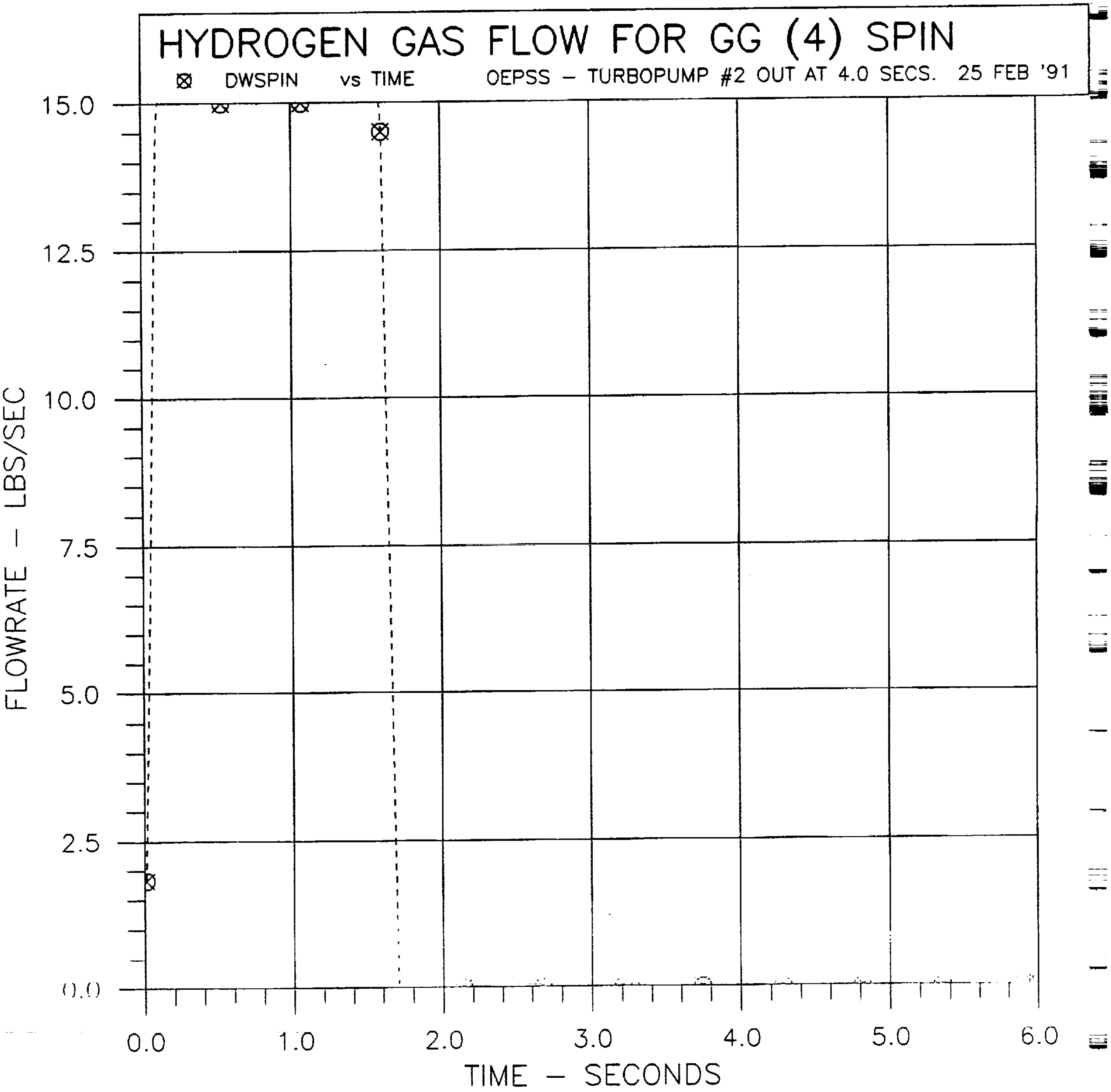

FUEL INJECTOR (7,8) TEMPERATURES
○ TFIM7 vs TIME OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
□ TFIM8 vs TIME OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
540.0
480.0
420.0
360.0
300.0
240.0
180.0
120.0
TEMPERATURE – DEG R
0.0
1.0
2.0
3.0
4.0
5.0
6.0
TIME – SECONDS

Figure D19



HYDROGEN GAS FLOW FOR GG (4) SPIN
⊗ DWSPIN vs TIME
OEPSS – TURBOPUMP #2 OUT AT 4.0 SECS. 25 FEB '91
FLOWRATE – LBS/SEC
15.0
12.5
10.0
7.5
5.0
2.5
0.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
TIME – SECONDS

Figure D20

APPENDIX E

COMBINED THRUST CHAMBER/TURBOPUMP OUT CONDITION RESULTS

FOR SYSTEM 1

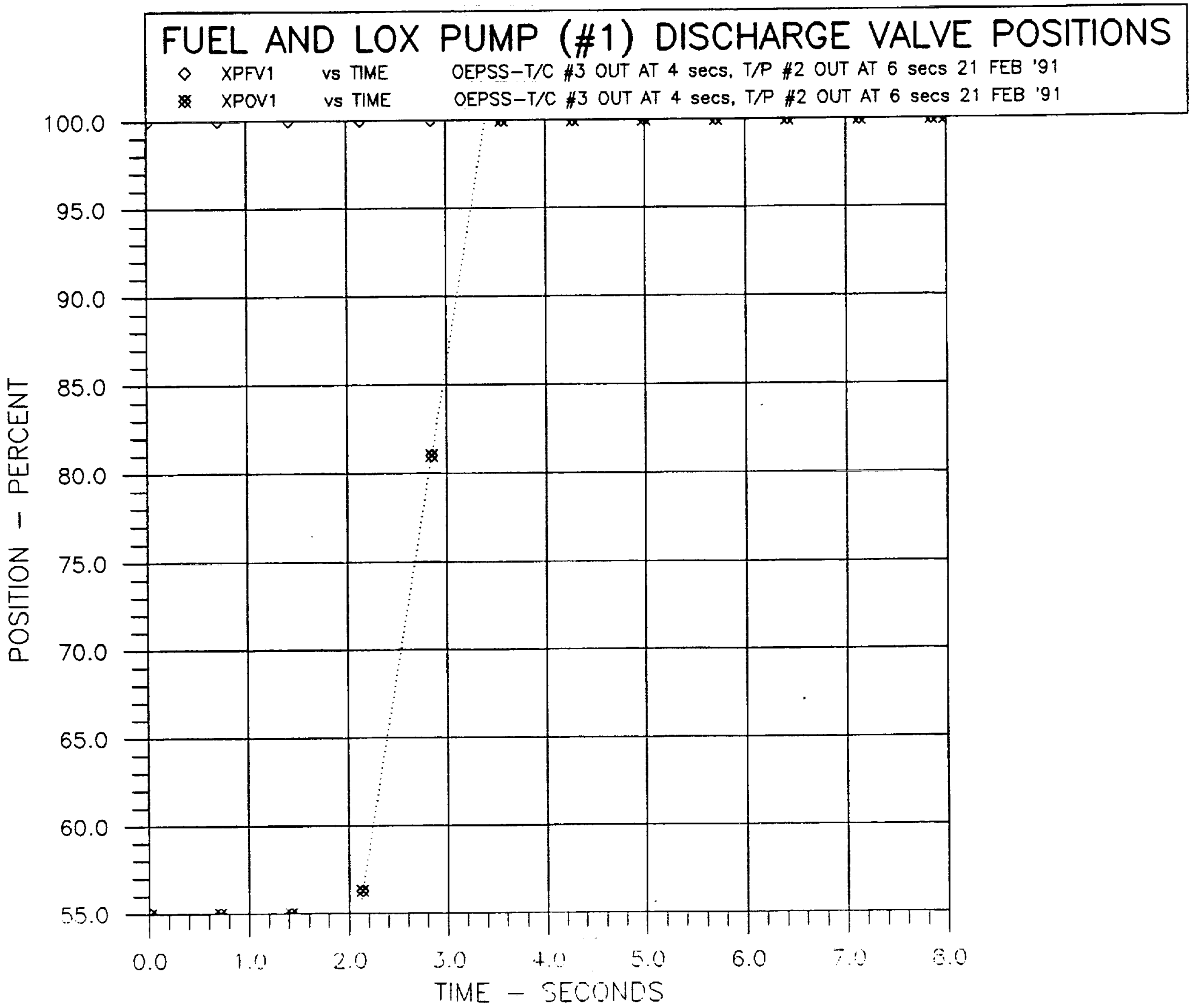
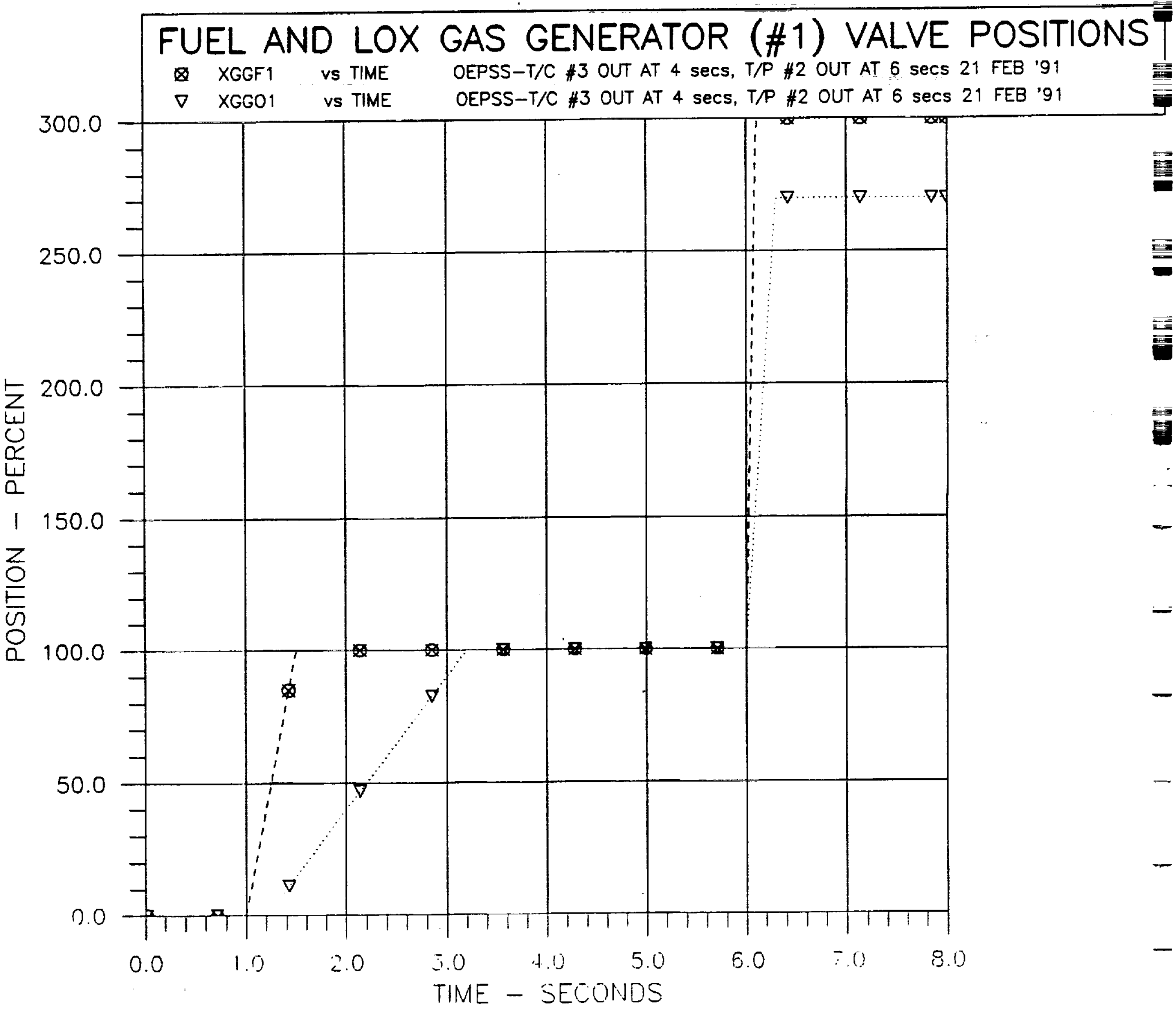

FUEL AND LOX PUMP (#1) DISCHARGE VALVE POSITIONS
◇ XPFV1 vs TIME OEPSS–T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
⋇ XPOV1 vs TIME OEPSS–T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
100.0
95.0
90.0
85.0
80.0
75.0
70.0
65.0
60.0
55.0
POSITION – PERCENT
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
TIME – SECONDS

Figure E1



FUEL AND LOX GAS GENERATOR (#1) VALVE POSITIONS
⊠ XGGF1 vs TIME OEPSS–T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
▽ XGGO1 vs TIME OEPSS–T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
300.0
250.0
200.0
150.0
100.0
50.0
0.0
POSITION – PERCENT
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
TIME – SECONDS

Figure E2

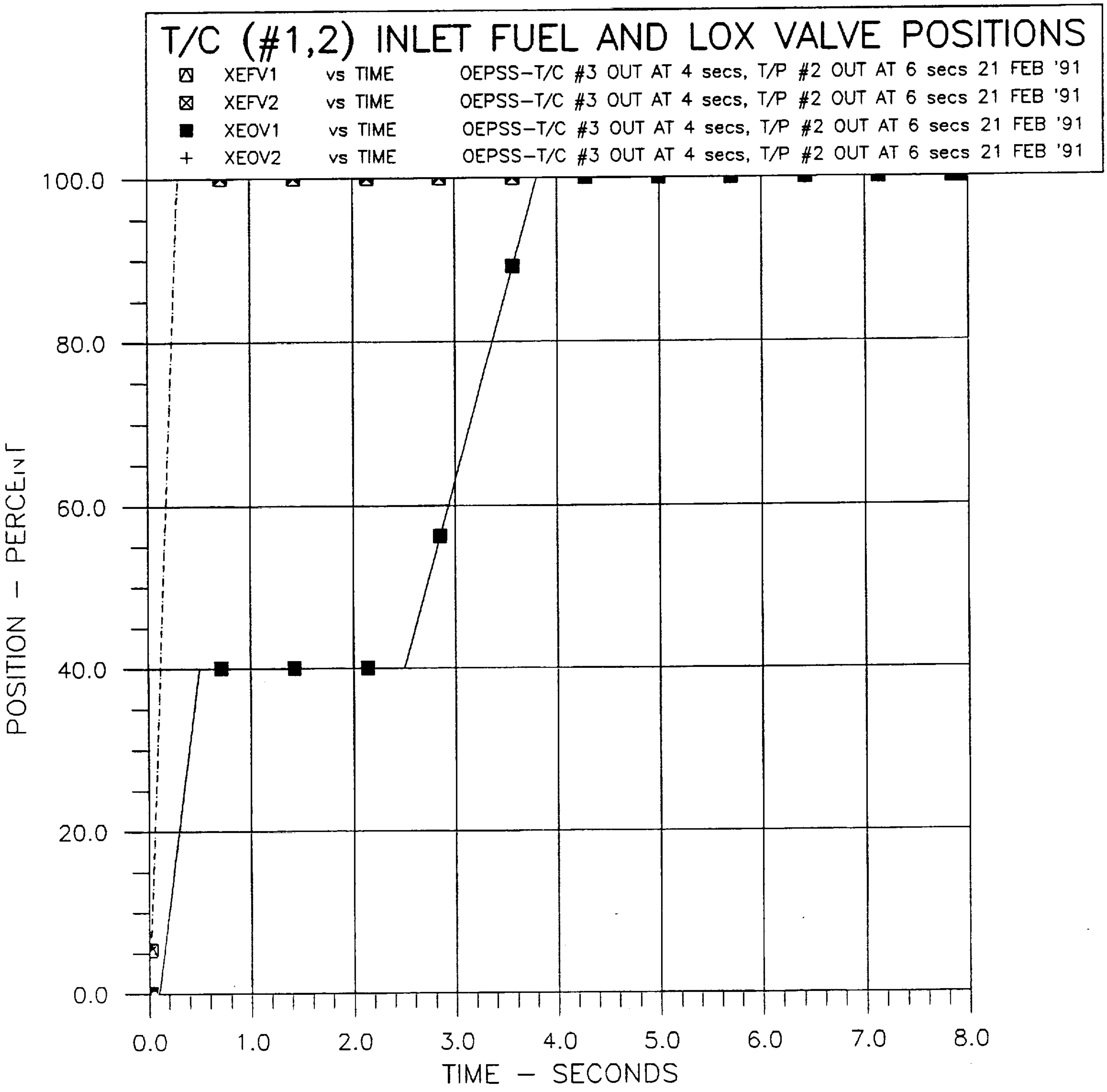

T/C (#1,2) INLET FUEL AND LOX VALVE POSITIONS
XEFV1 vs TIME OEPSS-T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
XEFV2 vs TIME OEPSS-T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
XEOV1 vs TIME OEPSS-T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
XEOV2 vs TIME OEPSS-T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
100.0
80.0
60.0
40.0
20.0
0.0
POSITION - PERCENT
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
TIME - SECONDS

Figure E3

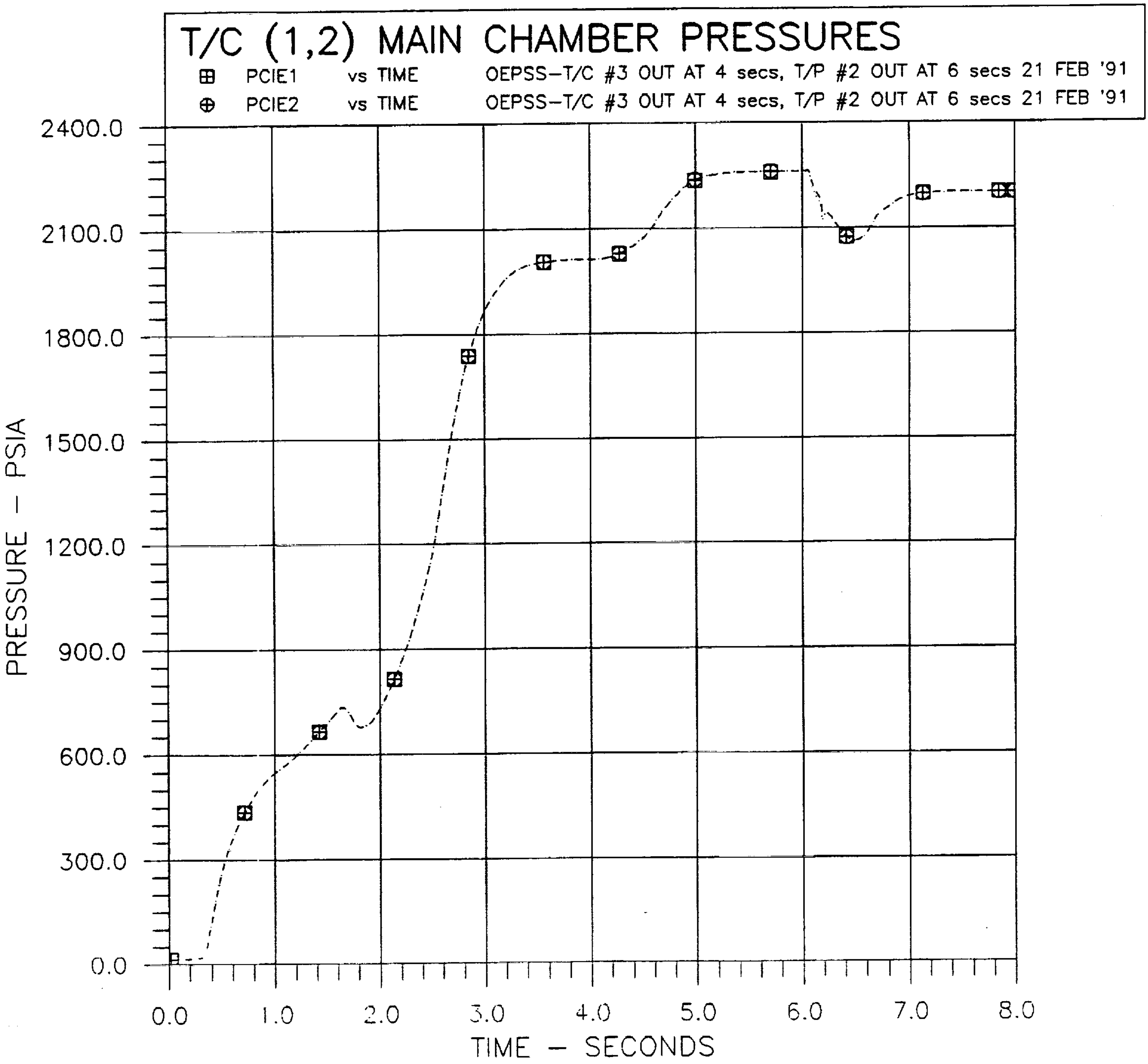

T/C (1,2) MAIN CHAMBER PRESSURES
⊞ PCIE1 vs TIME OEPSS–T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
⊕ PCIE2 vs TIME OEPSS–T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
2400.0
2100.0
1800.0
1500.0
1200.0
900.0
600.0
300.0
0.0
PRESSURE – PSIA
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
TIME – SECONDS

Figure E4

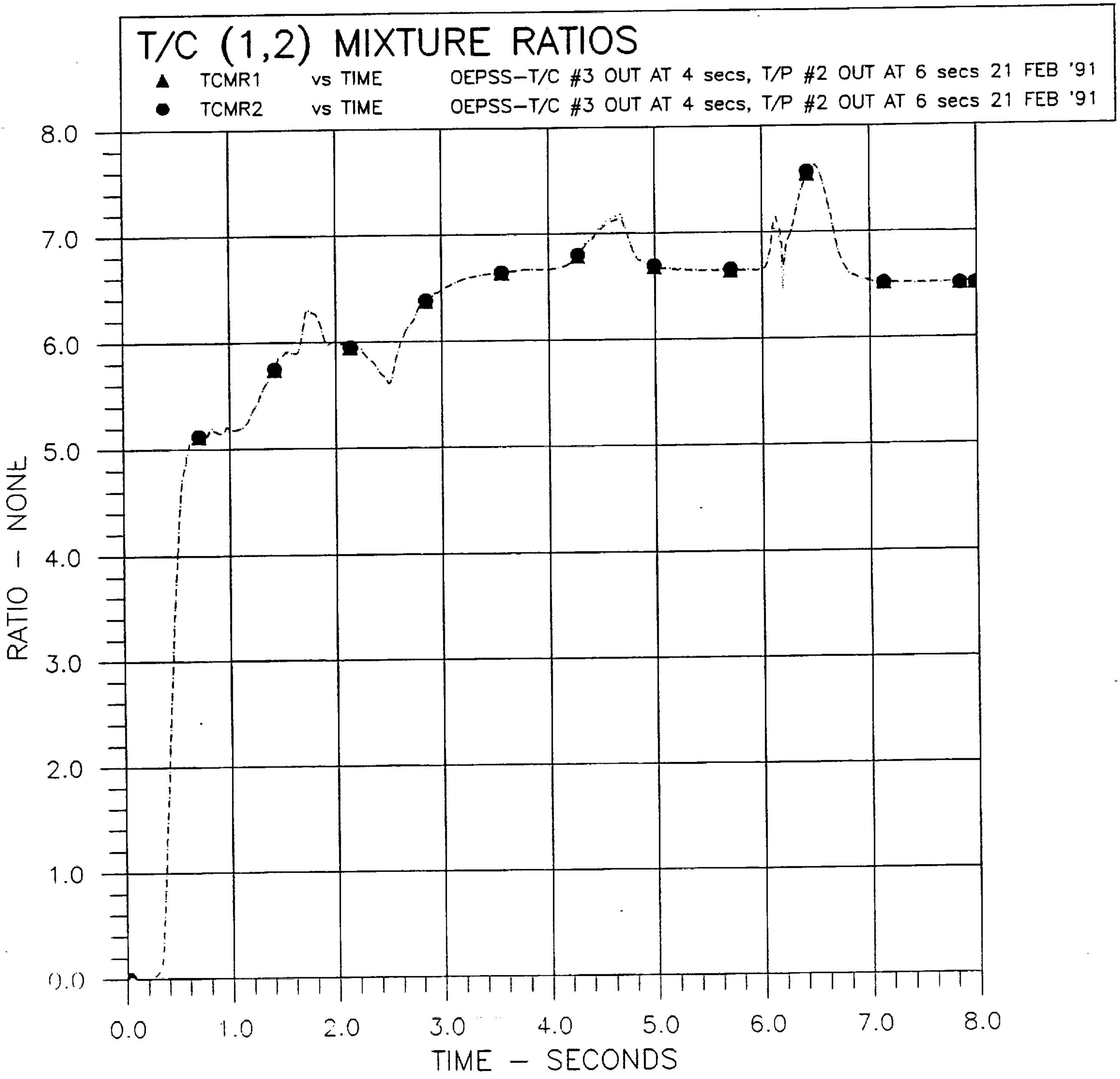

T/C (1,2) MIXTURE RATIOS
▲ TCMR1 vs TIME OEPSS–T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
● TCMR2 vs TIME OEPSS–T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
RATIO – NONE
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
TIME – SECONDS

Figure E5

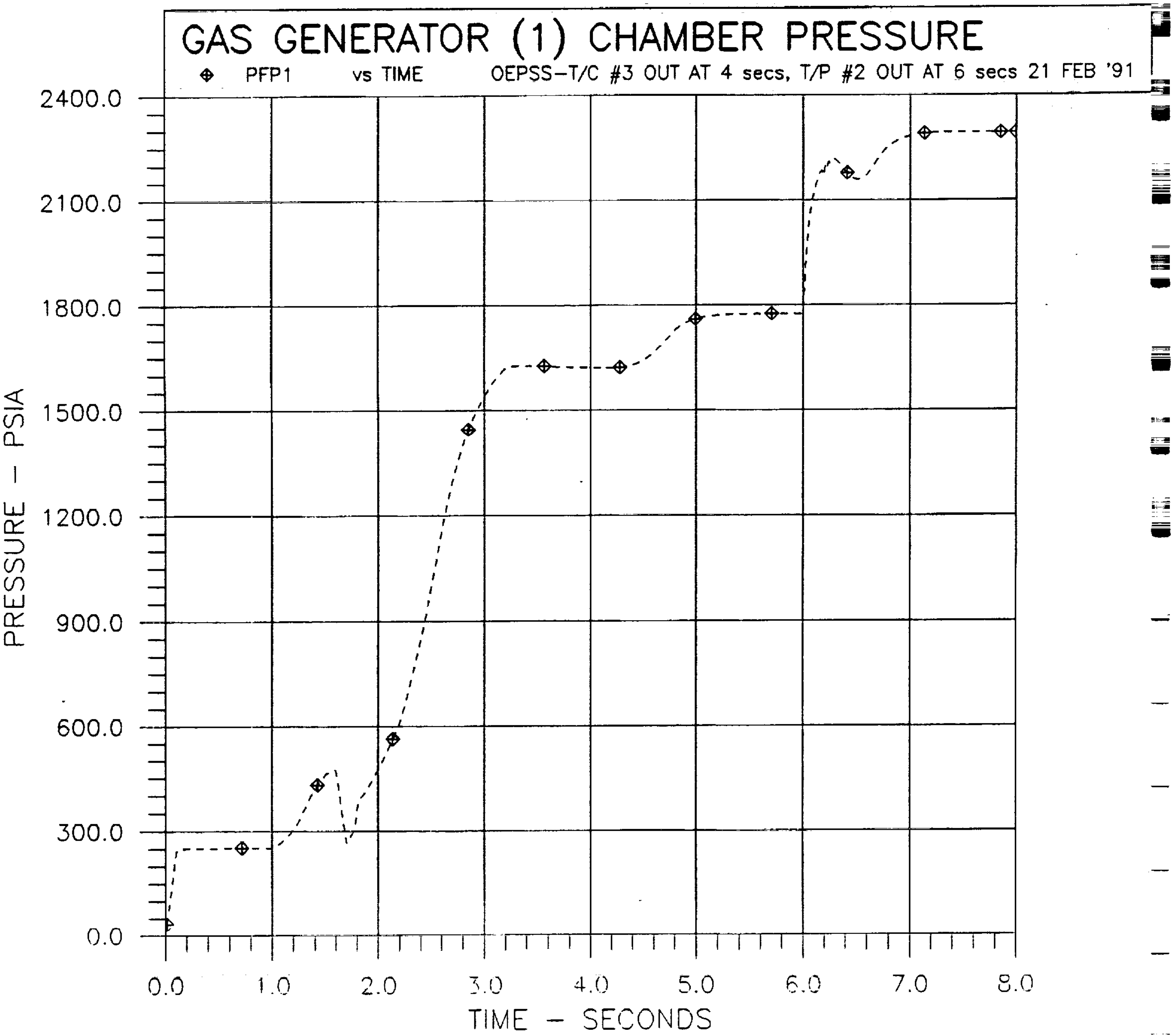

GAS GENERATOR (1) CHAMBER PRESSURE
⊕ PFP1 vs TIME OEPSS-T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
PRESSURE - PSIA
2400.0
2100.0
1800.0
1500.0
1200.0
900.0
600.0
300.0
0.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
TIME - SECONDS

Figure E6

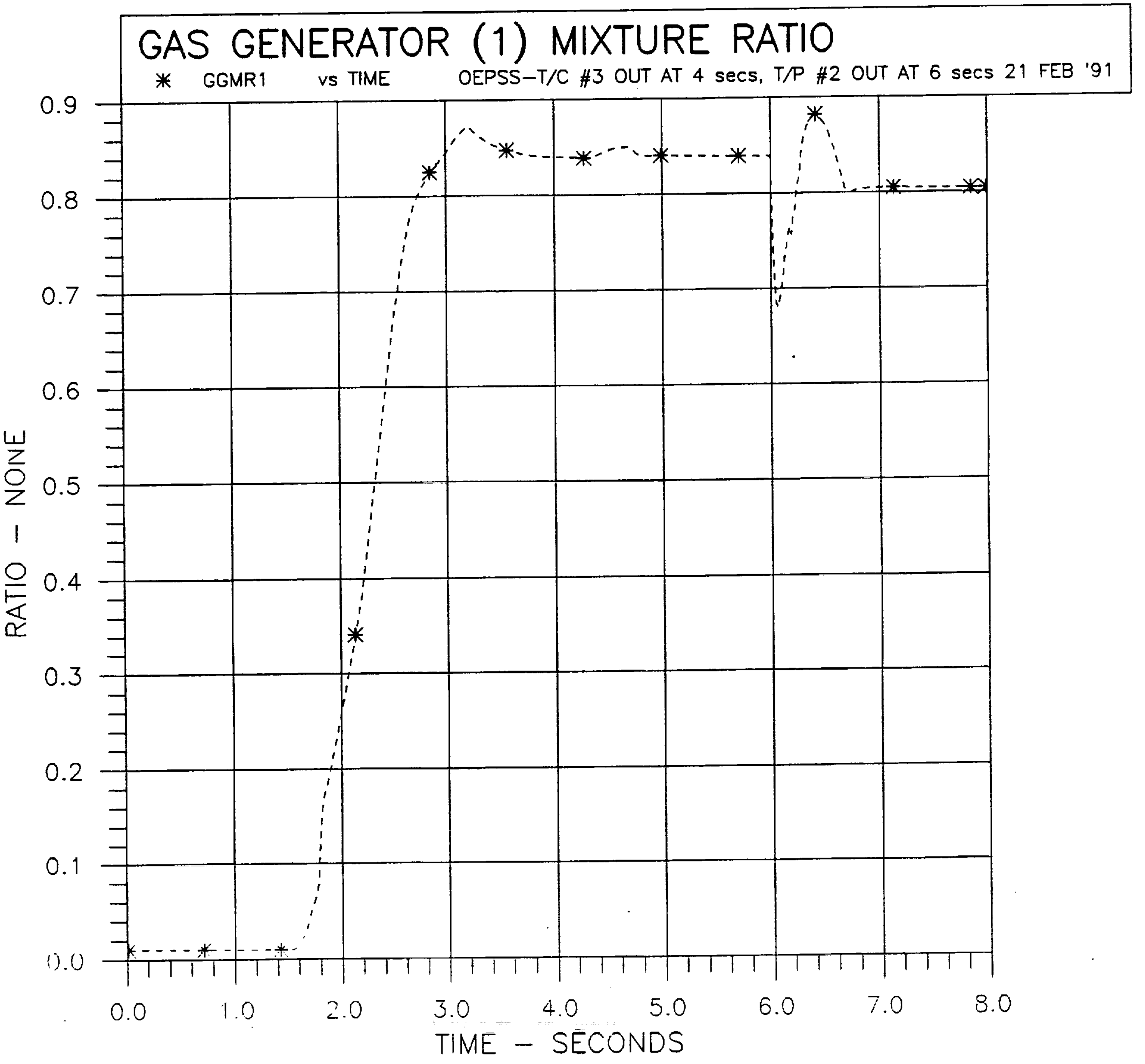

GAS GENERATOR (1) MIXTURE RATIO
* GGMR1 vs TIME OEPSS–T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
RATIO – NONE
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
TIME – SECONDS

Figure E7

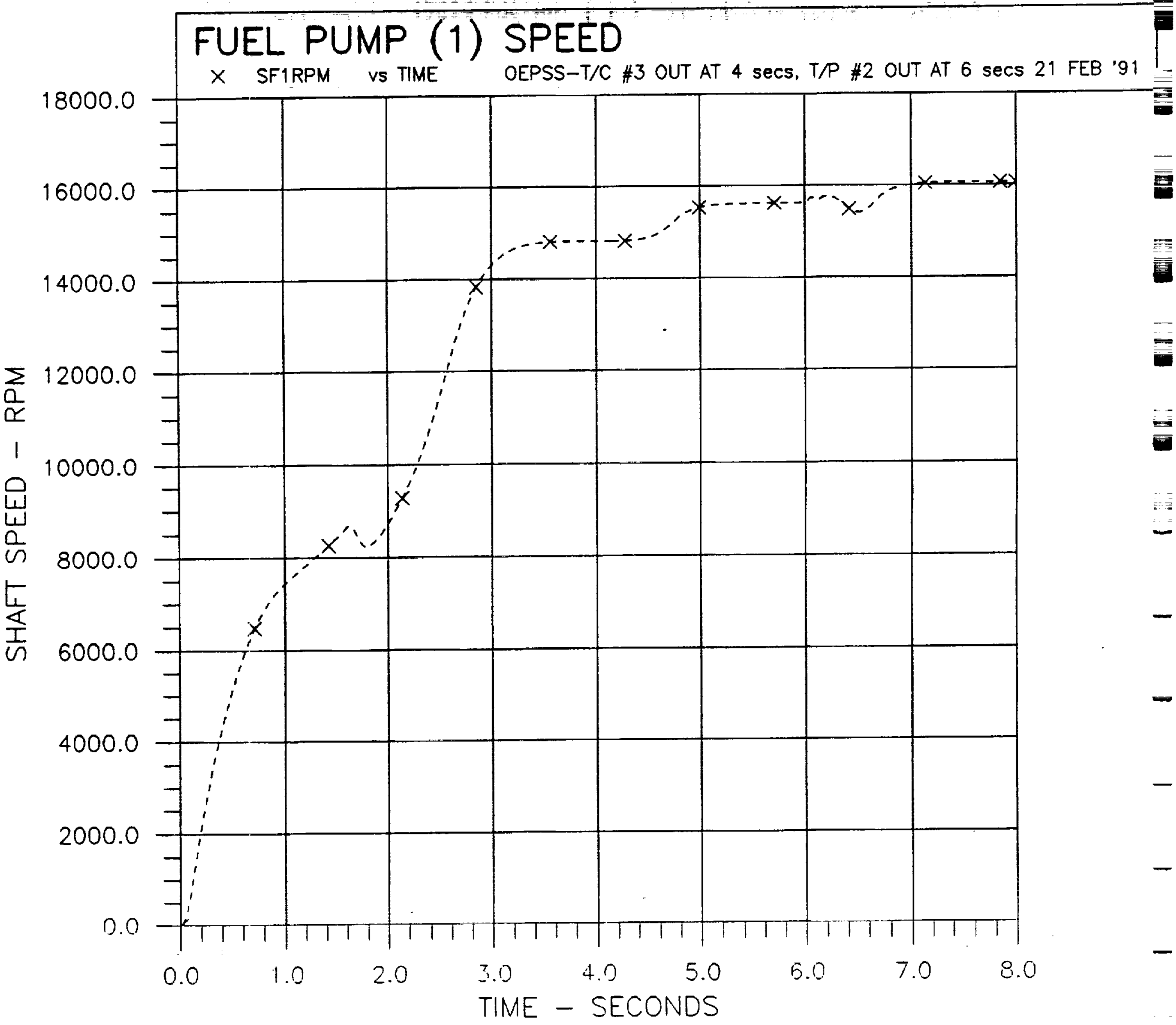

FUEL PUMP (1) SPEED
× SF1RPM vs TIME OEPSS–T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
18000.0
16000.0
14000.0
12000.0
10000.0
8000.0
6000.0
4000.0
2000.0
0.0
SHAFT SPEED – RPM
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
TIME – SECONDS

Figure E8

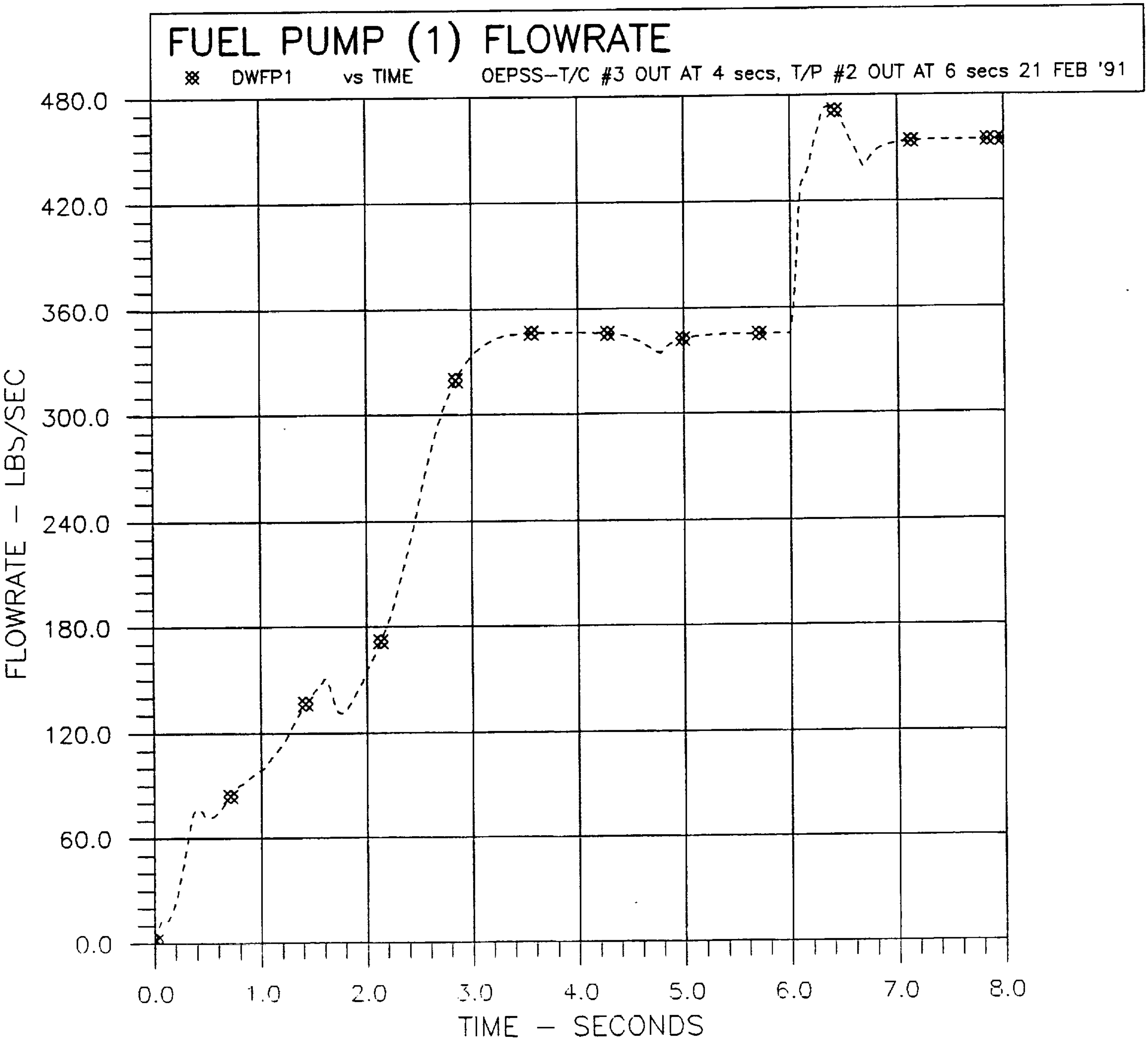

FUEL PUMP (1) FLOWRATE
※ DWFP1 vs TIME
OEPSS–T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
FLOWRATE – LBS/SEC
480.0
420.0
360.0
300.0
240.0
180.0
120.0
60.0
0.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
TIME – SECONDS

Figure E9

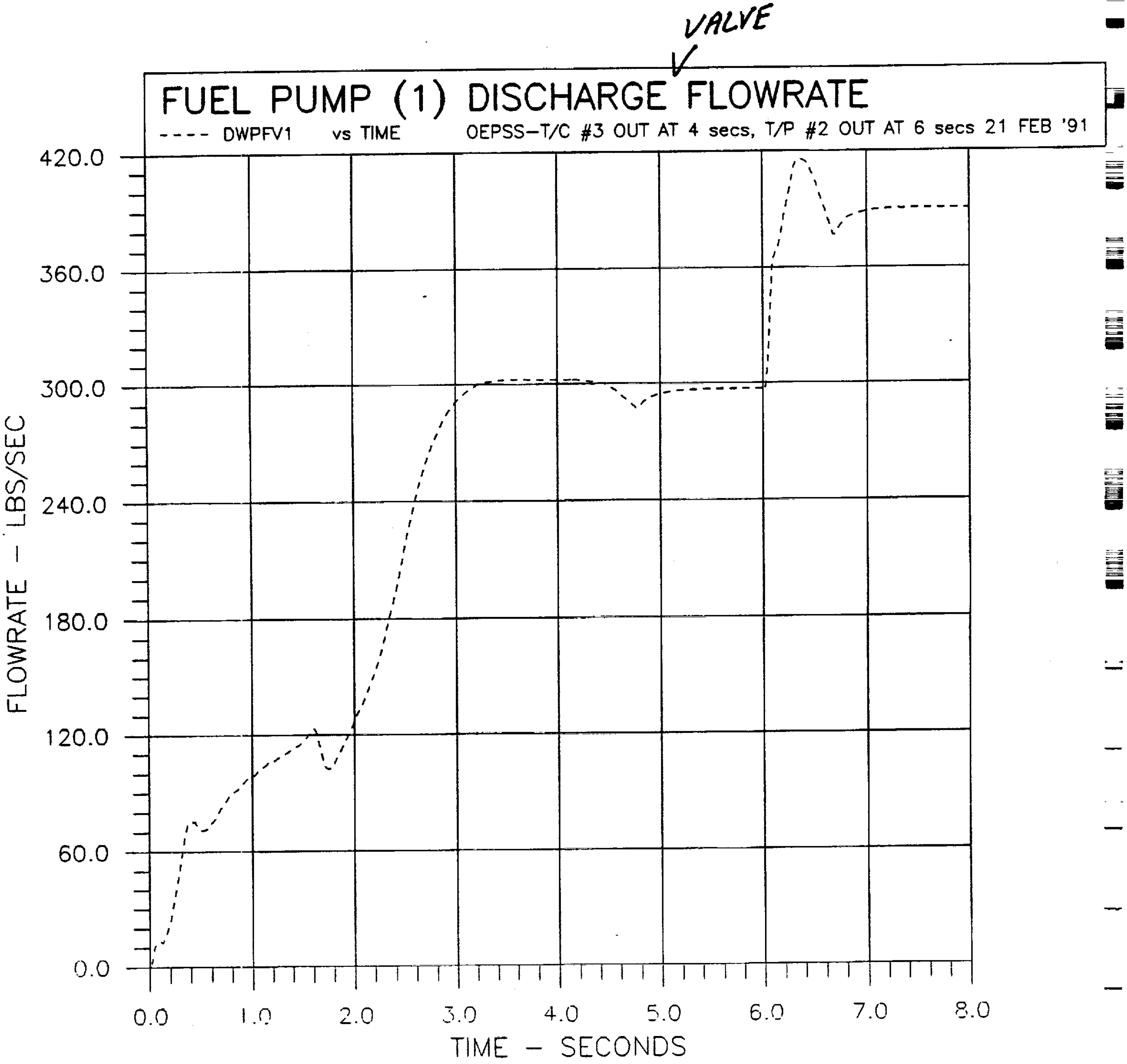

VALVE
FUEL PUMP (1) DISCHARGE FLOWRATE
---- DWPFV1 vs TIME
OEPSS–T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
FLOWRATE – LBS/SEC
420.0
360.0
300.0
240.0
180.0
120.0
60.0
0.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
TIME – SECONDS

Figure E10

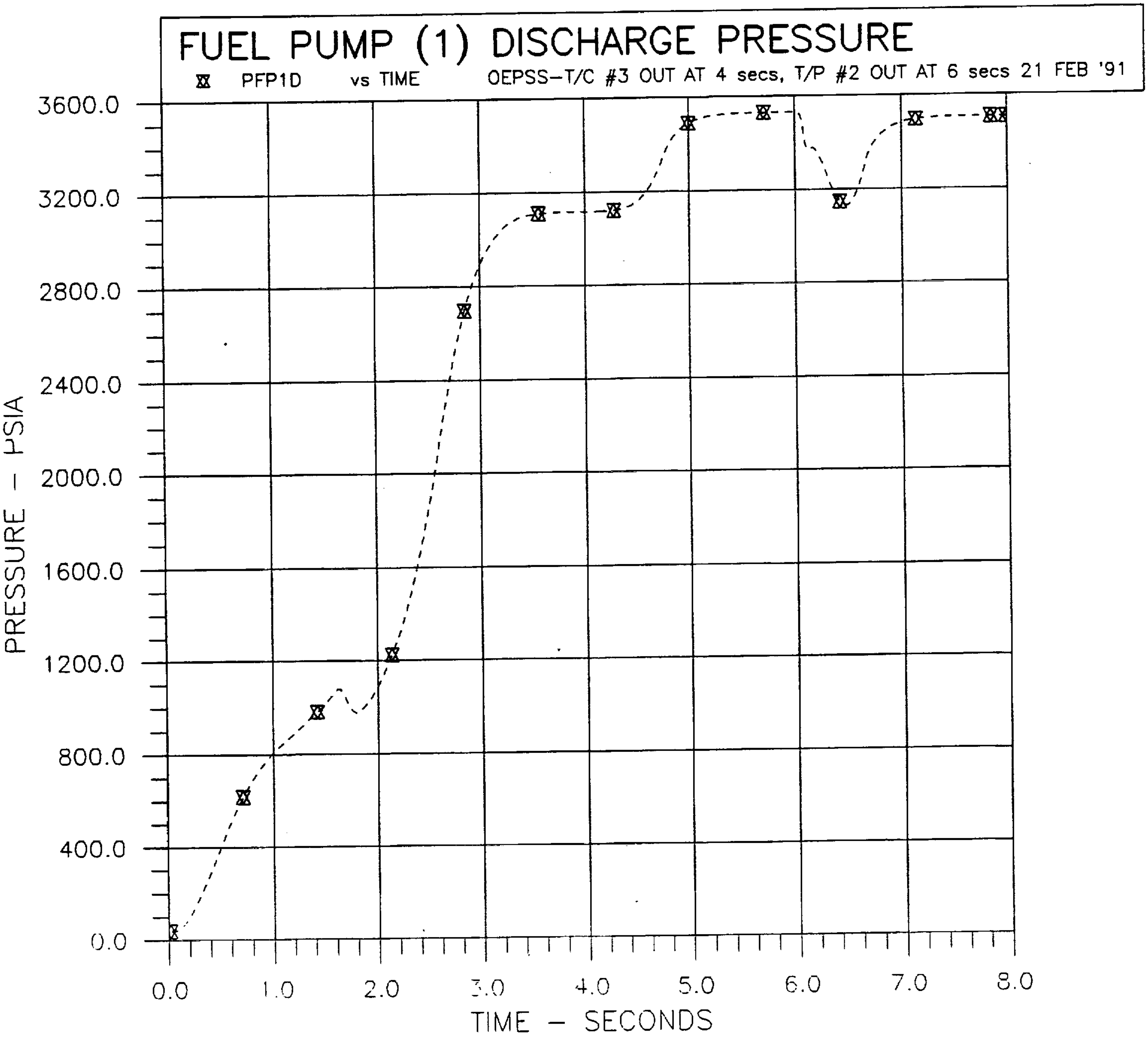
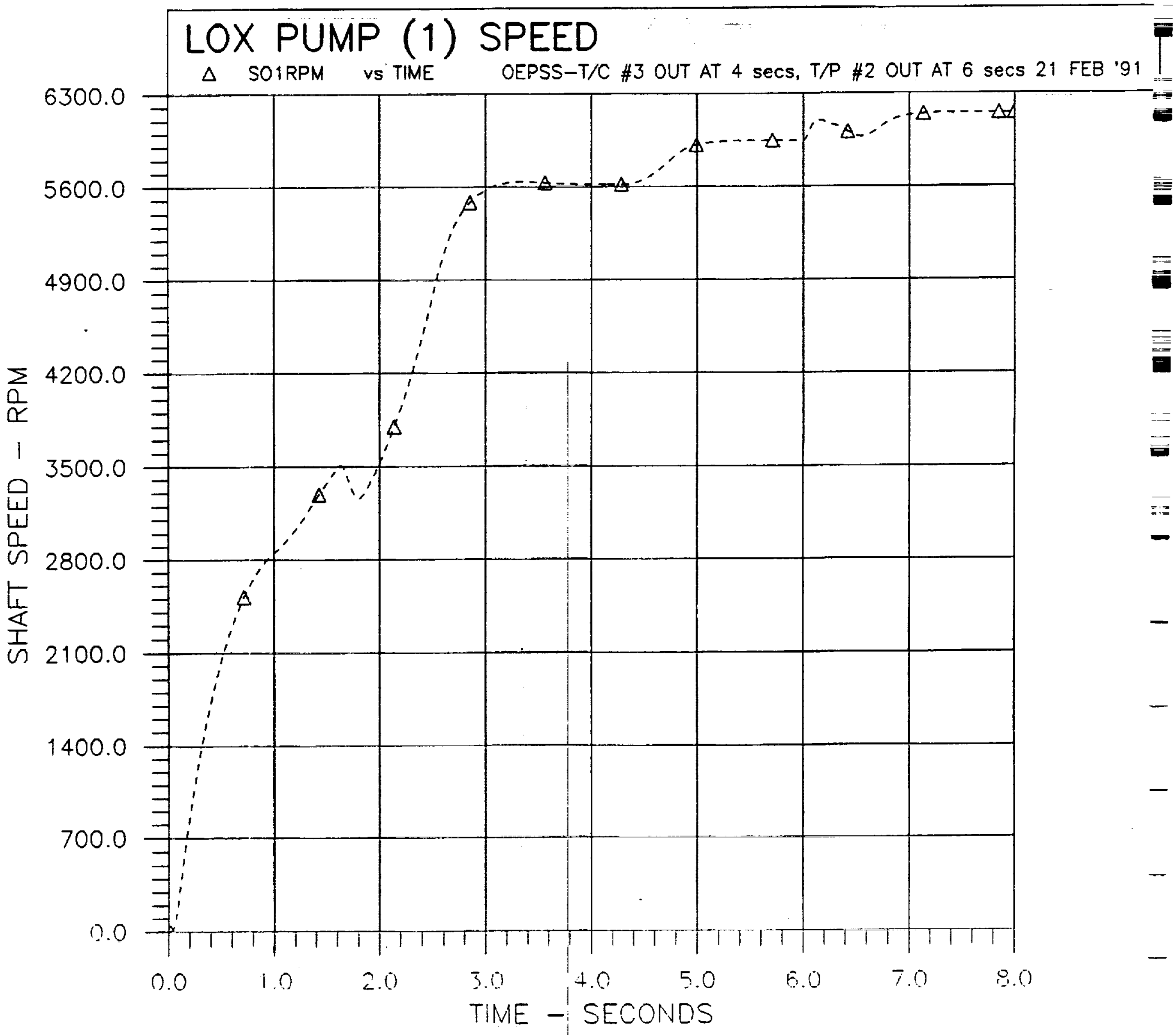

FUEL PUMP (1) DISCHARGE PRESSURE
☒ PFP1D vs TIME
OEPSS–T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
PRESSURE – PSIA
3600.0
3200.0
2800.0
2400.0
2000.0
1600.0
1200.0
800.0
400.0
0.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
TIME – SECONDS

Figure E11



LOX PUMP (1) SPEED
△ S01RPM vs TIME OEPSS–T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
6300.0
5600.0
4900.0
4200.0
3500.0
2800.0
2100.0
1400.0
700.0
0.0
SHAFT SPEED – RPM
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
TIME – SECONDS

Figure E12

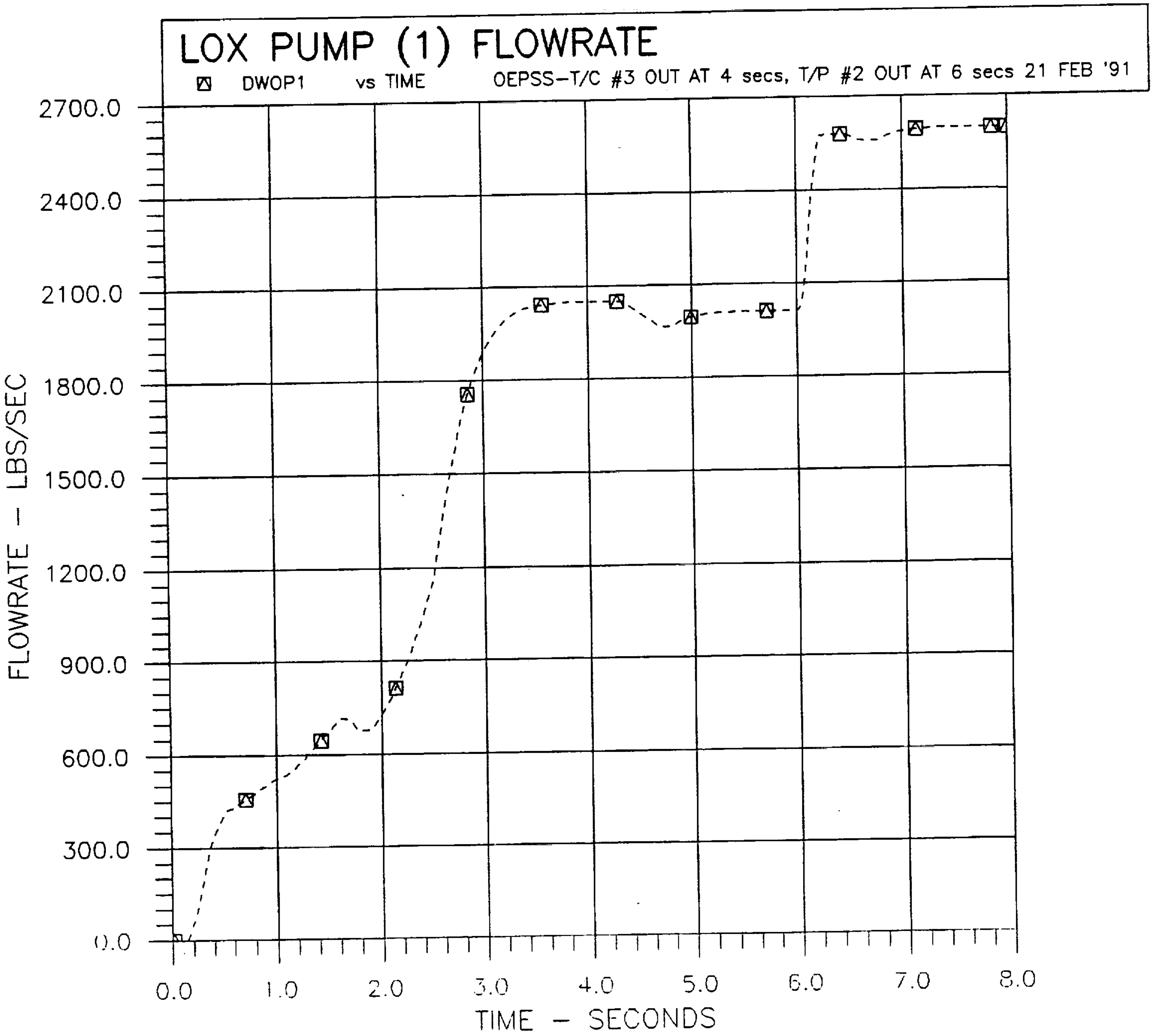

LOX PUMP (1) FLOWRATE
DWOP1 vs TIME
OEPSS–T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
FLOWRATE – LBS/SEC
2700.0
2400.0
2100.0
1800.0
1500.0
1200.0
900.0
600.0
300.0
0.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
TIME – SECONDS

Figure E13

VALVE

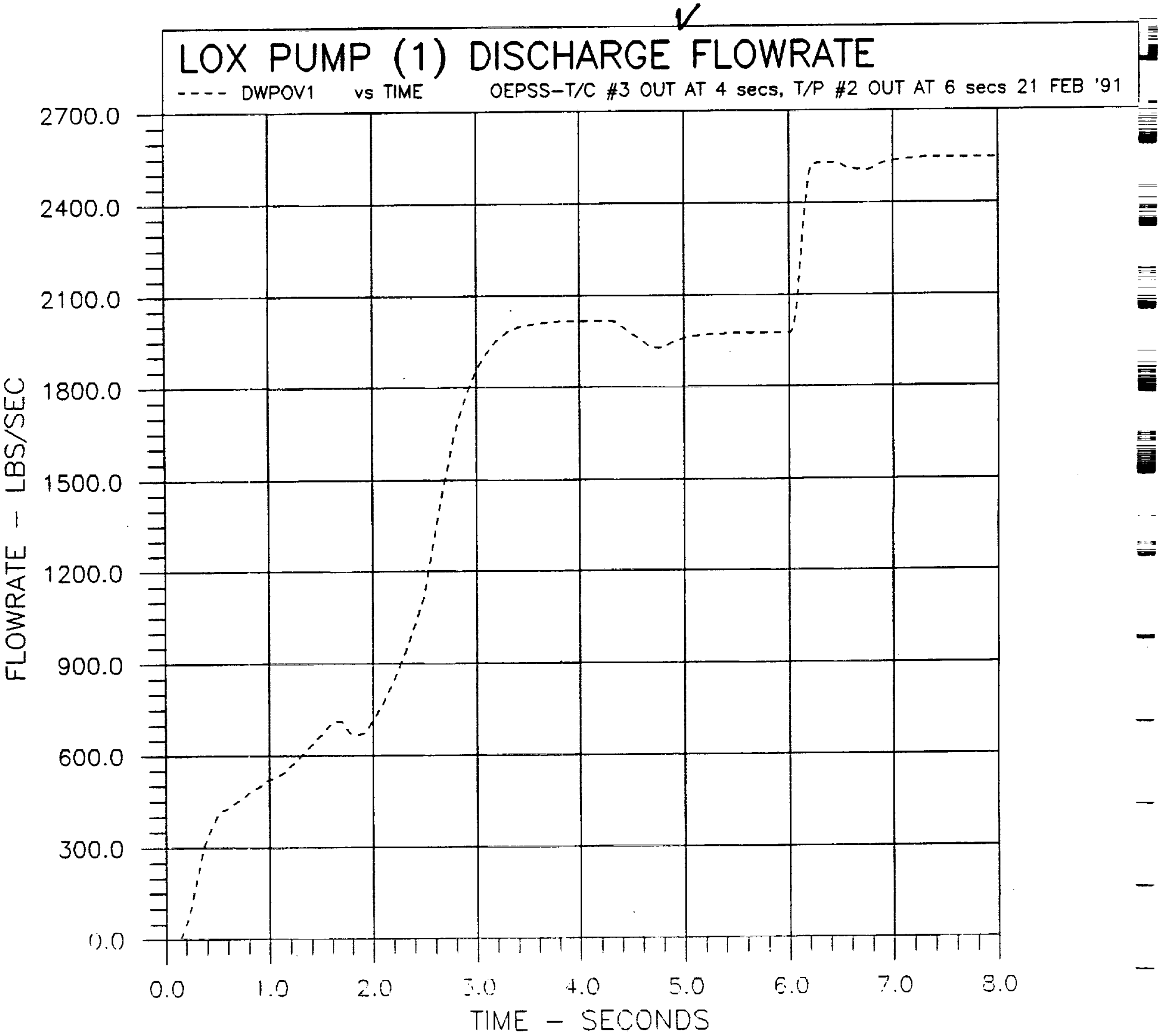


Figure E14

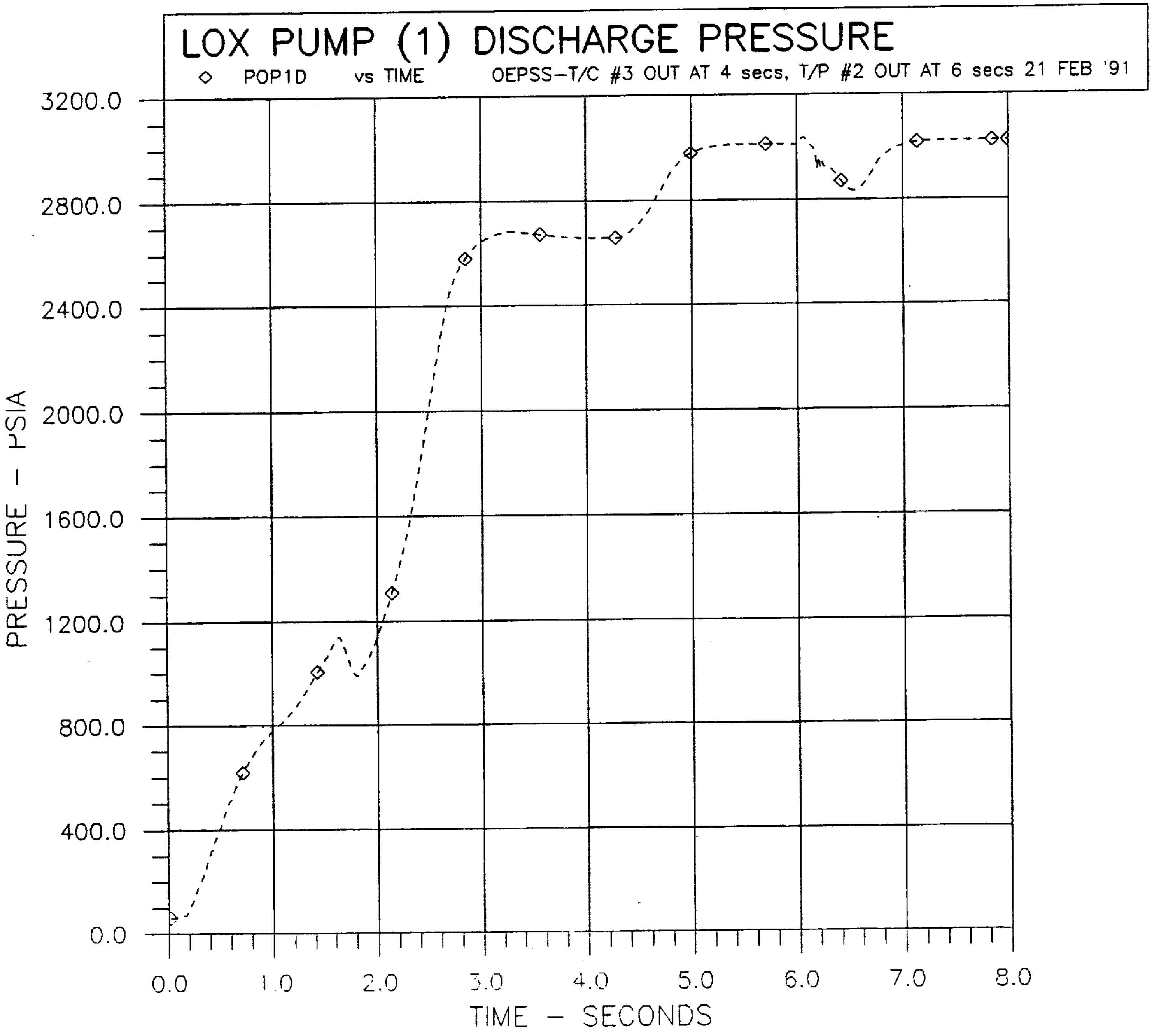
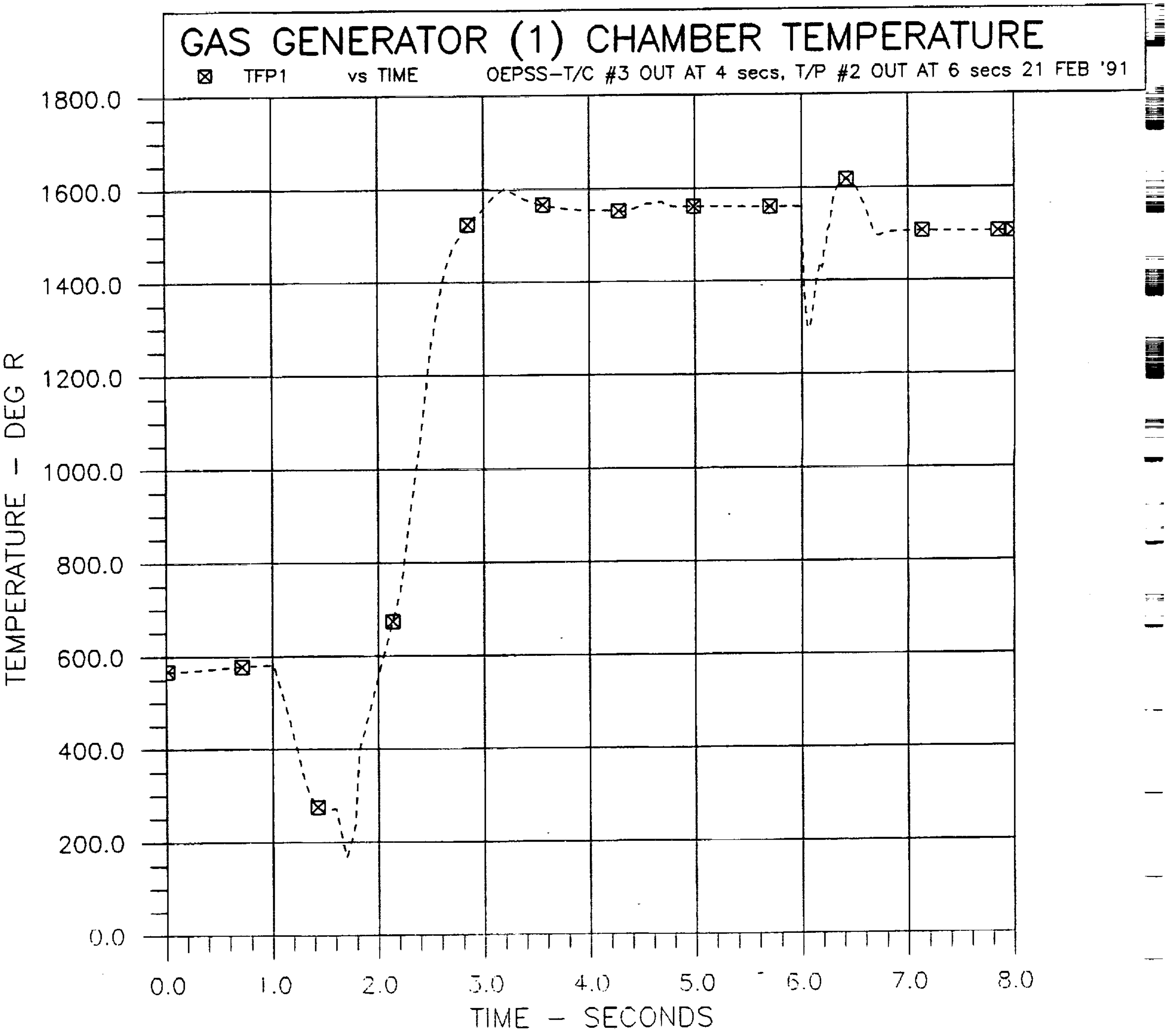

LOX PUMP (1) DISCHARGE PRESSURE
◇ POP1D vs TIME OEPSS–T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
PRESSURE – PSIA
3200.0
2800.0
2400.0
2000.0
1600.0
1200.0
800.0
400.0
0.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
TIME – SECONDS

Figure E15



GAS GENERATOR (1) CHAMBER TEMPERATURE
⊠ TFP1 vs TIME OEPSS–T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
1800.0
1600.0
1400.0
1200.0
1000.0
800.0
600.0
400.0
200.0
0.0
TEMPERATURE – DEG R
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
TIME – SECONDS

Figure E16

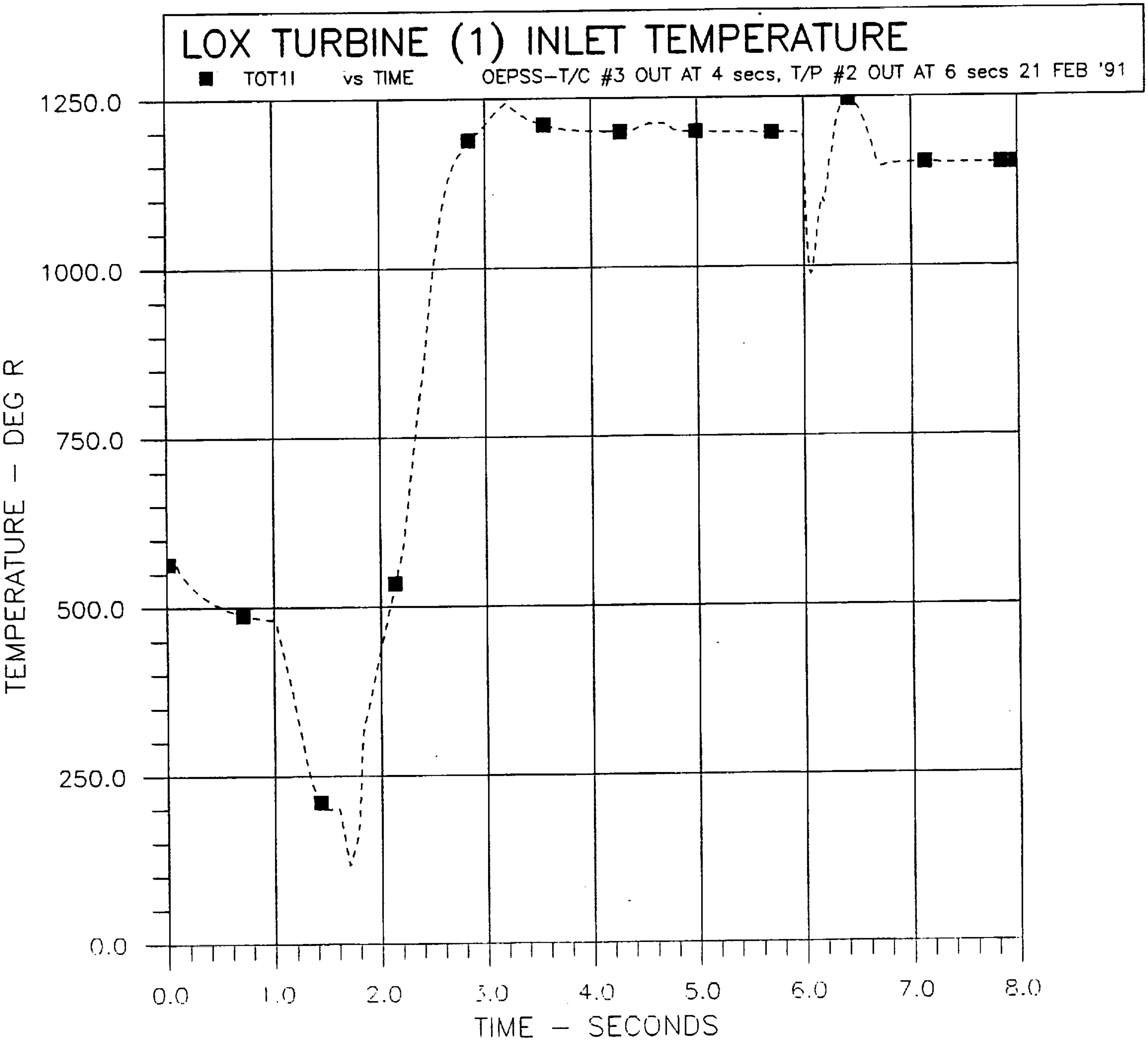

LOX TURBINE (1) INLET TEMPERATURE
■ TOT1I vs TIME OEPSS–T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
1250.0
1000.0
750.0
500.0
250.0
0.0
TEMPERATURE – DEG R
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
TIME – SECONDS

Figure E17

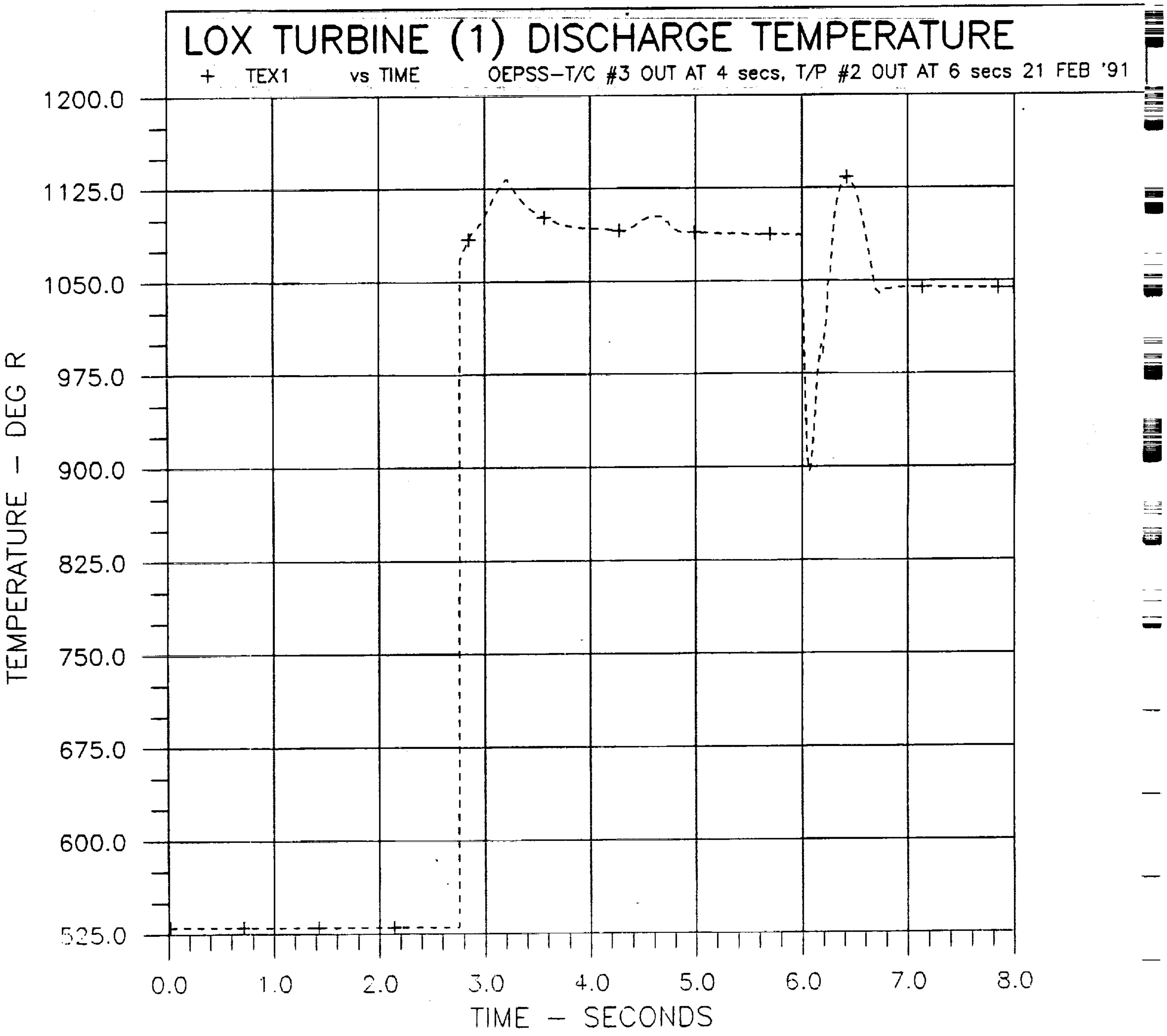

LOX TURBINE (1) DISCHARGE TEMPERATURE
+ TEX1 vs TIME OEPSS–T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
1200.0
1125.0
1050.0
975.0
900.0
825.0
750.0
675.0
600.0
525.0
TEMPERATURE – DEG R
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
TIME – SECONDS

Figure E18

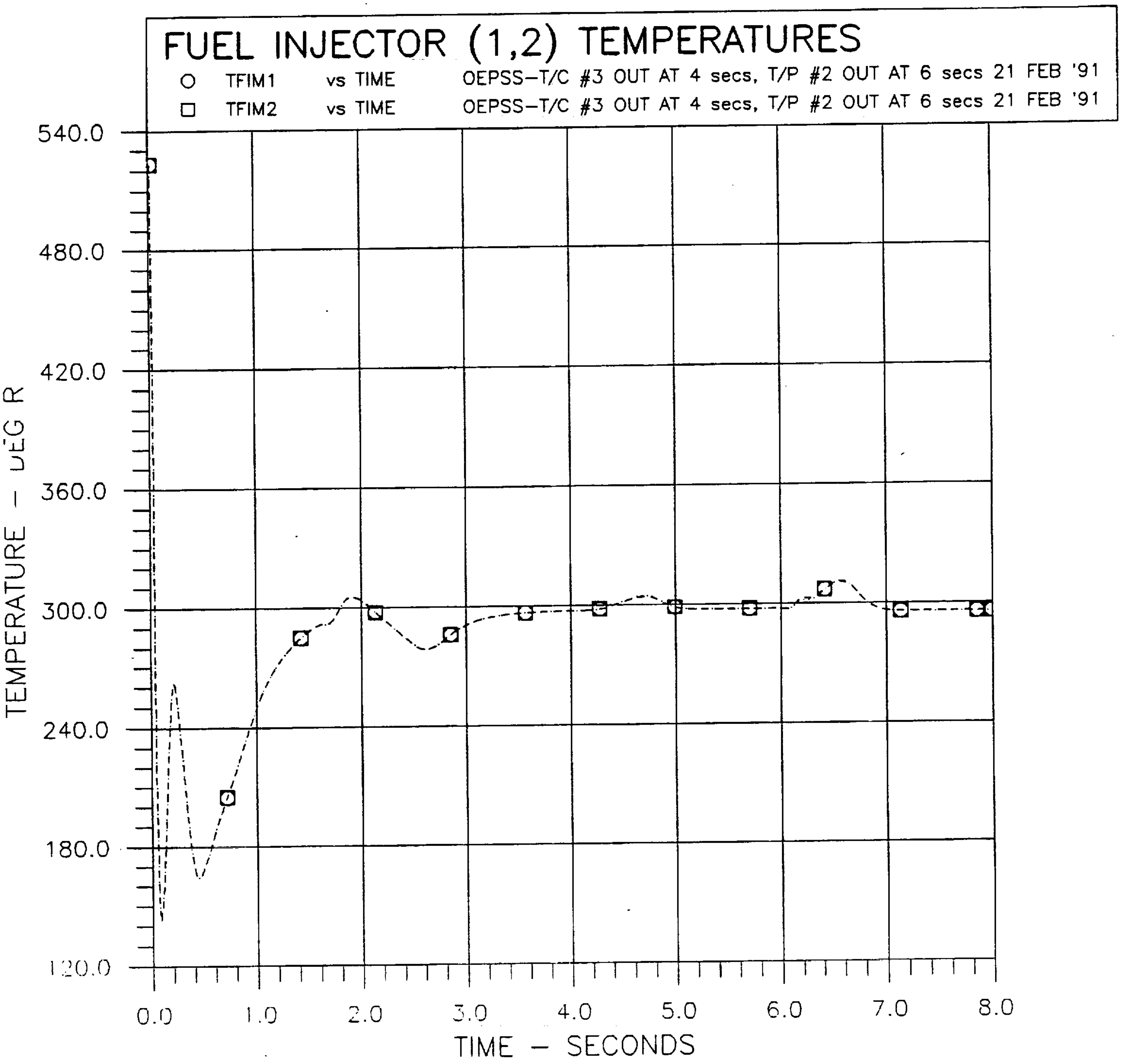

FUEL INJECTOR (1,2) TEMPERATURES
○ TFIM1 vs TIME OEPSS–T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
□ TFIM2 vs TIME OEPSS–T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
540.0
480.0
420.0
360.0
300.0
240.0
180.0
120.0
TEMPERATURE – DEG R
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
TIME – SECONDS

Figure E19

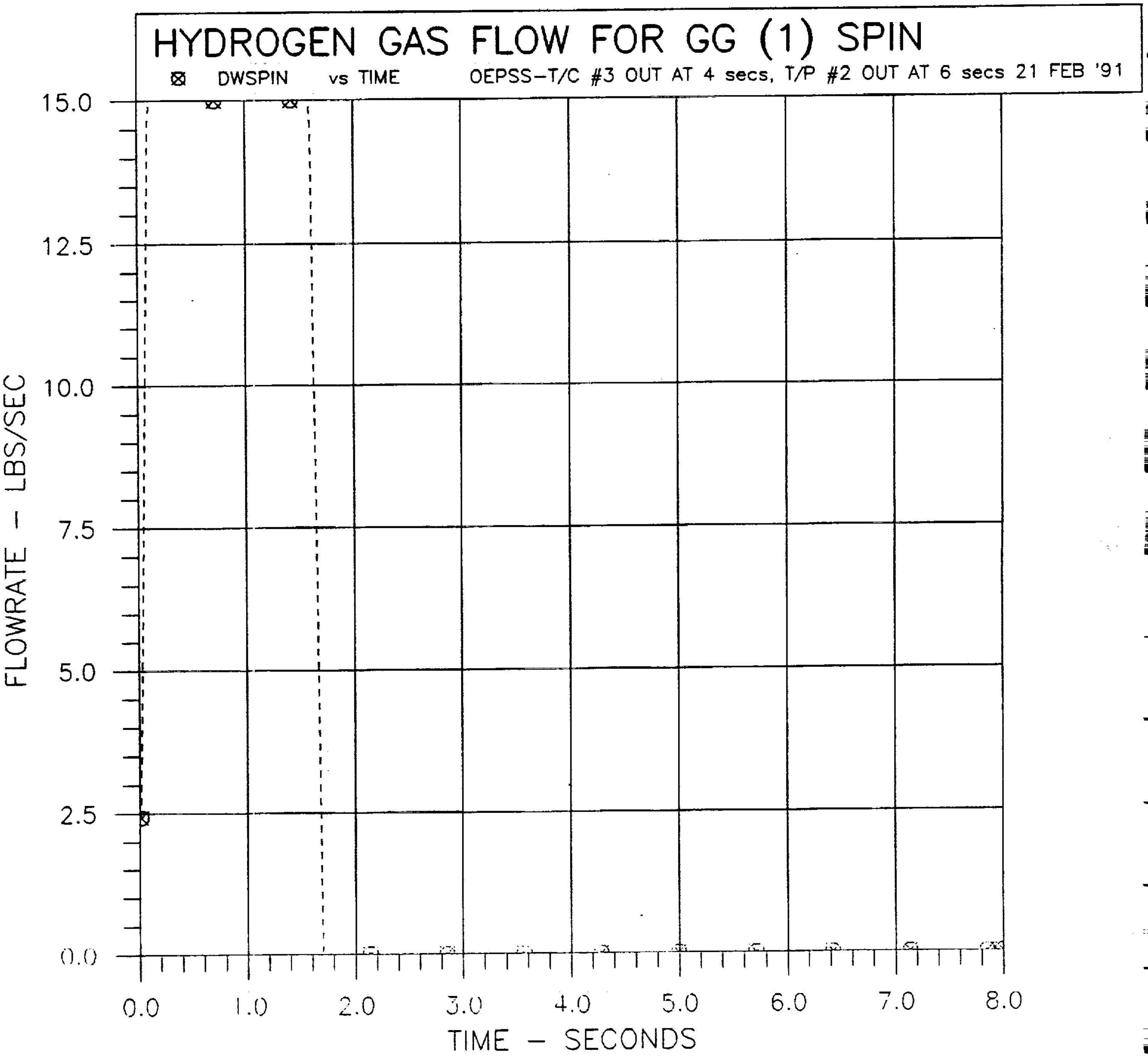

HYDROGEN GAS FLOW FOR GG (1) SPIN
⊠ DWSPIN vs TIME OEPSS–T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
FLOWRATE – LBS/SEC
15.0
12.5
10.0
7.5
5.0
2.5
0.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
TIME – SECONDS

Figure E20

APPENDIX F

COMBINED THRUST CHAMBER/TURBOPUMP OUT CONDITION RESULTS

FOR SYSTEM 2

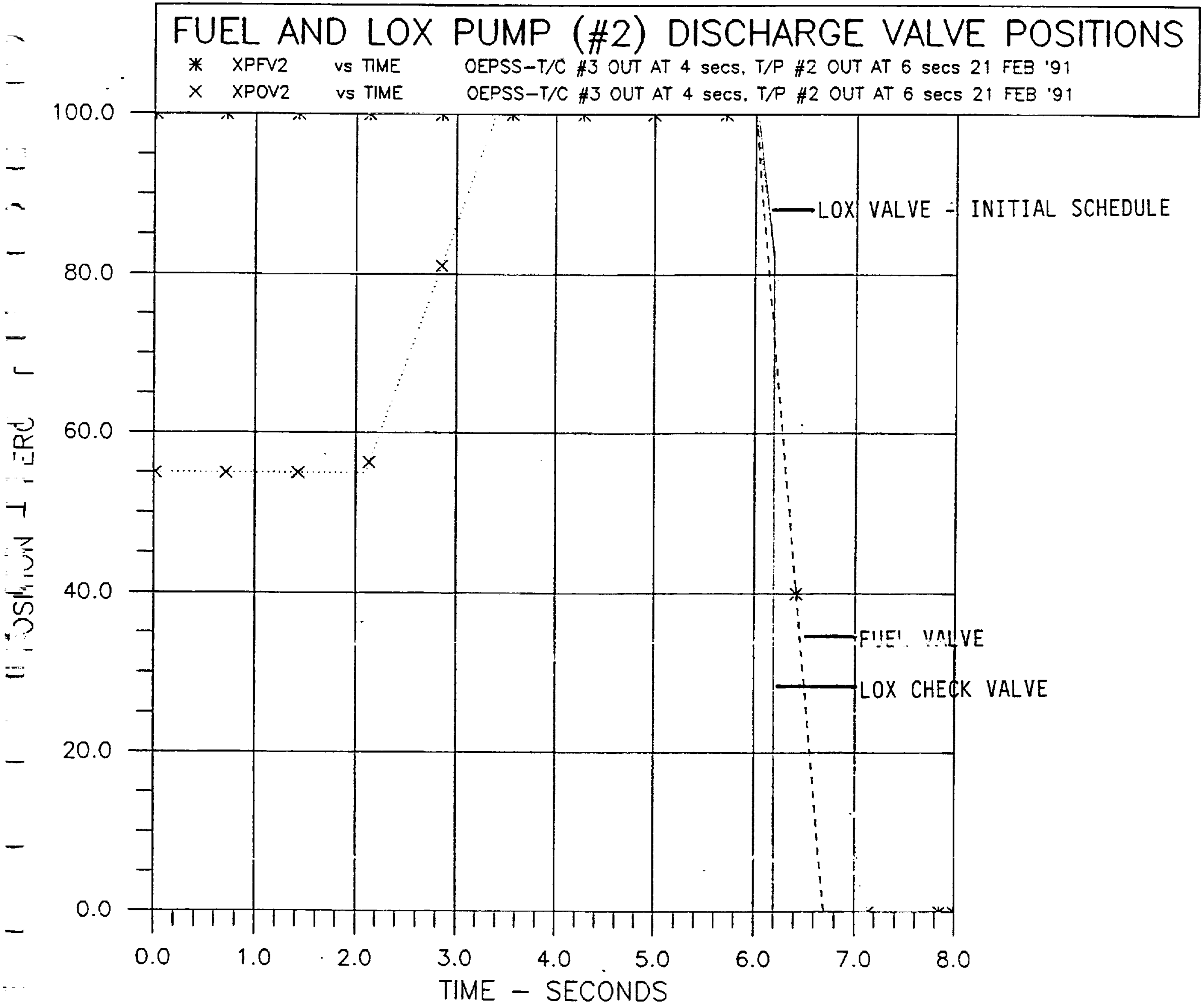

FUEL AND LOX PUMP (#2) DISCHARGE VALVE POSITIONS
✳ XPFV2 vs TIME OEPSS–T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
× XPOV2 vs TIME OEPSS–T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
LOX VALVE – INITIAL SCHEDULE
FUEL VALVE
LOX CHECK VALVE
100.0
80.0
60.0
40.0
20.0
0.0
POSITION – PERCENT
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
TIME – SECONDS

Figure F1

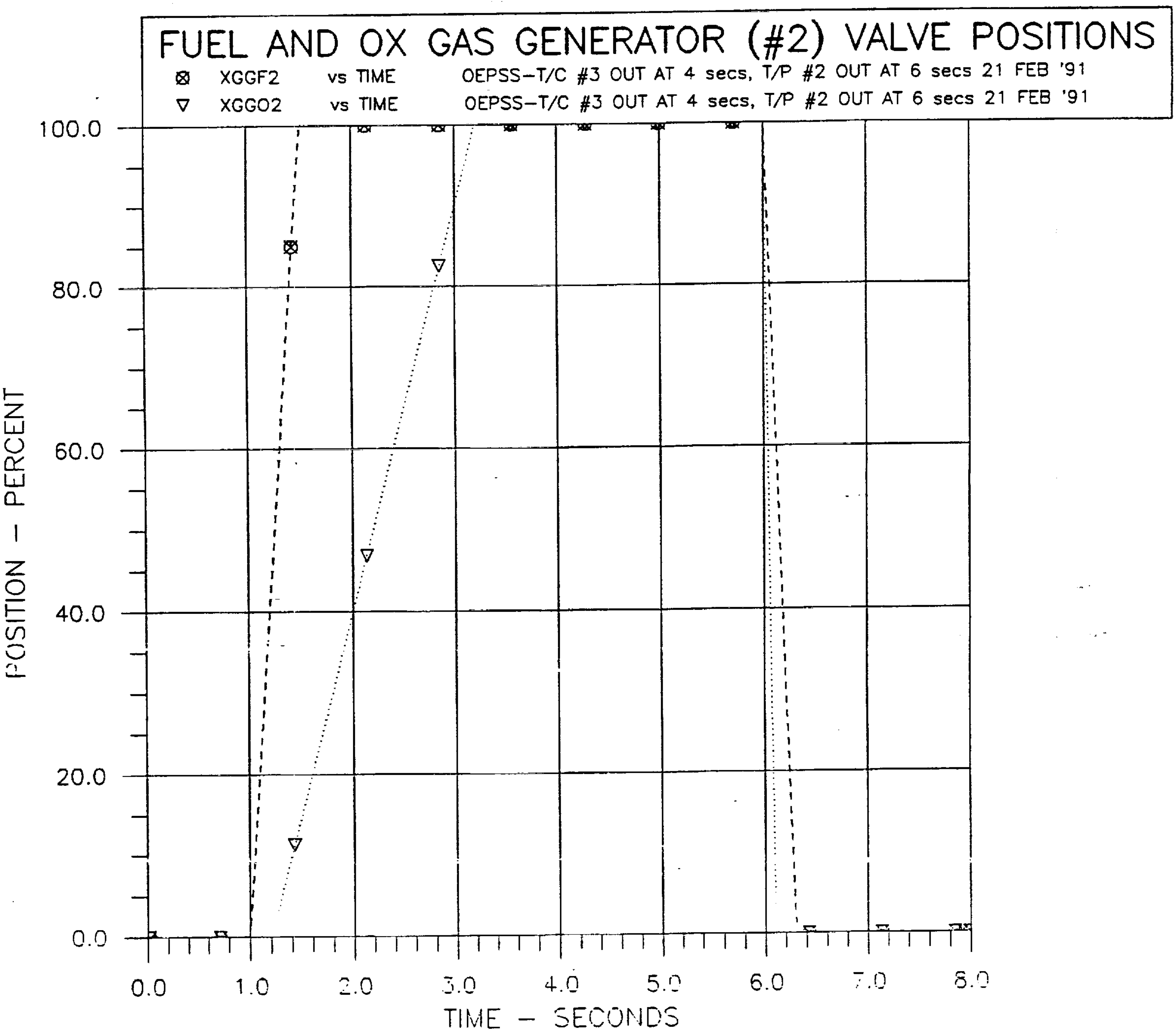

FUEL AND OX GAS GENERATOR (#2) VALVE POSITIONS
⊗ XGGF2 vs TIME OEPSS-T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
▽ XGGO2 vs TIME OEPSS-T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
100.0
80.0
60.0
40.0
20.0
0.0
POSITION - PERCENT
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
TIME - SECONDS

Figure F2

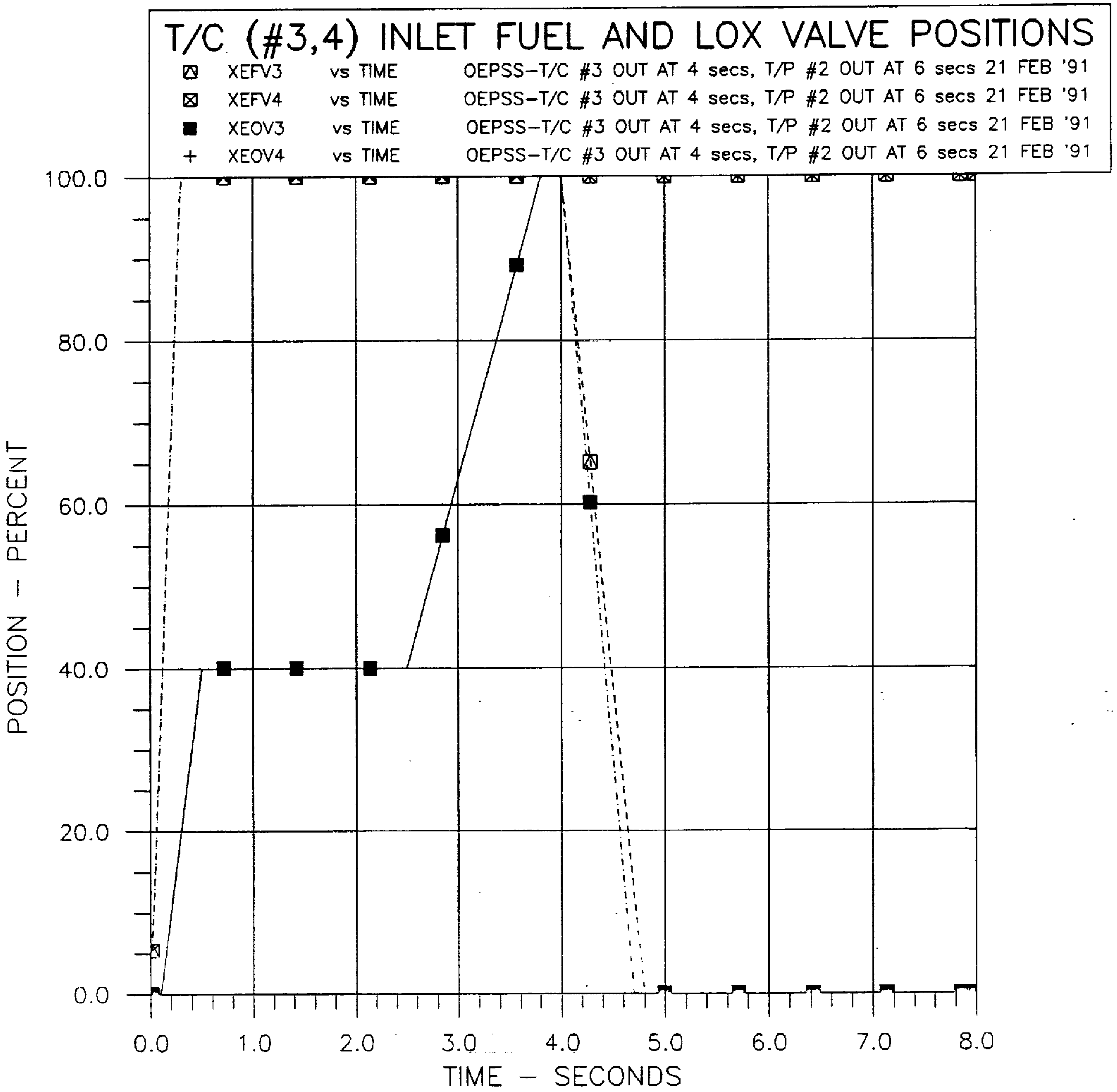
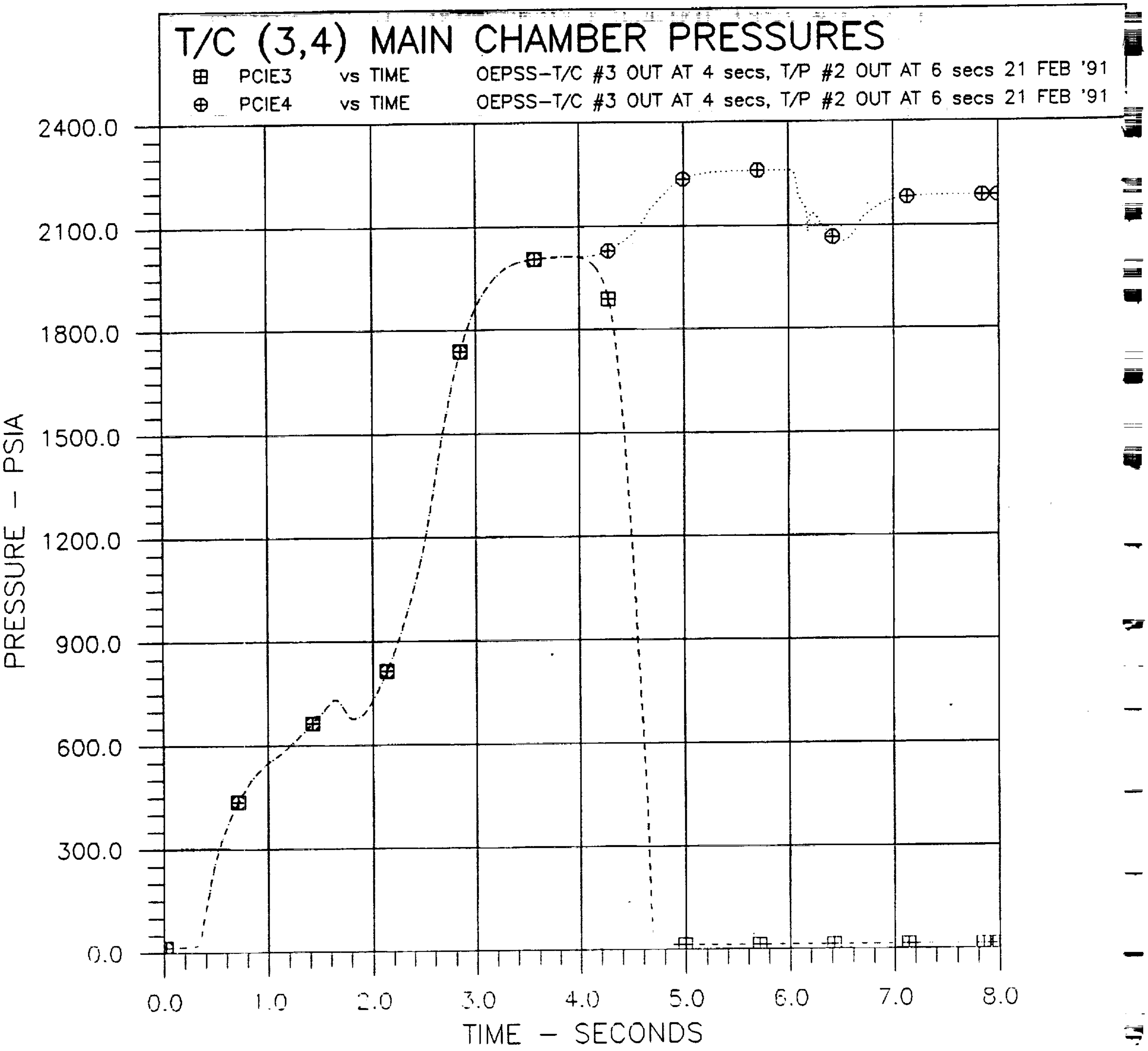

T/C (#3,4) INLET FUEL AND LOX VALVE POSITIONS
XEFV3 vs TIME OEPSS–T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
XEFV4 vs TIME OEPSS–T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
XEOV3 vs TIME OEPSS–T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
XEOV4 vs TIME OEPSS–T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
POSITION – PERCENT
100.0
80.0
60.0
40.0
20.0
0.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
TIME – SECONDS

Figure F3


T/C (3,4) MAIN CHAMBER PRESSURES
⊞ PCIE3 vs TIME OEPSS–T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
⊕ PCIE4 vs TIME OEPSS–T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
PRESSURE – PSIA
2400.0
2100.0
1800.0
1500.0
1200.0
900.0
600.0
300.0
0.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
TIME – SECONDS

Figure_F4

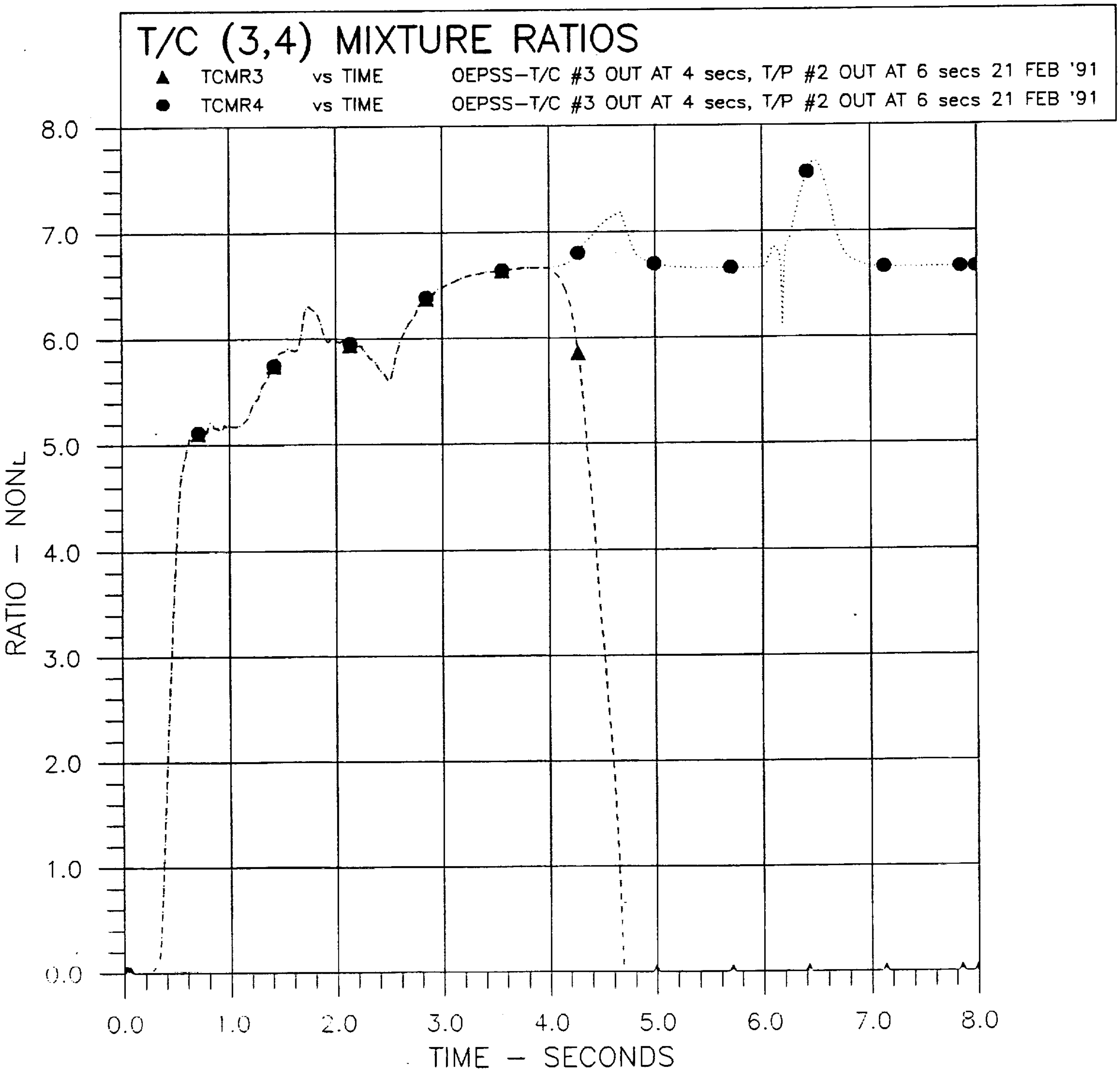

T/C (3,4) MIXTURE RATIOS
▲ TCMR3 vs TIME OEPSS–T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
● TCMR4 vs TIME OEPSS–T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
RATIO – NONE
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
TIME – SECONDS

Figure F5

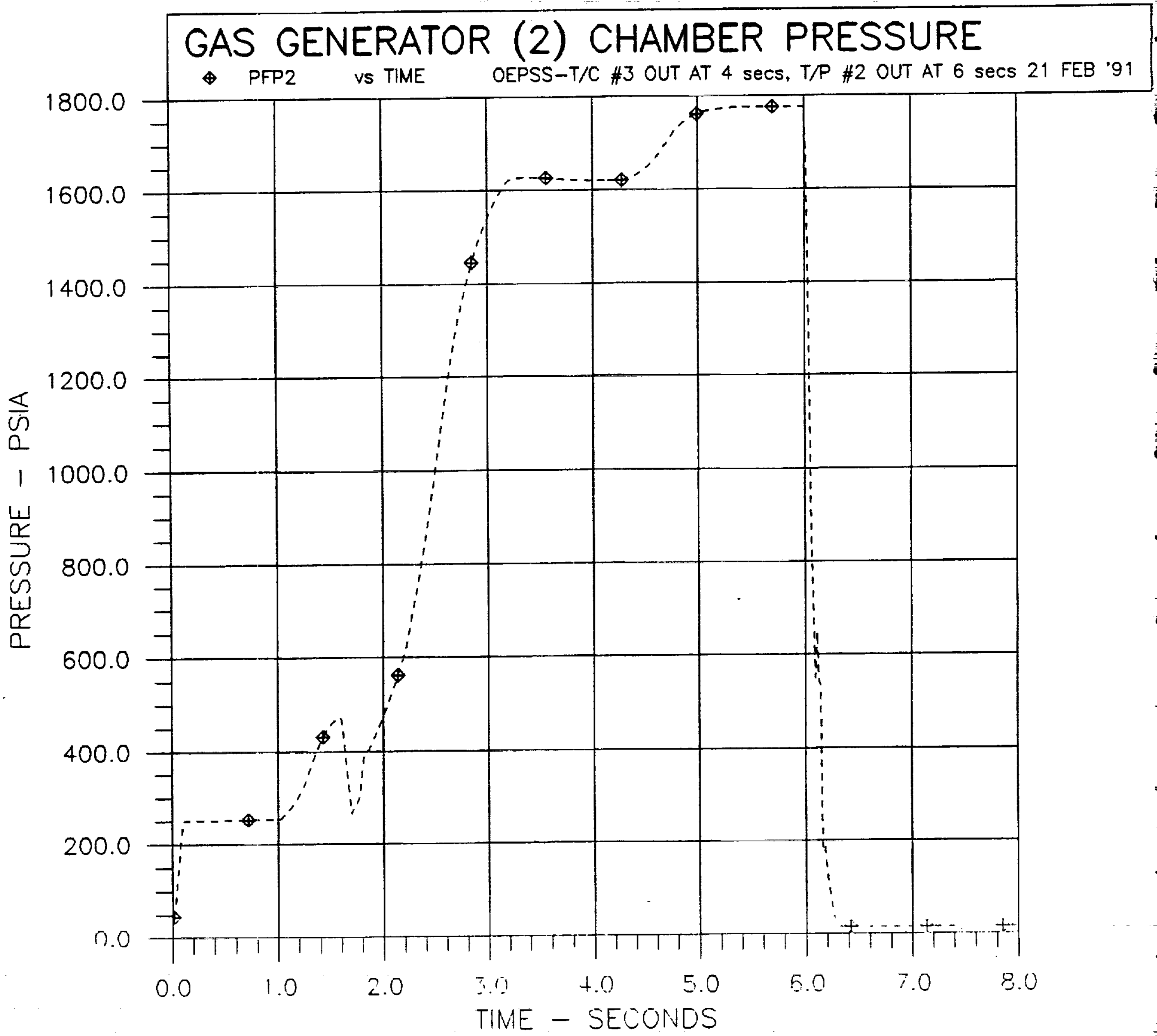

GAS GENERATOR (2) CHAMBER PRESSURE
PFP2 vs TIME
OEPSS-T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
PRESSURE - PSIA
1800.0
1600.0
1400.0
1200.0
1000.0
800.0
600.0
400.0
200.0
0.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
TIME - SECONDS

Figure F6

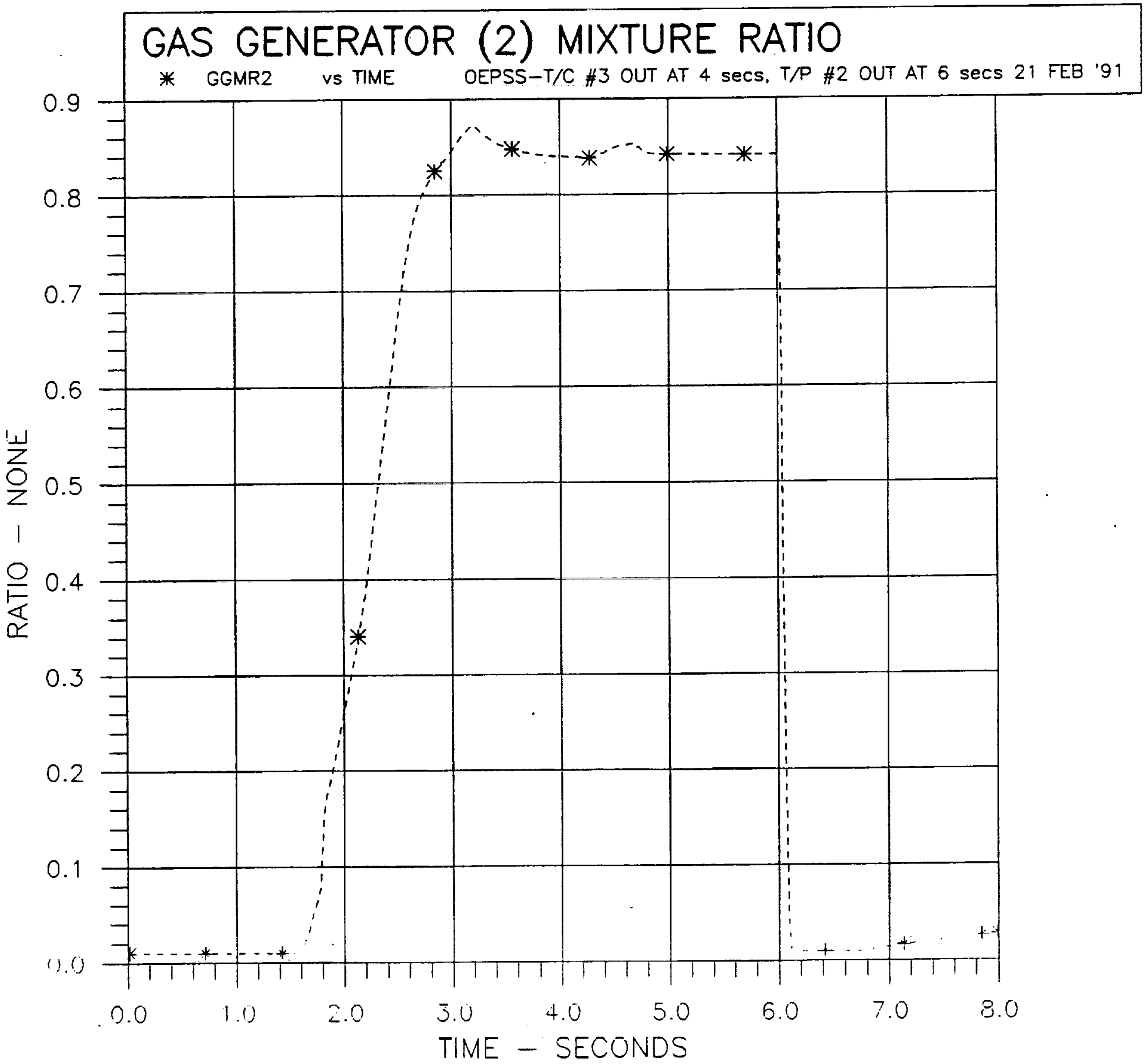

GAS GENERATOR (2) MIXTURE RATIO
* GGMR2 vs TIME
OEPSS–T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
RATIO – NONE
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
TIME – SECONDS

Figure F7

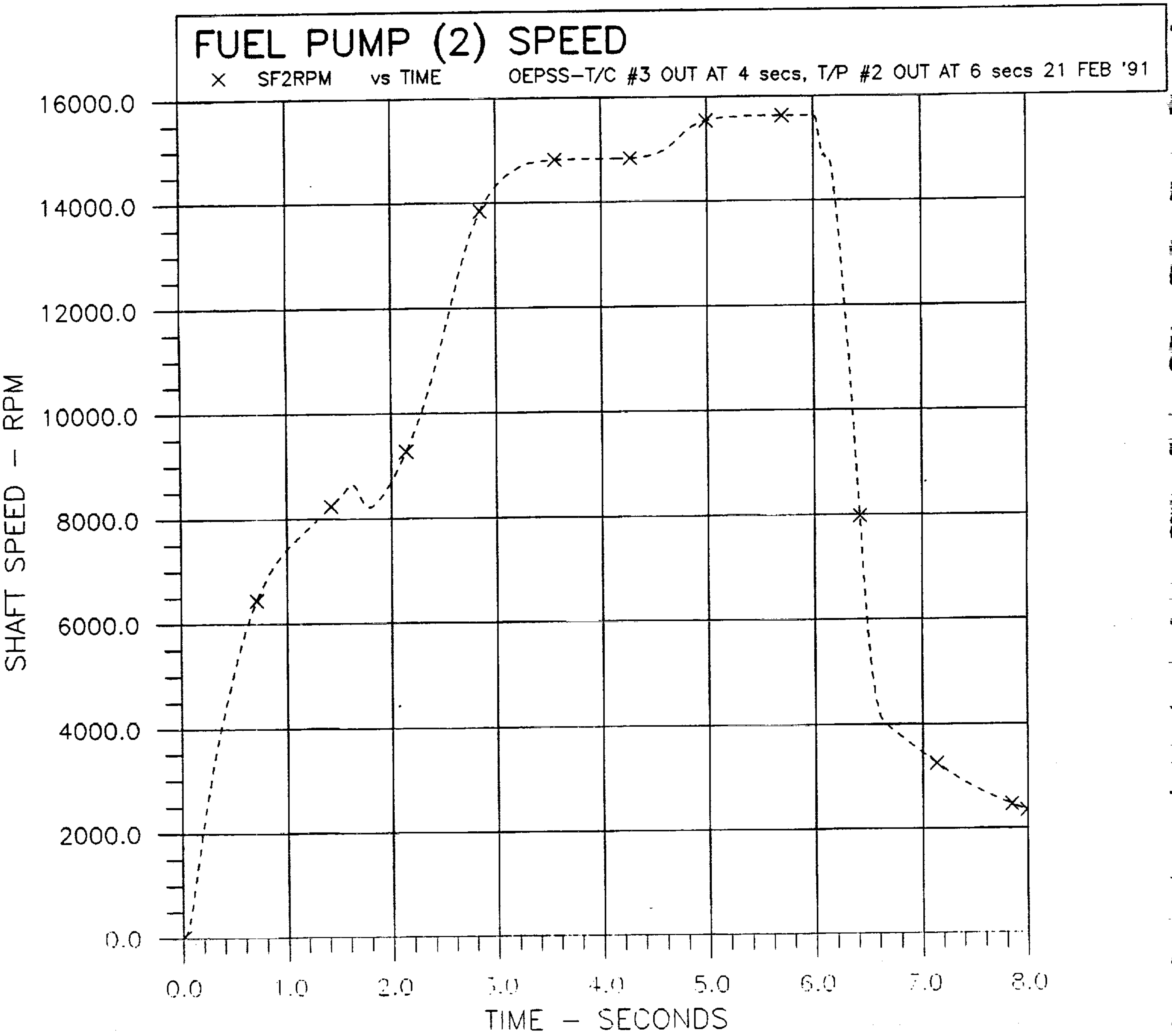

FUEL PUMP (2) SPEED
× SF2RPM vs TIME OEPSS–T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
SHAFT SPEED – RPM
16000.0
14000.0
12000.0
10000.0
8000.0
6000.0
4000.0
2000.0
0.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
TIME – SECONDS

Figure F8

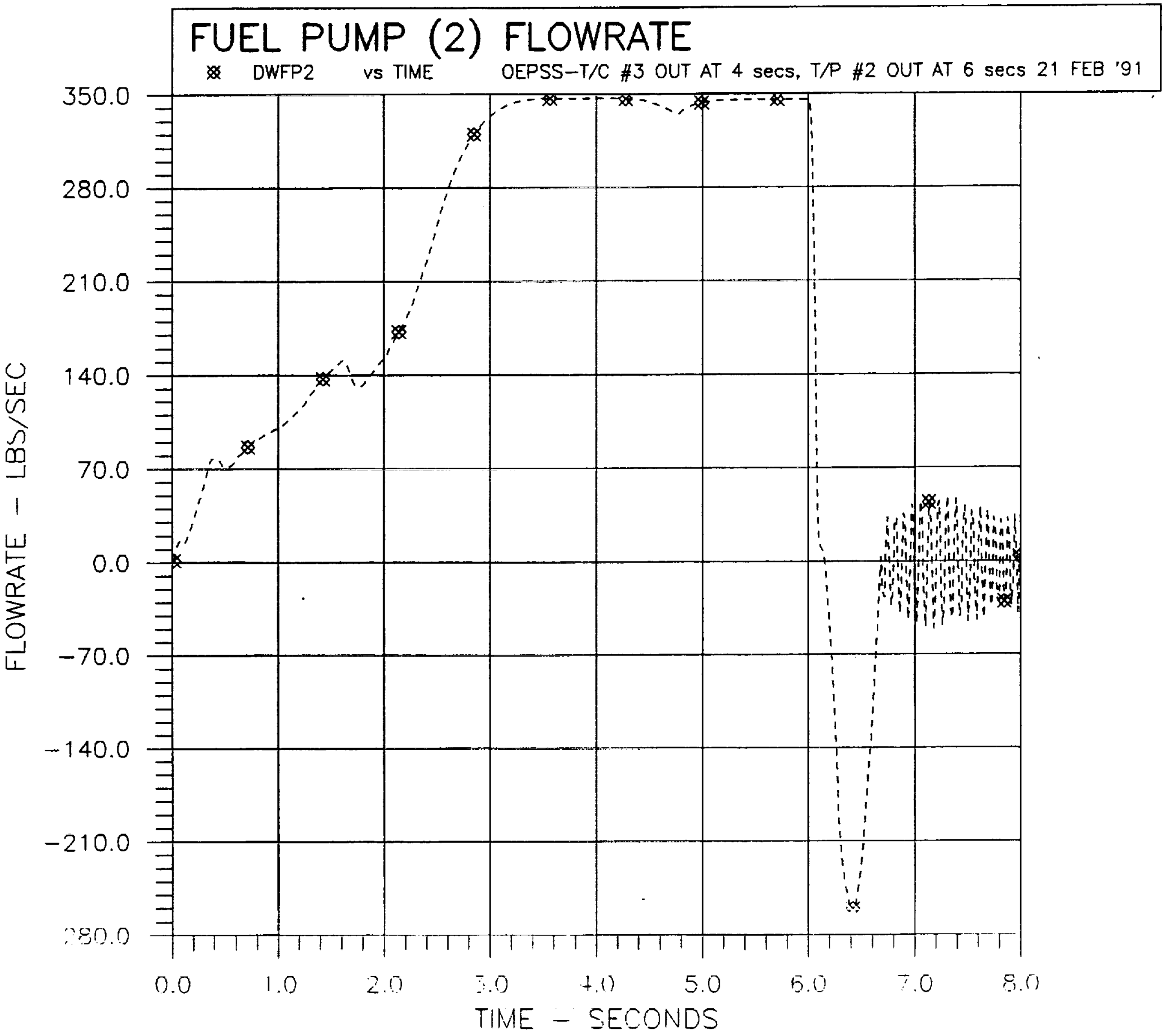

FUEL PUMP (2) FLOWRATE
⊗ DWFP2 vs TIME
OEPSS–T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
350.0
280.0
210.0
140.0
70.0
0.0
−70.0
−140.0
−210.0
−280.0
FLOWRATE – LBS/SEC
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
TIME – SECONDS

Figure F9

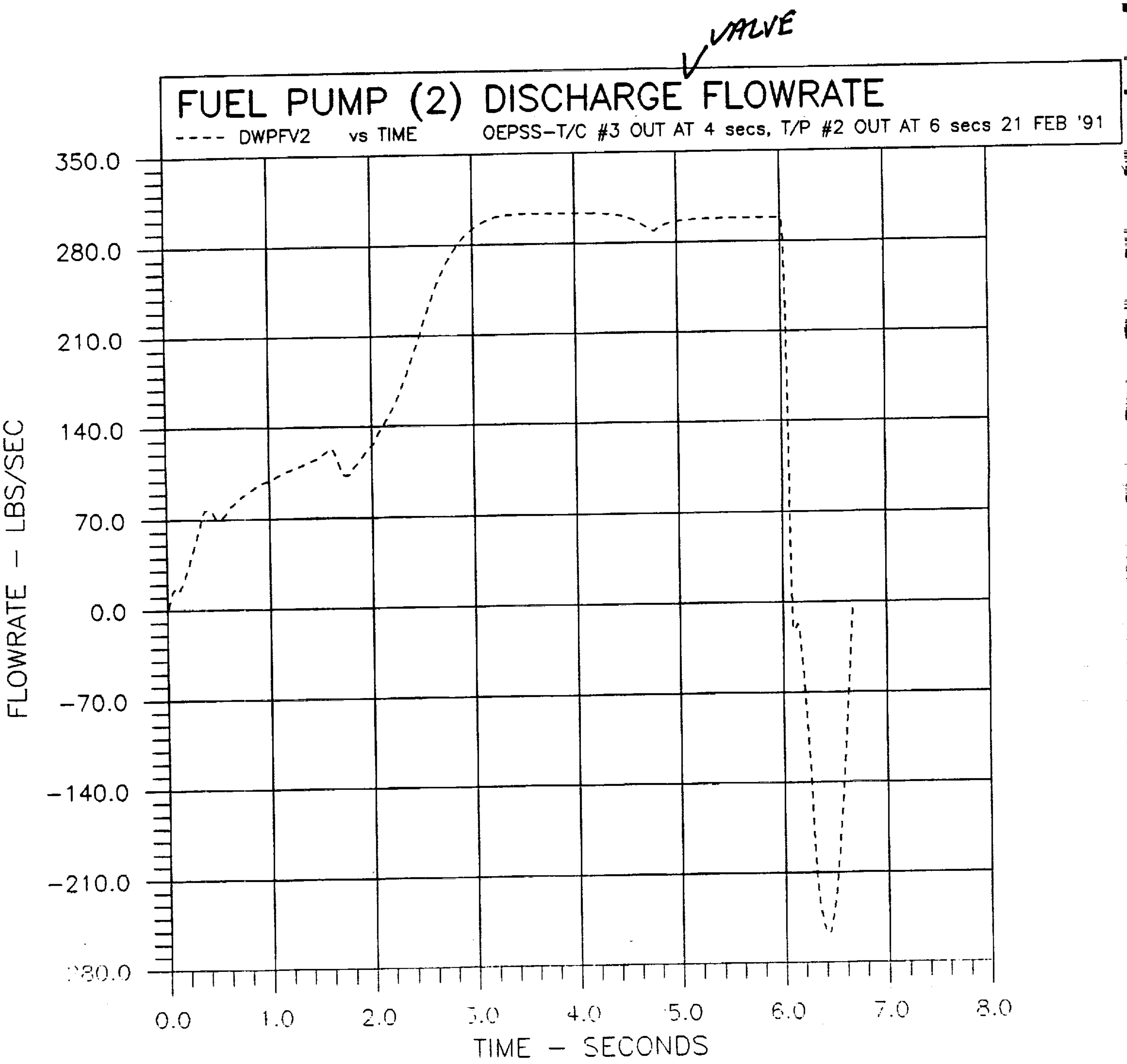

VALVE
FUEL PUMP (2) DISCHARGE FLOWRATE
---- DWPFV2 vs TIME
OEPSS-T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
350.0
280.0
210.0
140.0
70.0
0.0
-70.0
-140.0
-210.0
-280.0
FLOWRATE - LBS/SEC
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
TIME - SECONDS

Figure F10

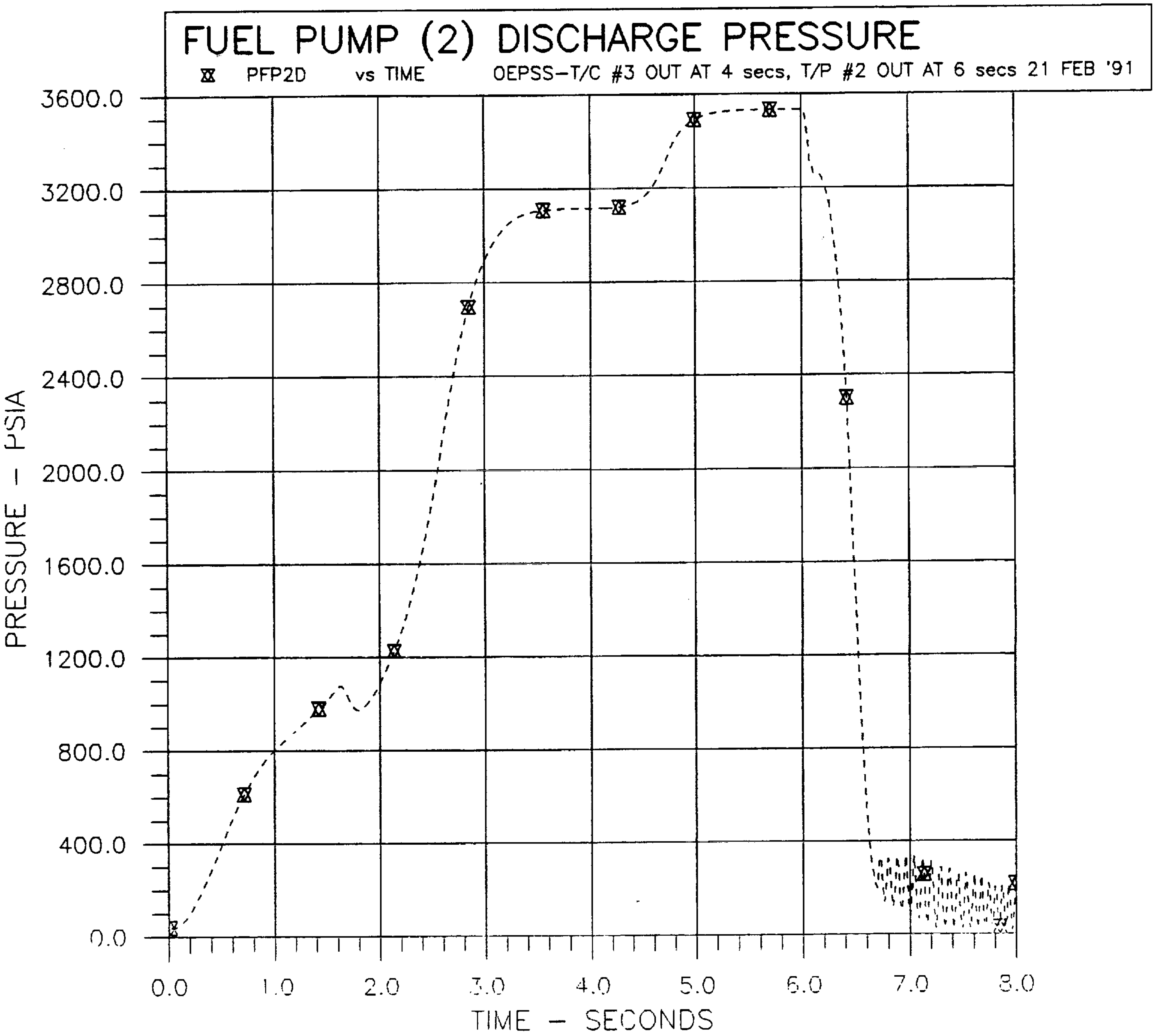

FUEL PUMP (2) DISCHARGE PRESSURE
PFP2D vs TIME
OEPSS-T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
PRESSURE - PSIA
3600.0
3200.0
2800.0
2400.0
2000.0
1600.0
1200.0
800.0
400.0
0.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
TIME - SECONDS

Figure F11

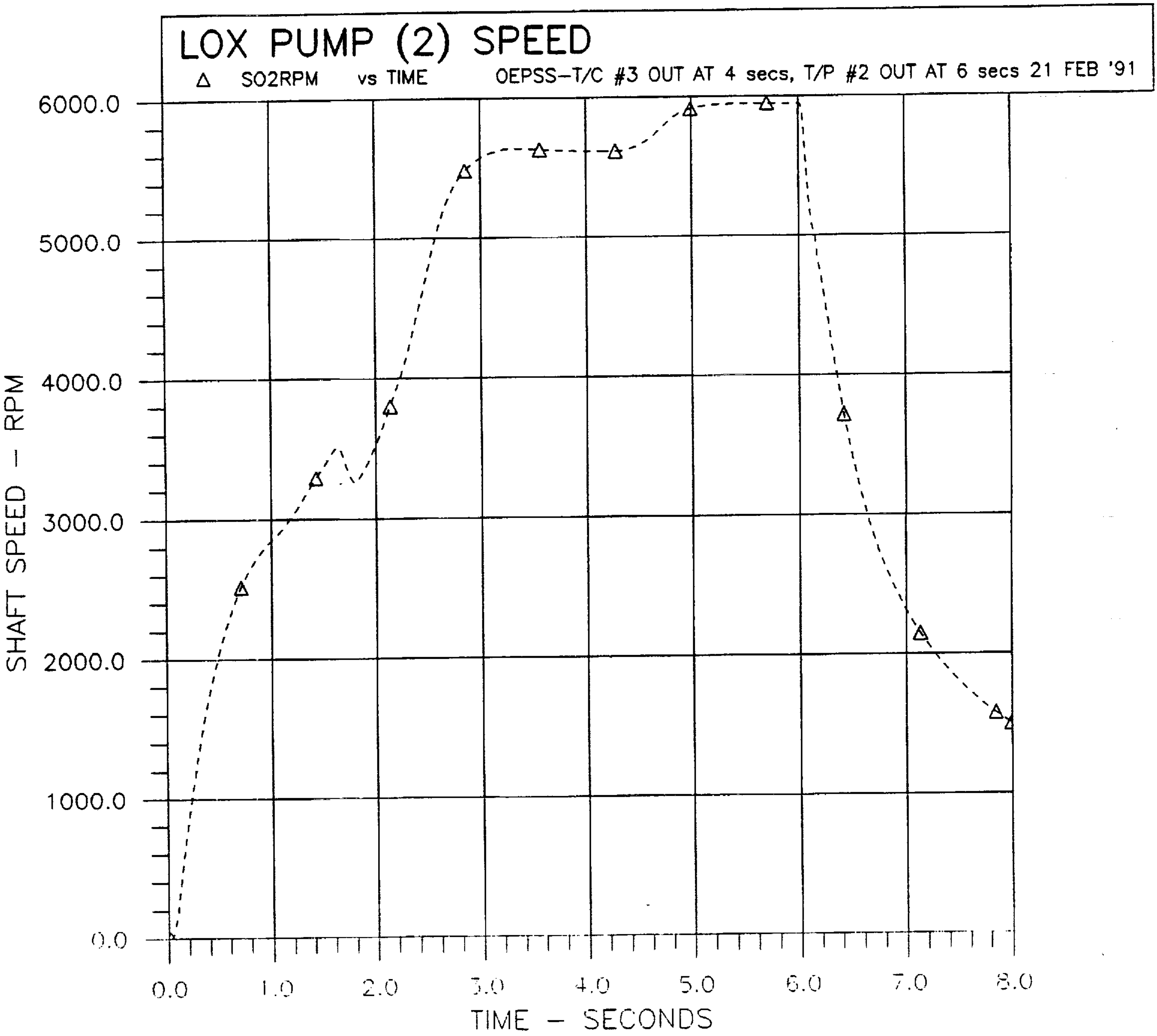

LOX PUMP (2) SPEED
△ SO2RPM vs TIME OEPSS–T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
SHAFT SPEED – RPM
6000.0
5000.0
4000.0
3000.0
2000.0
1000.0
0.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
TIME – SECONDS

Figure F12

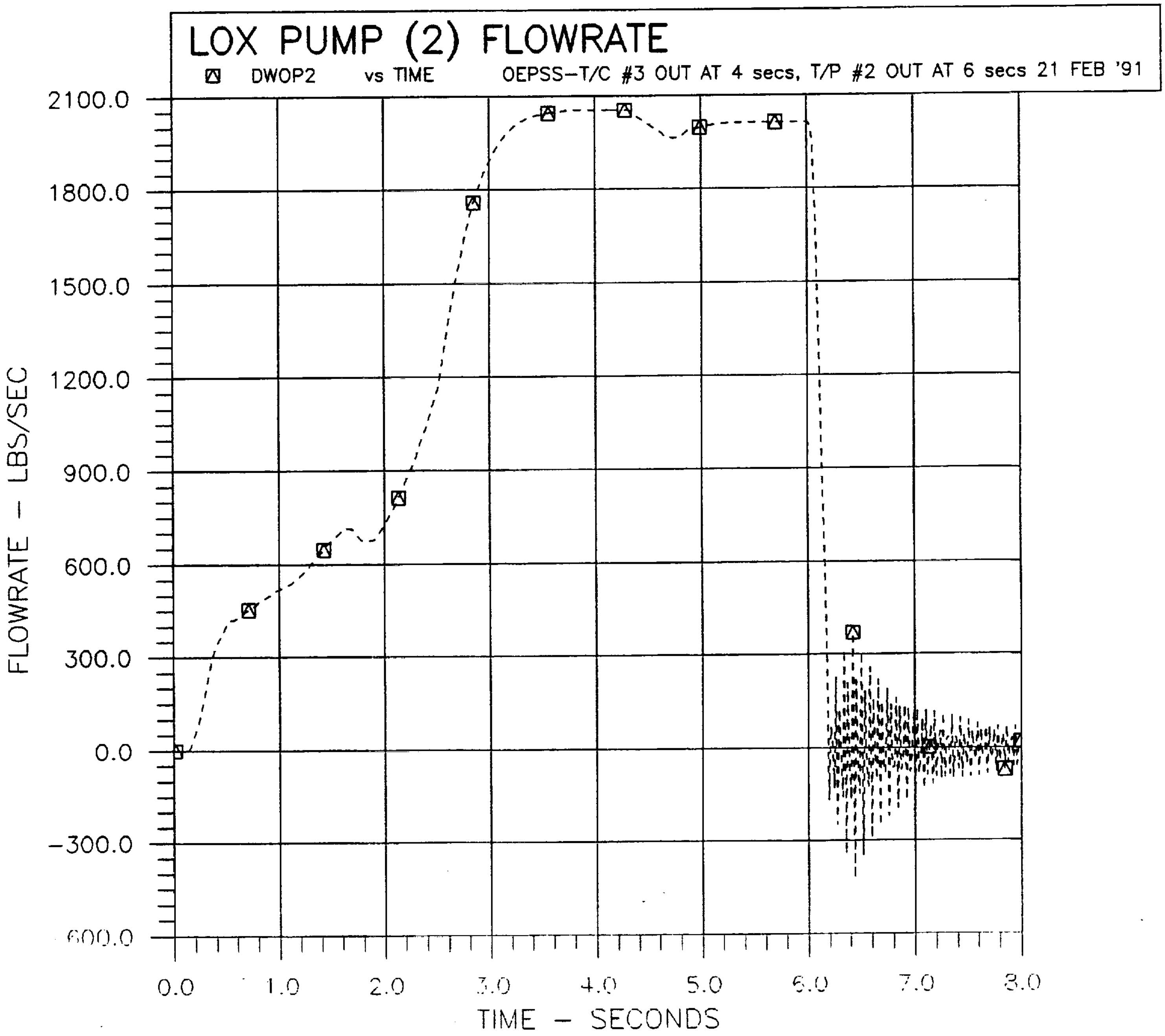

LOX PUMP (2) FLOWRATE
DWOP2 vs TIME
OEPSS–T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
FLOWRATE – LBS/SEC
2100.0
1800.0
1500.0
1200.0
900.0
600.0
300.0
0.0
–300.0
–600.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
TIME – SECONDS

Figure F13

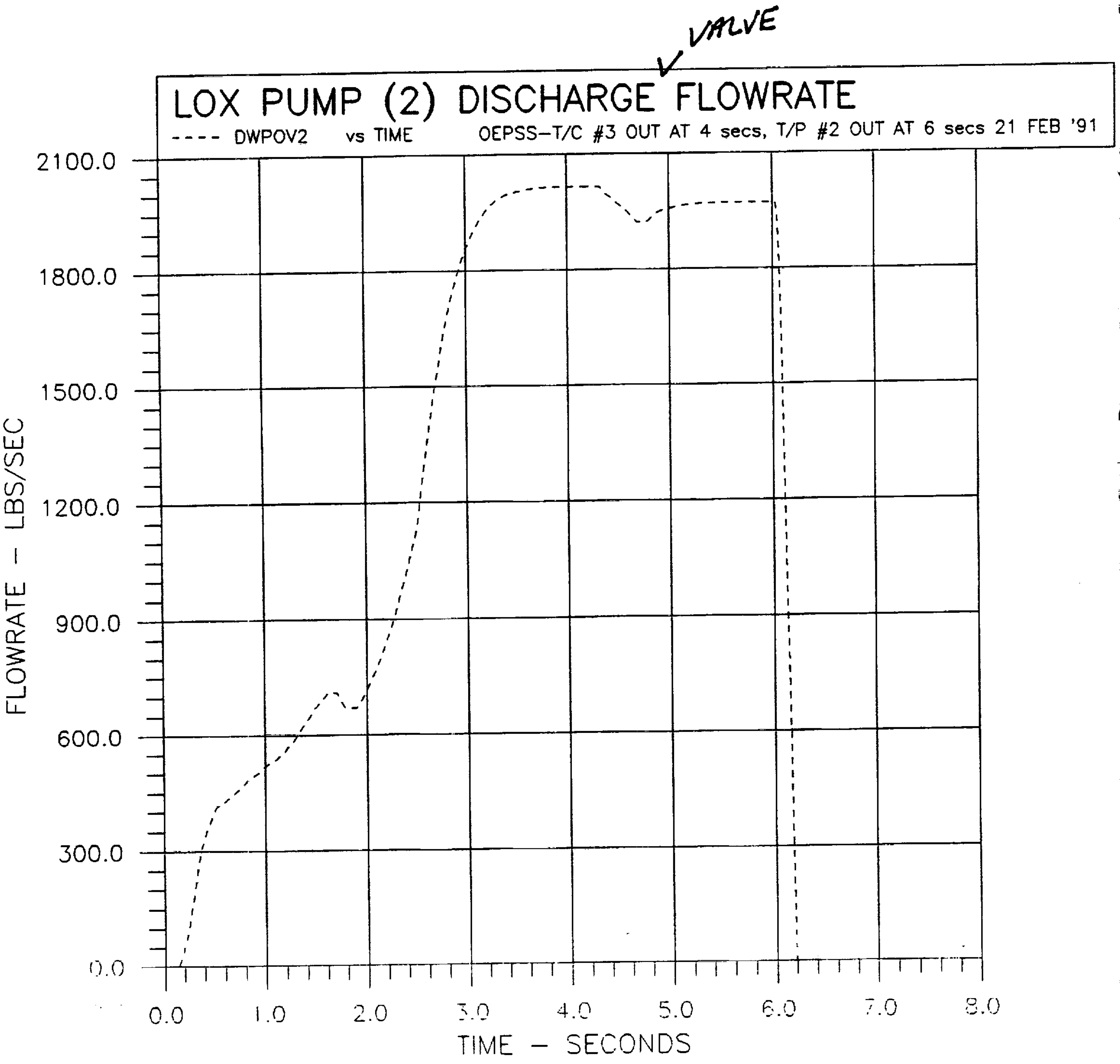

VALVE
LOX PUMP (2) DISCHARGE FLOWRATE
---- DWPOV2 vs TIME
OEPSS–T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
FLOWRATE – LBS/SEC
2100.0
1800.0
1500.0
1200.0
900.0
600.0
300.0
0.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
TIME – SECONDS

Figure F14

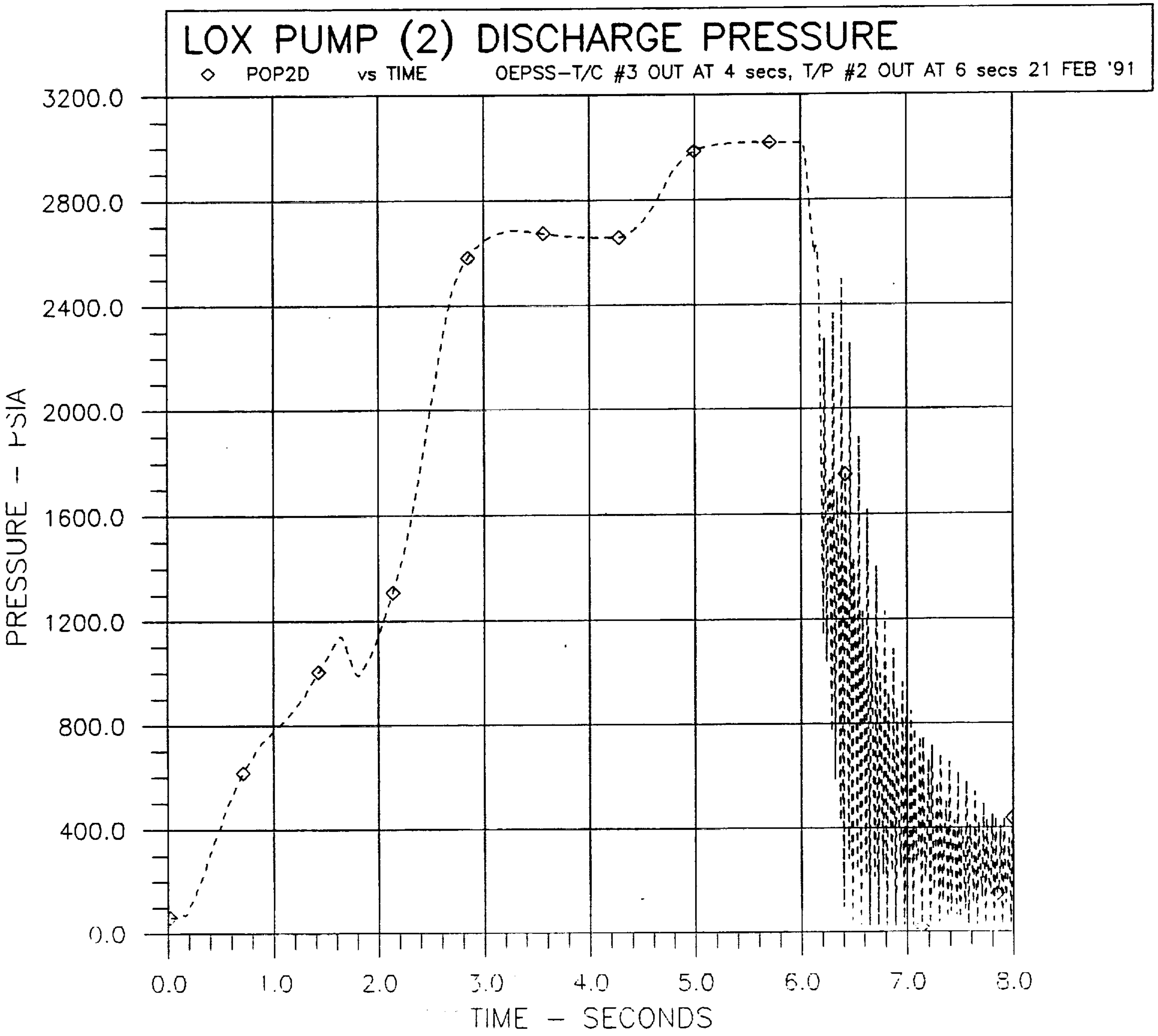
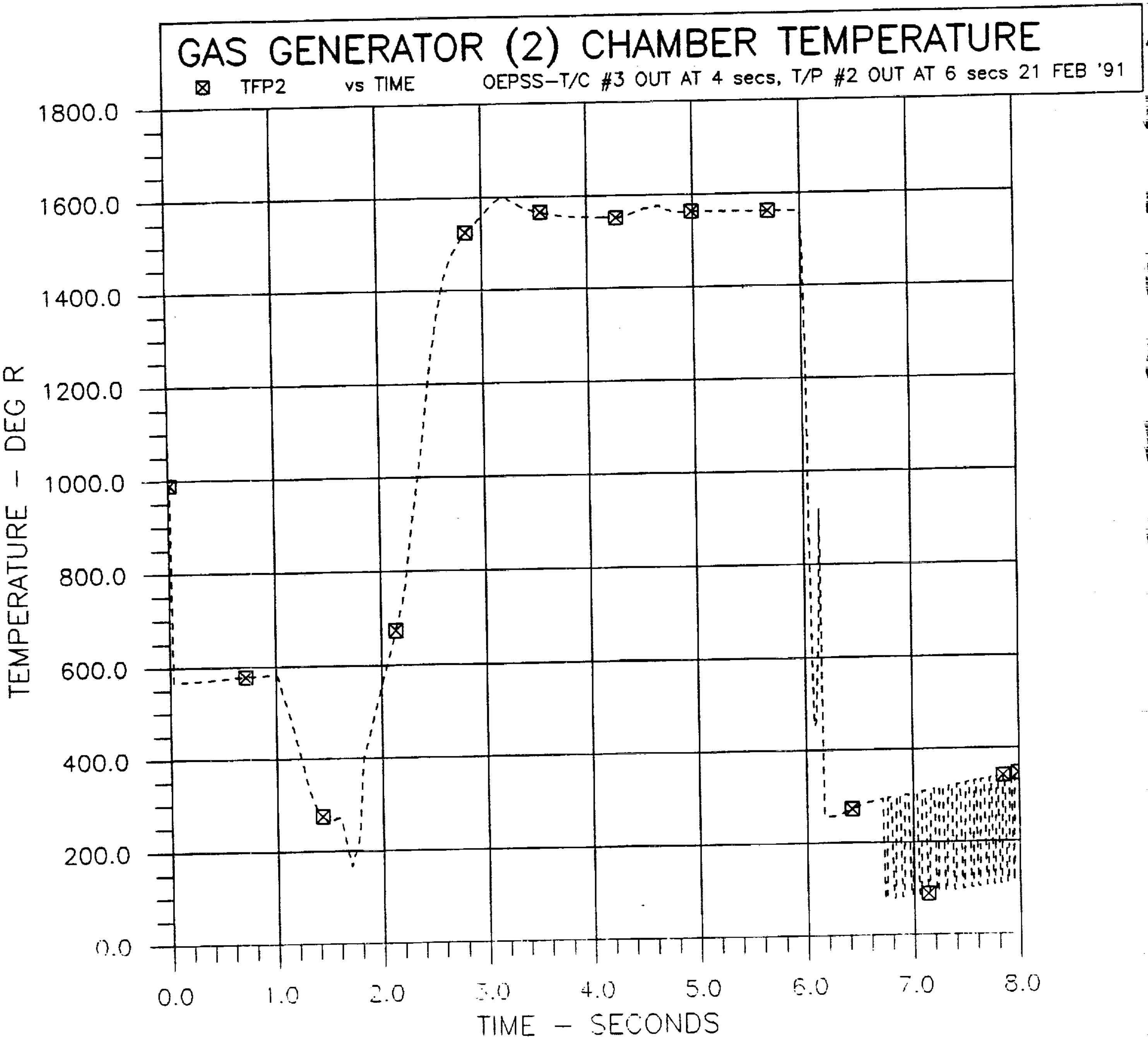

LOX PUMP (2) DISCHARGE PRESSURE
◇ POP2D vs TIME OEPSS-T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
PRESSURE - PSIA
3200.0
2800.0
2400.0
2000.0
1600.0
1200.0
800.0
400.0
0.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
TIME - SECONDS

Figure F15



GAS GENERATOR (2) CHAMBER TEMPERATURE
⊠ TFP2 vs TIME
OEPSS–T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
1800.0
1600.0
1400.0
1200.0
1000.0
800.0
600.0
400.0
200.0
0.0
TEMPERATURE – DEG R
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
TIME – SECONDS

Figure F16

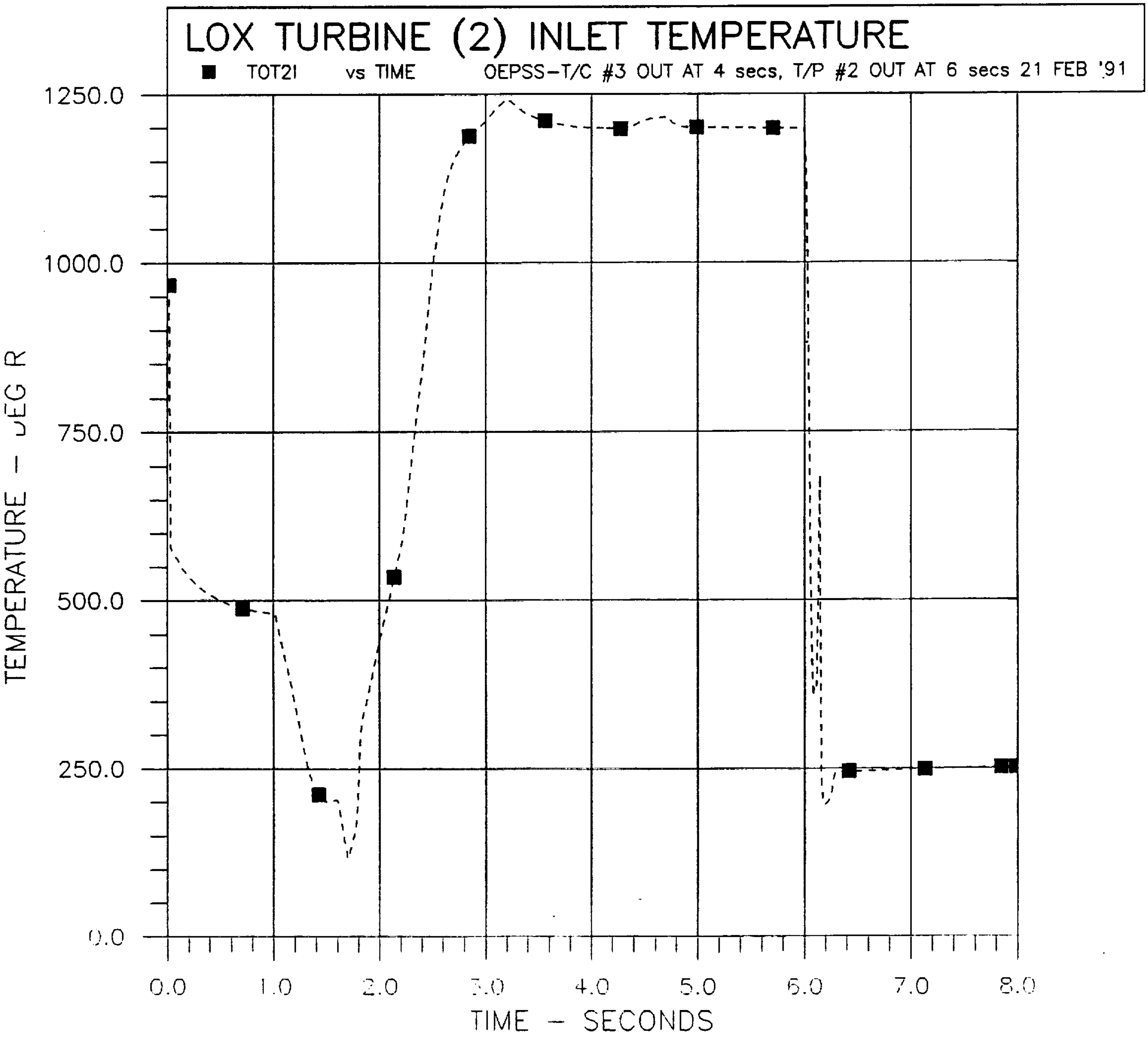

LOX TURBINE (2) INLET TEMPERATURE
■ TOT2I vs TIME OEPSS-T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
1250.0
1000.0
750.0
500.0
250.0
0.0
TEMPERATURE - DEG R
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
TIME - SECONDS

Figure E17

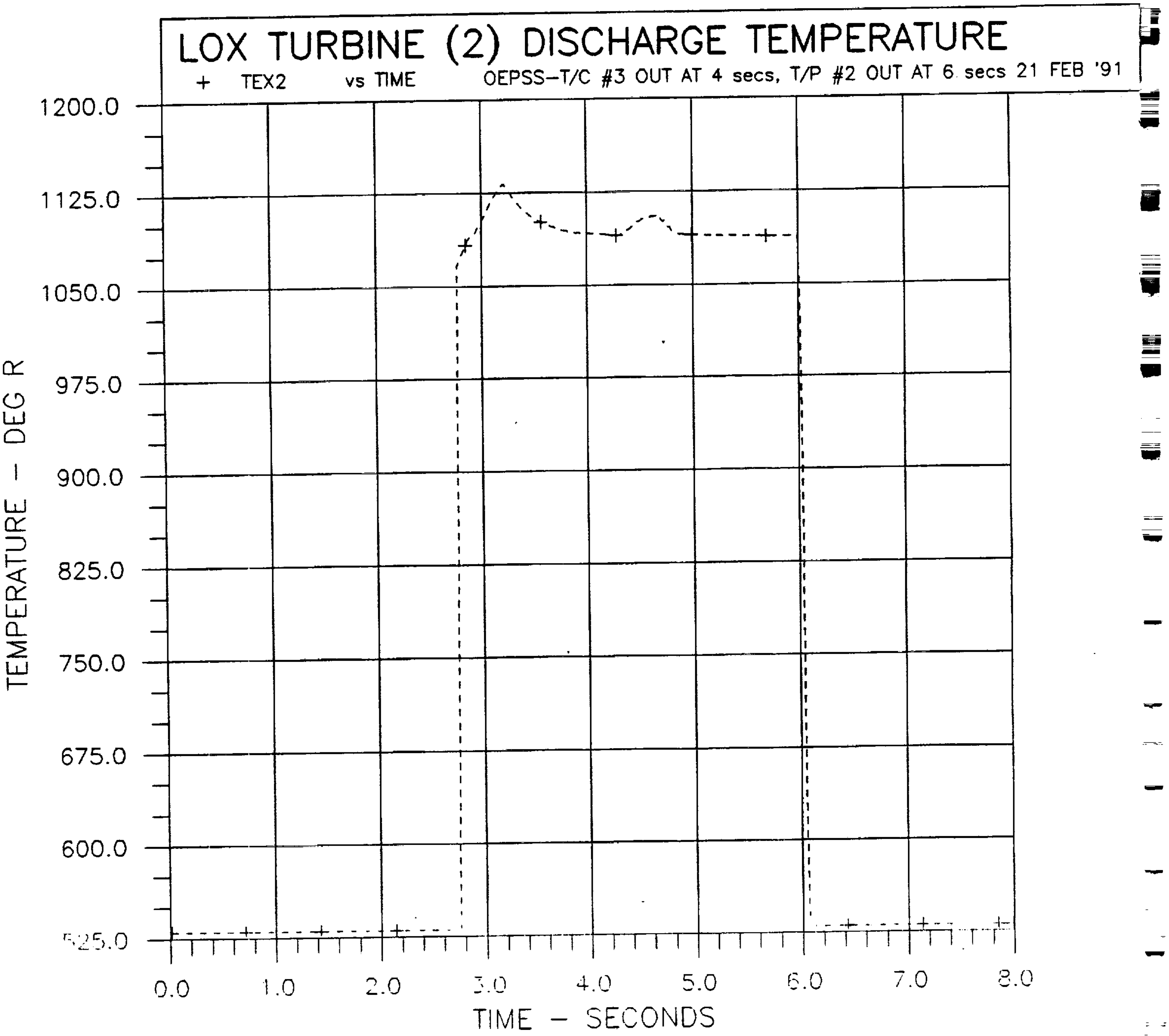

LOX TURBINE (2) DISCHARGE TEMPERATURE
+ TEX2 vs TIME OEPSS-T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
1200.0
1125.0
1050.0
975.0
900.0
825.0
750.0
675.0
600.0
525.0
TEMPERATURE - DEG R
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
TIME - SECONDS

Figure F18

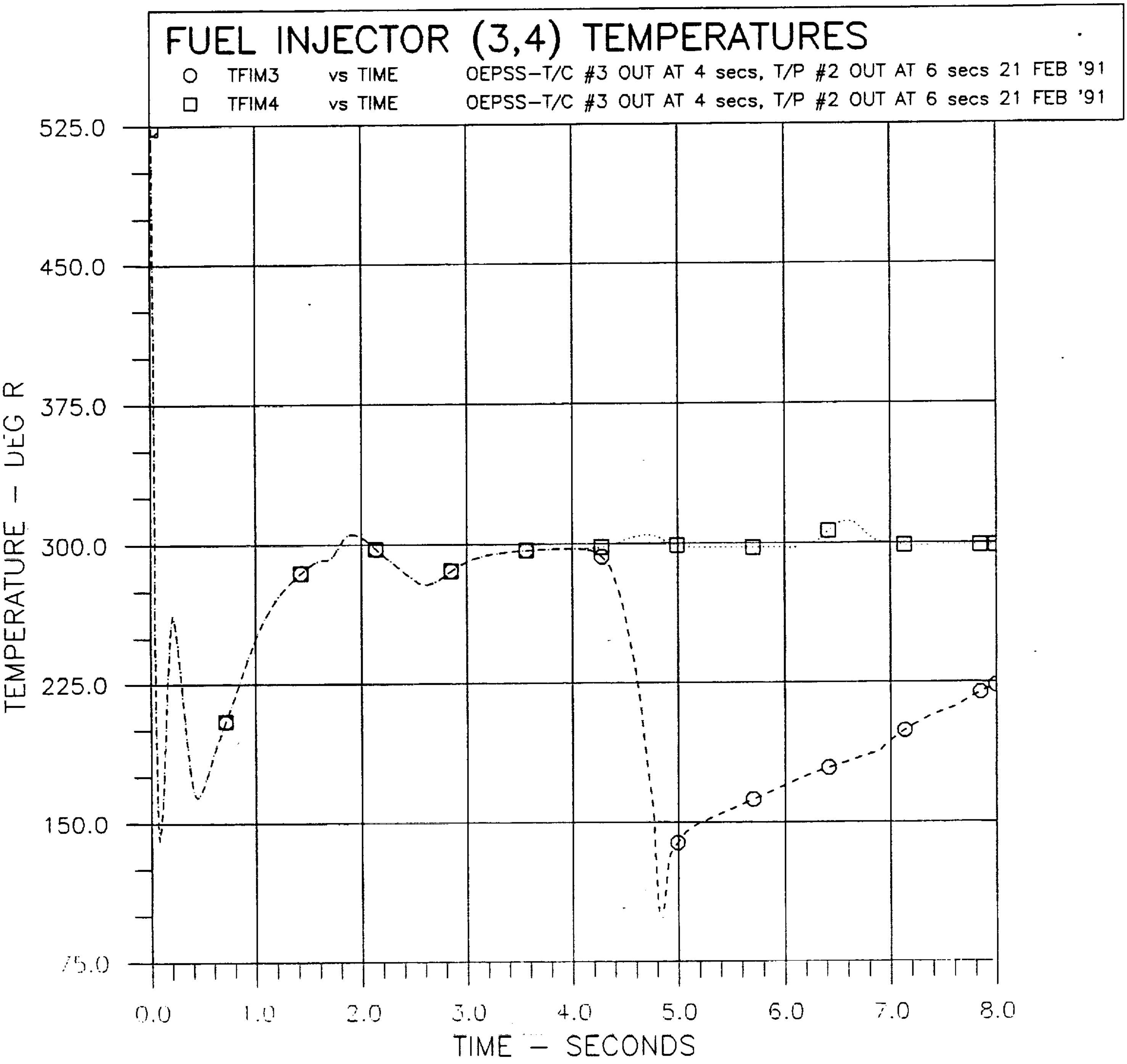

FUEL INJECTOR (3,4) TEMPERATURES
○ TFIM3 vs TIME OEPSS–T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
☐ TFIM4 vs TIME OEPSS–T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
TEMPERATURE – DEG R
525.0
450.0
375.0
300.0
225.0
150.0
75.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
TIME – SECONDS

Figure F19

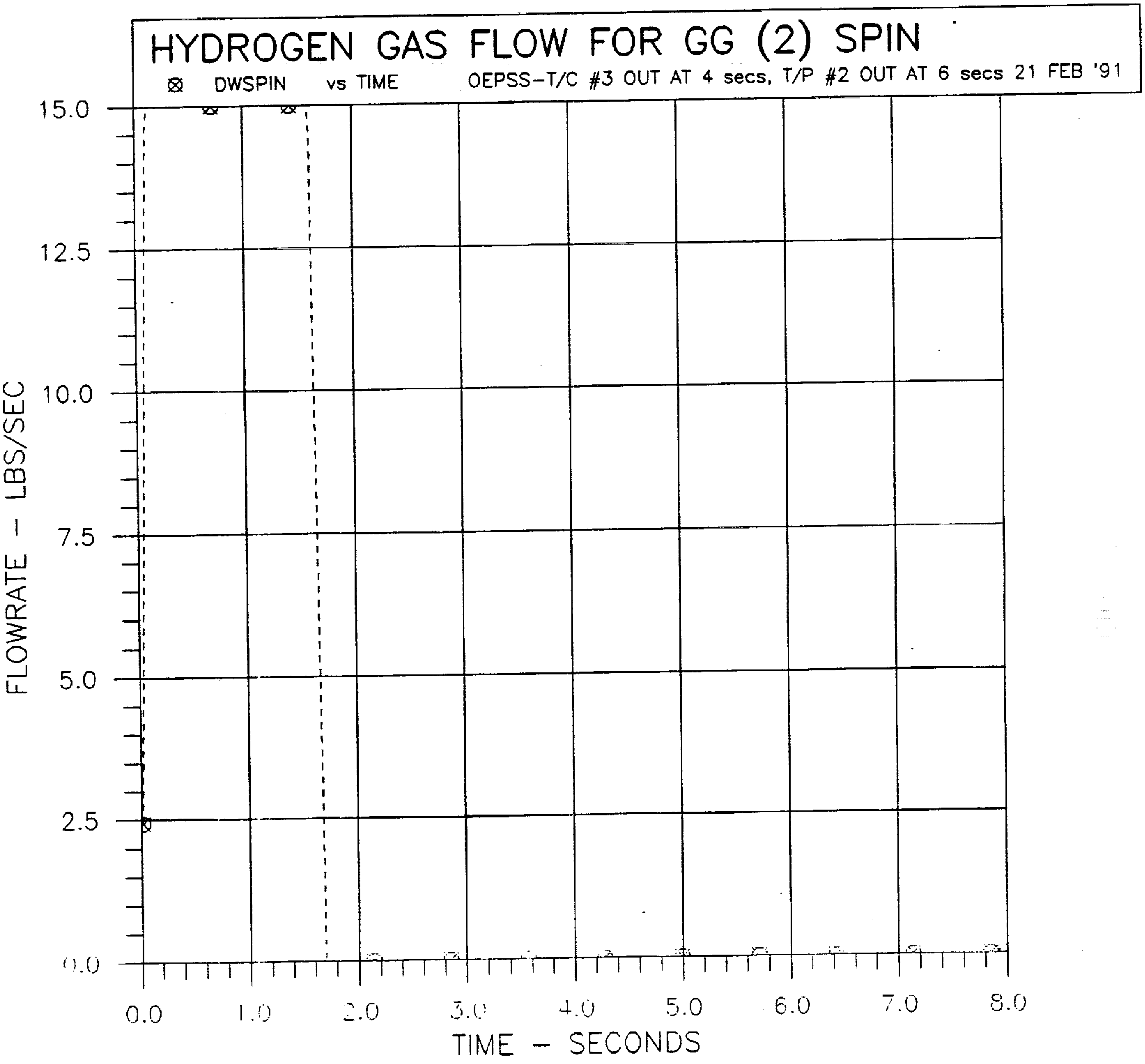

HYDROGEN GAS FLOW FOR GG (2) SPIN
⊠ DWSPIN vs TIME
OEPSS-T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
FLOWRATE - LBS/SEC
15.0
12.5
10.0
7.5
5.0
2.5
0.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
TIME - SECONDS

Figure F20

APPENDIX G

COMBINED THRUST CHAMBER/TURBOPUMP OUT CONDITION RESULTS

FOR SYSTEM 3

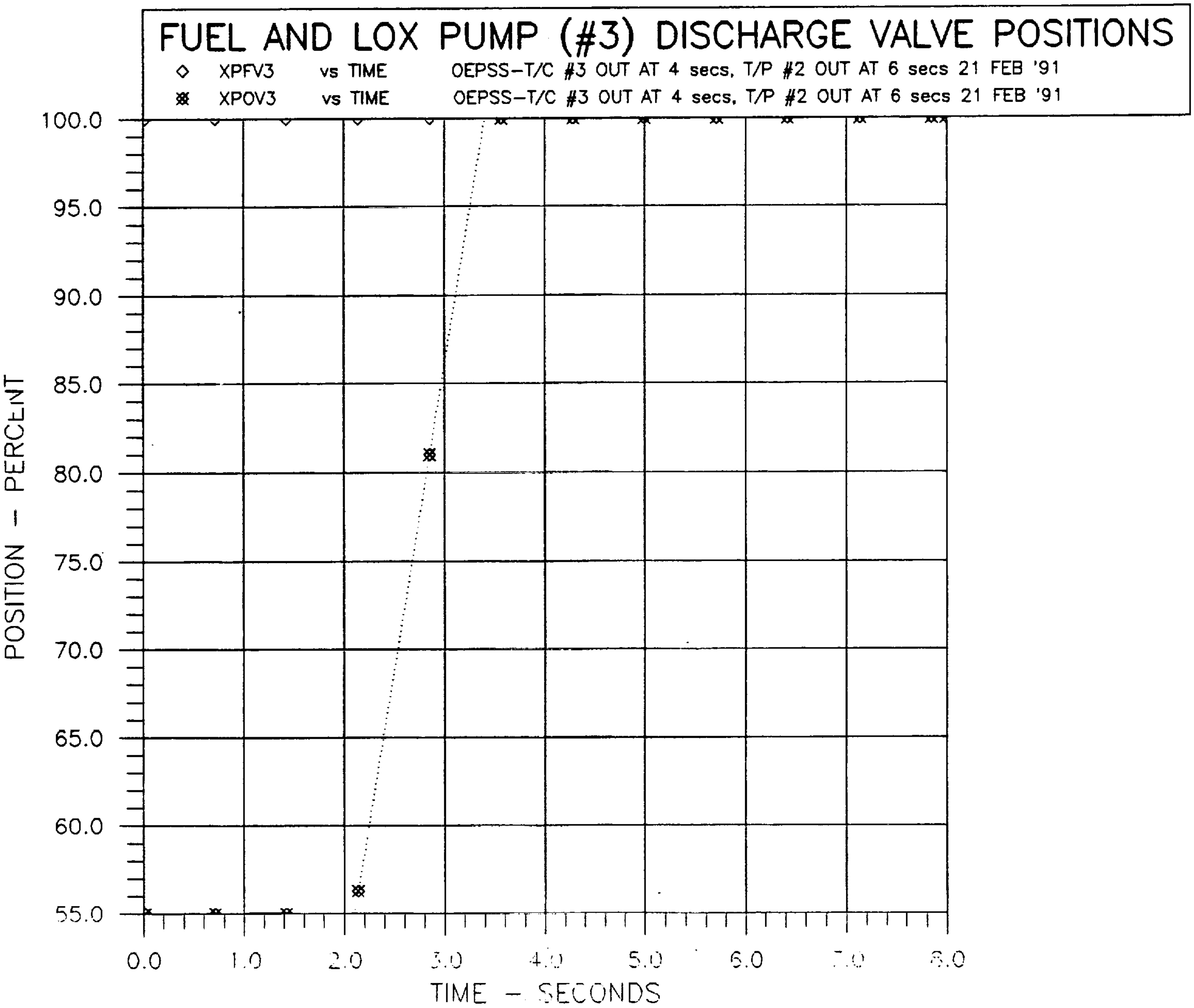

FUEL AND LOX PUMP (#3) DISCHARGE VALVE POSITIONS
◇ XPFV3 vs TIME OEPSS–T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
⊗ XPOV3 vs TIME OEPSS–T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
POSITION – PERCENT
100.0
95.0
90.0
85.0
80.0
75.0
70.0
65.0
60.0
55.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
TIME – SECONDS

Figure G1

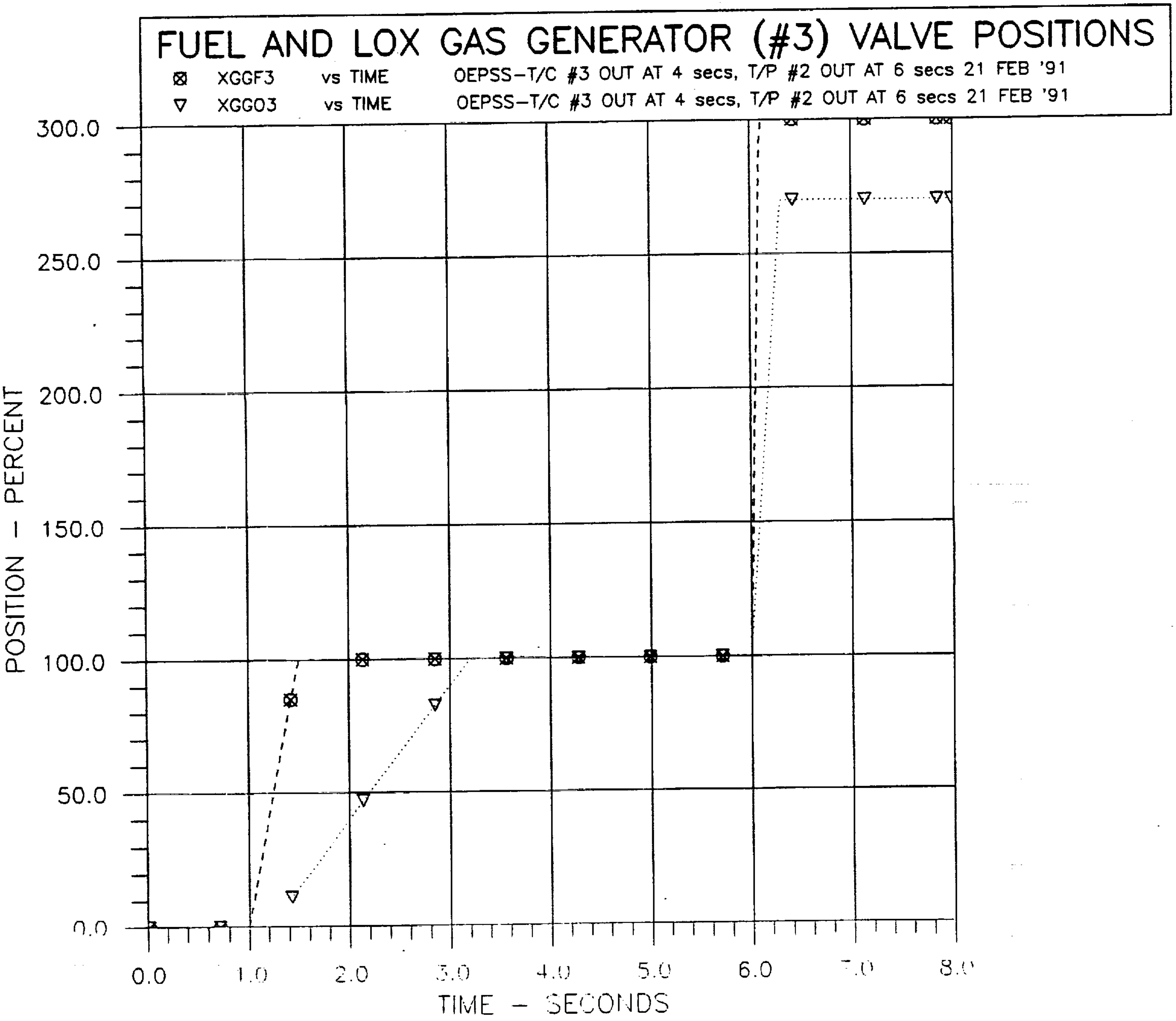

FUEL AND LOX GAS GENERATOR (#3) VALVE POSITIONS
⊠ XGGF3 vs TIME OEPSS-T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
▽ XGGO3 vs TIME OEPSS-T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
POSITION - PERCENT
300.0
250.0
200.0
150.0
100.0
50.0
0.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
TIME - SECONDS

Figure G2

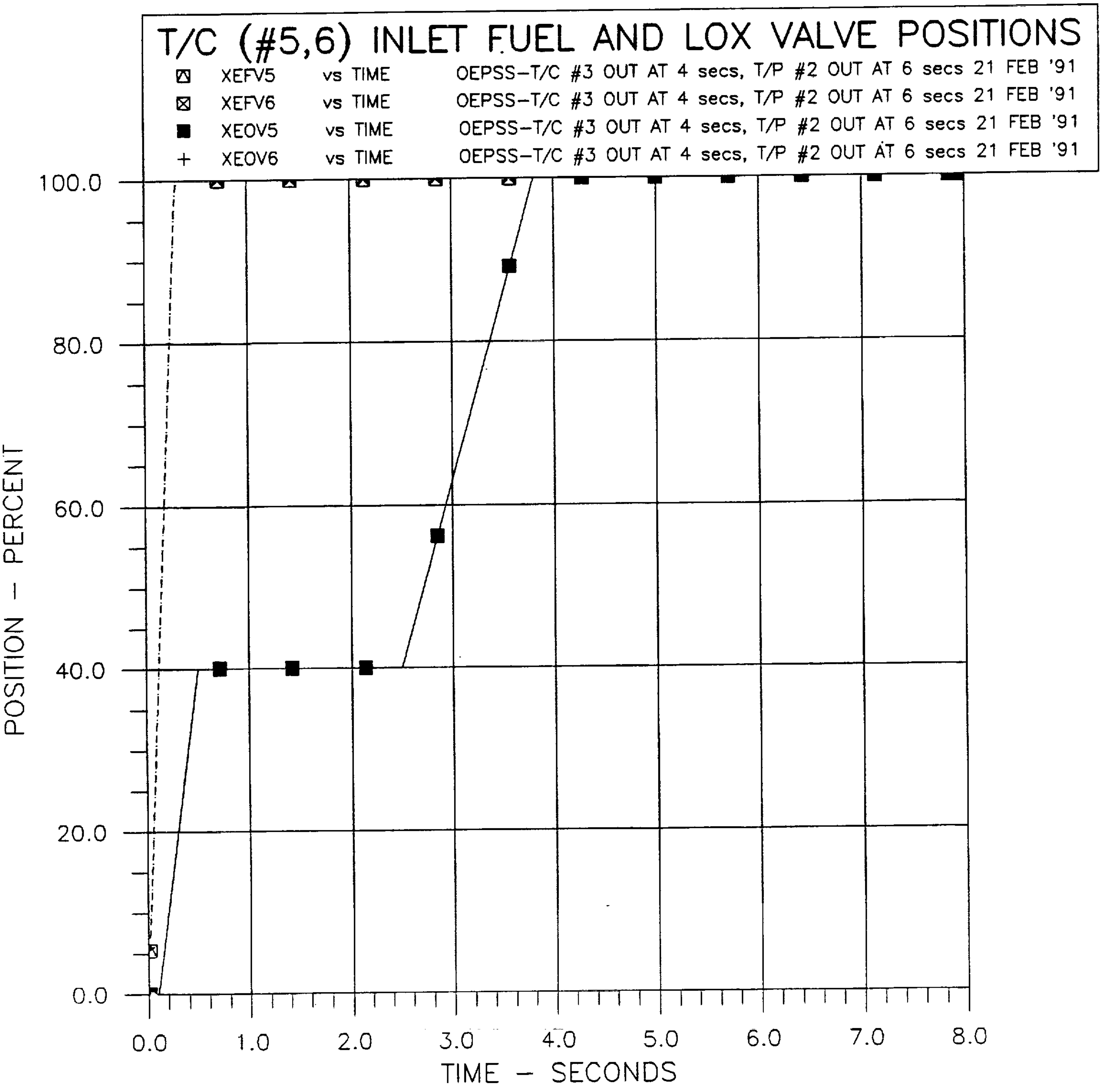

T/C (#5,6) INLET FUEL AND LOX VALVE POSITIONS
XEFV5 vs TIME OEPSS–T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
XEFV6 vs TIME OEPSS–T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
XEOV5 vs TIME OEPSS–T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
XEOV6 vs TIME OEPSS–T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
POSITION – PERCENT
0.0
20.0
40.0
60.0
80.0
100.0
TIME – SECONDS
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0

Figure G3

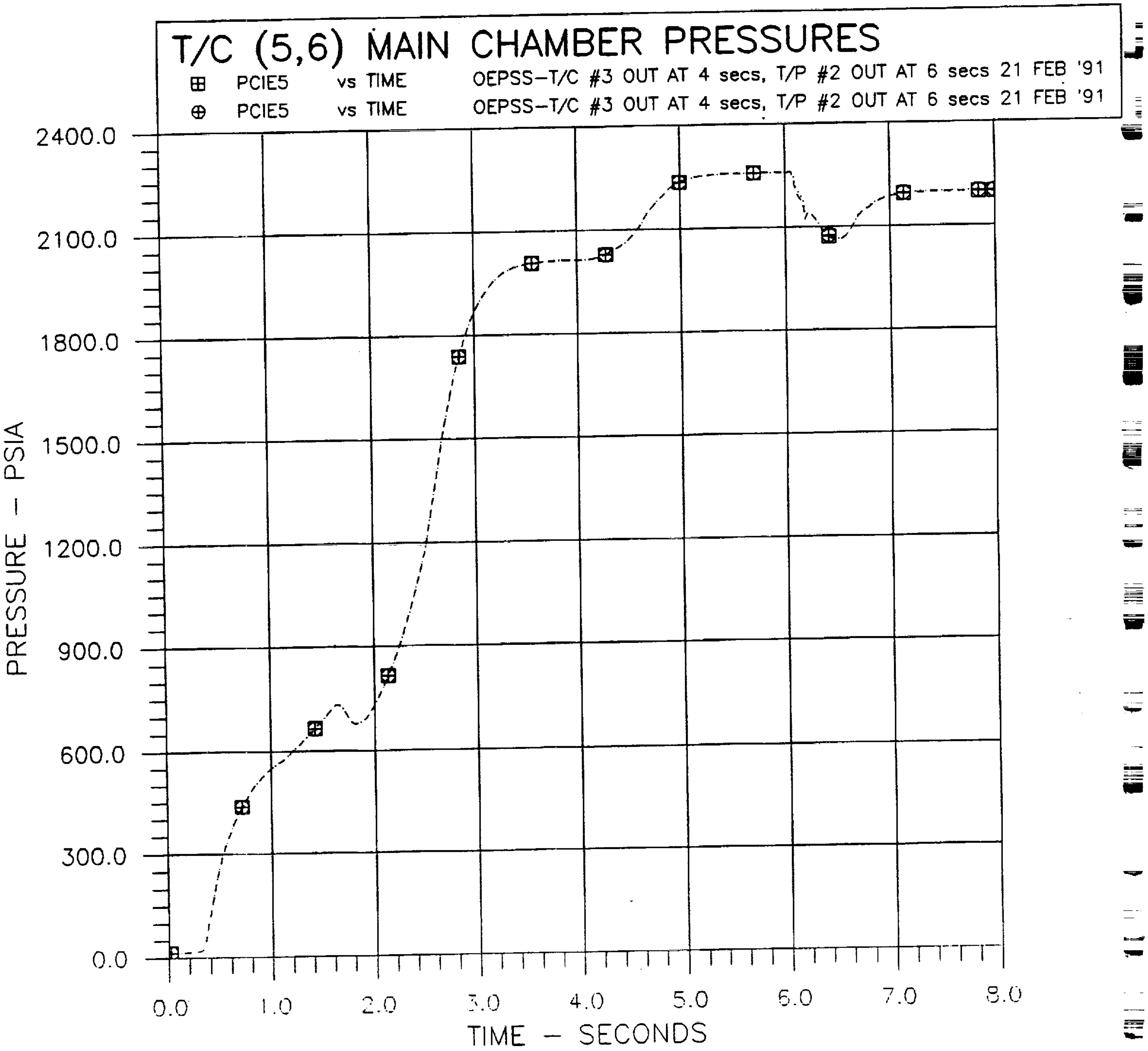

T/C (5,6) MAIN CHAMBER PRESSURES
⊞ PCIE5 vs TIME OEPSS–T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
⊕ PCIE5 vs TIME OEPSS–T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
2400.0
2100.0
1800.0
1500.0
1200.0
900.0
600.0
300.0
0.0
PRESSURE – PSIA
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
TIME – SECONDS

Figure G4

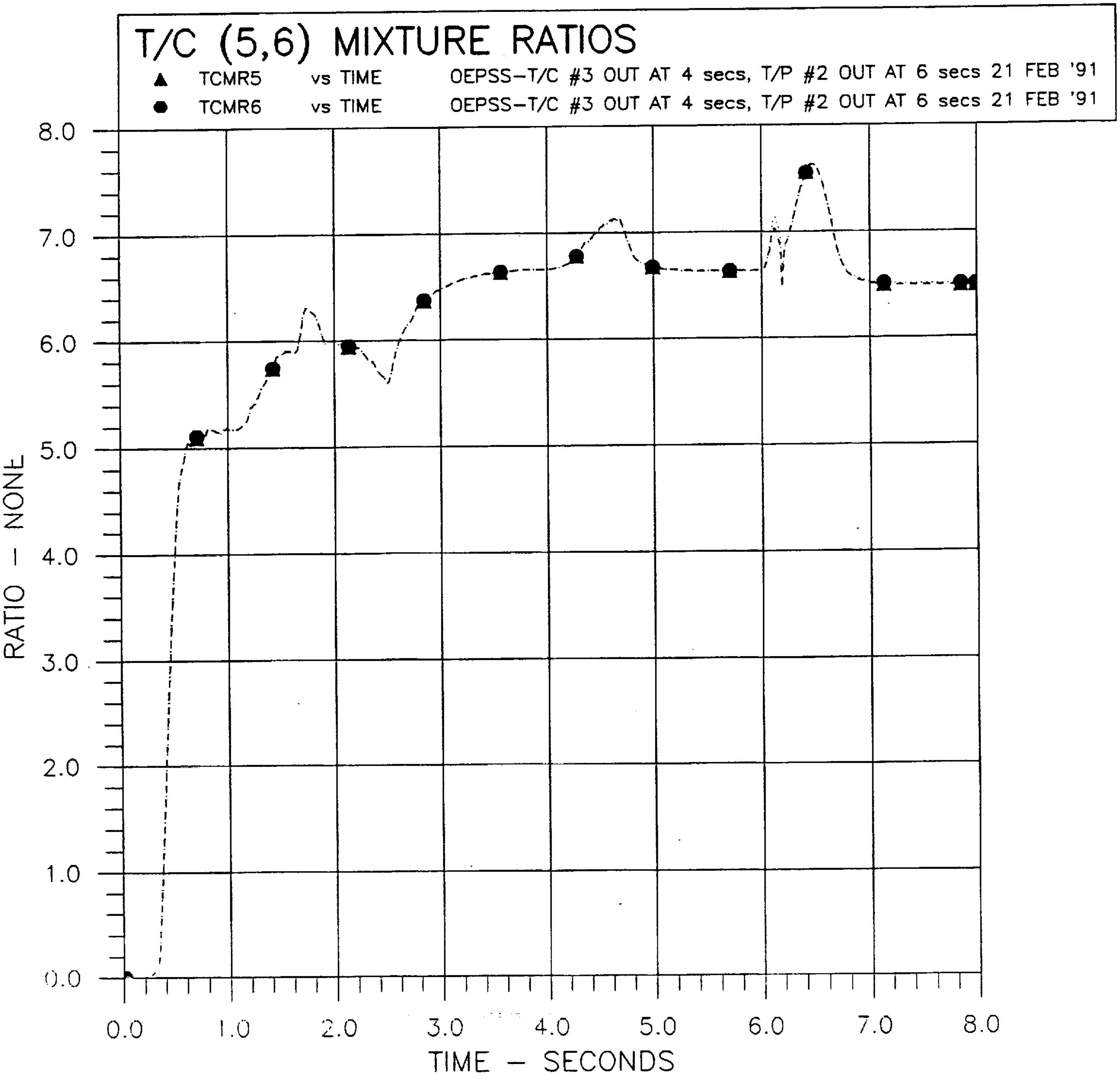

T/C (5,6) MIXTURE RATIOS
▲ TCMR5 vs TIME OEPSS-T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
● TCMR6 vs TIME OEPSS-T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
RATIO - NONE
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
TIME - SECONDS

Figure G5

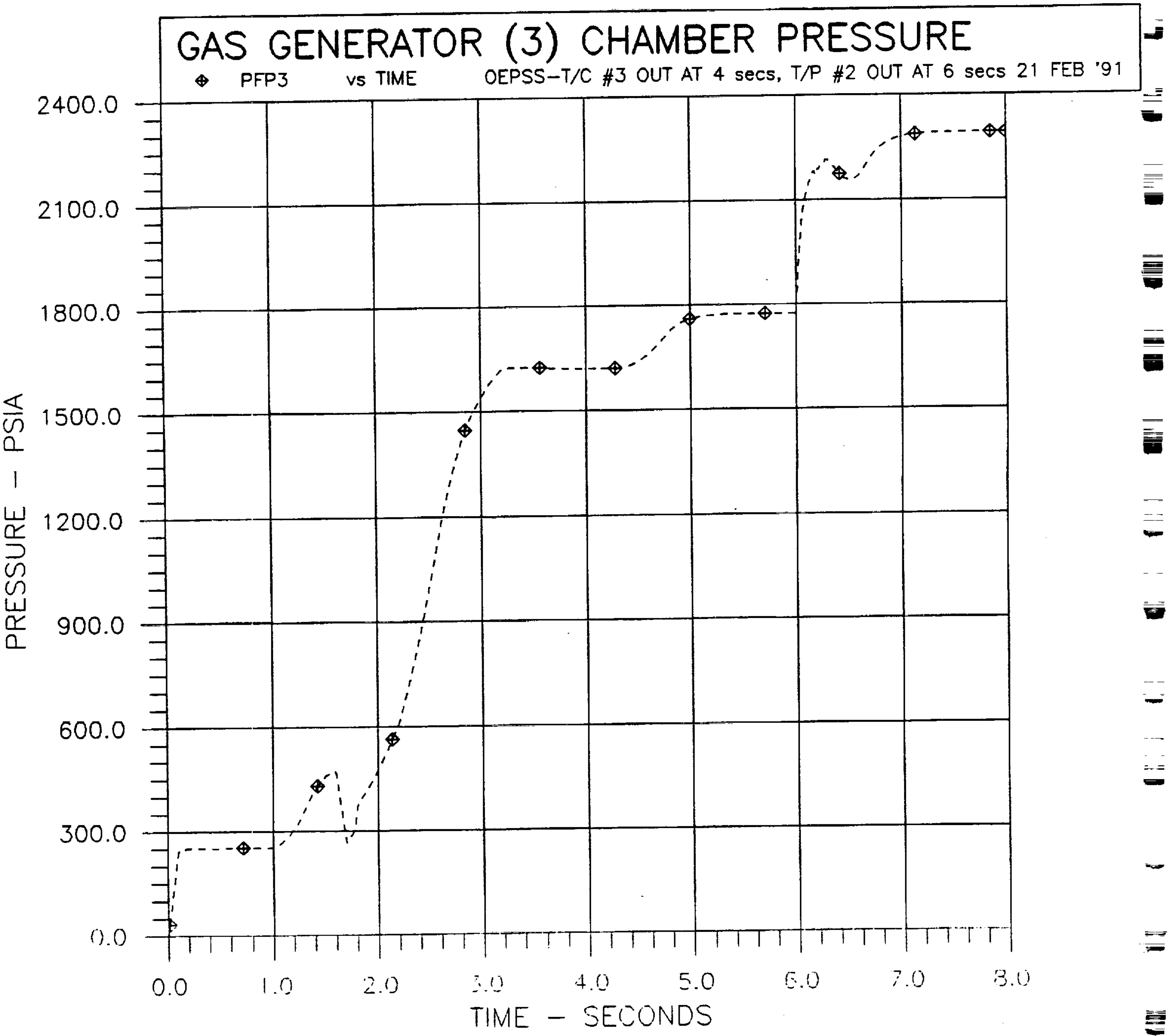

GAS GENERATOR (3) CHAMBER PRESSURE
⊕ PFP3 vs TIME OEPSS–T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
PRESSURE – PSIA
2400.0
2100.0
1800.0
1500.0
1200.0
900.0
600.0
300.0
0.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
TIME – SECONDS

Figure G6

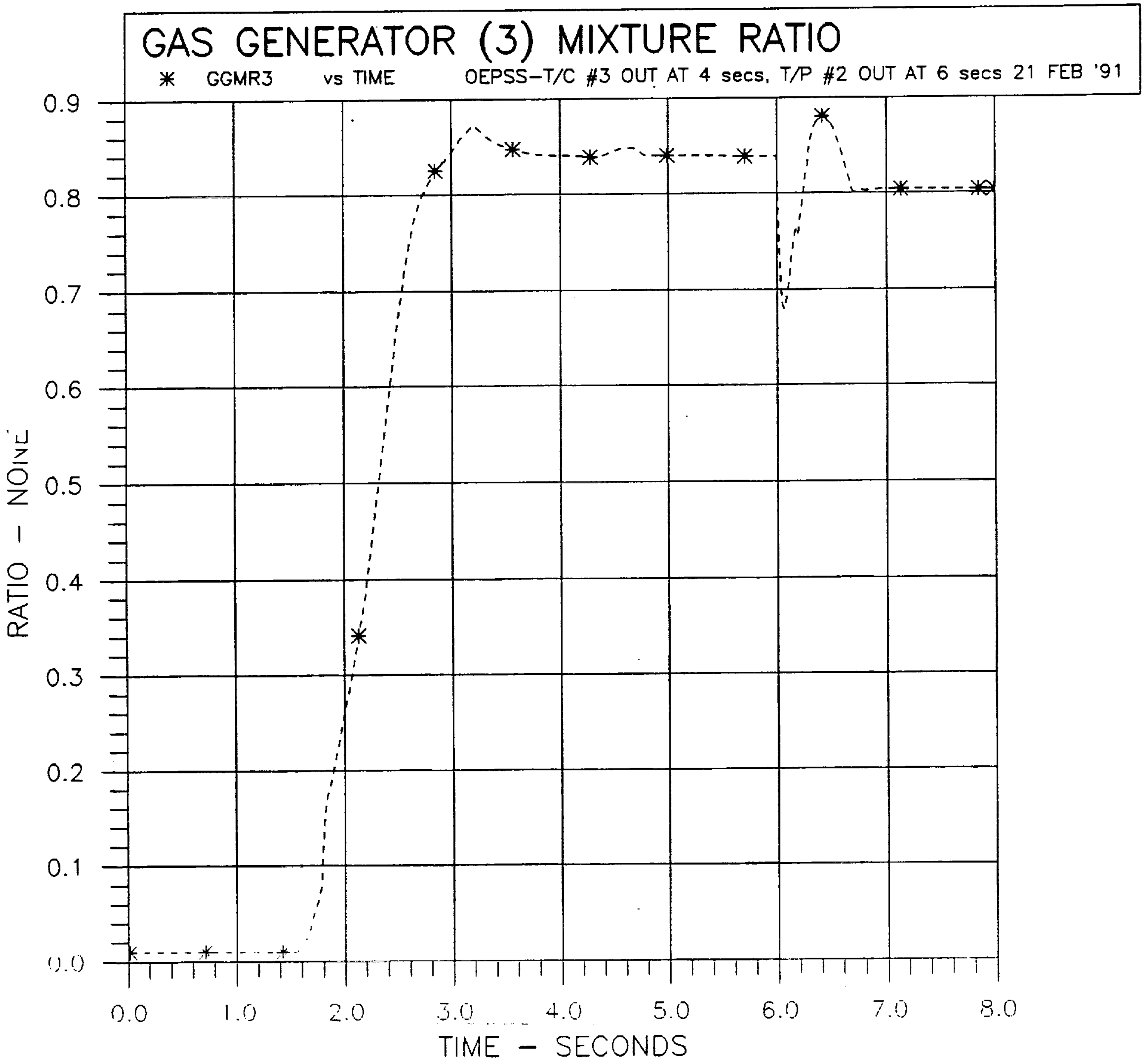
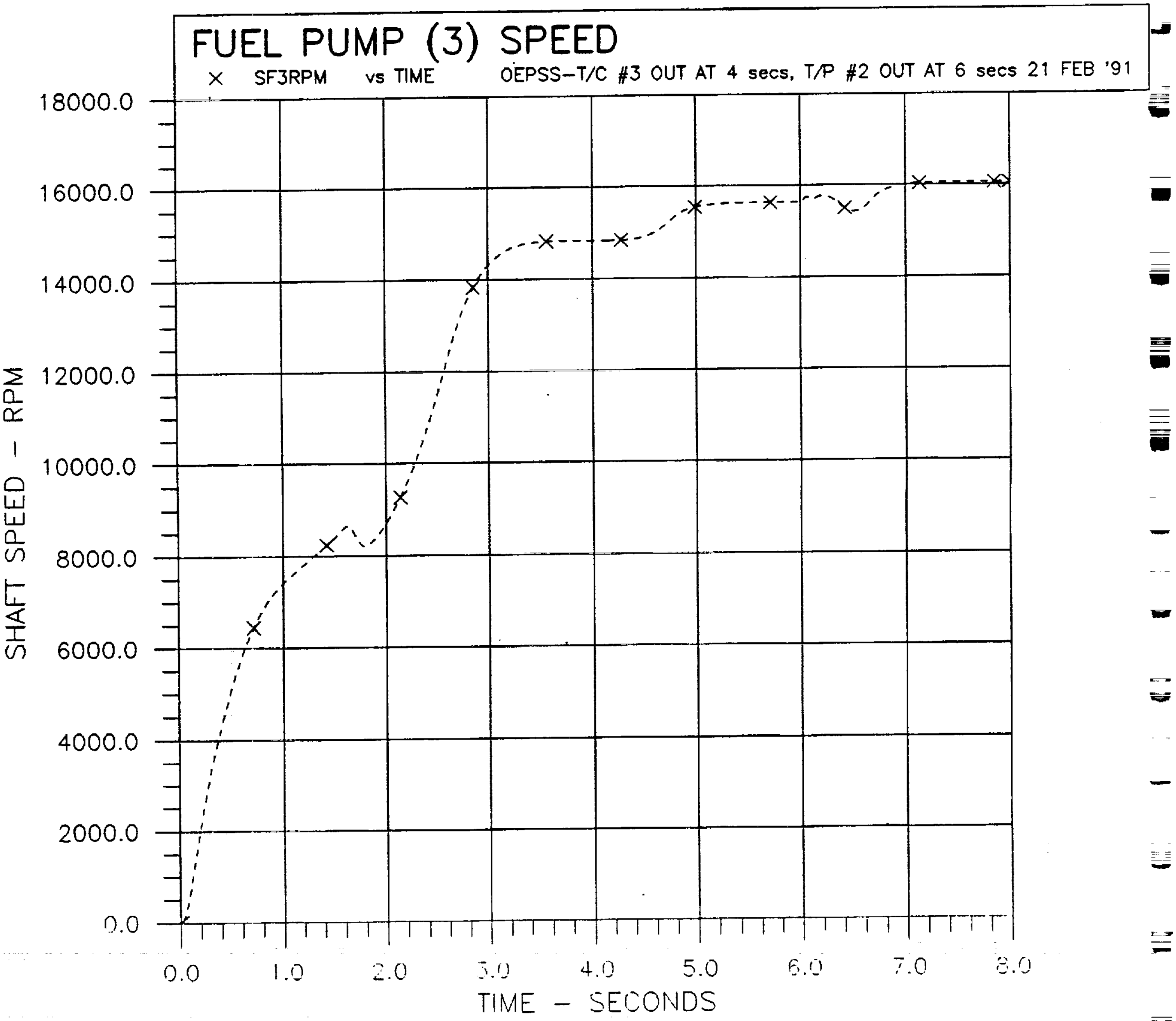

GAS GENERATOR (3) MIXTURE RATIO
✳ GGMR3 vs TIME OEPSS–T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
RATIO – NONE
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
TIME – SECONDS

Figure G7



FUEL PUMP (3) SPEED
× SF3RPM vs TIME
OEPSS-T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
SHAFT SPEED - RPM
18000.0
16000.0
14000.0
12000.0
10000.0
8000.0
6000.0
4000.0
2000.0
0.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
TIME - SECONDS

Figure G8

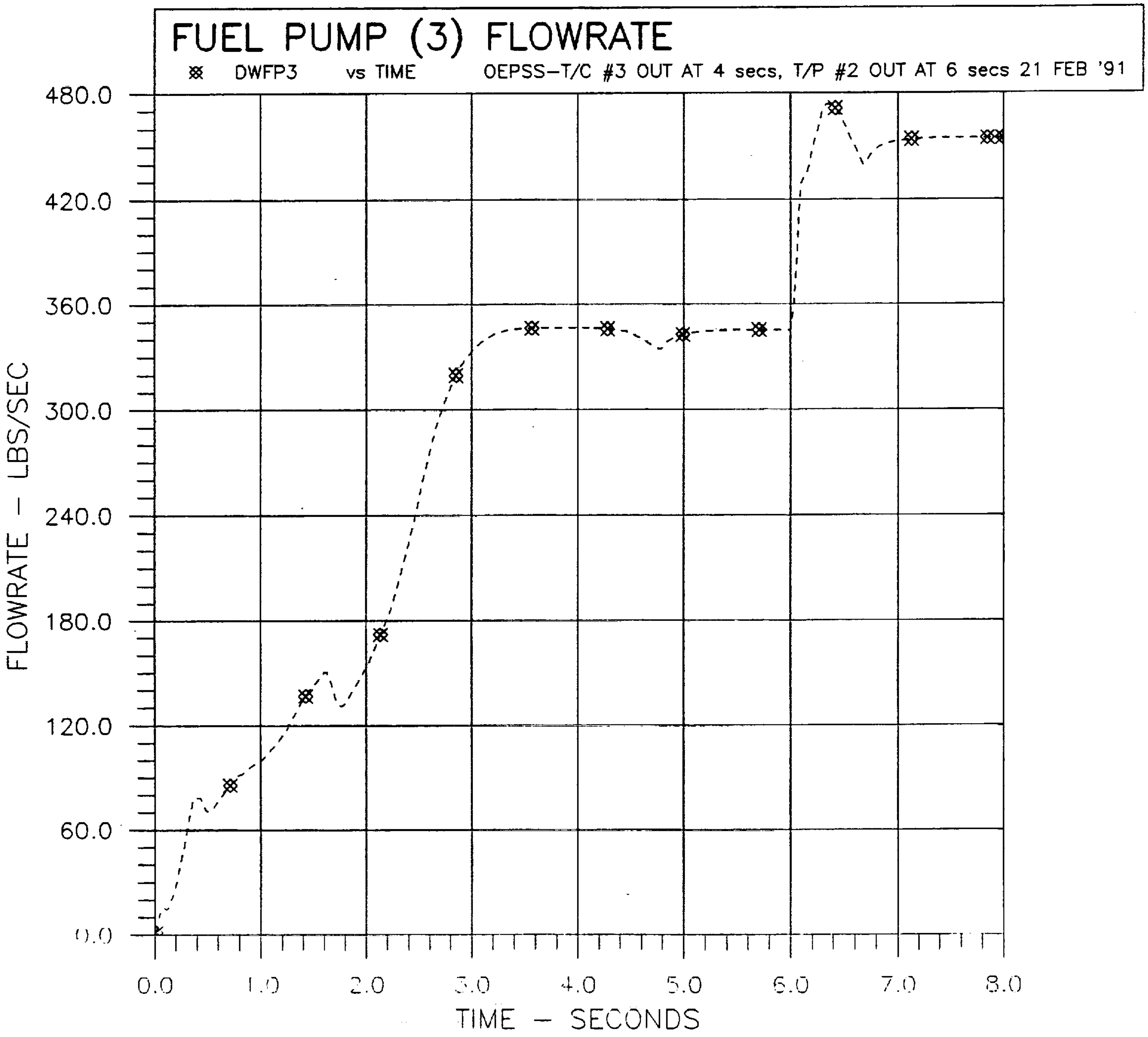

FUEL PUMP (3) FLOWRATE
⊗ DWFP3 vs TIME OEPSS–T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
FLOWRATE – LBS/SEC
480.0
420.0
360.0
300.0
240.0
180.0
120.0
60.0
0.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
TIME – SECONDS

Figure G9

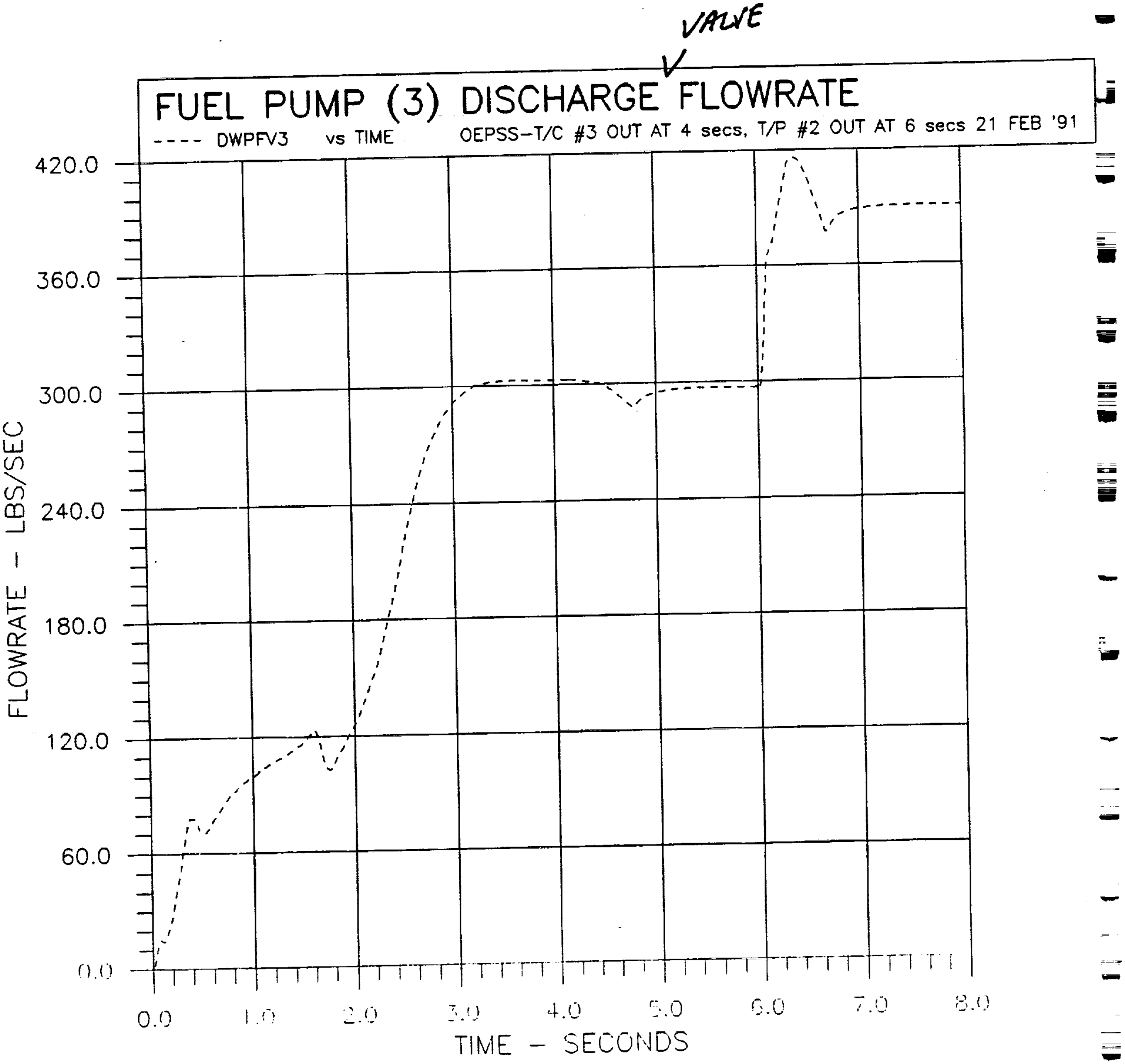

VALVE
FUEL PUMP (3) DISCHARGE FLOWRATE
---- DWPFV3 vs TIME
OEPSS–T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
420.0
360.0
300.0
240.0
180.0
120.0
60.0
0.0
FLOWRATE – LBS/SEC
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
TIME – SECONDS

Figure G10

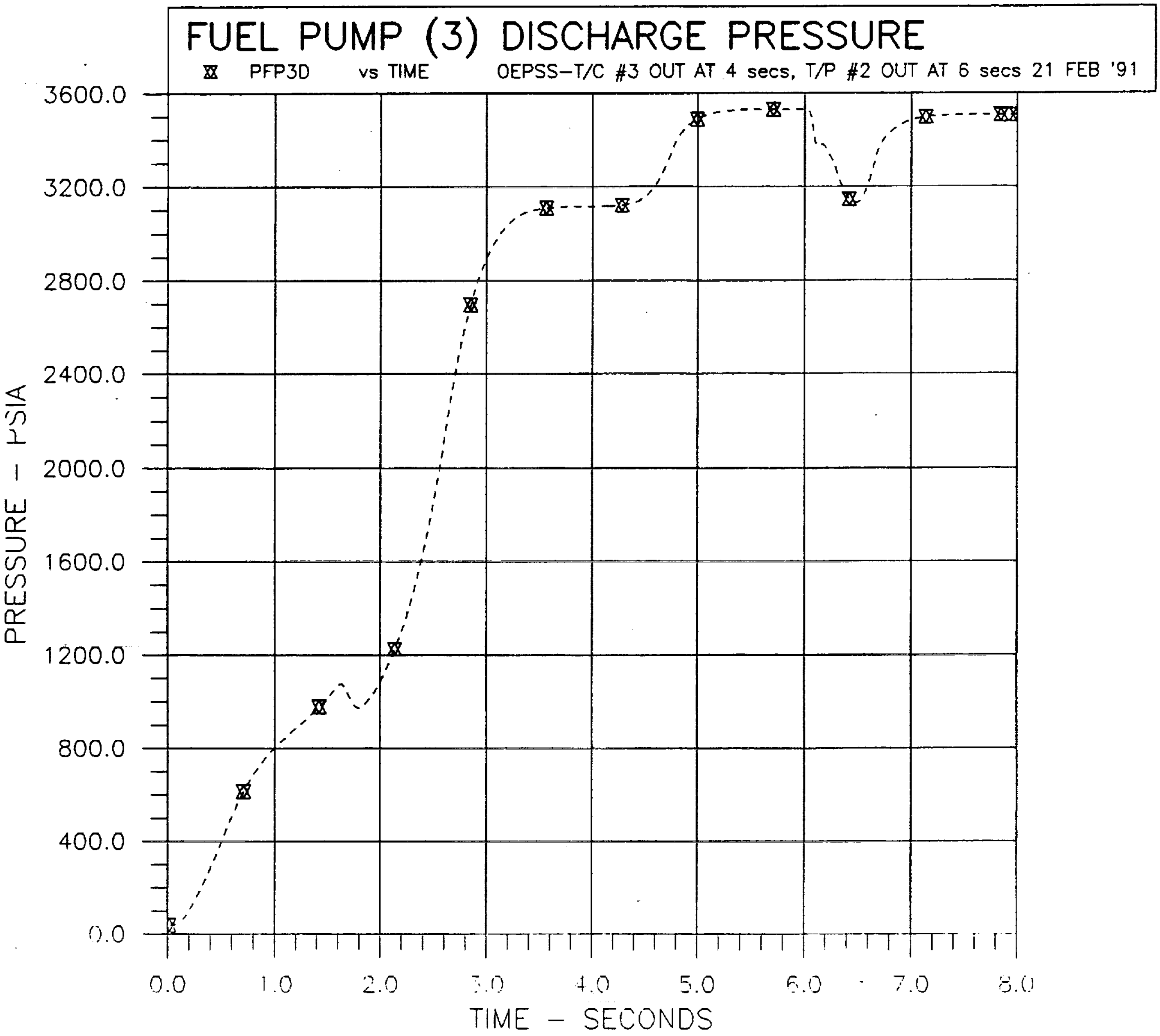

FUEL PUMP (3) DISCHARGE PRESSURE
PFP3D vs TIME OEPSS–T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
3600.0
3200.0
2800.0
2400.0
2000.0
1600.0
1200.0
800.0
400.0
0.0
PRESSURE – PSIA
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
TIME – SECONDS

Figure G11

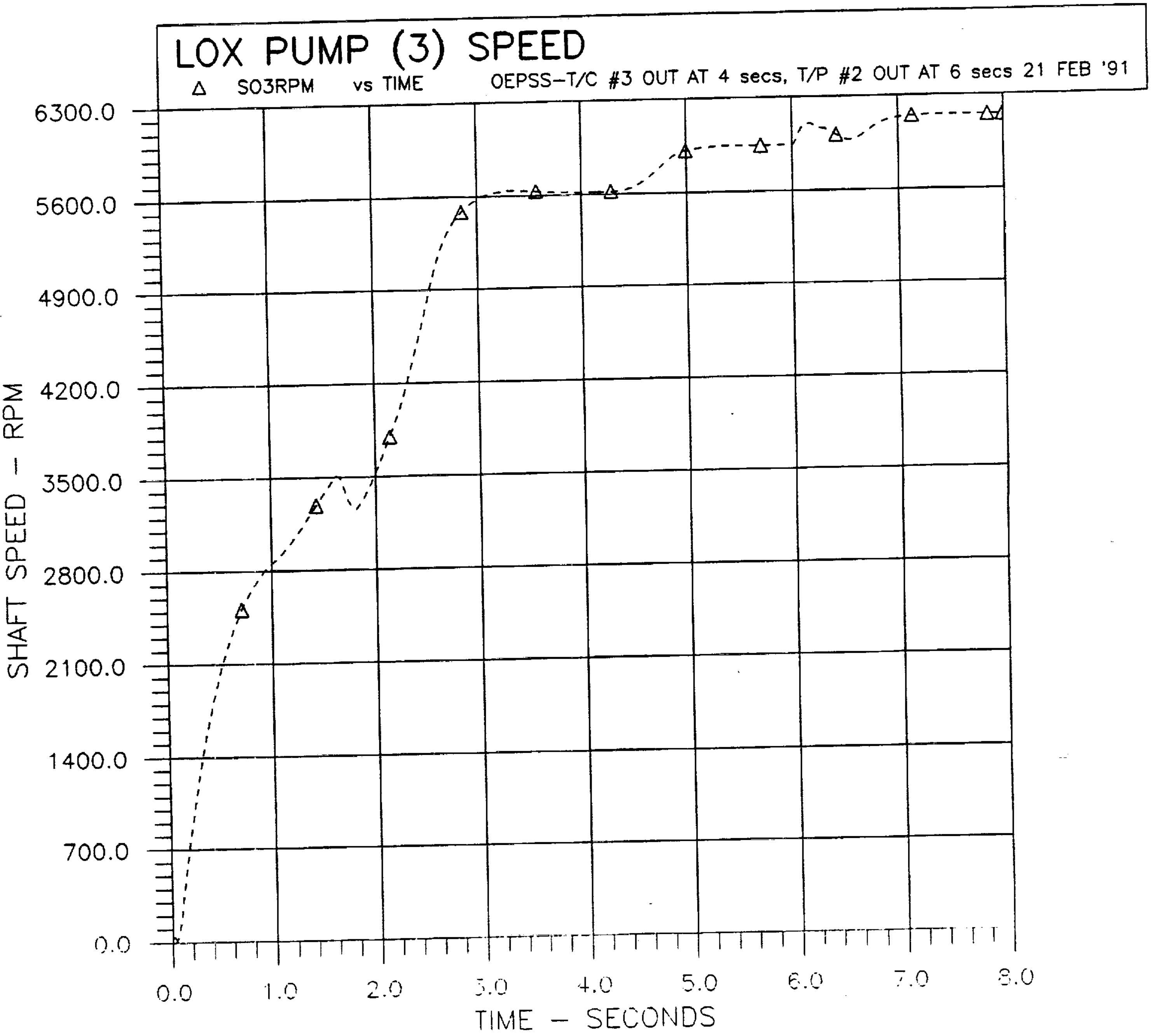

LOX PUMP (3) SPEED
△ S03RPM vs TIME OEPSS–T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
SHAFT SPEED – RPM
6300.0
5600.0
4900.0
4200.0
3500.0
2800.0
2100.0
1400.0
700.0
0.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
TIME – SECONDS

Figure G12

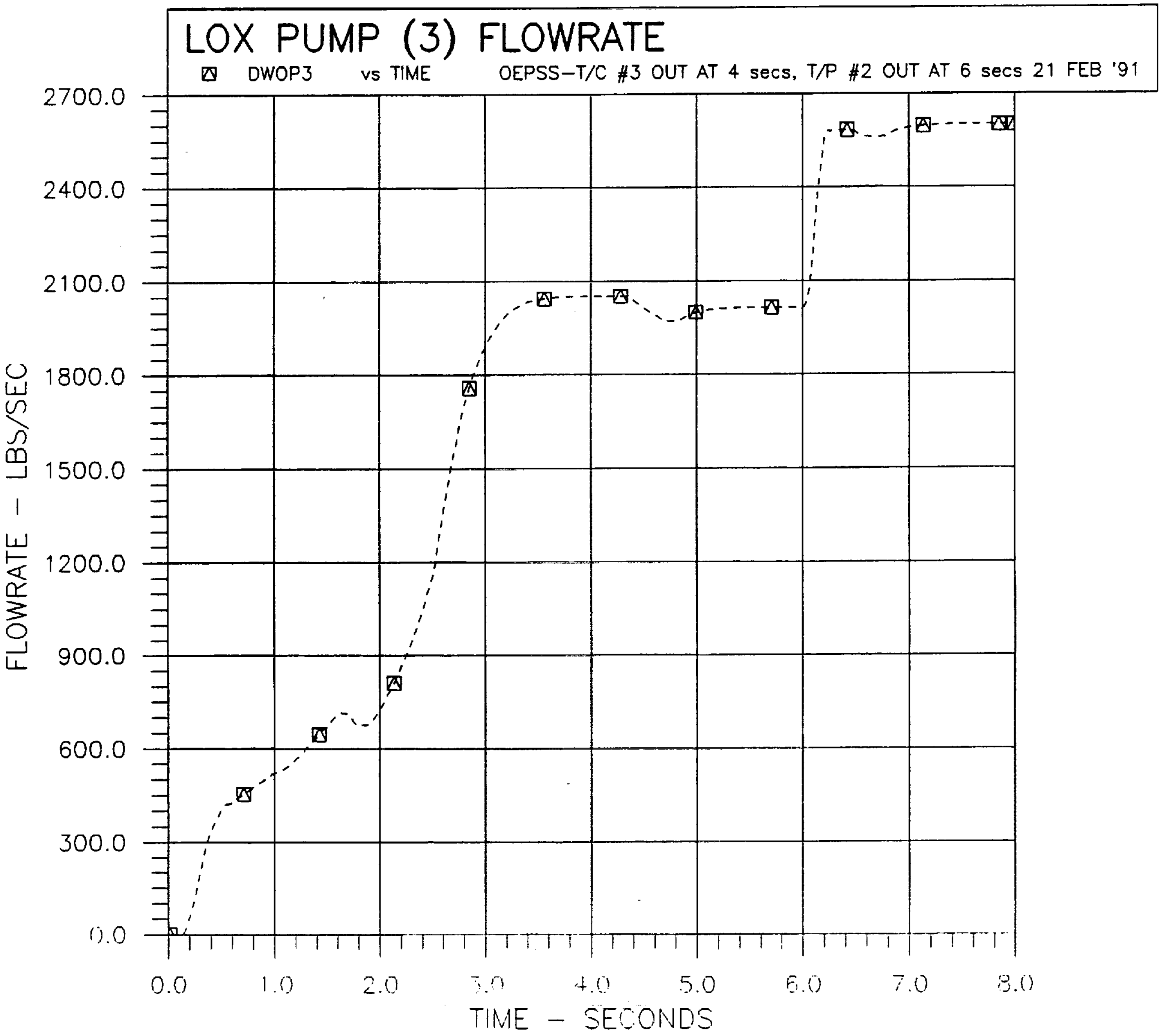

LOX PUMP (3) FLOWRATE
☒ DWOP3 vs TIME OEPSS–T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
2700.0
2400.0
2100.0
1800.0
1500.0
1200.0
900.0
600.0
300.0
0.0
FLOWRATE – LBS/SEC
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
TIME – SECONDS

Figure G13

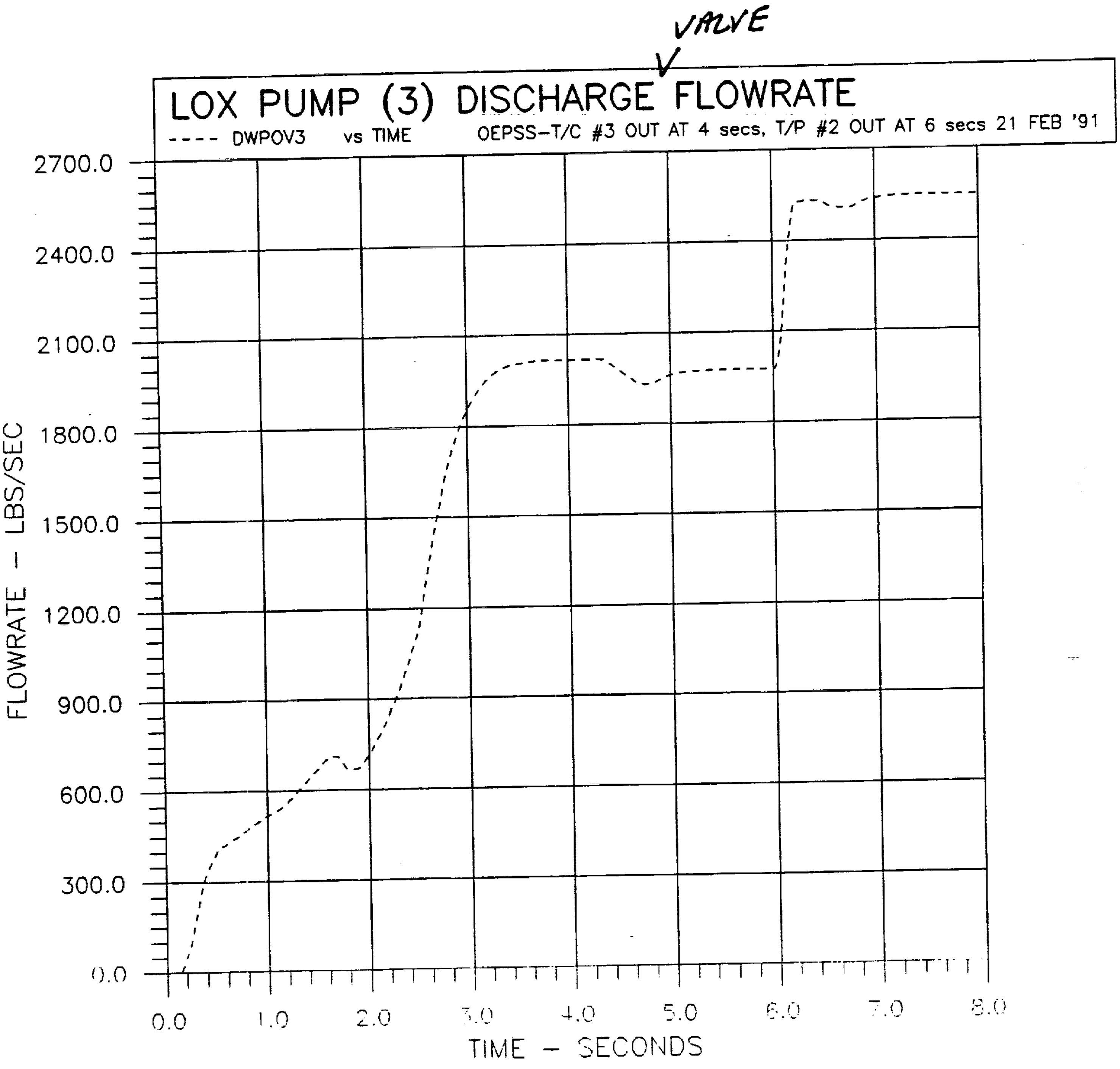

VALVE
LOX PUMP (3) DISCHARGE FLOWRATE
---- DWPOV3 vs TIME
OEPSS-T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
FLOWRATE - LBS/SEC
2700.0
2400.0
2100.0
1800.0
1500.0
1200.0
900.0
600.0
300.0
0.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
TIME - SECONDS

Figure G14

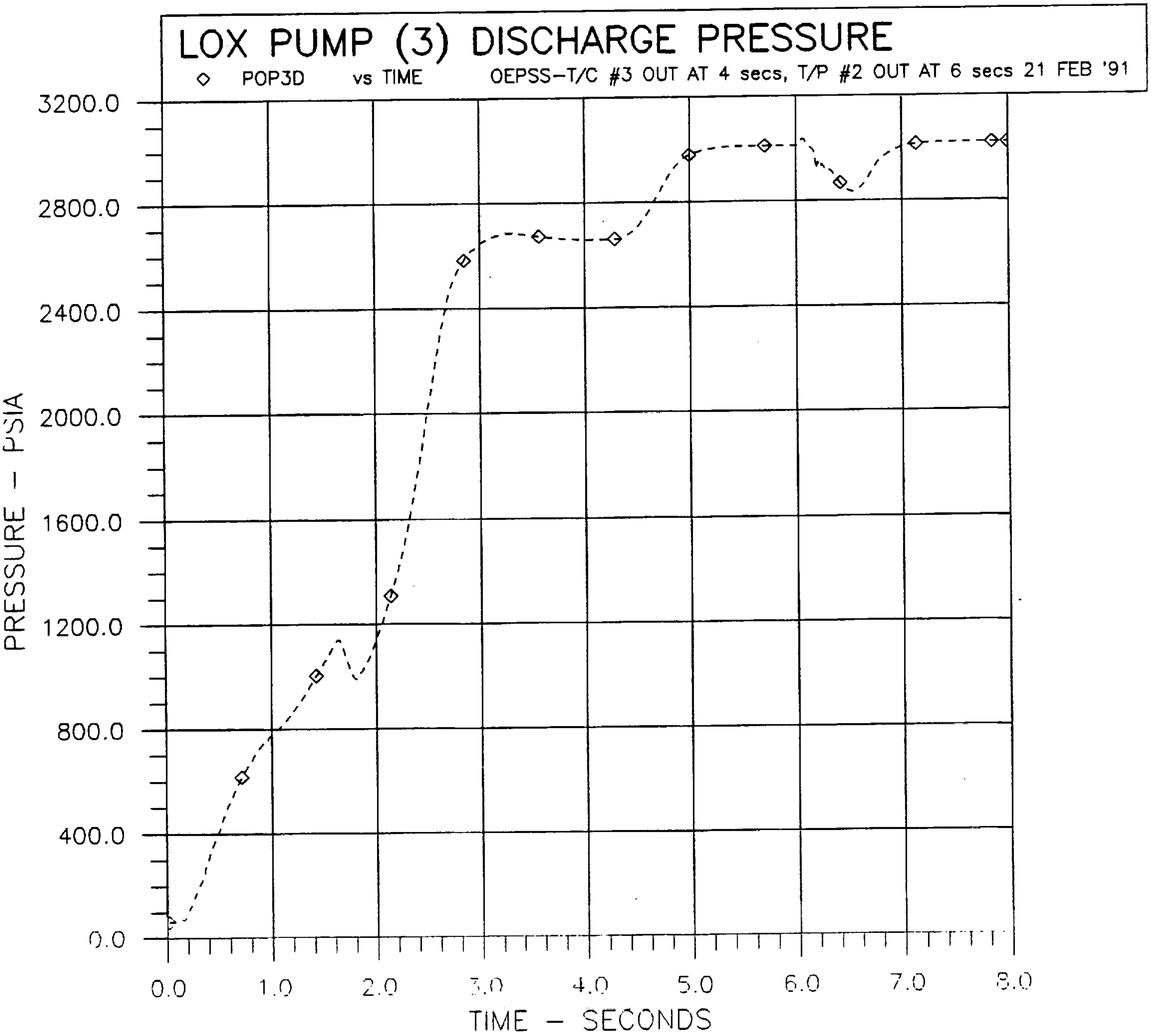

LOX PUMP (3) DISCHARGE PRESSURE
◇ POP3D vs TIME OEPSS-T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
3200.0
2800.0
2400.0
2000.0
1600.0
1200.0
800.0
400.0
0.0
PRESSURE – PSIA
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
TIME – SECONDS

Figure G15

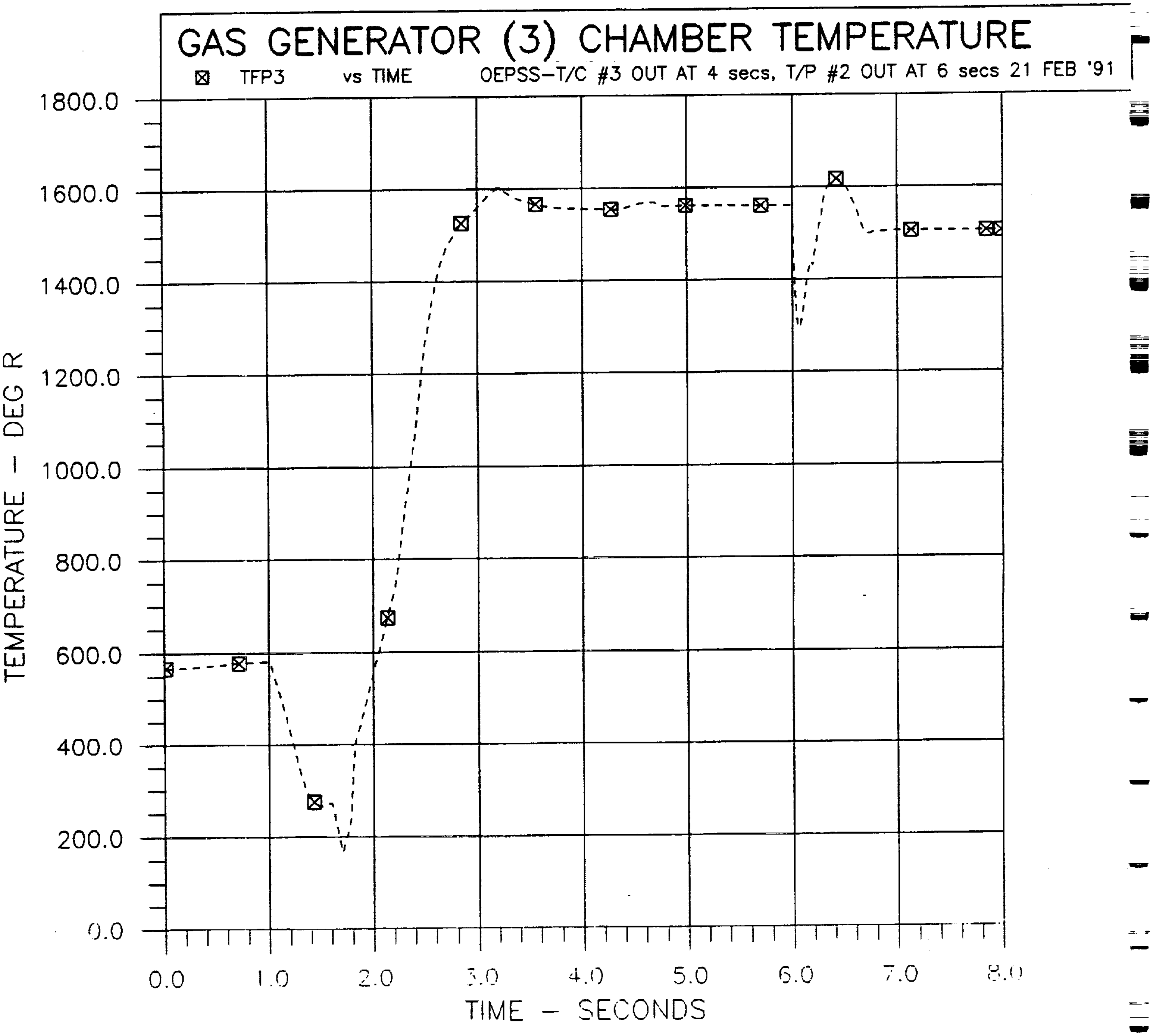

GAS GENERATOR (3) CHAMBER TEMPERATURE
☒ TFP3 vs TIME OEPSS–T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
TEMPERATURE – DEG R
1800.0
1600.0
1400.0
1200.0
1000.0
800.0
600.0
400.0
200.0
0.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
TIME – SECONDS

Figure G16

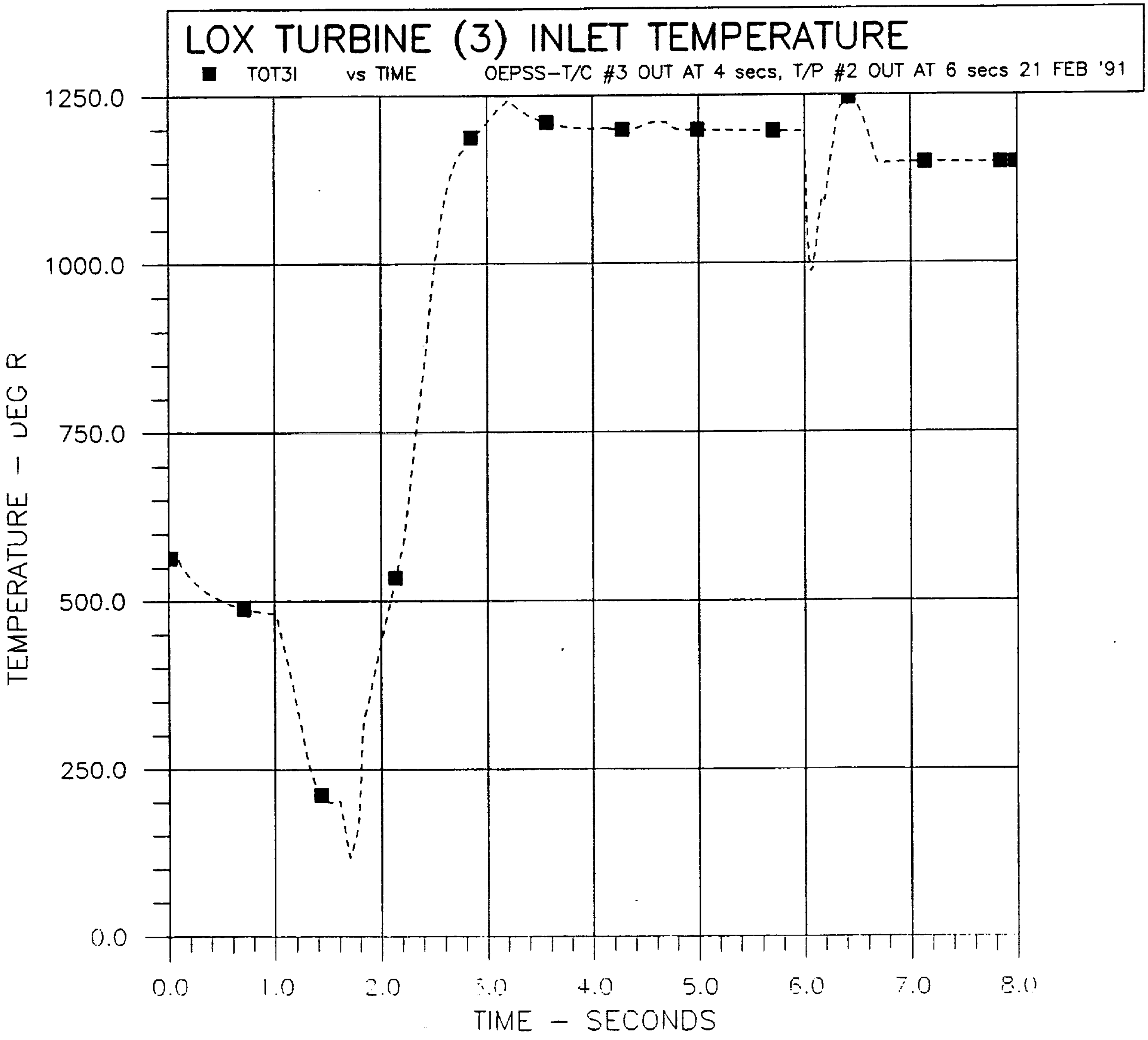

LOX TURBINE (3) INLET TEMPERATURE
■ TOT3I vs TIME OEPSS-T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
1250.0
1000.0
750.0
500.0
250.0
0.0
TEMPERATURE - DEG R
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
TIME - SECONDS

Figure G17

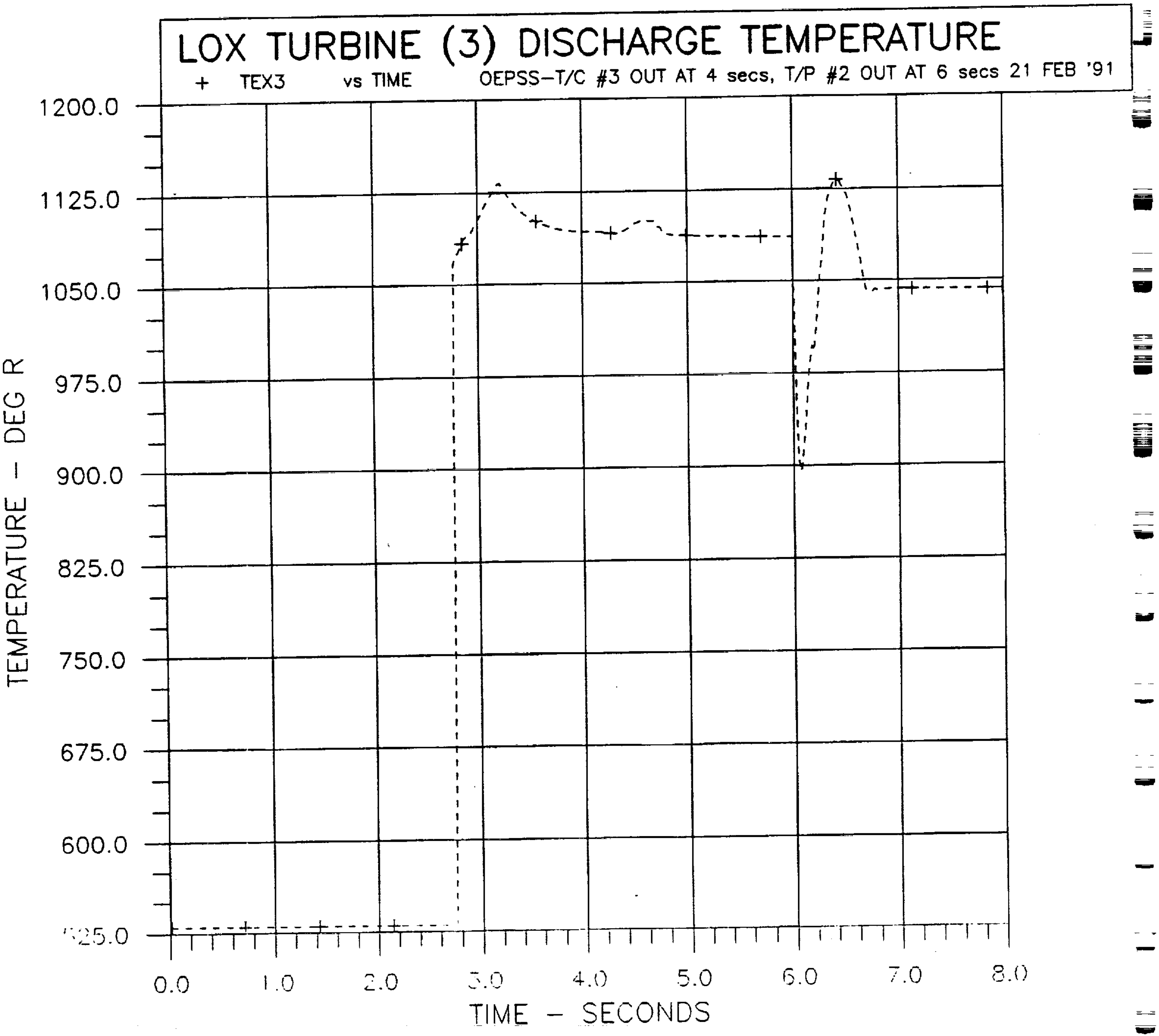

LOX TURBINE (3) DISCHARGE TEMPERATURE
+ TEX3 vs TIME OEPSS—T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
TEMPERATURE - DEG R
1200.0
1125.0
1050.0
975.0
900.0
825.0
750.0
675.0
600.0
525.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
TIME - SECONDS

Figure 618

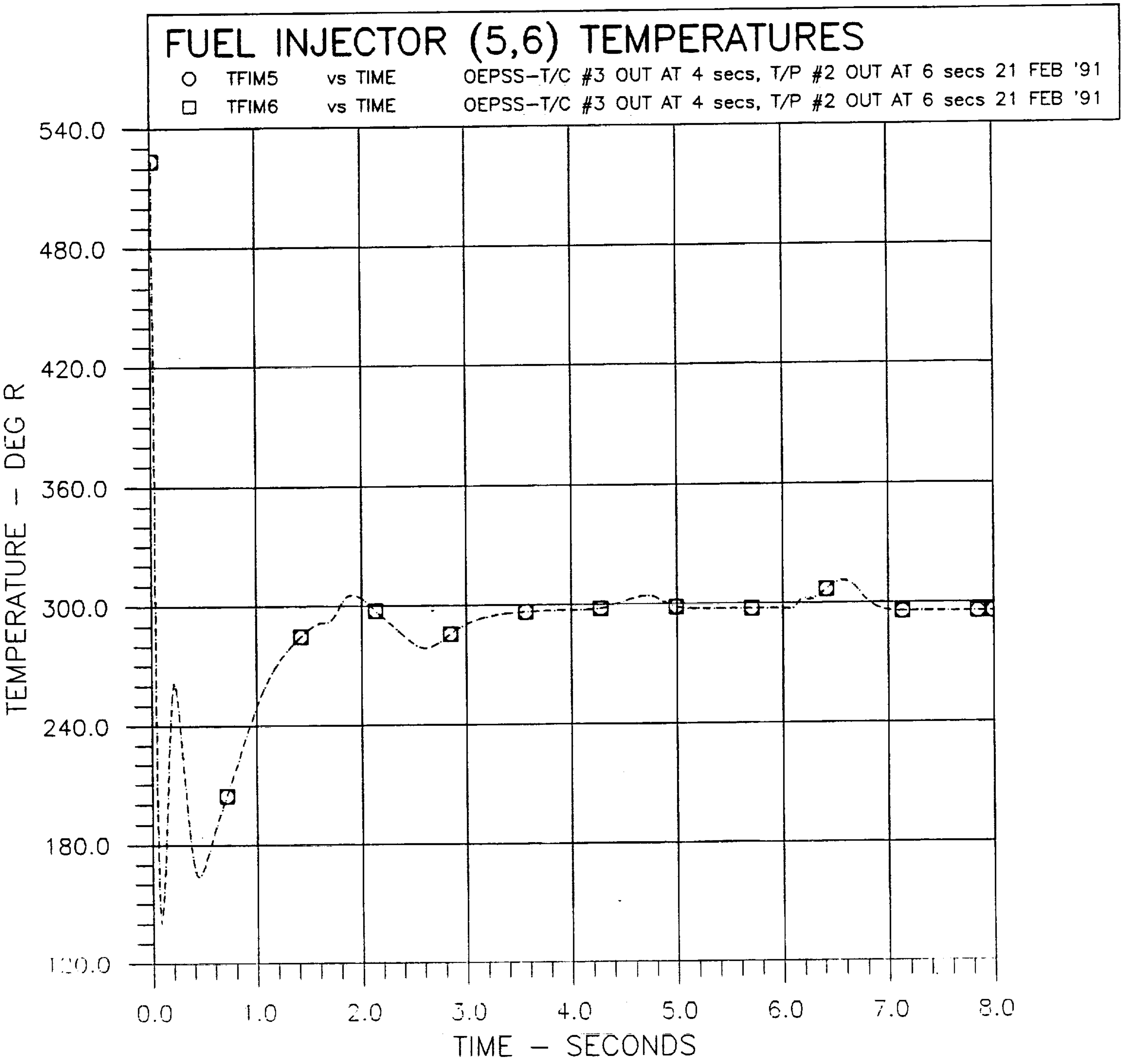

FUEL INJECTOR (5,6) TEMPERATURES
○ TFIM5 vs TIME OEPSS–T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
☐ TFIM6 vs TIME OEPSS–T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
540.0
480.0
420.0
360.0
300.0
240.0
180.0
120.0
TEMPERATURE – DEG R
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
TIME – SECONDS

Figure G19

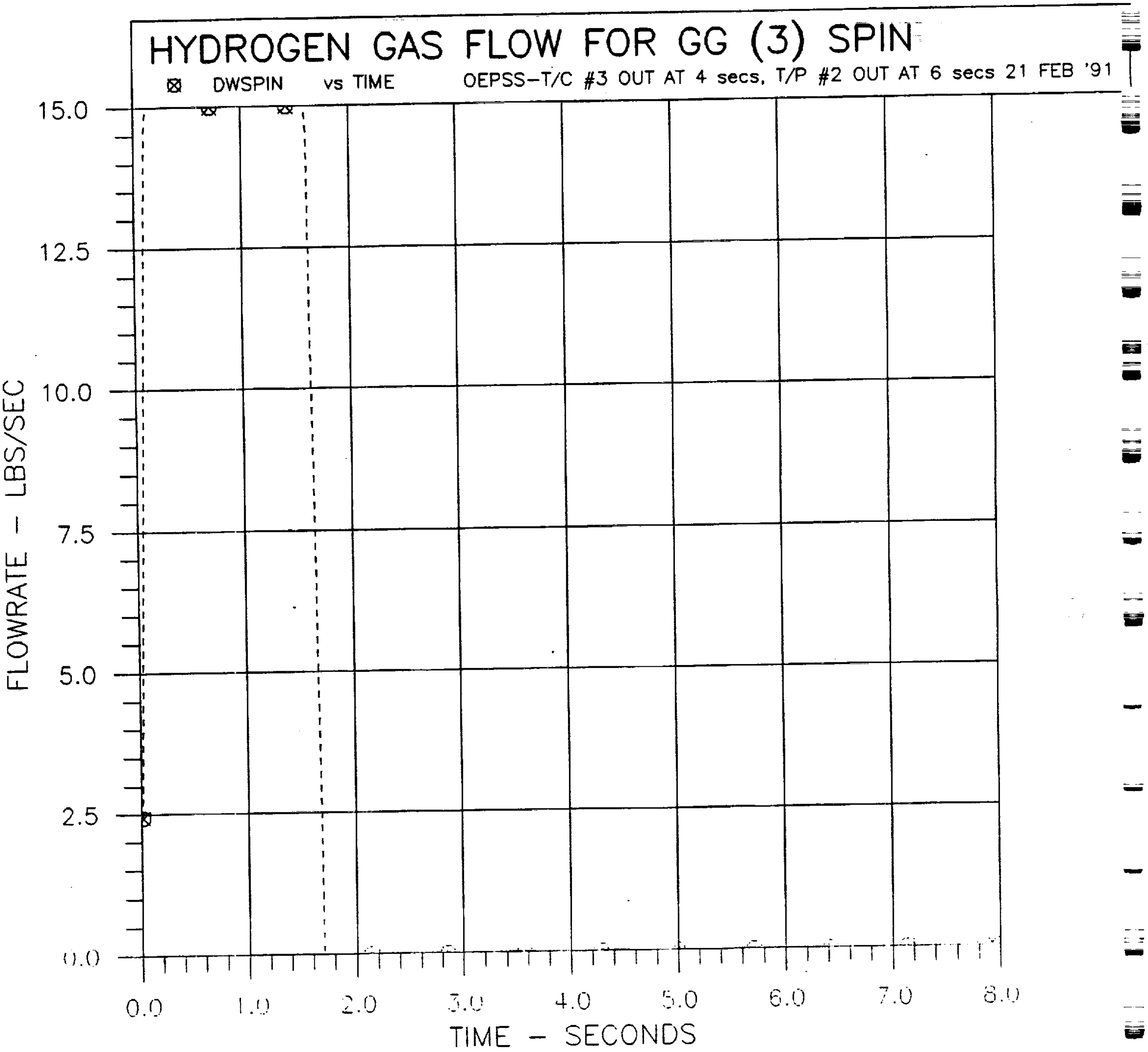

HYDROGEN GAS FLOW FOR GG (3) SPIN
⊠ DWSPIN vs TIME
OEPSS–T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
FLOWRATE – LBS/SEC
15.0
12.5
10.0
7.5
5.0
2.5
0.0
TIME – SECONDS
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0

Figure G20

APPENDIX H

COMBINED THRUST CHAMBER/TURBOPUMP OUT CONDITION RESULTS

FOR SYSTEM 4

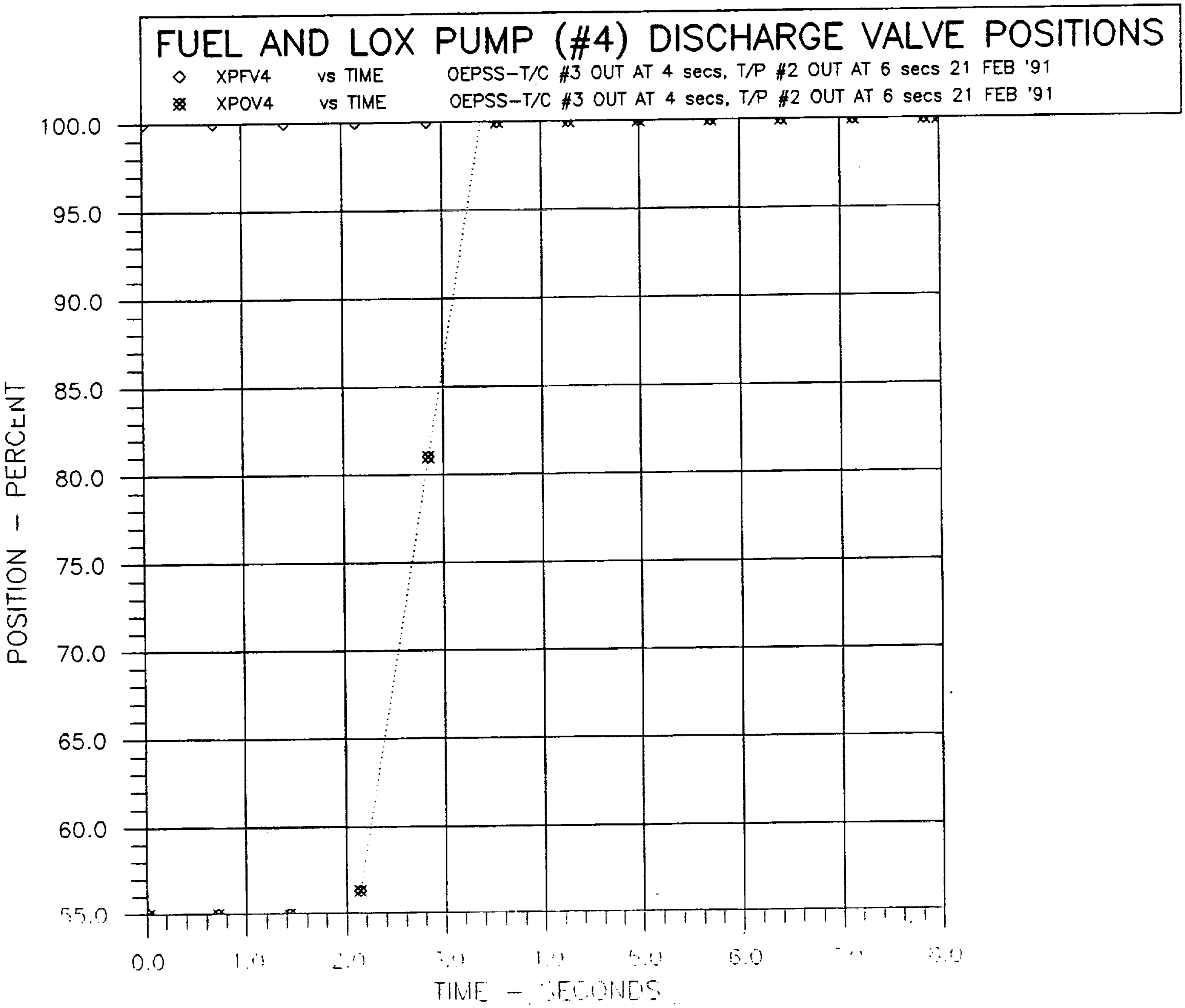

FUEL AND LOX PUMP (#4) DISCHARGE VALVE POSITIONS
◇ XPFV4 vs TIME OEPSS-T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
⊗ XPOV4 vs TIME OEPSS-T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
100.0
95.0
90.0
85.0
80.0
75.0
70.0
65.0
60.0
55.0
POSITION - PERCENT
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
TIME - SECONDS

Figure H1

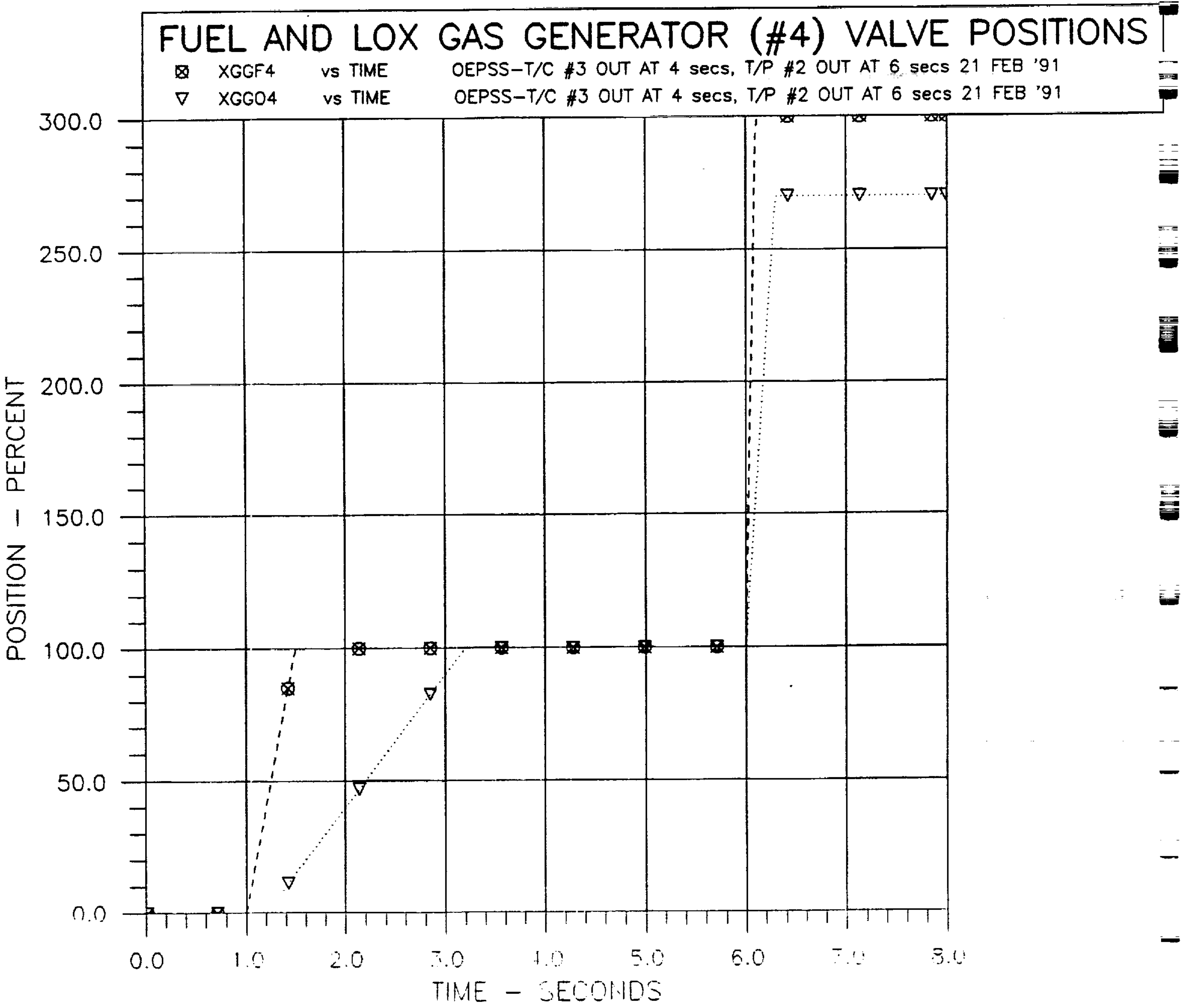

FUEL AND LOX GAS GENERATOR (#4) VALVE POSITIONS
⊠ XGGF4 vs TIME OEPSS–T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
▽ XGGO4 vs TIME OEPSS–T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
300.0
250.0
200.0
150.0
100.0
50.0
0.0
POSITION – PERCENT
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
TIME – SECONDS

Figure H2

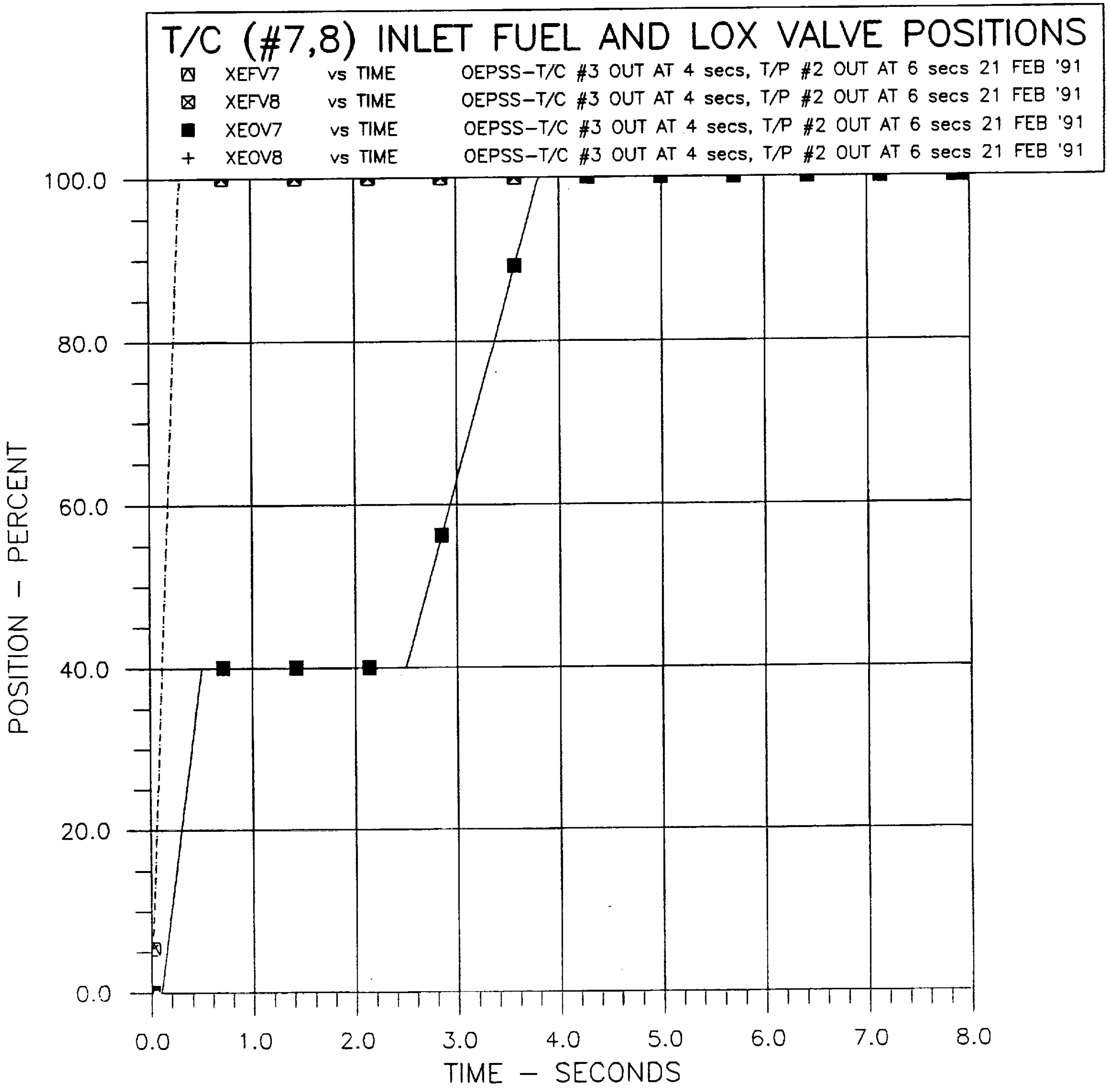
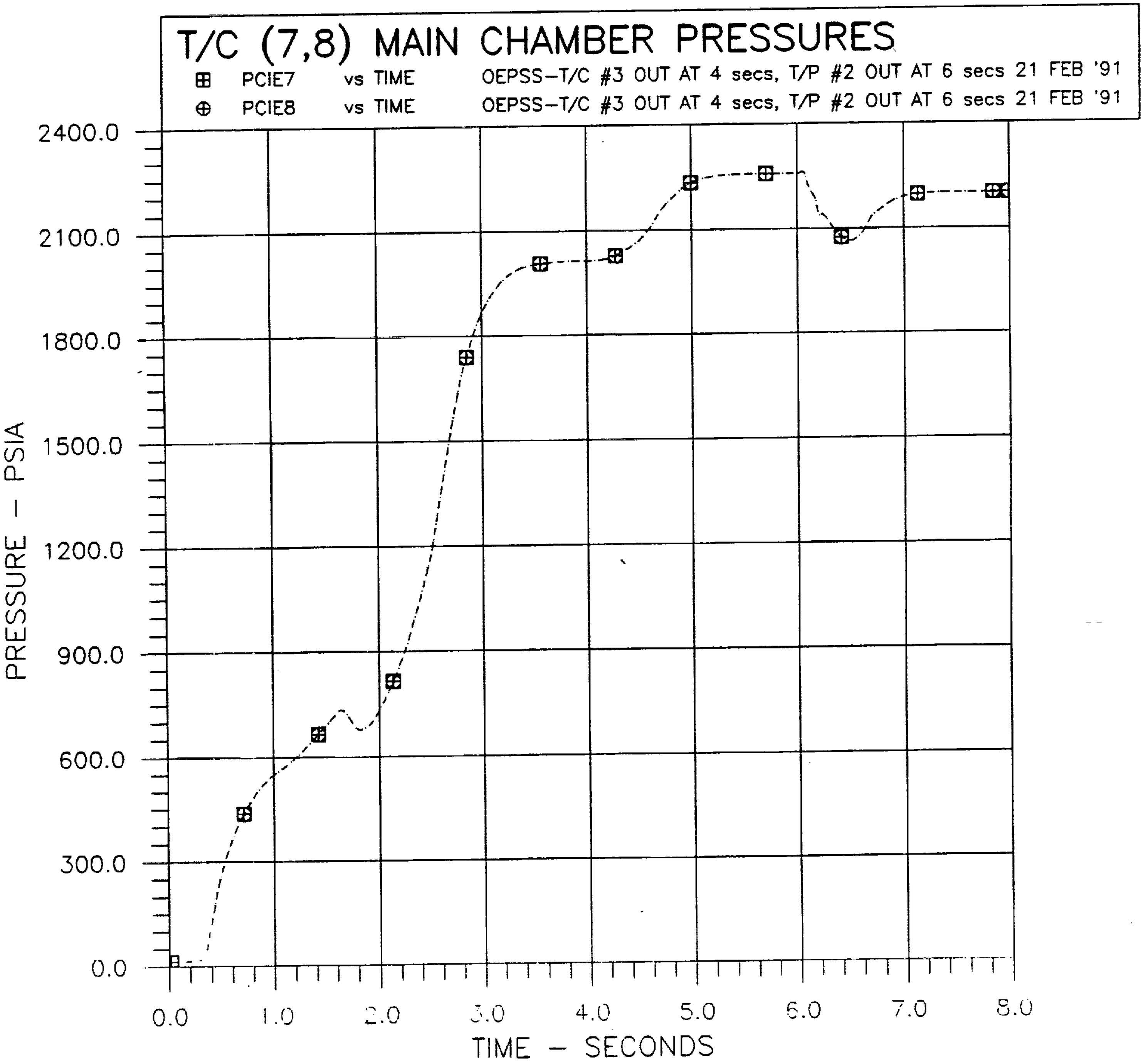

T/C (#7,8) INLET FUEL AND LOX VALVE POSITIONS
XEFV7 vs TIME OEPSS-T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
XEFV8 vs TIME OEPSS-T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
XEOV7 vs TIME OEPSS-T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
XEOV8 vs TIME OEPSS-T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
100.0
80.0
60.0
40.0
20.0
0.0
POSITION - PERCENT
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
TIME - SECONDS

Figure H3



T/C (7,8) MAIN CHAMBER PRESSURES
⊞ PCIE7 vs TIME OEPSS–T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
⊕ PCIE8 vs TIME OEPSS–T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
2400.0
2100.0
1800.0
1500.0
1200.0
900.0
600.0
300.0
0.0
PRESSURE – PSIA
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
TIME – SECONDS

Figure H4

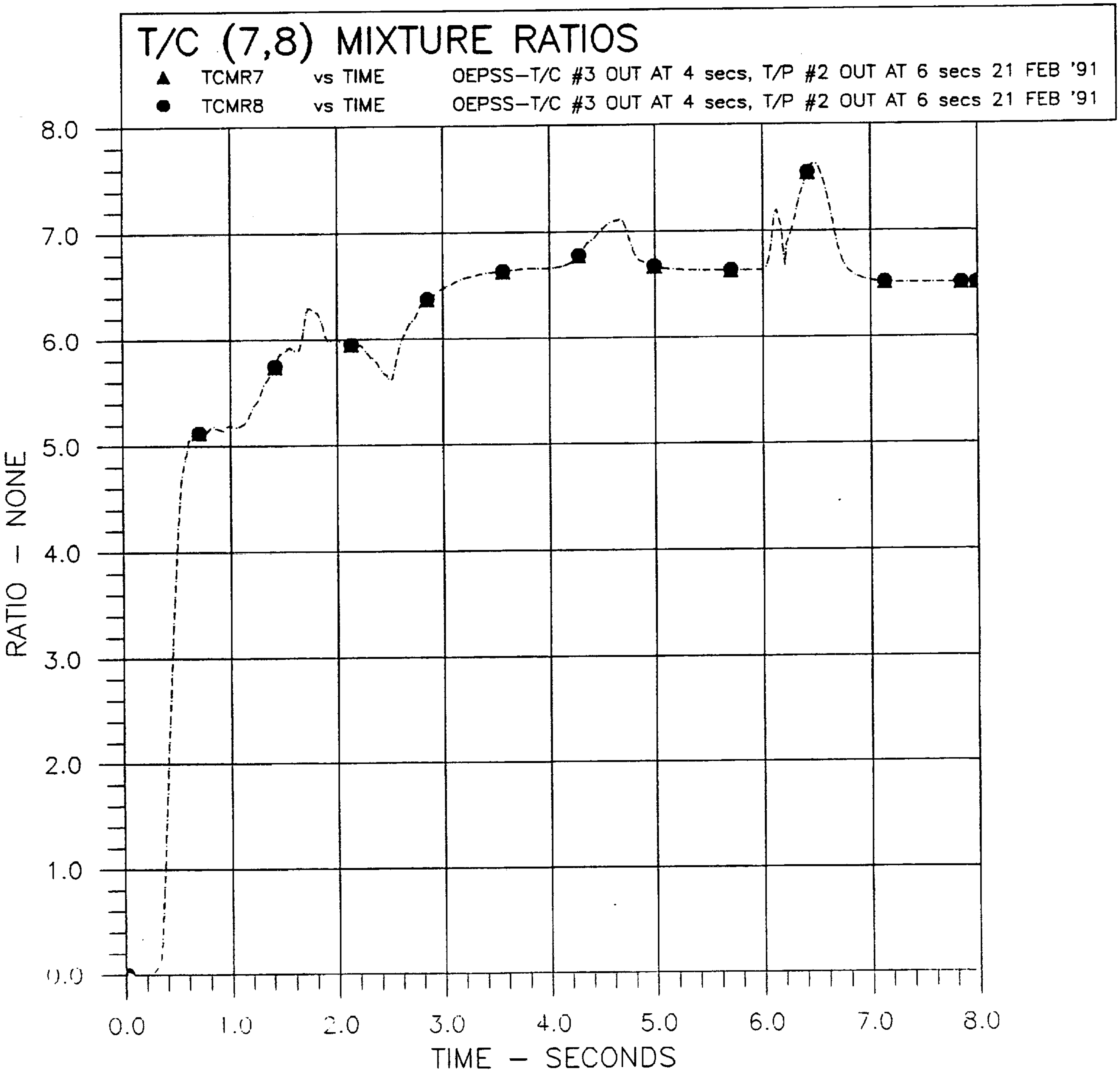

T/C (7,8) MIXTURE RATIOS
▲ TCMR7 vs TIME OEPSS–T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
● TCMR8 vs TIME OEPSS–T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
RATIO – NONE
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
TIME – SECONDS
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0

Figure A5

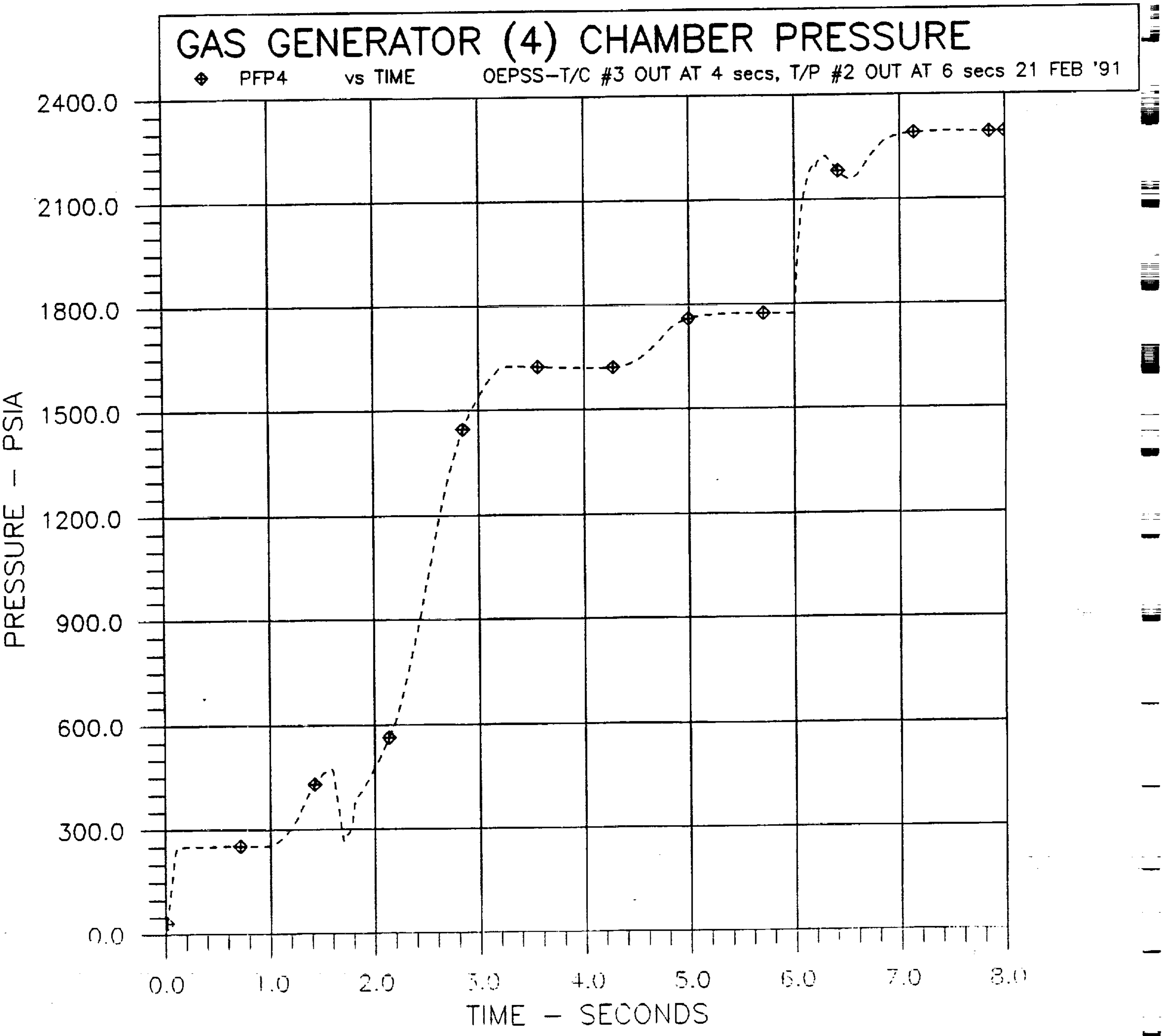

GAS GENERATOR (4) CHAMBER PRESSURE
⊕ PFP4 vs TIME OEPSS—T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
2400.0
2100.0
1800.0
1500.0
1200.0
900.0
600.0
300.0
0.0
PRESSURE — PSIA
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
TIME — SECONDS

Figure H6

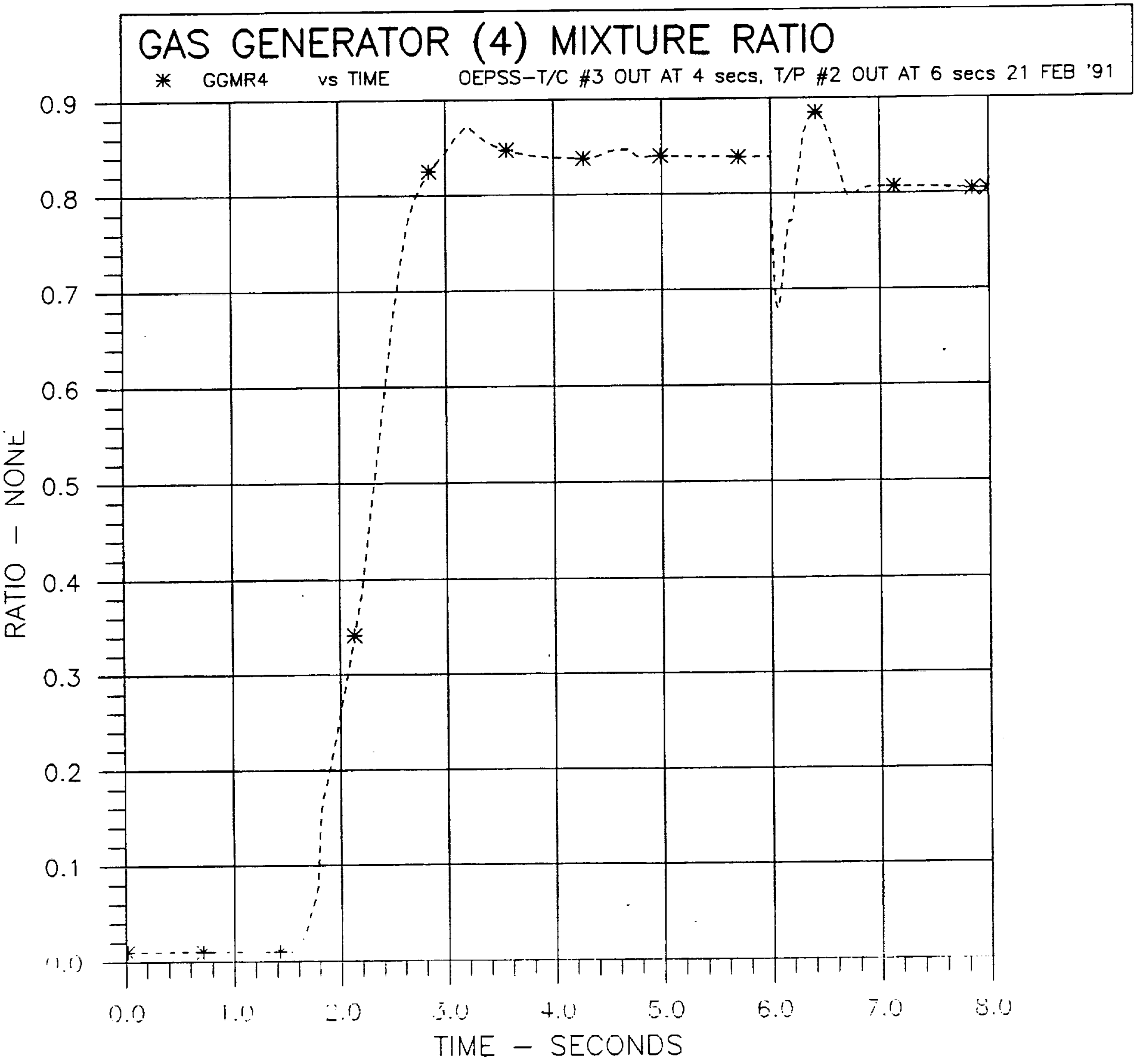

GAS GENERATOR (4) MIXTURE RATIO
✳ GGMR4 vs TIME OEPSS–T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
RATIO – NONE
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
TIME – SECONDS

Figure H7

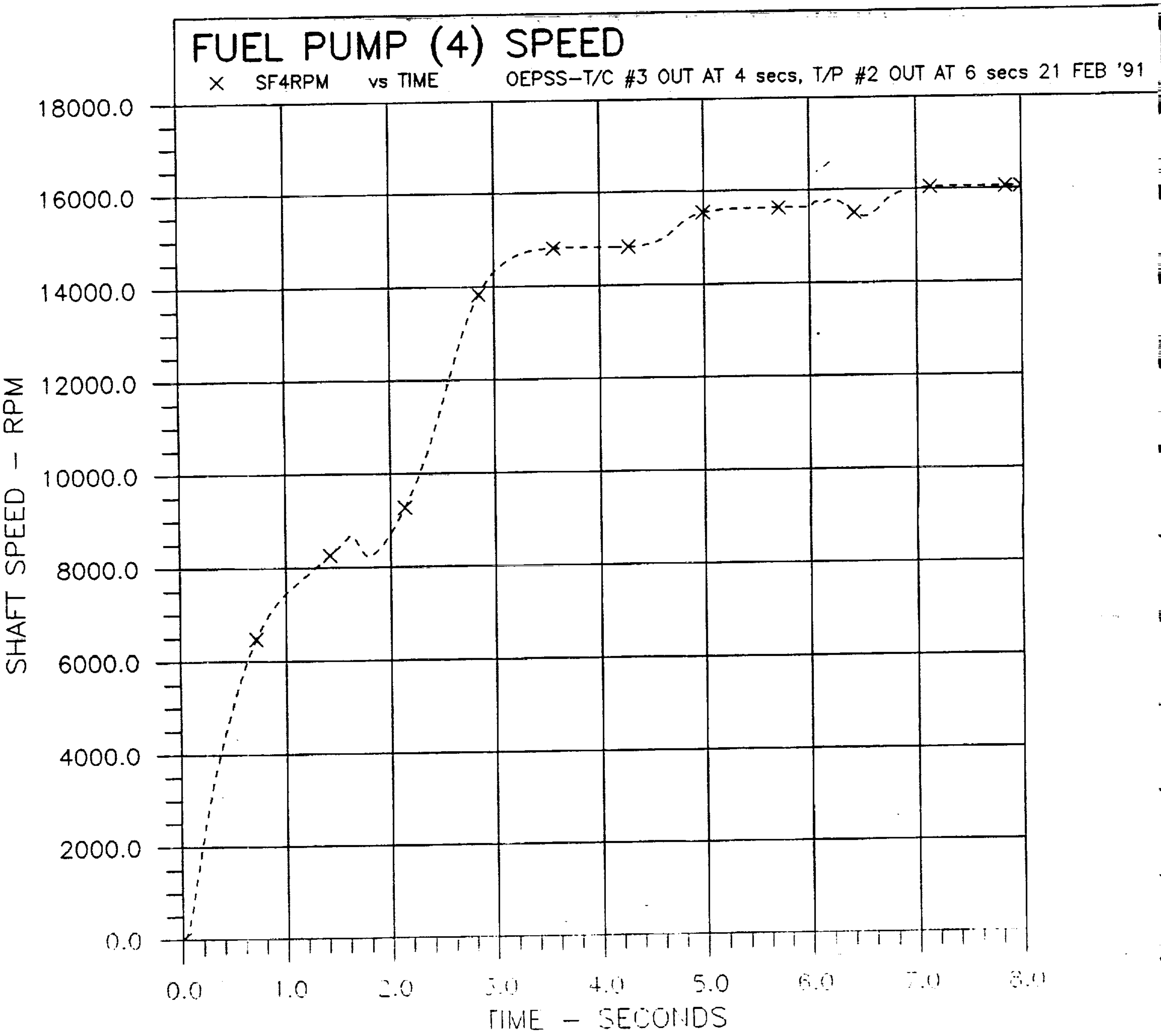

FUEL PUMP (4) SPEED
× SF4RPM vs TIME
OEPSS-T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
SHAFT SPEED - RPM
18000.0
16000.0
14000.0
12000.0
10000.0
8000.0
6000.0
4000.0
2000.0
0.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
TIME - SECONDS

Figure H8

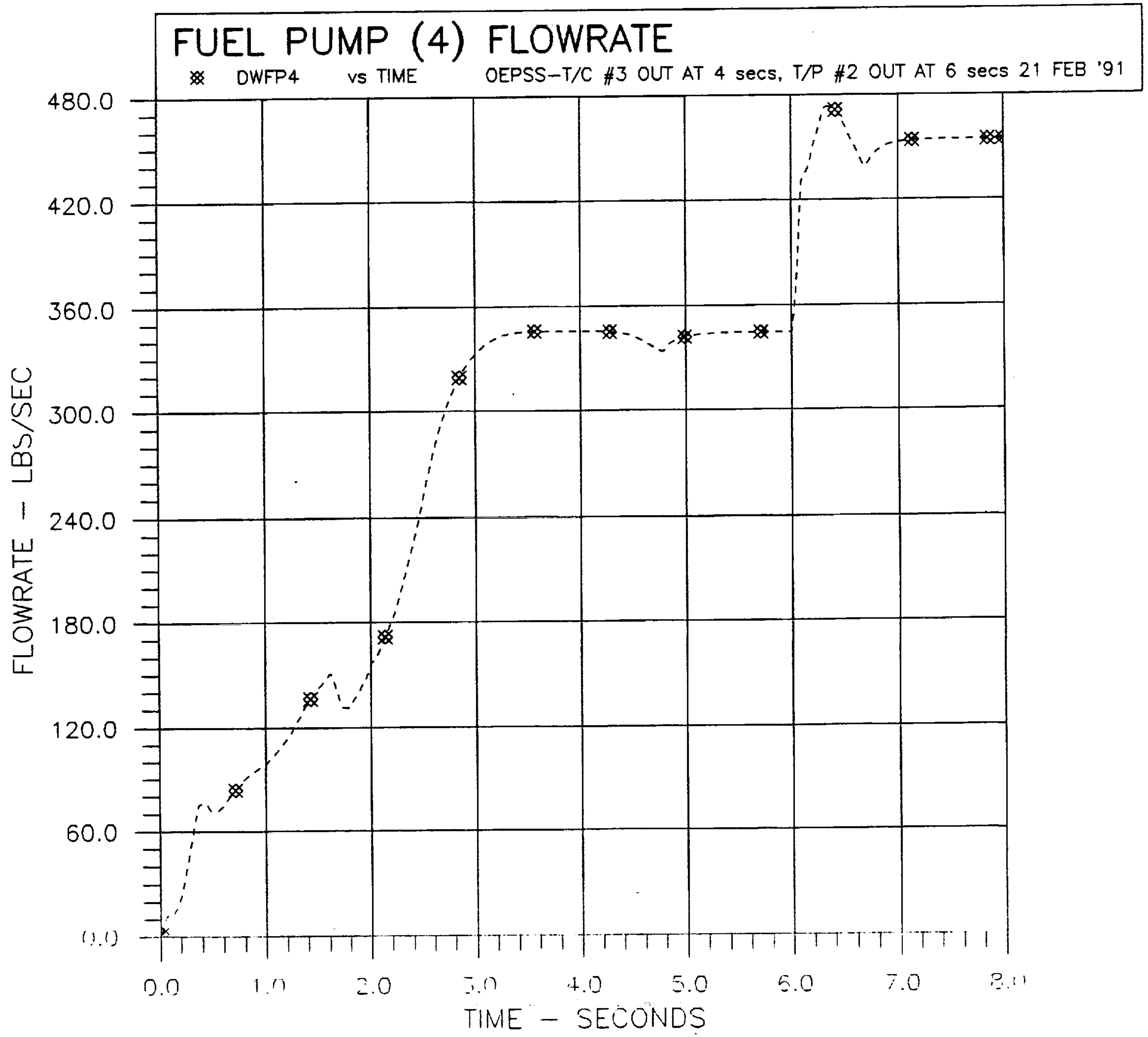

FUEL PUMP (4) FLOWRATE
DWFP4 vs TIME
OEPSS-T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
480.0
420.0
360.0
300.0
240.0
180.0
120.0
60.0
0.0
FLOWRATE - LBS/SEC
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
TIME - SECONDS

Figure H9

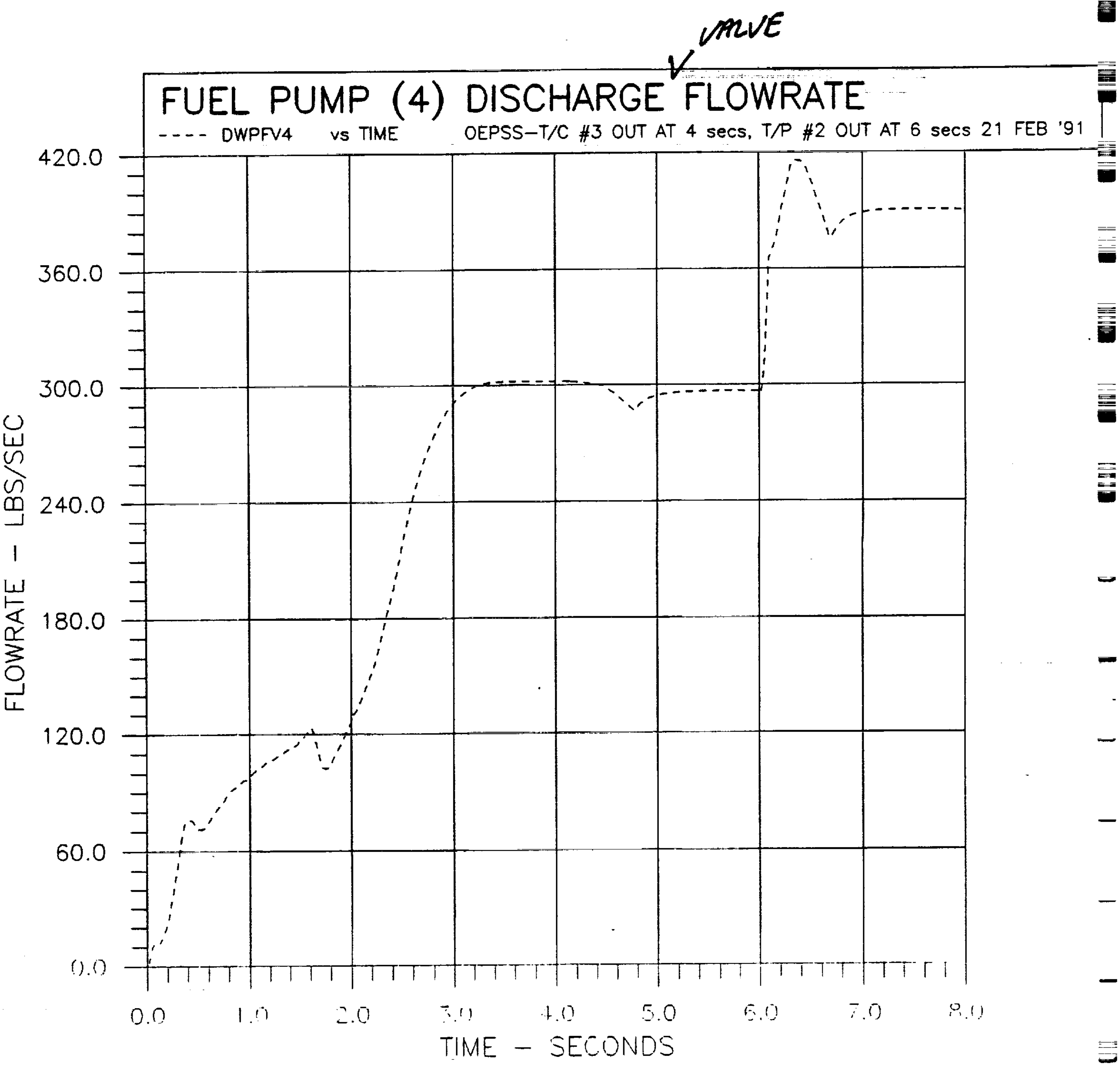

VALVE
FUEL PUMP (4) DISCHARGE FLOWRATE
---- DWPFV4 vs TIME
OEPSS–T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
420.0
360.0
300.0
240.0
180.0
120.0
60.0
0.0
FLOWRATE – LBS/SEC
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
TIME – SECONDS

Figure H10

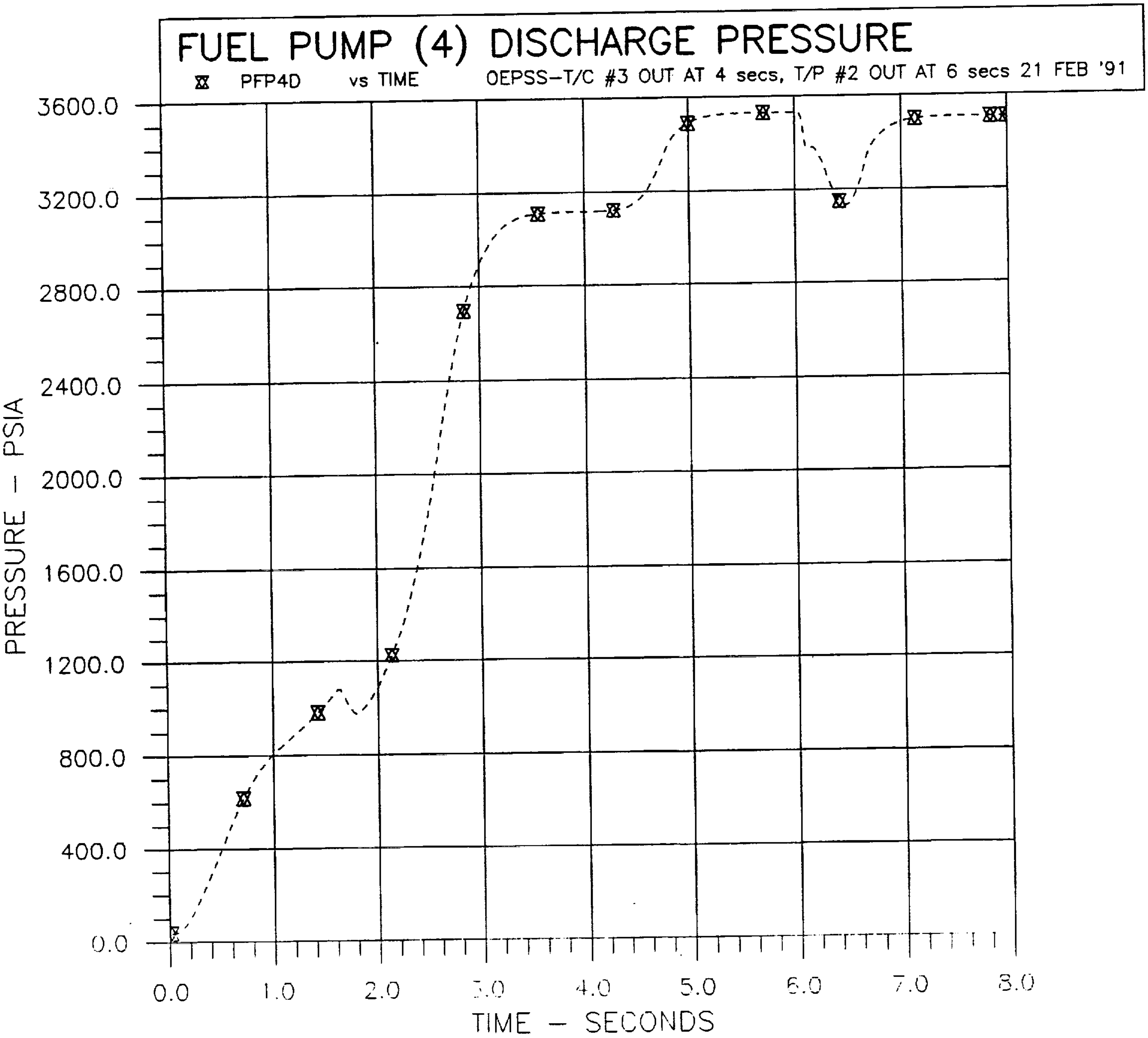

FUEL PUMP (4) DISCHARGE PRESSURE
PFP4D vs TIME
OEPSS–T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
PRESSURE – PSIA
3600.0
3200.0
2800.0
2400.0
2000.0
1600.0
1200.0
800.0
400.0
0.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
TIME – SECONDS

Figure H11

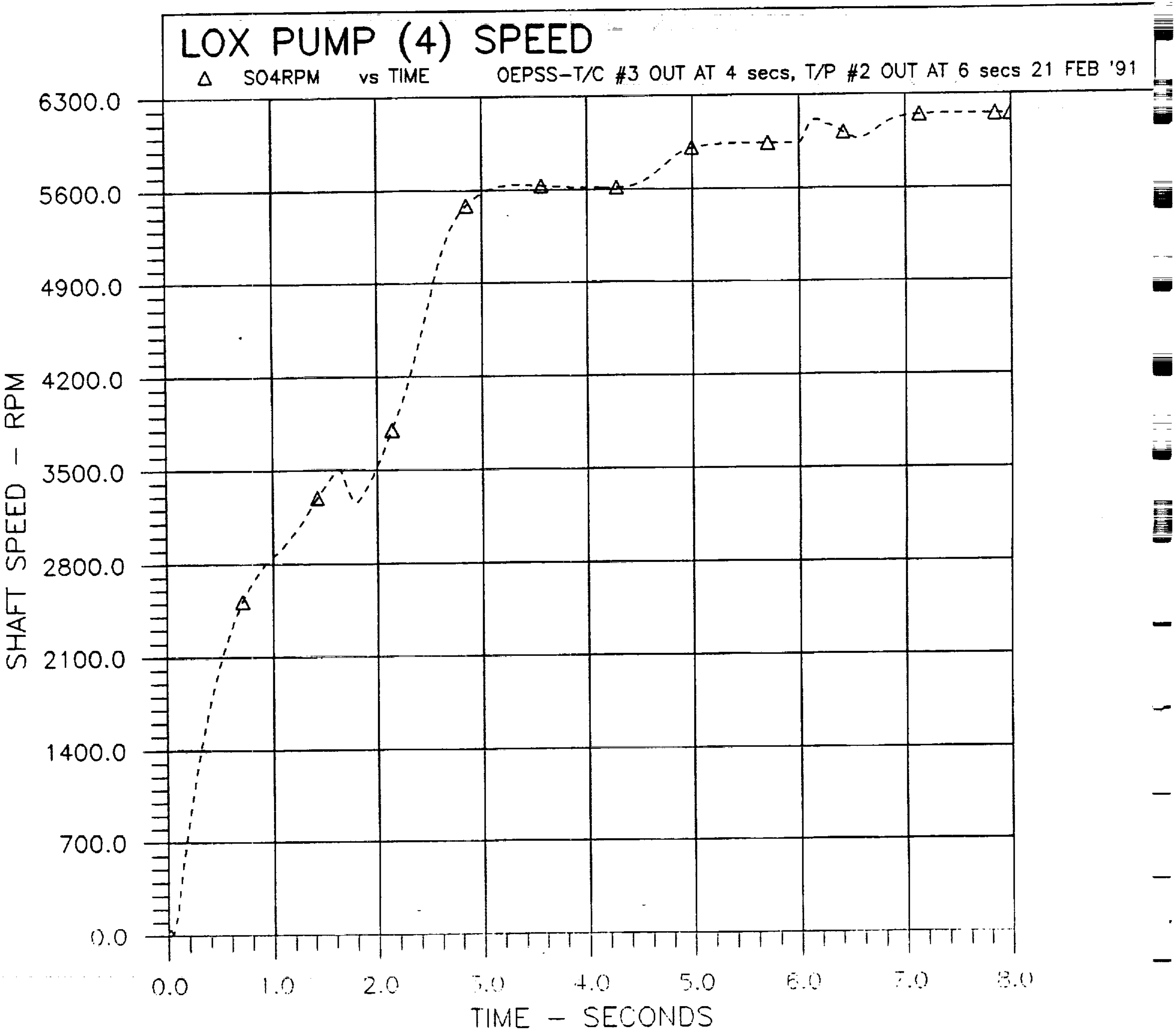
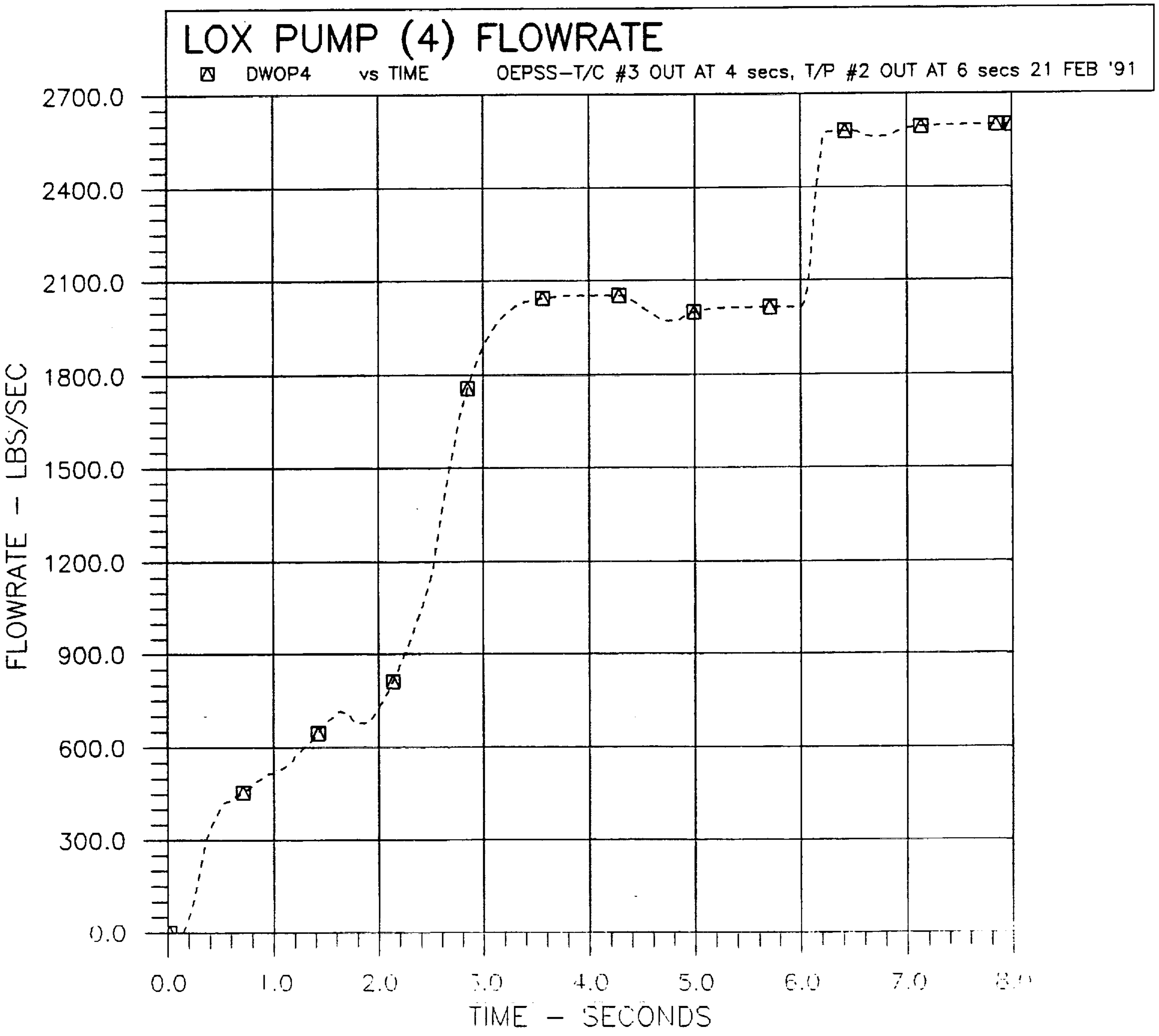

LOX PUMP (4) SPEED
△ SO4RPM vs TIME
OEPSS-T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
SHAFT SPEED - RPM
6300.0
5600.0
4900.0
4200.0
3500.0
2800.0
2100.0
1400.0
700.0
0.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
TIME - SECONDS

Figure H12



LOX PUMP (4) FLOWRATE
DWOP4 vs TIME OEPSS–T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
FLOWRATE – LBS/SEC
2700.0
2400.0
2100.0
1800.0
1500.0
1200.0
900.0
600.0
300.0
0.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
TIME – SECONDS

Figure H13

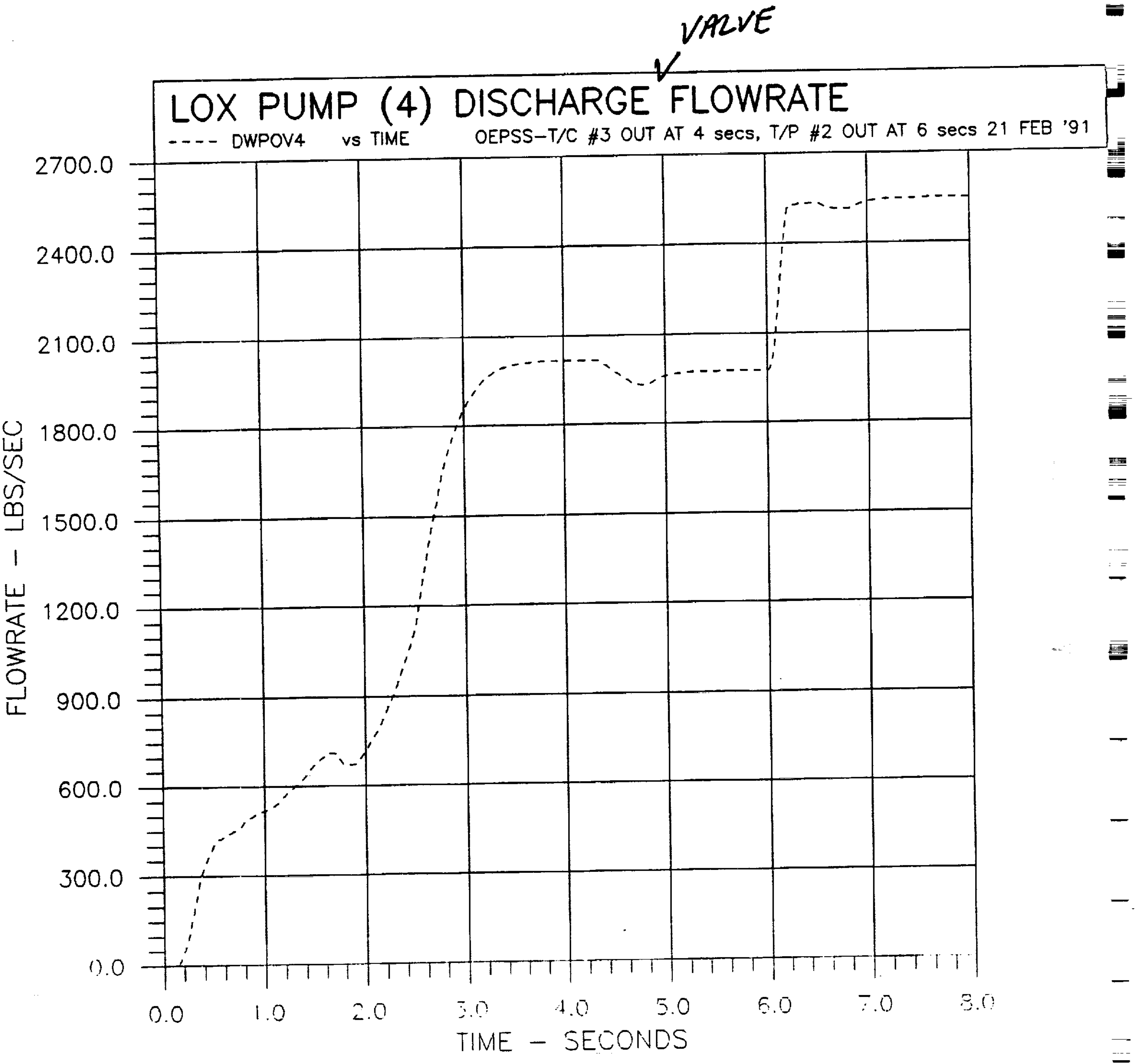

VALVE
LOX PUMP (4) DISCHARGE FLOWRATE
---- DWPOV4 vs TIME
OEPSS-T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
FLOWRATE - LBS/SEC
2700.0
2400.0
2100.0
1800.0
1500.0
1200.0
900.0
600.0
300.0
0.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
TIME - SECONDS

Figure H14

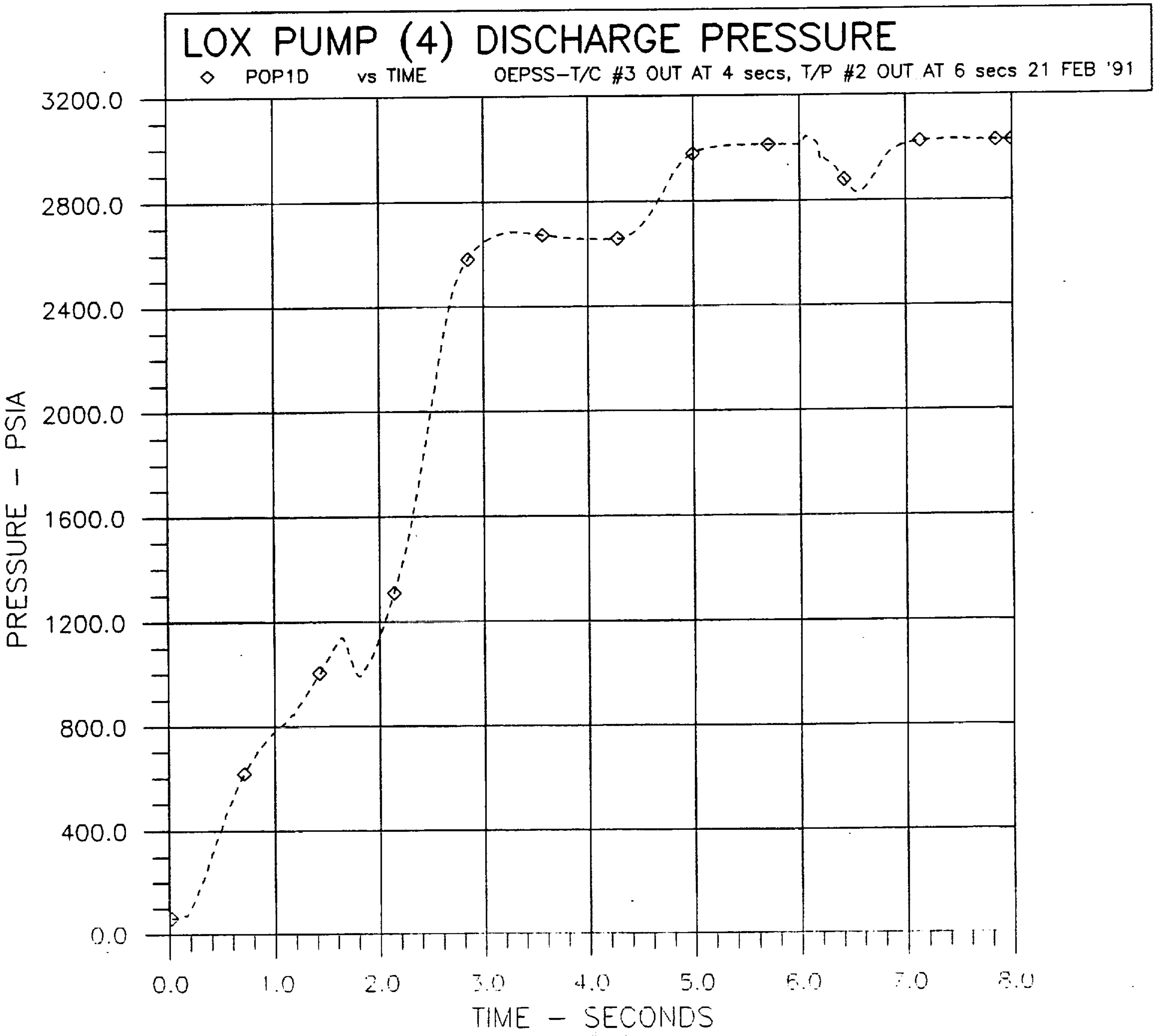

LOX PUMP (4) DISCHARGE PRESSURE
◇ POP1D vs TIME OEPSS–T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
PRESSURE – PSIA
3200.0
2800.0
2400.0
2000.0
1600.0
1200.0
800.0
400.0
0.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
TIME – SECONDS

Figure H15

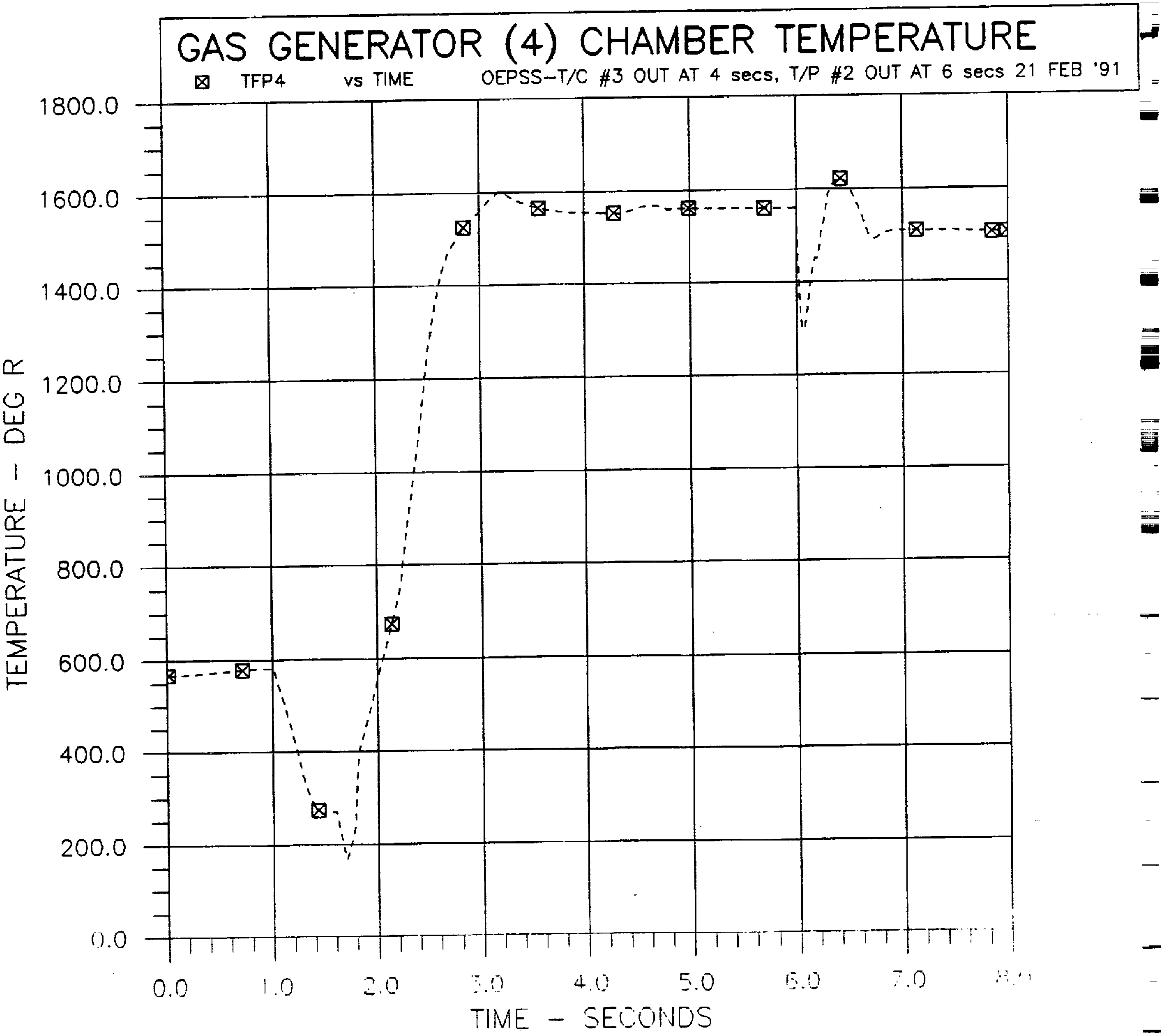

GAS GENERATOR (4) CHAMBER TEMPERATURE
☒ TFP4 vs TIME
OEPSS–T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
TEMPERATURE – DEG R
1800.0
1600.0
1400.0
1200.0
1000.0
800.0
600.0
400.0
200.0
0.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
TIME – SECONDS

Figure H16

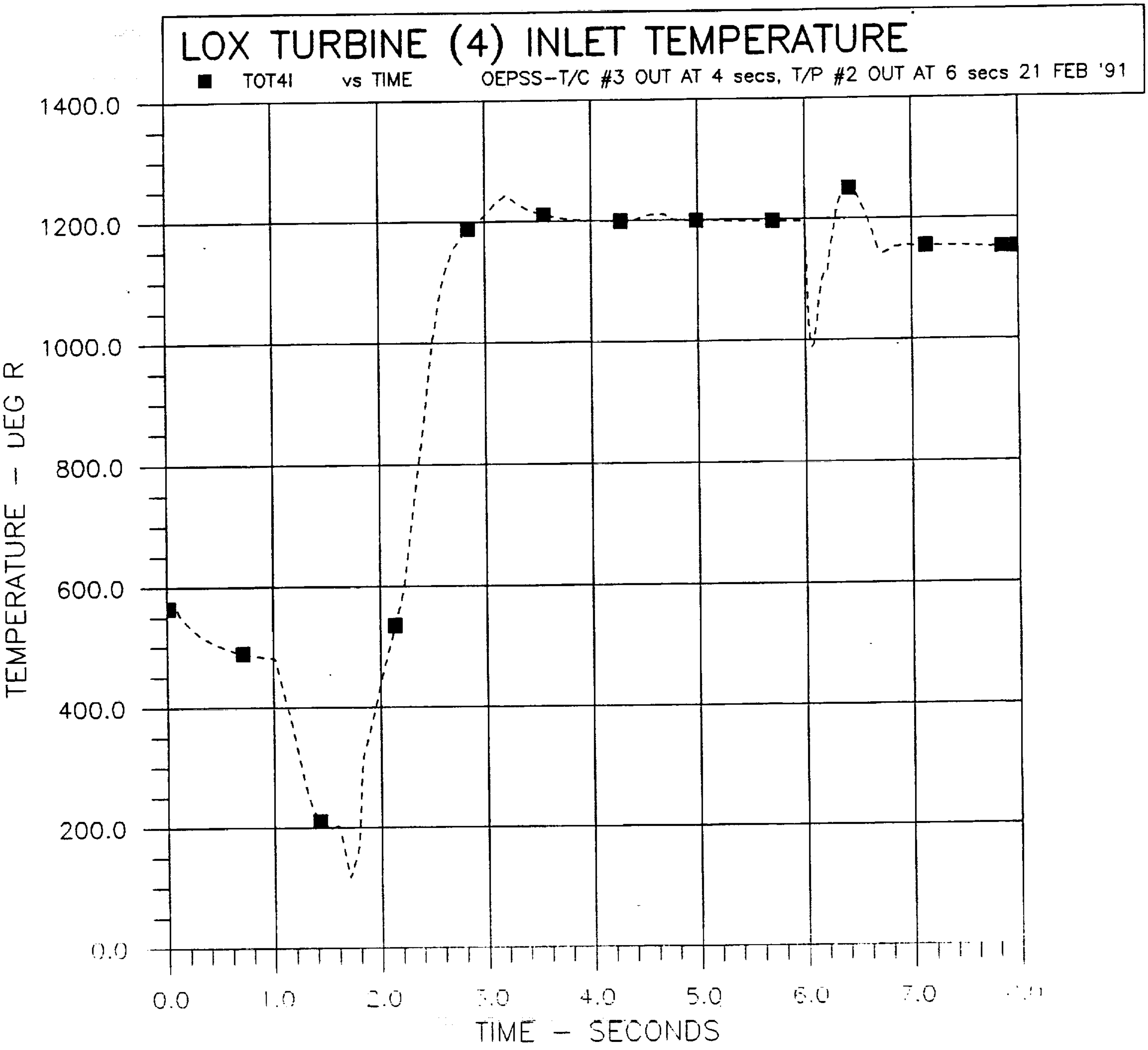

LOX TURBINE (4) INLET TEMPERATURE
■ TOT4I vs TIME
OEPSS-T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
TEMPERATURE - DEG R
1400.0
1200.0
1000.0
800.0
600.0
400.0
200.0
0.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
TIME - SECONDS

Figure H17

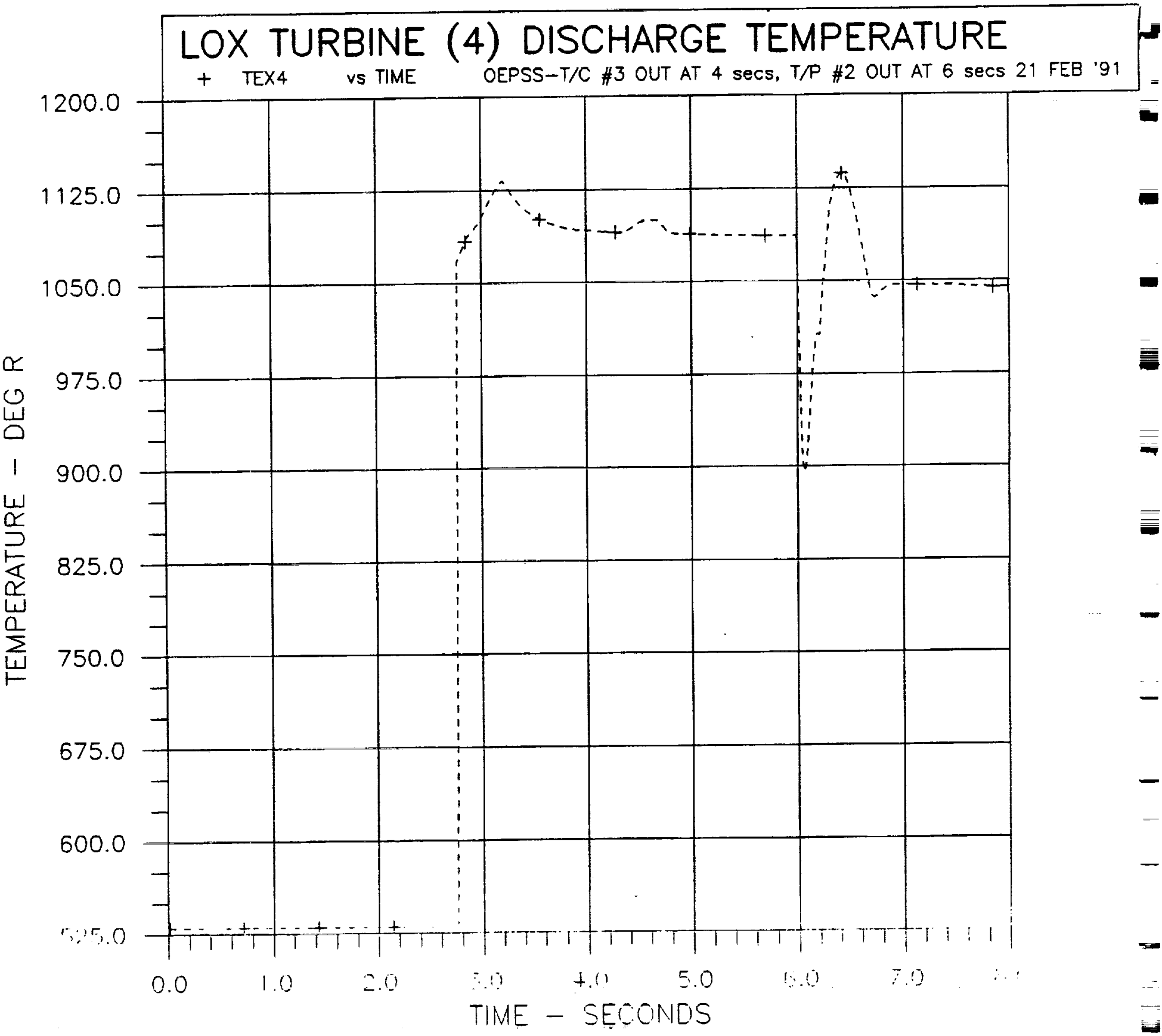

LOX TURBINE (4) DISCHARGE TEMPERATURE
+ TEX4 vs TIME
OEPSS–T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
TEMPERATURE – DEG R
1200.0
1125.0
1050.0
975.0
900.0
825.0
750.0
675.0
600.0
525.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
TIME – SECONDS

Figure H18

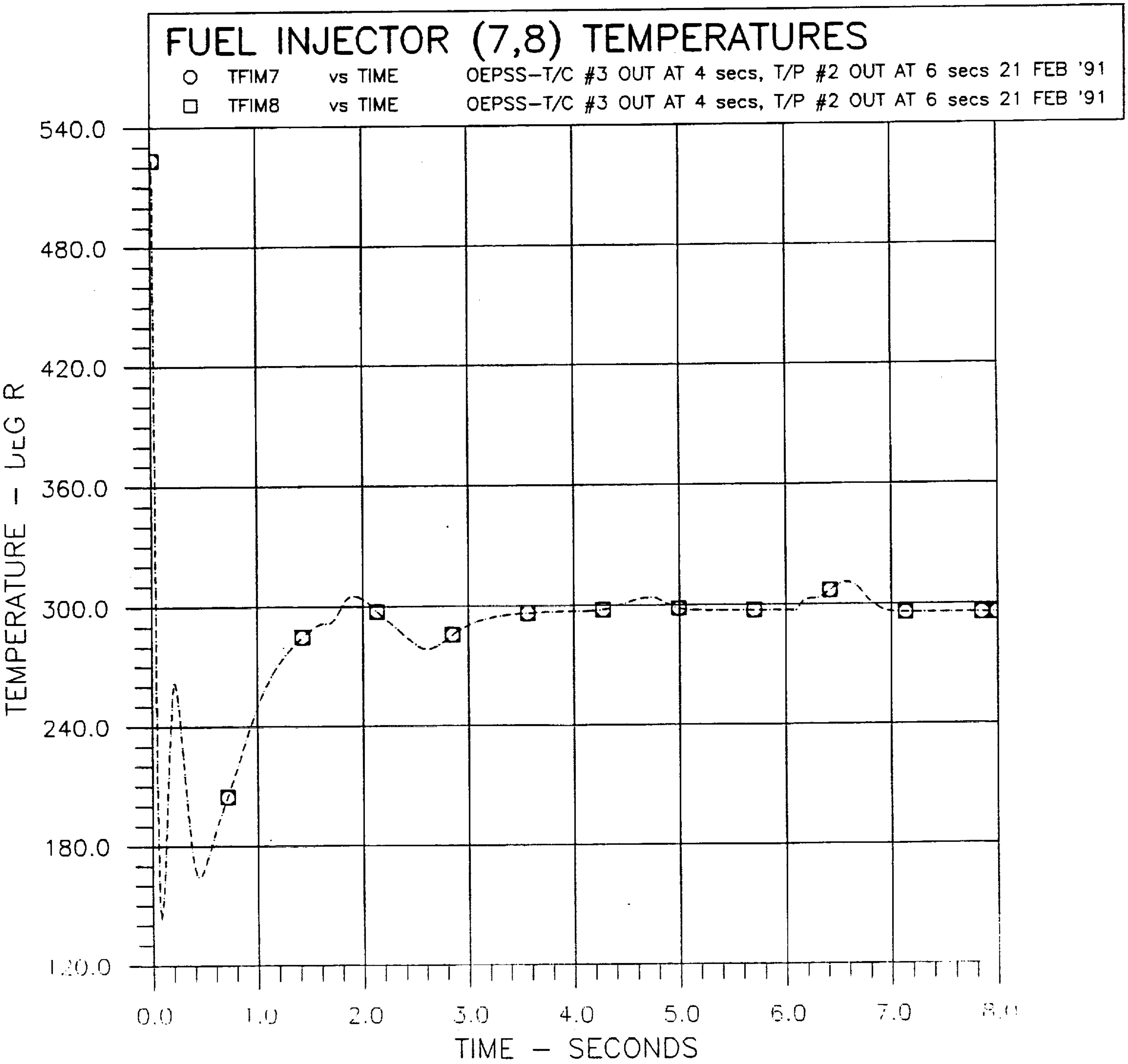

FUEL INJECTOR (7,8) TEMPERATURES
○ TFIM7 vs TIME OEPSS–T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
□ TFIM8 vs TIME OEPSS–T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
TEMPERATURE – DEG R
540.0
480.0
420.0
360.0
300.0
240.0
180.0
120.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
TIME – SECONDS

Figure H19

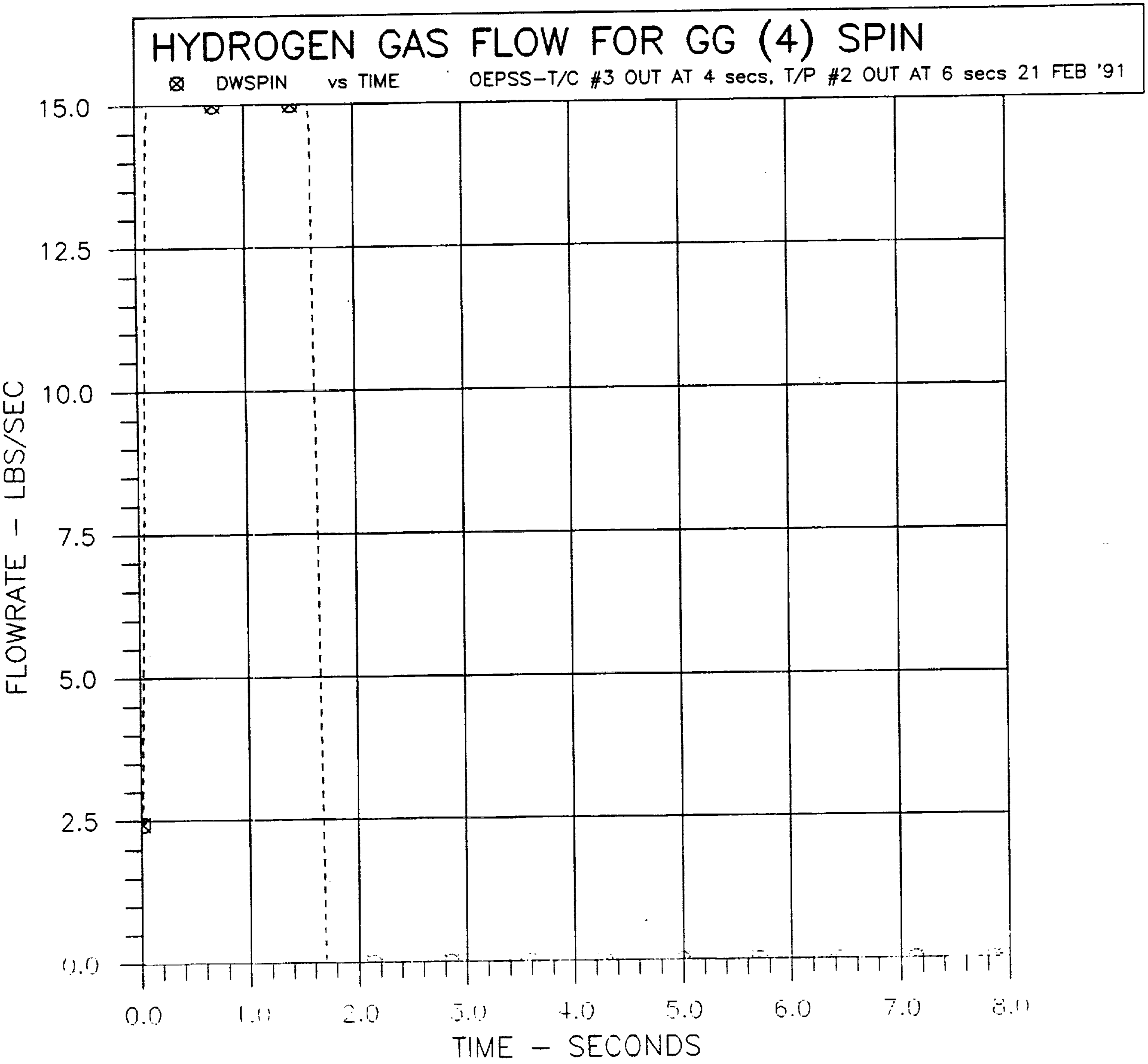

HYDROGEN GAS FLOW FOR GG (4) SPIN
⊠ DWSPIN vs TIME
OEPSS-T/C #3 OUT AT 4 secs, T/P #2 OUT AT 6 secs 21 FEB '91
FLOWRATE - LBS/SEC
15.0
12.5
10.0
7.5
5.0
2.5
0.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
TIME - SECONDS

Figure H20

Section 3

Internal Letter 2128-0041, "Operationally Efficient Propulsion System Study,
Option 2, Transient Analysis Study: Sensitivity Studies in Staggered Gas Generator
Spin Start and in Pump Performance Characteristics,"
Victoria Kemp, dated April 6, 1992.

Internal Letter **Rockwell International**

Date: April 6, 1992
No. IL 2128-0041

TO:
Ron P. Pauckert
Rocketdyne-Plummer
D589, IB43
x4875

FROM:
Victoria R. Kemp
Rocketdyne-Plummer
D545-128, JB11
x5530

Subject: Operationally Efficient Propulsion System Study, Option 2, Transient Analysis Study: Sensitivity Studies in Staggered Gas Generator Spin Start and in Pump Performance Characteristics

References :

[1] Internal Letter 2128-0037, "Operationally Efficient Propulsion System Study, Option 2, Transient Analysis Study: Turbopump Out and Combined Thrust Chamber/Turbopump Out Conditions",V.Kemp, 5 March 1992.

[2] Internal Letter 1128-0014, "Operationally Efficient Propulsion System Transient Analysis Study, Task 1.0", V. Kemp, 28 January 1991.

[3] Internal Letter EA90-011, "Operationally Efficient Propulsion System Study", W. Geniec, P. Chen, W. Bissell, C. Erickson to G.S. Wong, 22 March 1990.

[4} Notes: Additional steady state engine balance data, P. Chen, W. Bissell, 2 February 1990.

[5] Centrifugal and Axial Flow Pumps, Second Edition, A.J. Stepanoff, John Wiley & Sons, 1957, p.270.

Introduction

In support of the NASA/KSC program (contract no. NAS 10-11568, mod.no. 2), Operationally Efficient Propulsion System Study (OEPSS), Option 2, Task 1.0, sensitivity studies were made for a delayed spin start of one gas generator (GG) and for variations in pump performance characteristics. In a system with multiple pumps in parallel, a delay in start of one or more of the pumps relative to the others may prevent the corresponding pump set(s), and thus the system, from attaining acceptable mainstage operation. In addition, slight variations will always exist between pumps built to the same specifications. No two pumps will have exactly the same inertias or performance characteristics. In a system with multiple pumps in parallel, variations in operating conditions among the pumps can result in oscillations in the feed system dynamic behavior. Simulations were conducted to examine (1) the feasibility of attaining a nominal mainstage for a delay in start of one pump relative to the other three, and (2) the potential for steady state instabilities due to variations in pump operation.

A fluid-thermo dynamic digital transient model of the engine was used to perform the simulations. The nominal start/cutoff transient behavior for the 8 chamber/4 turbopump system and valve sequencing is described in reference [2]. The feasibility of the integrated engine system concept in regards to the transient behavior with a component out has also been examined. Transient operation during the transition from an 8/4 chamber/turbopump system to a 7/4 system in the case of a chamber out condition is also described in reference [2]. An analysis of the transient operation during the transition from an 8/4 chamber/pump system to either an 8/3 system in the case of a pump out condition, or to a 7/3 system in the case of a combined chamber/pump out condition is documented in reference [1]. References 1 and 2 provide a more comprehensive overview of the system transient behavior under nominal and component out conditions. The simulations were carried out on the SUN workstation.

Summary

This report presents the results of transient analyses performed for (1) a delay in start by 100 msec of one GG relative to three other parallel GGs (see Appendix A), and (2) three cases in which the performance characteristics of the four parallel turbopump sets vary among the pumps (see Appendices B,C, and D). In each of these simulations, the fuel and LOX pump performance characteristics of pumps 1 and 3 were varied from the nominal performance characteristics of pumps 2 and 4. Pump sets 1 and 3 operated with a 5% higher head output (Case I), 5% lower torque output (Case II), and a 5% higher output in both head and torque (Case III) in the three cases, respectively. Directories to selected parameter profiles are provided on pages 17 and 18.

The simulation of a delay in start for one GG was made to investigate whether the delay in start would preclude the associated pumps from attaining an otherwise nominal start. In a system of parallel pumps with common manifold, a long enough delay in starting one pump could preclude that pump from starting due to backpressure from the manifold. The simulation was performed for a 100 msec delay which is of sufficient duration that might result, for example, from variations in spin valve opening times or rates. In spite of the delay in start of one GG, the engine system reached the same operating conditions at mainstage as would result for a simultaneous start of the GGs. While variations resulted in the transient behavior between System 2 and Systems 1,3, and 4, the transient behavior in all four parallel "systems"

was acceptable. The method of analysis section on the following page describes the components associated with Systems 1, 2, 3, and 4.

Simulations were made to evaluate the potential for feed system oscillations and general unstable operation at mainstage due to variations in performance characteristics among the four parallel pump sets. In the three simulation cases conducted for variations of ± 5% in head and torque performance, stable operating conditions at mainstage were reached with satisfactory transient behavior during start. Slight variations resulted in the mainstage conditions between the four parallel feed systems as a result of the pump performance variations. Further, slightly higher chamber pressures compared to nominal resulted in Case I and Case II due to the increase in pump efficiency.

Method Of Analysis

Simulation of the integrated propulsion system (Figure 1) was accomplished using a one-dimensional thermodynamic model which simulates the states of fluid parameters such as pressure, temperature, and flowrate for the propellants throughout the system, propellant mixture ratios for the GG chambers and thrust chambers, temperatures for the combustor and nozzle walls, pump speeds, and valve actuator positions. The system encompassed in the model includes the pump inlets to the thrust chambers. A generalized fluid flow schematic of the integrated system is shown in Figure 2. A more detailed flow schematic with engine balance of part of the system, showing the basic flow configuration of one turbopump set, one gas generator, and one thrust chamber, is shown in Figure 3. The system may be envisioned as four sub-systems where each sub-system is comprised of a fuel and an oxidizer turbopump powered by a GG, eight valves, and two thrust chambers, interconnected by ducts and fuel/oxidizer torroidal manifolds. The eight valves consist of a pump discharge valve, a GG valve, and two thrust chamber inlet valves on each of the fuel and LOX sides. Reference will be made to each of these sub-systems as Systems 1, 2 , 3, and 4 where System 1 is comprised of GG 1 and thrust chambers (T/C) 1 and 2, System 2 is comprised of GG 2 and T/Cs 3 and 4, and so on. Each engine sub-system is configured as a gas generator cycle. A hydrogen spin is used on each of the four gas generators to assist in start.

The LOX and fuel pump performance maps are shown in Figures 4 through 7. These are based on the pump characteristics documented in reference [3]. Generalized pump maps from reference [5] were also used to expand the maps to encompass negative flow coefficients. The valve schedules used for start are based on reference [2] and are shown in Table 1.

Figure 1
8 - Engine Booster Propulsion Module

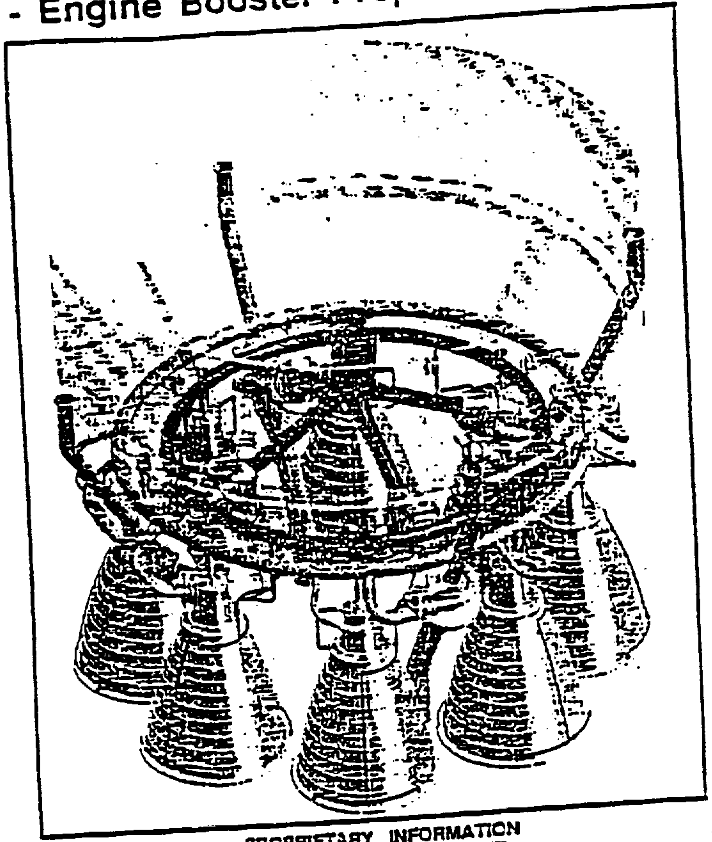


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Figure 2
Integrated System Fluid Flow Schematic

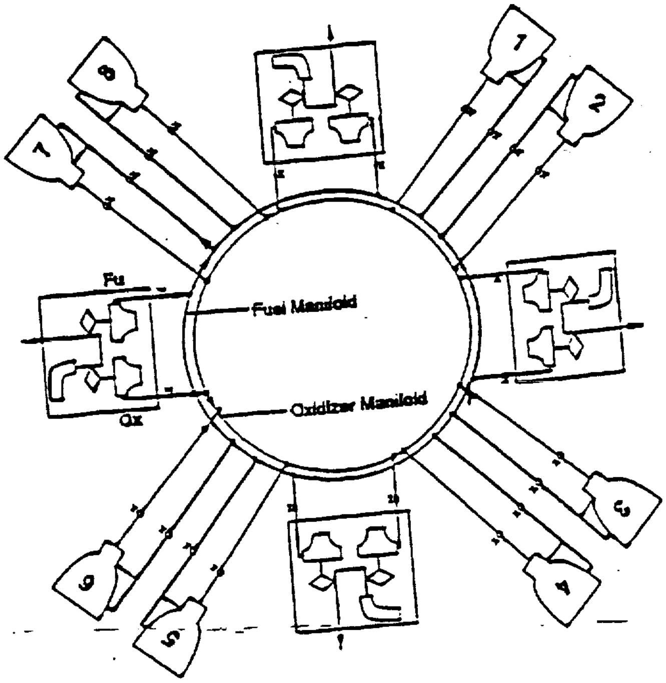
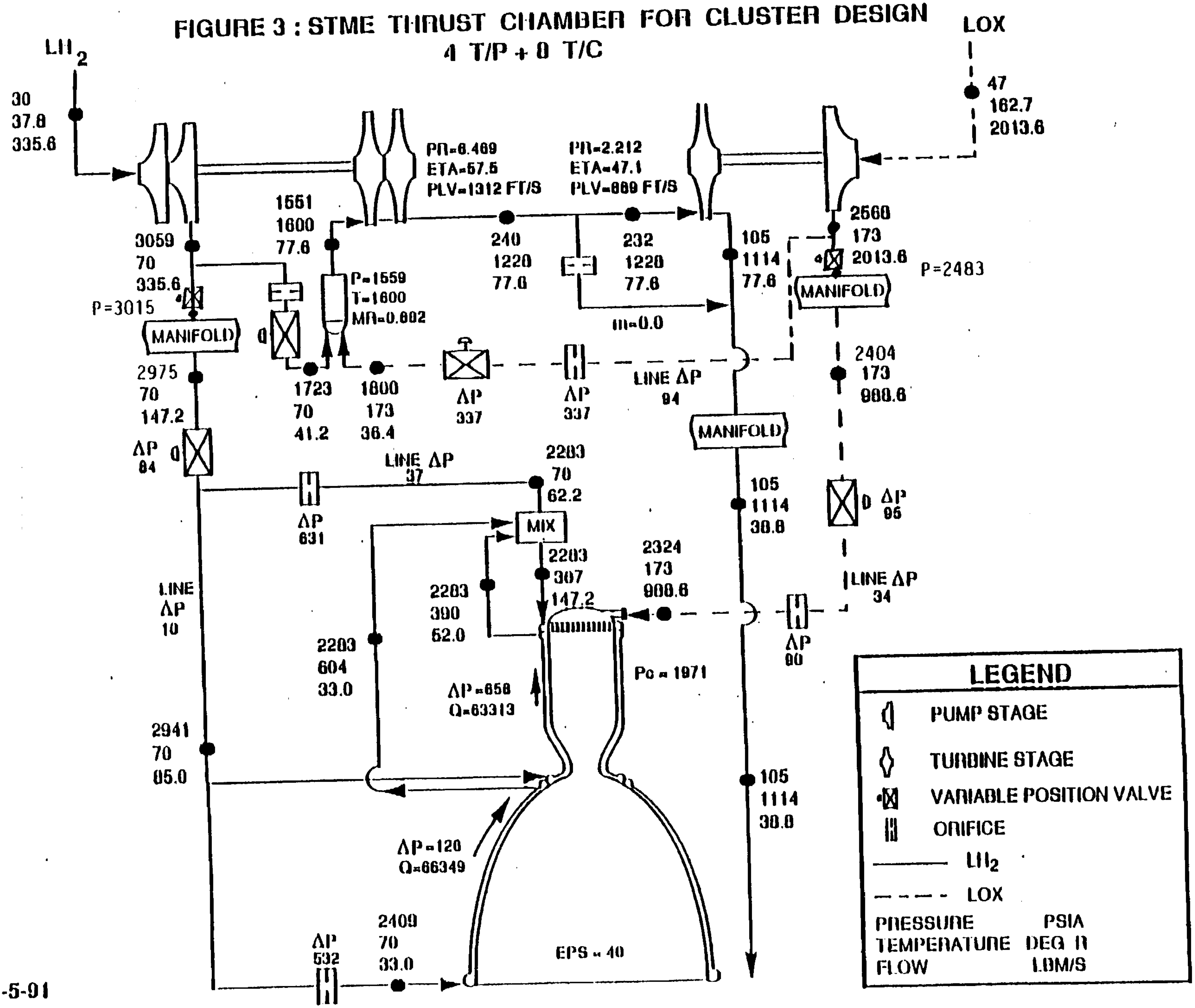
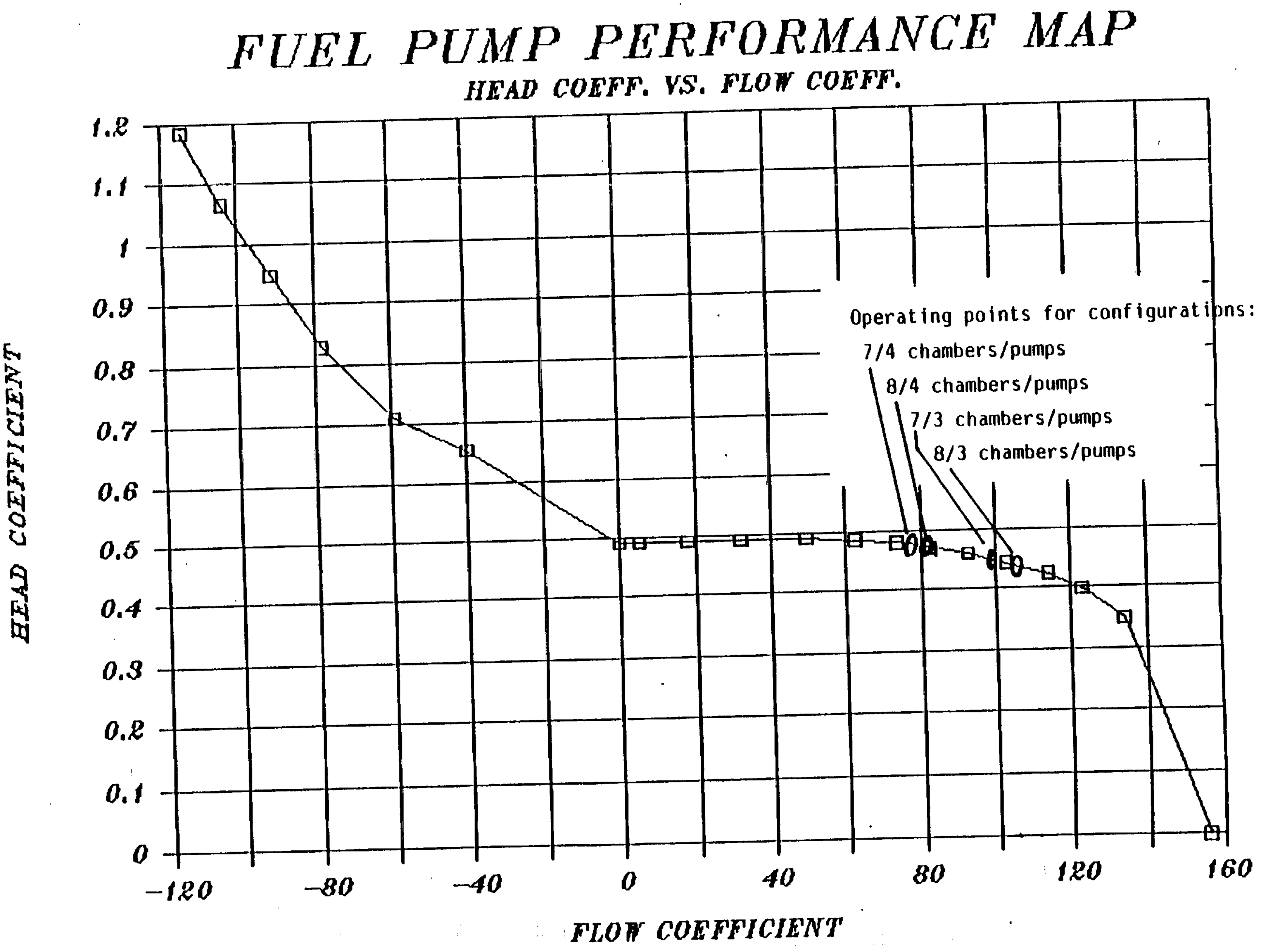


FIGURE 3 : STME THRUST CHAMBER FOR CLUSTER DESIGN
4 T/P + 0 T/C



2-5-91



FUEL PUMP PERFORMANCE MAP

HEAD COEFF. VS. FLOW COEFF.

Operating points for configurations:
7/4 chambers/pumps
8/4 chambers/pumps
7/3 chambers/pumps
8/3 chambers/pumps

Figure 4

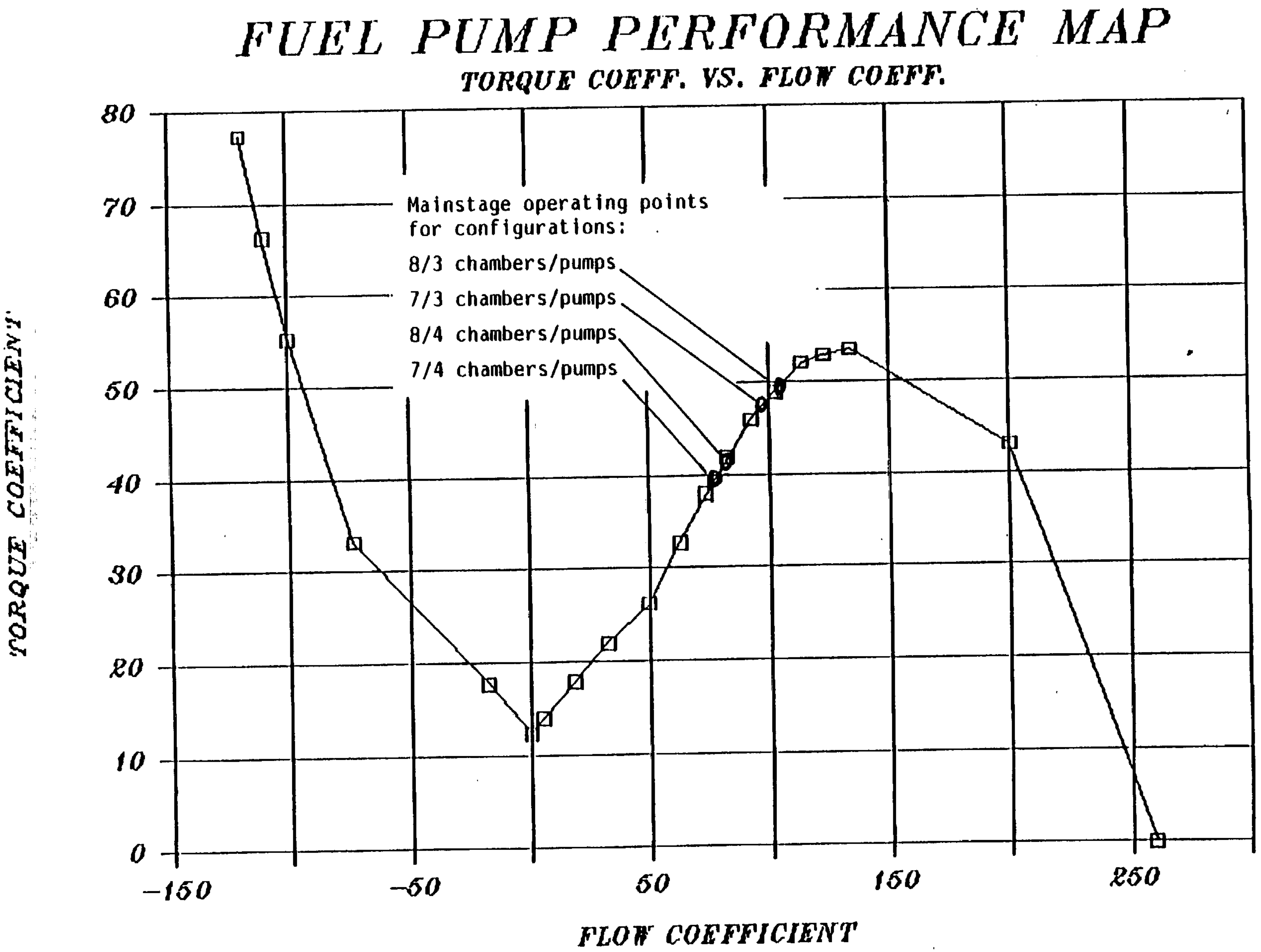

FUEL PUMP PERFORMANCE MAP
TORQUE COEFF. VS. FLOW COEFF.
Mainstage operating points
for configurations:
8/3 chambers/pumps
7/3 chambers/pumps
8/4 chambers/pumps
7/4 chambers/pumps
TORQUE COEFFICIENT
80
70
60
50
40
30
20
10
0
FLOW COEFFICIENT
−150
−50
50
150
250

Figure 5

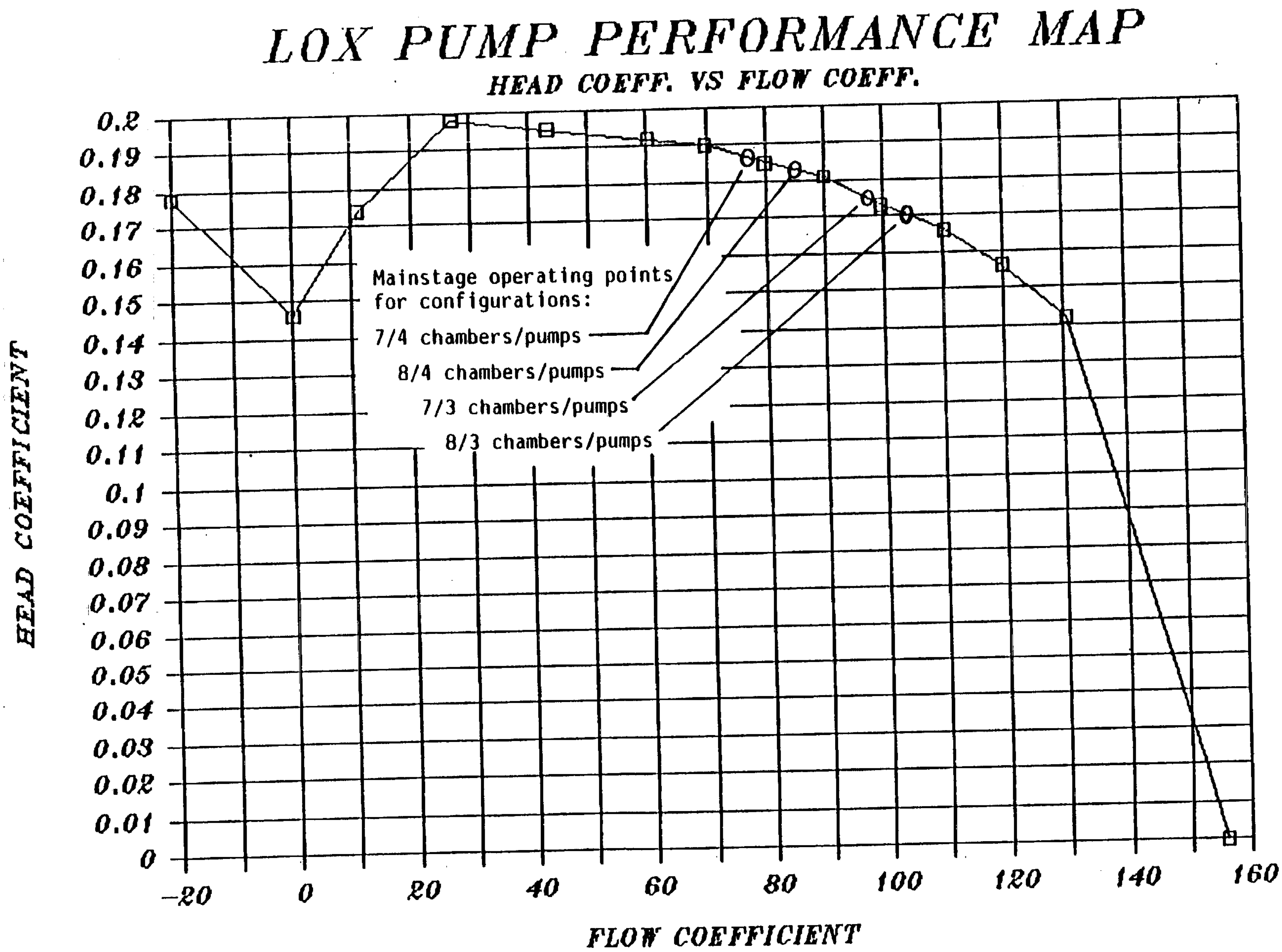

LOX PUMP PERFORMANCE MAP
HEAD COEFF. VS FLOW COEFF.
Mainstage operating points
for configurations:
7/4 chambers/pumps
8/4 chambers/pumps
7/3 chambers/pumps
8/3 chambers/pumps
HEAD COEFFICIENT
0.2
0.19
0.18
0.17
0.16
0.15
0.14
0.13
0.12
0.11
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
-20
0
20
40
60
80
100
120
140
160
FLOW COEFFICIENT

Figure 6

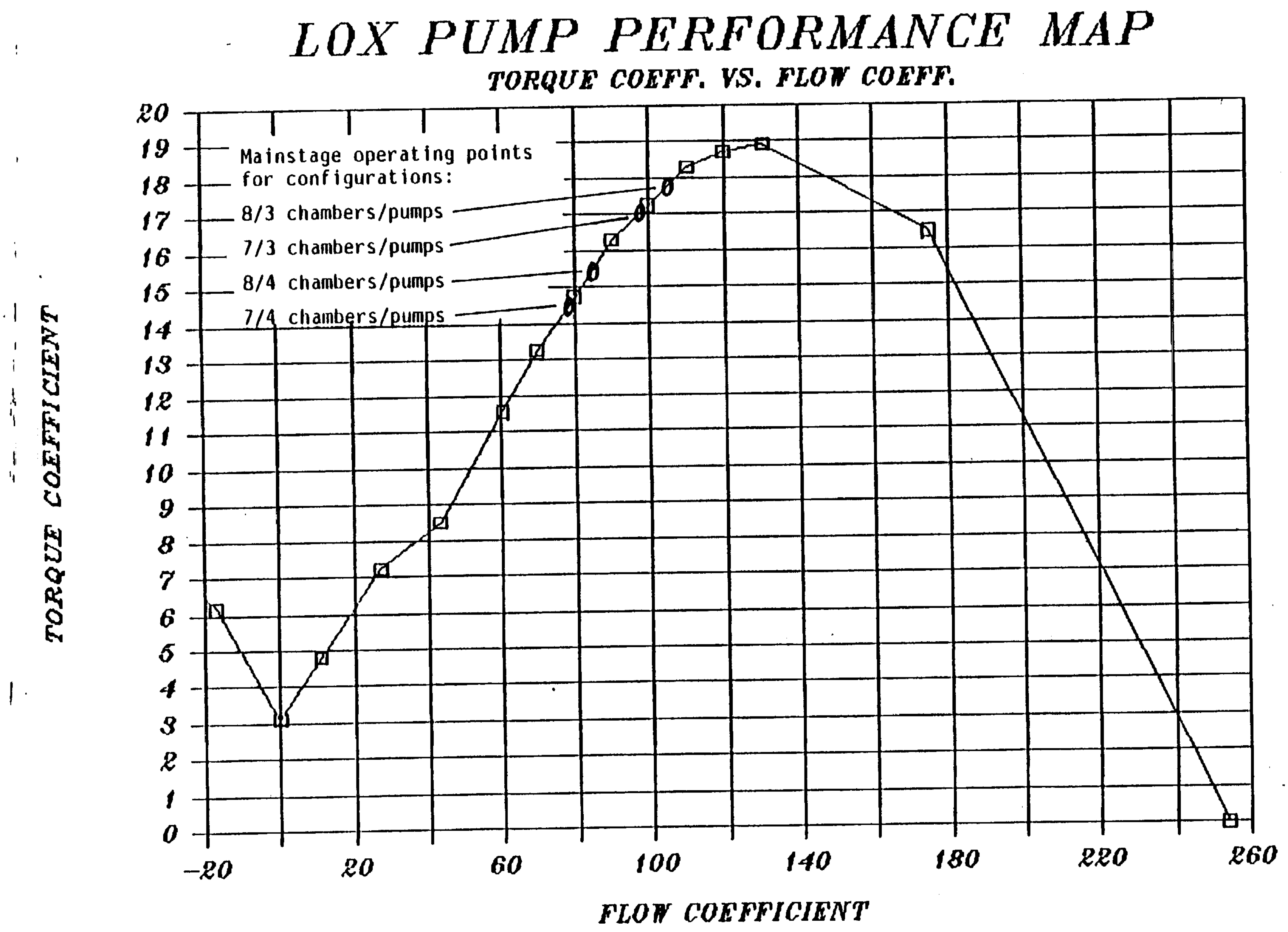

LOX PUMP PERFORMANCE MAP
TORQUE COEFF. VS. FLOW COEFF.
Mainstage operating points
for configurations:
8/3 chambers/pumps
7/3 chambers/pumps
8/4 chambers/pumps
7/4 chambers/pumps
TORQUE COEFFICIENT
20
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
-20
20
60
100
140
180
220
260
FLOW COEFFICIENT

Figure 7

Table 1
Valve Schedules For Hydrogen Spin-Assisted Start

Valve	Start/End (sec)	Rate (%/sec)	Final Position (%)
Fuel Pump Discharge (4)	0./0.	instantaneous	100.
LOX Pump Discharge (4)	0./0.	instantaneous	55.
	2.1/3.4	35.	100.
Fuel Gas Generator (4)	0./1.0	0.	0.
	1.0/1.5	200.	100.
LOX Gas Generator (4)	0./1.2	0.	0.
	1.2/3.2	50.	100.
Fuel Thrust Chamber Inlet (8)	0./0.3	333.	100.
LOX Thrust Chamber Inlet (8)	0./0.1	0.	0.
	0.1/0.5	100.	40.
	0.5/2.5	0.	40.
	2.5/3.8	46.	100.

Discussion and Results

Delayed Start Of One Gas Generator

Slight variations in ignition between the four GGs are possible under nominal circumstances. Variations in GG ignition times could result, for example, from variations in opening of the spin valves. Simulations were made for a delay in spin start of one GG (#2) relative to the other three by 50 msec and 100 msec. The time delays selected for simulation are of sufficient duration compared to variations in valve opening times which could be expected. For example, a 10% variation between spin valves with opening rates of 100 msec would result in a 10 msec delay in start of one of the GGs. The simulations were made to examine the feasibility to start all four pump sets and achieve an acceptable mainstage under such circumstances. Should the delay in ignition of one GG be of long duration, the corresponding pumps may not achieve an adequate start due to high backpressure from the downstream manifolds.

The figures in Appendix A present the simulation results for the 100 msec delay in start of GG#2 relative to the other three GGs. Figures A4 and A5 show the gas spin start profiles for the delayed start of GG #2 and the nominal start of GGs #1, 3, and 4. Table 2 shows the model conditions achieved at mainstage. In spite of the delayed start of GG #2, the engine system simulation reached the same operating conditions at mainstage as result for a simultaneous start of the GGs.

Some variations exist between the transient behavior of System 2 and Systems 1,3, and 4. The GG chamber pressures in Figures A10 and A11 show the delay in start by 100 msec for GG #2 compared to the start of GGs #1,3, and 4. Figure A10 also indicates an overshoot in the GG #2 pressure between 200 and 450 msec compared the the nominal GG start behavior. Figures A14-15 and A24-25 show the corresponding 100 msec delays in start for the fuel and LOX #2 pumps compared to the nominal pump start profiles. Around 120 msec, the fuel manifold pressure begins to be maintained slightly higher than the pump #2 discharge pressure. The resulting backpressure on pump #2 causes the fuel to flow back into the pump, indicated in Figure A16. By about 450 msec, the discharge pressure of pump #2 is sufficient resulting in positive flow. Figure A26 shows a delay in flow of LOX pump #2 of about 400 msec compared to the other LOX pumps. The delays in both the fuel and LOX pump flows result from backpressure exerted by the ring manifolds. The ring manifold pressures are higher than the pump #2 discharge pressures early on due to the earlier starts of the other three pump sets.

750
2000

Table 2
Steady State Engine Balance For The 8 Chamber/4 Turbopump Configuration Delayed Start of Gas Generator #2 By 100 msec

	Design Values	Model Results							
		T/P1 T/C1	TC2	T/P2 T/C3	T/C4	T/P3 T/C5	T/C6	T/P4 T/C7	T/C8
Thrust Chamber									
thrust (lb)	497000	425358	425358	425359	425362	425364	425358	425366	425366
pressure (psia)	1971	2013	2013	2013	2013	2013	2013	2013	2013
mixture ratio	6.701	6.66	6.66	6.66	6.66	6.66	6.66	6.66	6.66
fuel flowrate (lb/sec)	147	151	151	151	151	151	151	151	151
lox flowrate (lb/sec)	986	1008	1008	1008	1008	1008	1008	1008	1008
Fuel Pump									
speed (rpm)	14654	14825		14828		14826		14824	
torque (in-lb)	336295	350465		350778		350756		350747	
discharge pressure (psia)	3058	3117		3118		3117		3117	
flowrate (lb/sec)	336	346		347		347		346	
LOX Pump									
speed (rpm)	5521	5620		5620		5620		5621	
torque (in-lb)	274071	282639		282906		282943		282850	
discharge pressure (psia)	2568	2660		2660		2660		2661	
flowrate (lb/sec)	2014	2051		2053		2053		2052	
Gas Generator									
pressure (psia)	1559	1621		1621		1621		1621	
temperature (R)	1600	1556		1555		1555		1556	
mixture ratio	0.882	0.84		0.84		0.84		0.84	
fuel flowrate (lb/sec)	41.2	44		44		44		44	
lox flowrate (lb/sec)	36.4	37		37		37		37	

T/P - turbopump
T/C - thrust chamber

Variations in Pump Operating Characteristics

Three simulations were made to evaluate variations in pump performance characteristics between the four parallel turbopump sets. In each of the simulations, the fuel and LOX pump performance characteristics of pump sets 1 and 3 were varied from the nominal performance characteristics of pump sets 2 and 4. The nominal performance curves for the fuel and LOX pumps are shown in Figures 4-7. In the first simulation, the fuel and LOX pump head output for pumps 1 and 3 was increased by 5% (5% efficiency increase) over the nominal head performance of pumps 2 and 4. In the second simulation, the fuel and LOX pump torque output for pumps 1 and 3 was decreased by 5% (5% efficiency increase) compared to the nominal torque performance of pumps 2 and 4. In the third simulation, both the head and torque output for pumps 1 and 3 were increased by 5% (no net change in efficiency) compared to the nominal head and torque performance of pumps 2 and 4.

The simulation results are presented in Appendices B, C, and D. Table 3 shows the model conditions at mainstage for the nominal case and for the three simulations with variations in pump performance characteristics. In all three simulations, the mainstage operating conditions are slightly different between pump sets 1 and 3 and pump sets 2 and 4. The dynamic behavior of each of the four parallel feed systems is stable at mainstage.

In the first simulation (Appendix B), the higher head performance of pumps 1 and 3 result in higher pump discharge pressures and higher flowrates for pumps 1 and 3 compared to nominal (Table 3). Operation of these pumps at higher flow coefficients results. Thus, the pump torque requirements are increased which result in lower pump speeds compared to nominal. Operation of pumps 2 and 4 balance out at lower flow coefficients in order to match the head output of pumps 1 and 3. As a result, the pump torque requirements are slightly lower than for pump sets 1 and 3, resulting in higher pump speeds (Figures B9-12, B21-24). Slightly lower pump discharge pressures and lower flowrates (Figures B13-16, B25-28) result for pumps 2 and 4, relative to pumps 1 and 3. The effect on the main chambers is an increase in pressure of about 2 % compared to the nominal case (Table 3).

In the second simulation (Appendix C), the lower torque performance of pump sets 1 and 3 directly affect the pumps resulting in a reduced torque requirement and thus higher speeds for these pumps compared to nominal (Table 3). Higher pump discharge pressures and flowrates as well as GG pressures result for pump sets 1 and 3 compared to nominal (Table 3). Operation of pump sets 1 and 3 balance out at higher flow coefficients due to the increased pump efficiencies. Since the speeds are lower for pump sets 2 and 4 compared with pump sets

1 and 3, operation of pumps 2 and 4 balance out at lower flow coefficients compared with pump sets 1 and 3 in order to match the head output of pumps 1 and 3. Both the speeds (Figures C9-12, C21-24) and flowrates (Figures C13-16, C25-28) of pump sets 2 and 4 are lower than those of pump sets 1 and 3. The effect on the main chambers is an increase in pressure of 2.4% compared to the nominal case (Table 3).

In the third simulation (Appendix D), both the head and torque performance output for pump sets 1 and 3 are 5% higher than for pump sets 2 and 4. The results for this case are equivalent to the results of Case I combined with the opposite results as produced in Case II. The higher head performance results in operation of pump sets 1 and 3 at higher flow coefficients. The combined effect of operating at higher flow coefficients and with higher torque performance results in higher pump torque requirements, and thus even lower speeds, for pump sets 1 and 3 than resulted in Case I. Operation of these pumps balance out at only slightly higher flow coefficients than pumps 2 and 4. Pump sets 1 and 3 have lower speeds (Figures D9-12, D21-24) and slightly lower flowrates (Figures D13-16, D25-28) than pump sets 2 and 4. The higher head performance by 5% and higher torque performance by 5% counter each other in their effects on efficiency. The main chamber pressures are only slightly lower than in the nominal case by 0.4% (Table 3).

Table 3: Simulation Results At Mainstage For Variations In Pump Performance Characteristics

	Nominal Model Simulation				Case I Increased Head Performance Of Pumps 1 and 3 by 5%.				Case II Reduced Torque Performance Of Pumps 1 and 3 by 5%.				Case III Increased Head and Torque Performance Of Pumps 1 and 3 by 5%.			
PUMP #	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Head					5%		5%		-		-		5%		5%	
Torque					-		-		-5%		-5%		5%		5%	
Efficiency					5%		5%		5%		5%		-		-	
FUEL PUMP																
speed (rpm)	14620	14620	14620	14620	14479	14744	14483	14739	14867	14782	14869	14776	14249	14592	14250	14586
pump torque(in-lb)					365438	362315	366368	362304	362315	363287	362697	363268	362077	358018	362379	358002
turb torque (in-lb)					365338	362141	366142	362119	362124	363105	362556	363054	361759	357835	362127	357840
dis pressure (psia)	3226	3226	3226	3226	3298	3291	3298	3290	3321	3312	3321	3311	3208	3211	3208	3210
flowrate (lb/sec)	363	364	364	363	377	364	378	363	383	364	383	363	360	365	360	363
flow coefficient					91.3	86.5	91.5	86.3	90.1	86.2	90.2	86	88.6	87.6	88.7	87.4
LOX PUMP																
speed (rpm)	5644	5653	5644	5653	5592	5699	5601	5699	5748	5712	5748	5712	5506	5637	5506	5637
pump torque (in-lb)					290033	286588	290219	286509	286247	287294	286462	287258	287798	283694	287967	283635
turb torque (in-lb)					289537	286156	289857	286117	285791	286883	286113	286795	287196	283280	287553	283220
dis pressure (psia)	2689	2690	2687	2688	2742	2743	2751	2742	2767	2757	2769	2756	2673	2678	2674	2678
flowrate (lb/sec)	2049	2050	2050	2050	2128	2045	2125	2045	2145	2045	2146	2045	2034	2051	2035	2051
flow coefficient					88.2	83.2	87.9	83.2	86.5	83	86.5	83	85.6	84.3	85.7	84.3
MISC																
main chamber pressure (psia)	2045/2045	2045/2045	2045/2045	2045/2045	2083/2083	2083/2083	2083/2083	2083/2083	2094/2094	2094/2094	2094/2094	2094/2094	2037/2037	2037/2037	2037/2037	2037/2037
gas generator pressure (psia)	1642	1642	1642	1642	1663	1663	1666	1663	1673	1670	1674	1670	1633	1635	1633	1635

Conclusions

The simulations described in this report resulted in nominal mainstage operating conditions with satisfactory transient behavior in spite of a delay in ignition of one GG relative to three parallel GGs. Slight variations in GG ignition could be the result of variations in spin valve opening times or rates.

The simulations for variations in pump head and torque performance characteristics resulted in stable mainstage conditions for small variations (±5%) in performance between four parallel pumps. While variations resulted between the mainstage operating conditions of the parallel feed systems (as a result of variations in pump performance), the dynamic behavior of the parallel feed systems remained stable.

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Directory to Appendix A

Transient Analytical Results:
Delayed Start of Gas Generator #2 By 100 msec

Directory to Appendices B, C, and D

Transient Analytical Results: Variations In Pump Performance Characteristics

Appendix B - Case I: Increased Head Performance by 5% for Pumps 1 and 3
Appendix C - Case II: Decreased Torque Performance by 5% for Pumps 1 and 3
Appendix D - Case III: Increased Head and Torque Performances by 5% for Pumps 1 and 3

Figures	Description
B,C,D 1-4	Main Chamber Pressure
B,C,D 5-8	Main Chamber Mixture Ratio
B,C,D 9-12	Fuel Pump Speed
B,C,D 13-16	Fuel Pump Flowrate
B,C,D 17-20	Fuel Pump Discharge Pressure
B,C,D 21-24	Oxidizer Pump Speed
B,C,D 25-28	Oxidizer Pump Flowrate
B,C,D 29-32	Oxidizer Pump Discharge Pressure

APPENDIX A

TRANSIENT ANALYTICAL RESULTS: DELAYED START OF GAS GENERATOR #2 BY 100 MSEC

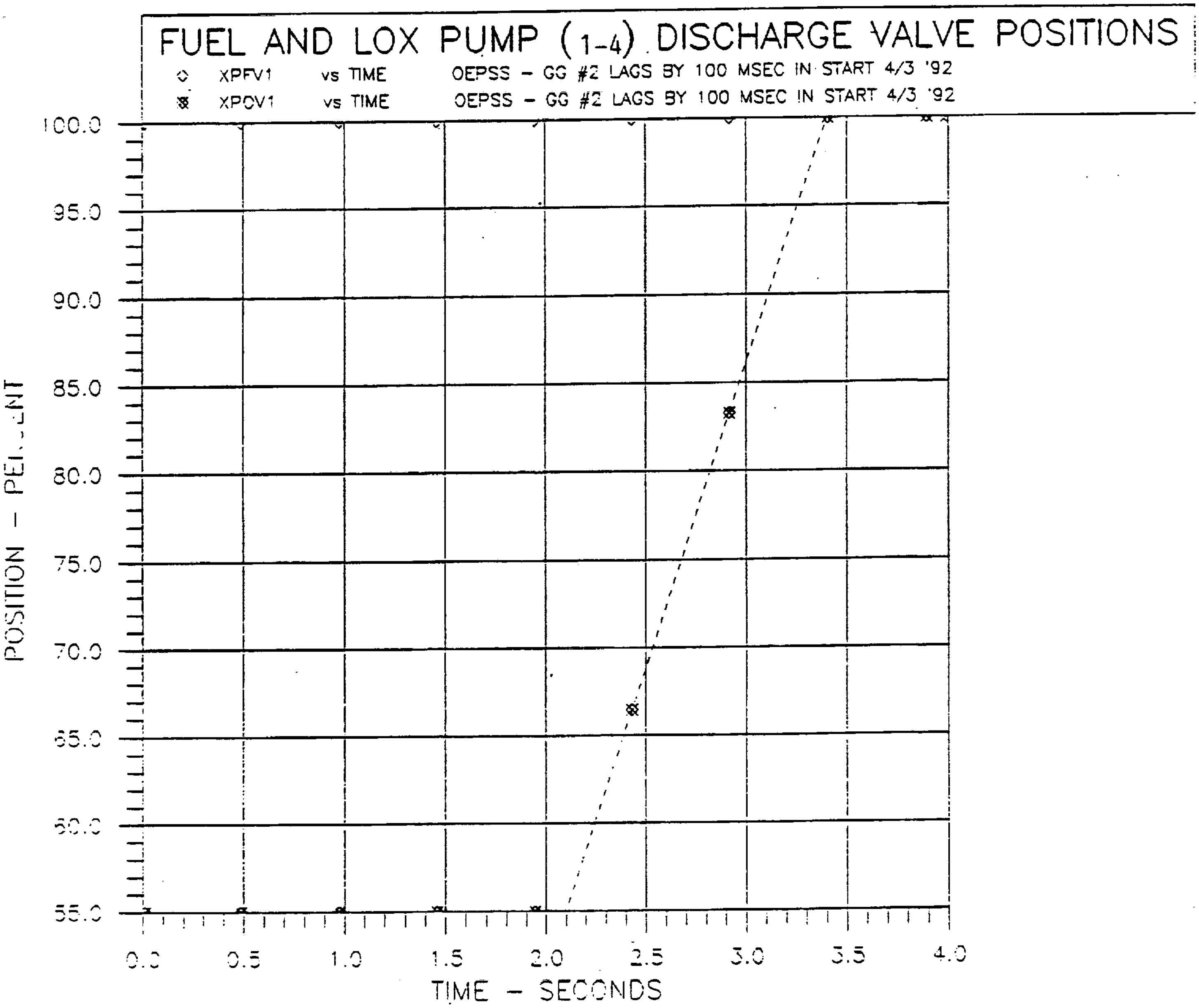

FUEL AND LOX PUMP (1-4) DISCHARGE VALVE POSITIONS
◇ XPFV1 vs TIME OEPSS - GG #2 LAGS BY 100 MSEC IN START 4/3 '92
⊗ XPOV1 vs TIME OEPSS - GG #2 LAGS BY 100 MSEC IN START 4/3 '92
100.0
95.0
90.0
85.0
80.0
75.0
70.0
65.0
60.0
55.0
POSITION - PERCENT
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
TIME - SECONDS

Figure A1

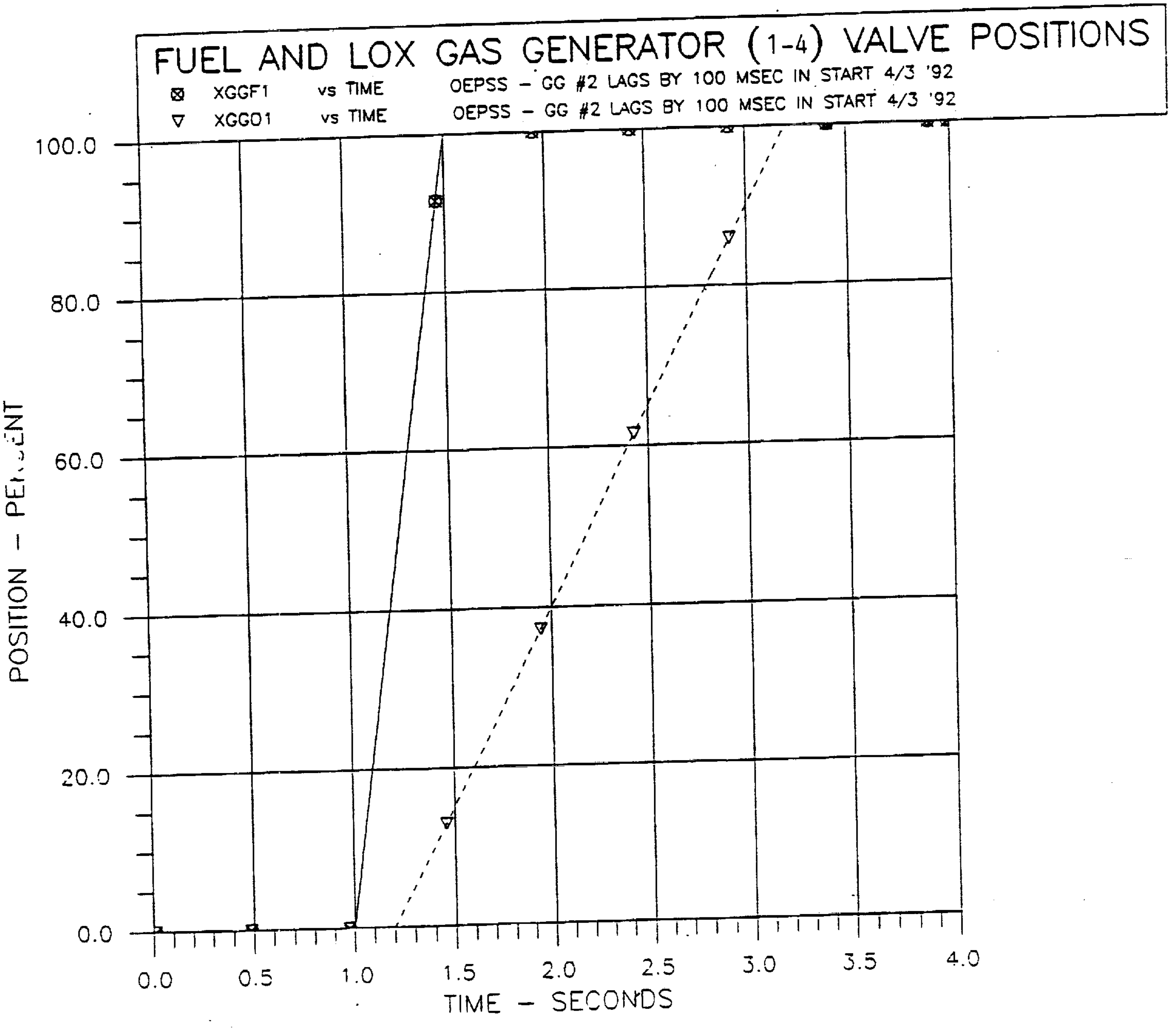

FUEL AND LOX GAS GENERATOR (1-4) VALVE POSITIONS
⊠ XGGF1 vs TIME OEPSS - GG #2 LAGS BY 100 MSEC IN START 4/3 '92
▽ XGGO1 vs TIME OEPSS - GG #2 LAGS BY 100 MSEC IN START 4/3 '92
POSITION - PERCENT
100.0
80.0
60.0
40.0
20.0
0.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
TIME - SECONDS

Figure A2

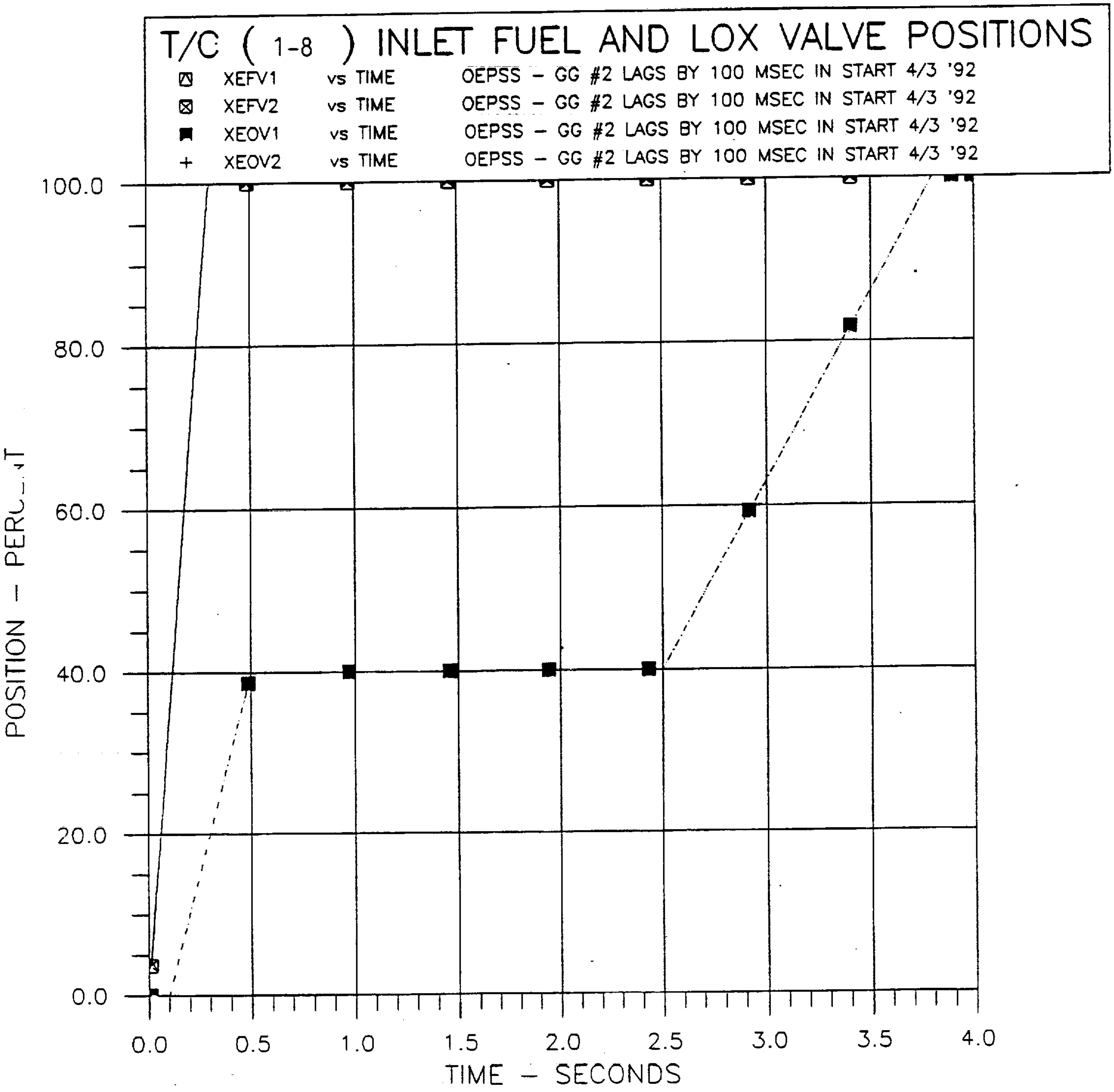

T/C (1-8) INLET FUEL AND LOX VALVE POSITIONS
XEFV1 vs TIME OEPSS – GG #2 LAGS BY 100 MSEC IN START 4/3 '92
XEFV2 vs TIME OEPSS – GG #2 LAGS BY 100 MSEC IN START 4/3 '92
XEOV1 vs TIME OEPSS – GG #2 LAGS BY 100 MSEC IN START 4/3 '92
XEOV2 vs TIME OEPSS – GG #2 LAGS BY 100 MSEC IN START 4/3 '92
100.0
80.0
60.0
40.0
20.0
0.0
POSITION – PERCENT
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
TIME – SECONDS

Figure A3

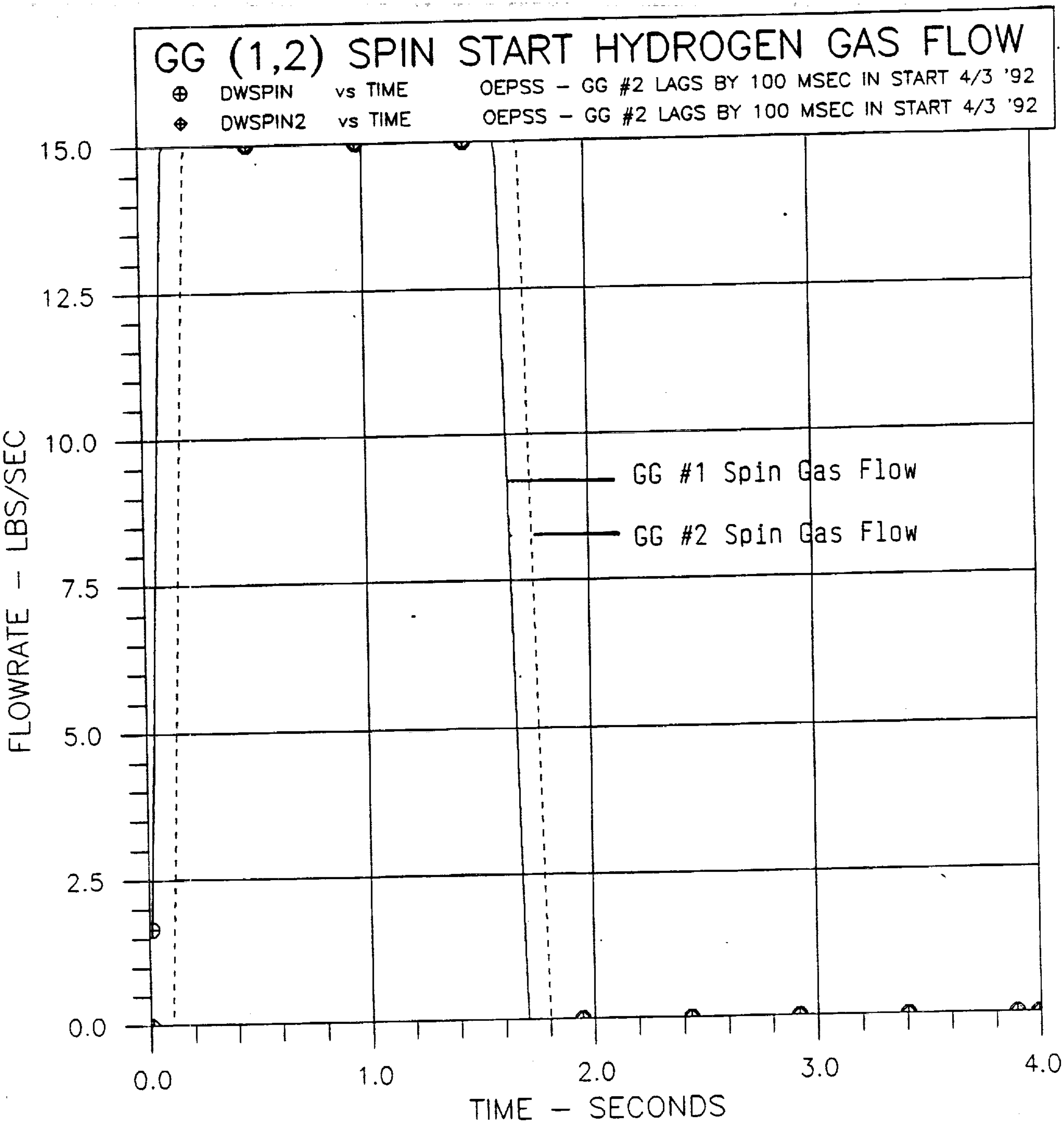

GG (1,2) SPIN START HYDROGEN GAS FLOW
DWSPIN vs TIME OEPSS – GG #2 LAGS BY 100 MSEC IN START 4/3 '92
DWSPIN2 vs TIME OEPSS – GG #2 LAGS BY 100 MSEC IN START 4/3 '92
GG #1 Spin Gas Flow
GG #2 Spin Gas Flow
FLOWRATE – LBS/SEC
15.0
12.5
10.0
7.5
5.0
2.5
0.0
0.0
1.0
2.0
3.0
4.0
TIME – SECONDS

Figure A4

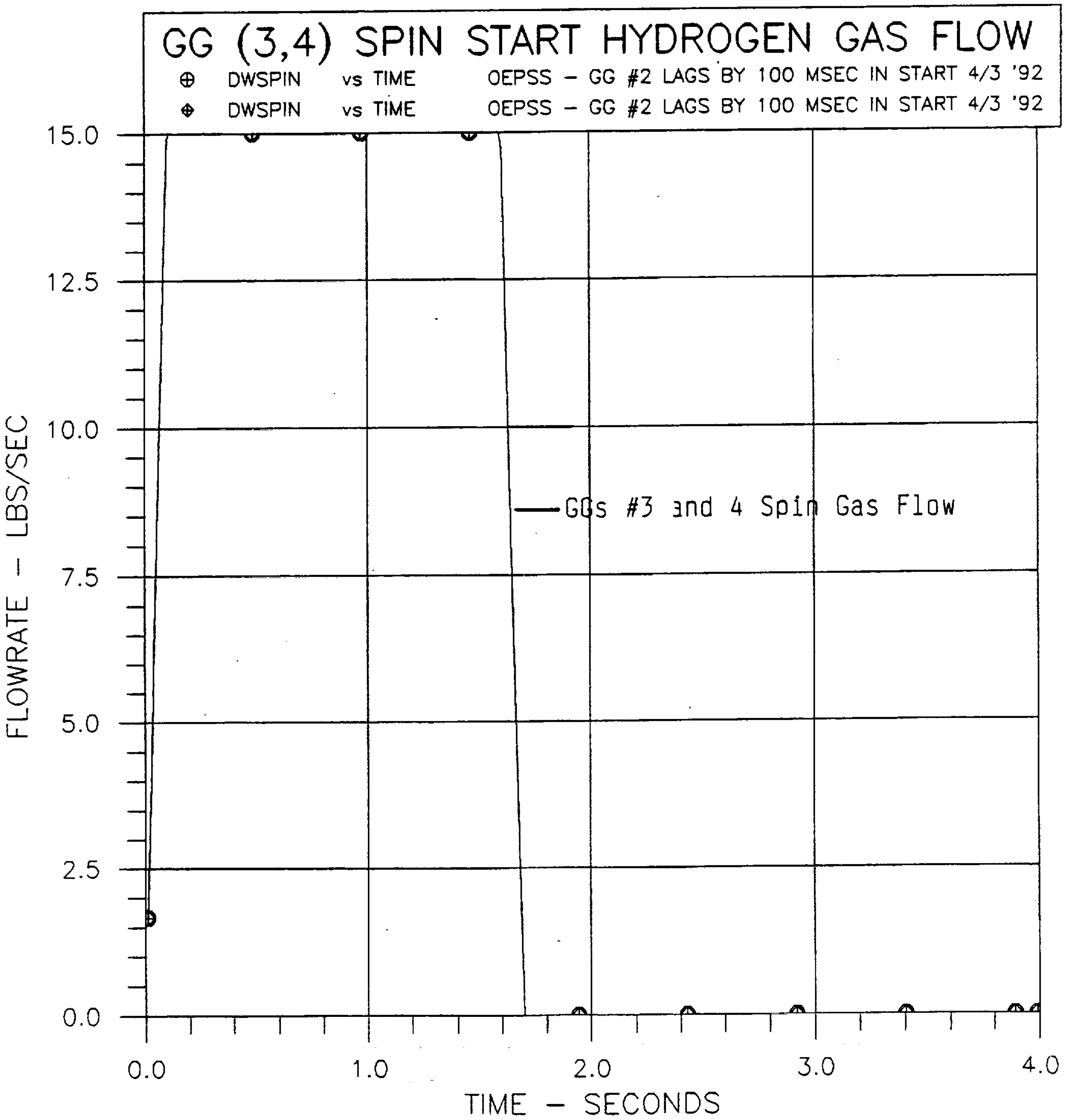
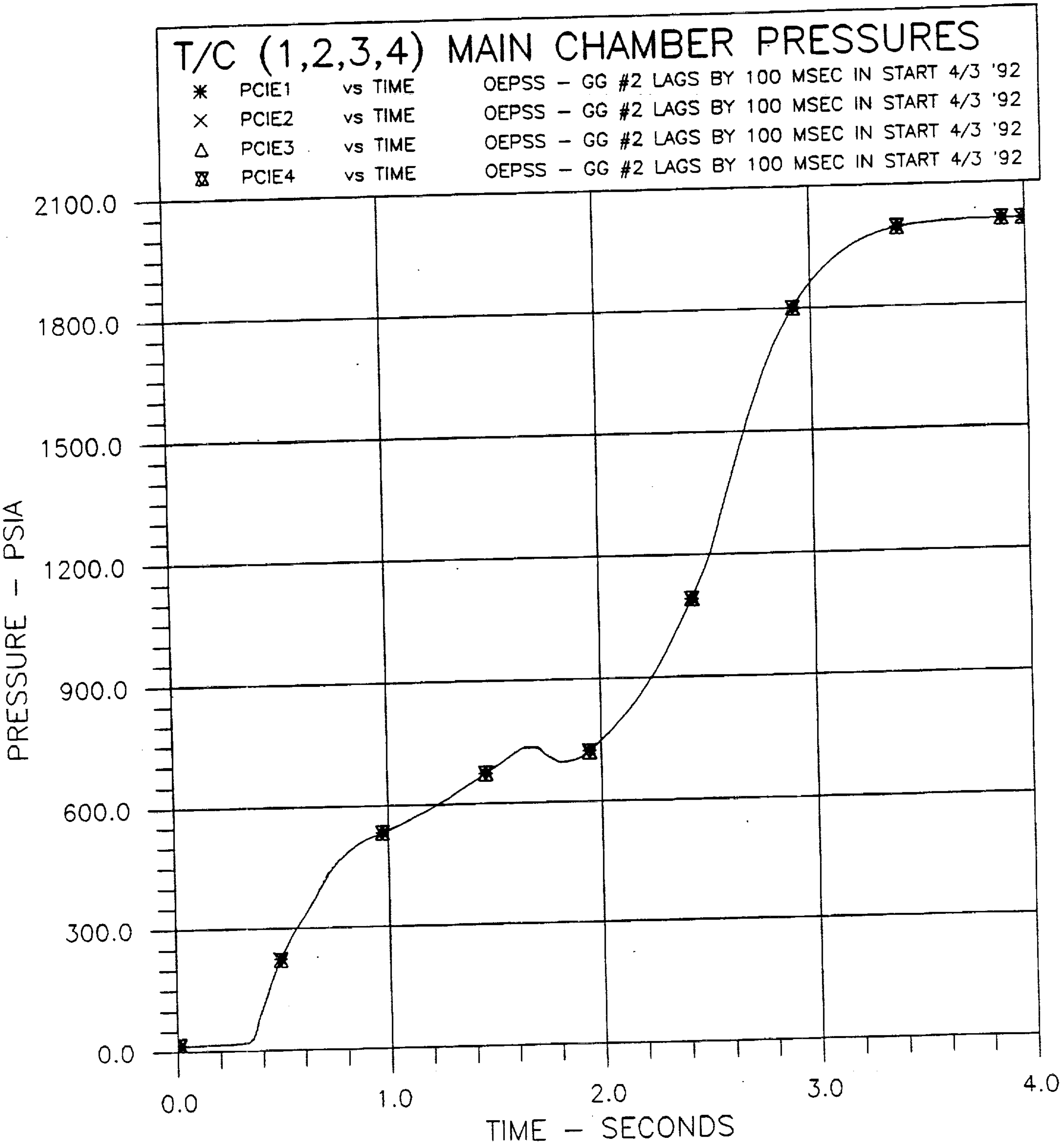

GG (3,4) SPIN START HYDROGEN GAS FLOW
⊕ DWSPIN vs TIME OEPSS – GG #2 LAGS BY 100 MSEC IN START 4/3 '92
⊕ DWSPIN vs TIME OEPSS – GG #2 LAGS BY 100 MSEC IN START 4/3 '92
15.0
12.5
10.0
7.5
5.0
2.5
0.0
FLOWRATE – LBS/SEC
GGs #3 and 4 Spin Gas Flow
0.0
1.0
2.0
3.0
4.0
TIME – SECONDS

Figure A5



T/C (1,2,3,4) MAIN CHAMBER PRESSURES
✱ PCIE1 vs TIME OEPSS - GG #2 LAGS BY 100 MSEC IN START 4/3 '92
× PCIE2 vs TIME OEPSS - GG #2 LAGS BY 100 MSEC IN START 4/3 '92
△ PCIE3 vs TIME OEPSS - GG #2 LAGS BY 100 MSEC IN START 4/3 '92
⧖ PCIE4 vs TIME OEPSS - GG #2 LAGS BY 100 MSEC IN START 4/3 '92
2100.0
1800.0
1500.0
1200.0
900.0
600.0
300.0
0.0
PRESSURE - PSIA
0.0
1.0
2.0
3.0
4.0
TIME - SECONDS

Figure A6

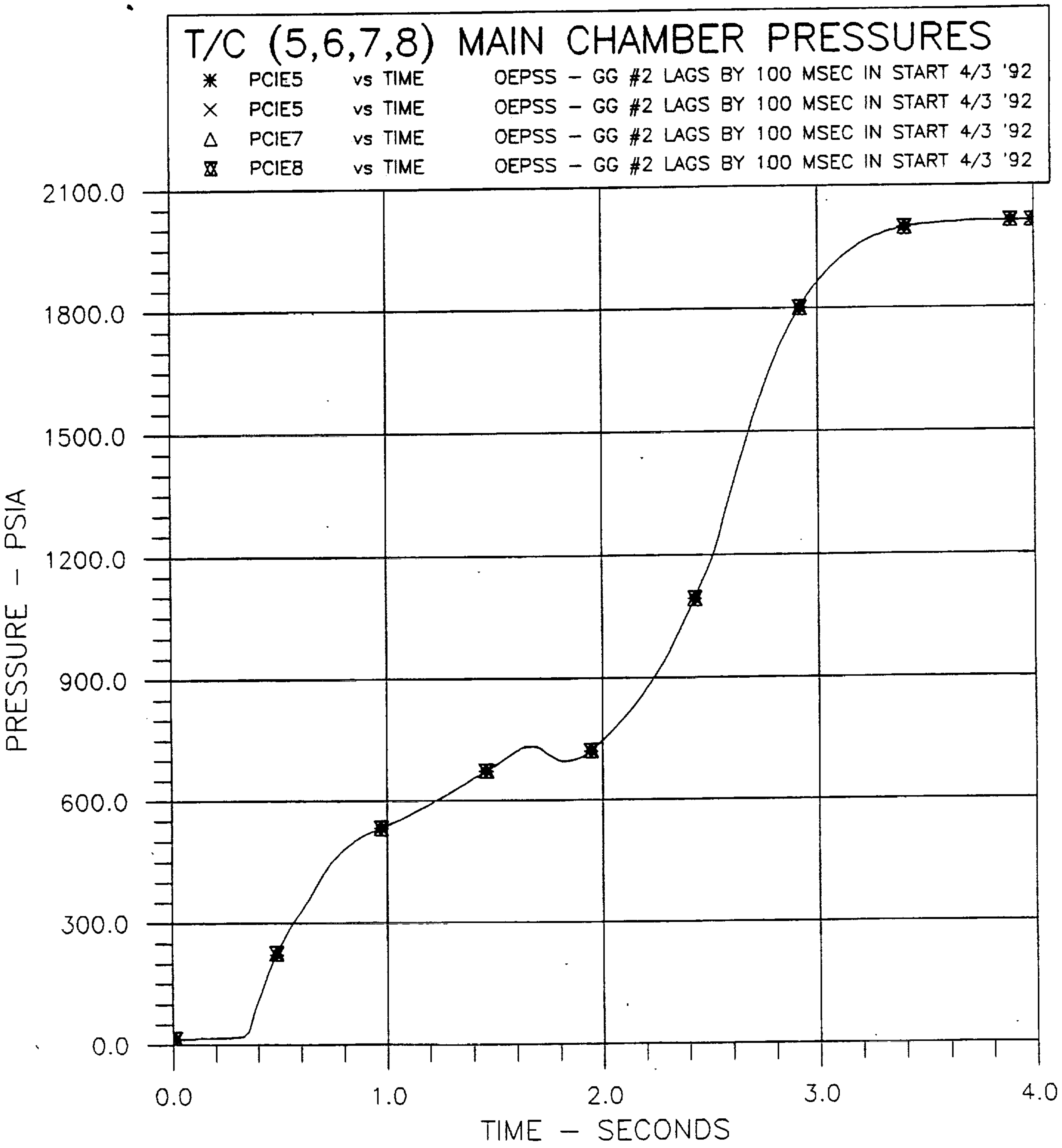
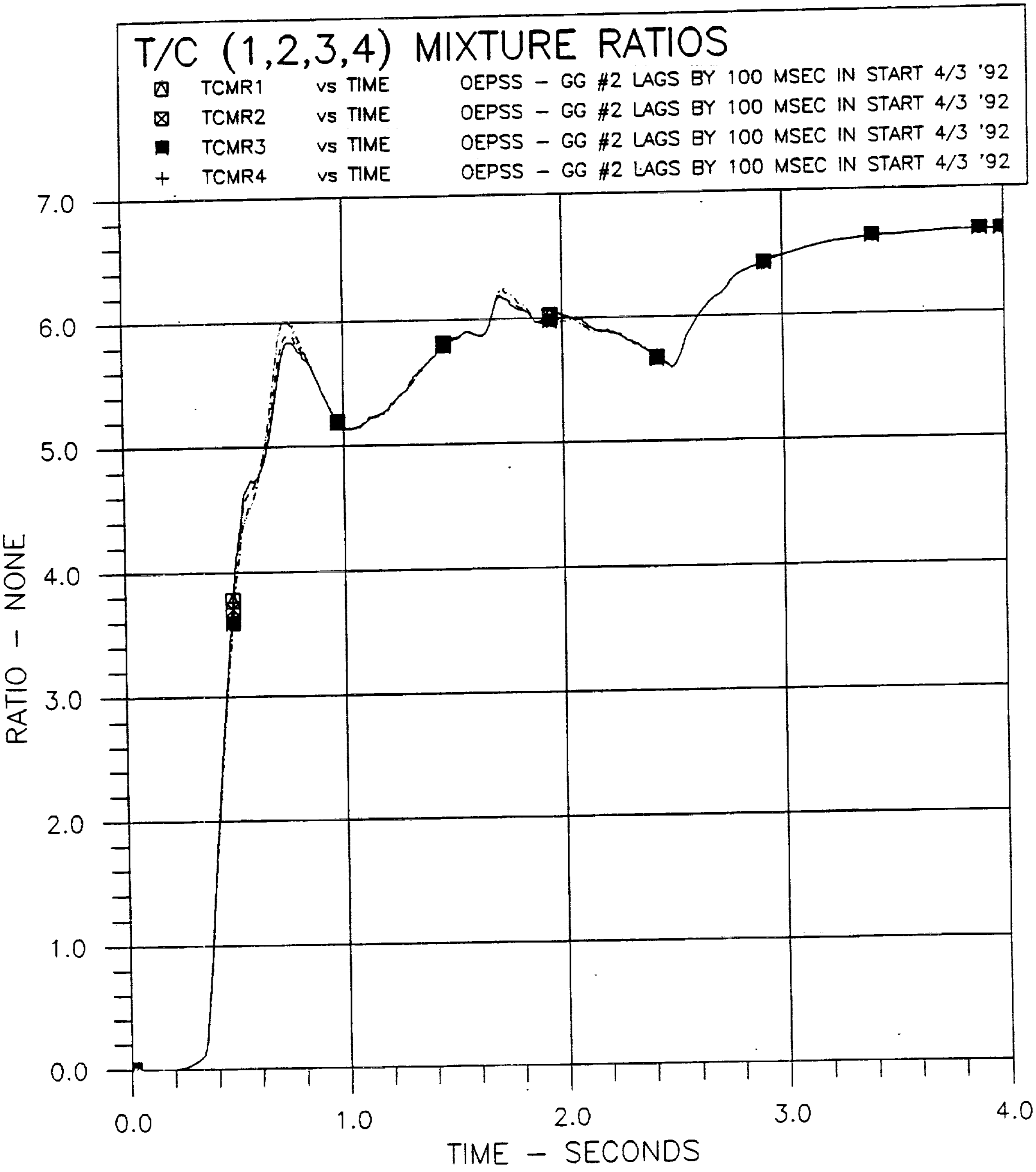
T/C (5,6,7,8) MAIN CHAMBER PRESSURES
✳ PCIE5 vs TIME OEPSS – GG #2 LAGS BY 100 MSEC IN START 4/3 '92
× PCIE5 vs TIME OEPSS – GG #2 LAGS BY 100 MSEC IN START 4/3 '92
△ PCIE7 vs TIME OEPSS – GG #2 LAGS BY 100 MSEC IN START 4/3 '92
⧗ PCIE8 vs TIME OEPSS – GG #2 LAGS BY 100 MSEC IN START 4/3 '92
2100.0
1800.0
1500.0
1200.0
900.0
600.0
300.0
0.0
PRESSURE – PSIA
0.0
1.0
2.0
3.0
4.0
TIME – SECONDS

Figure A7



T/C (1,2,3,4) MIXTURE RATIOS
TCMR1 vs TIME OEPSS - GG #2 LAGS BY 100 MSEC IN START 4/3 '92
TCMR2 vs TIME OEPSS - GG #2 LAGS BY 100 MSEC IN START 4/3 '92
TCMR3 vs TIME OEPSS - GG #2 LAGS BY 100 MSEC IN START 4/3 '92
TCMR4 vs TIME OEPSS - GG #2 LAGS BY 100 MSEC IN START 4/3 '92
RATIO - NONE
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
0.0
1.0
2.0
3.0
4.0
TIME - SECONDS

Figure A8

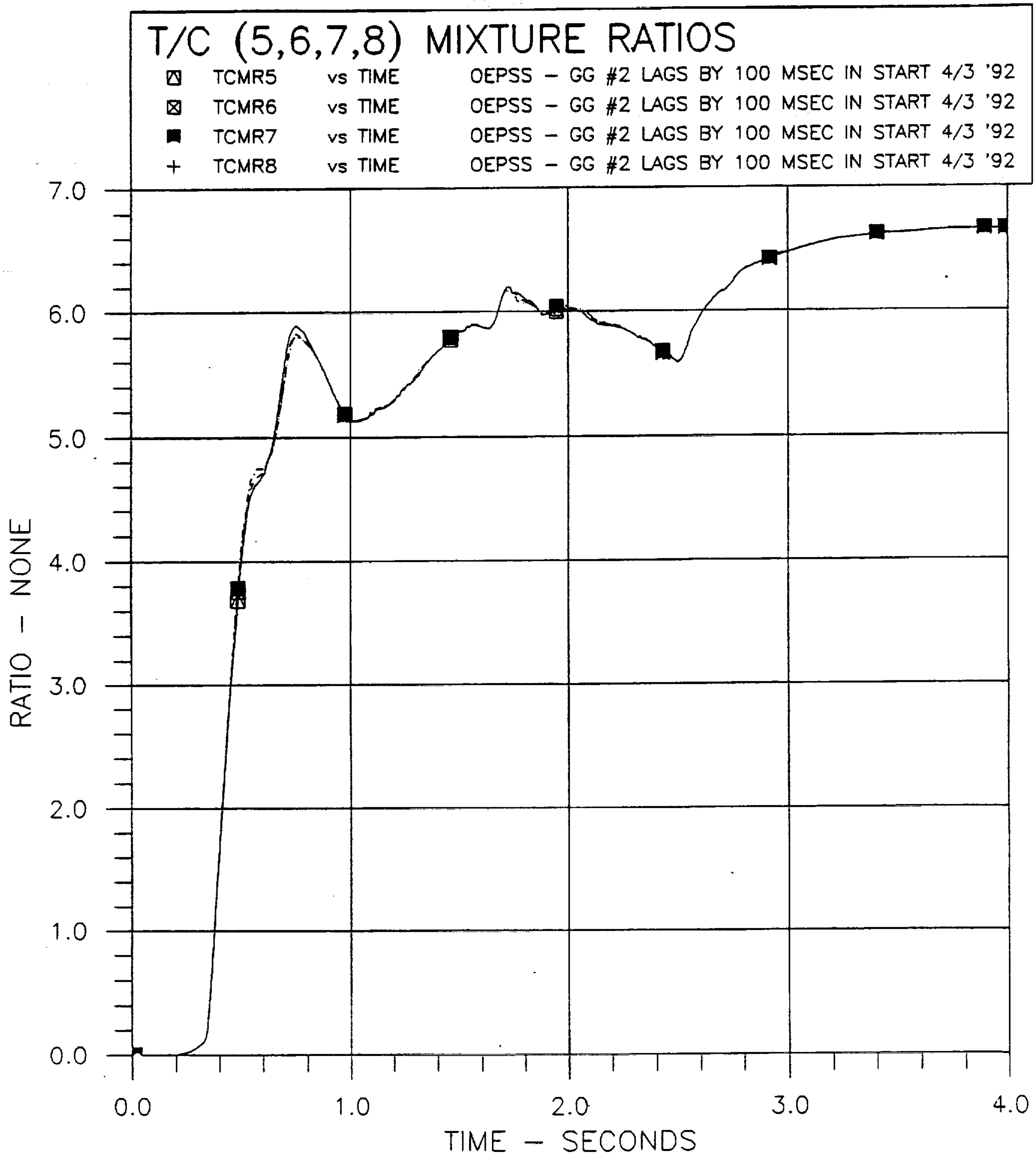

T/C (5,6,7,8) MIXTURE RATIOS
TCMR5 vs TIME OEPSS – GG #2 LAGS BY 100 MSEC IN START 4/3 '92
TCMR6 vs TIME OEPSS – GG #2 LAGS BY 100 MSEC IN START 4/3 '92
TCMR7 vs TIME OEPSS – GG #2 LAGS BY 100 MSEC IN START 4/3 '92
TCMR8 vs TIME OEPSS – GG #2 LAGS BY 100 MSEC IN START 4/3 '92
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
RATIO – NONE
0.0
1.0
2.0
3.0
4.0
TIME – SECONDS

Figure A9

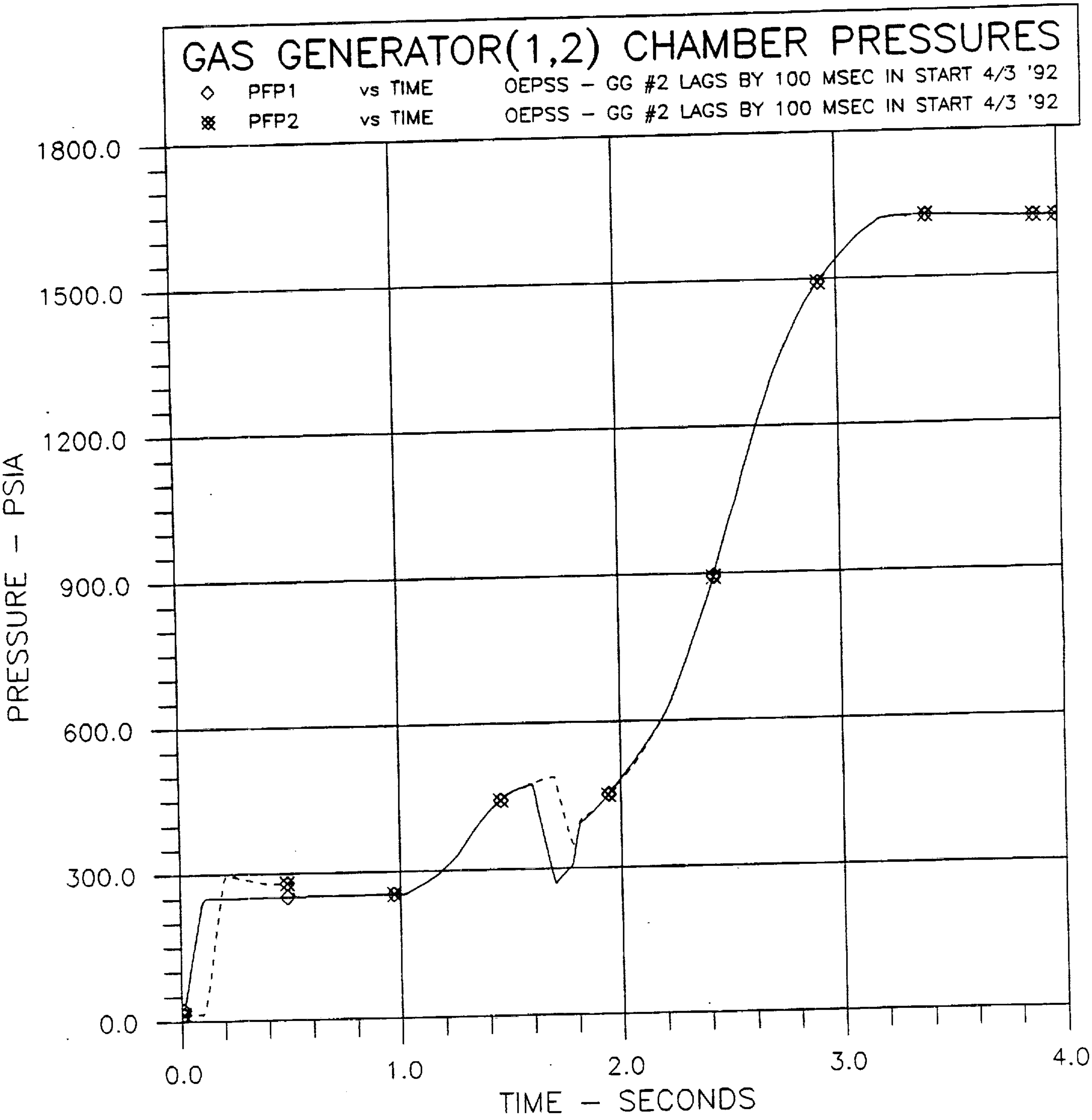

GAS GENERATOR(1,2) CHAMBER PRESSURES
◇ PFP1 vs TIME OEPSS – GG #2 LAGS BY 100 MSEC IN START 4/3 '92
⊗ PFP2 vs TIME OEPSS – GG #2 LAGS BY 100 MSEC IN START 4/3 '92
1800.0
1500.0
1200.0
900.0
600.0
300.0
0.0
PRESSURE – PSIA
0.0
1.0
2.0
3.0
4.0
TIME – SECONDS

Figure A10

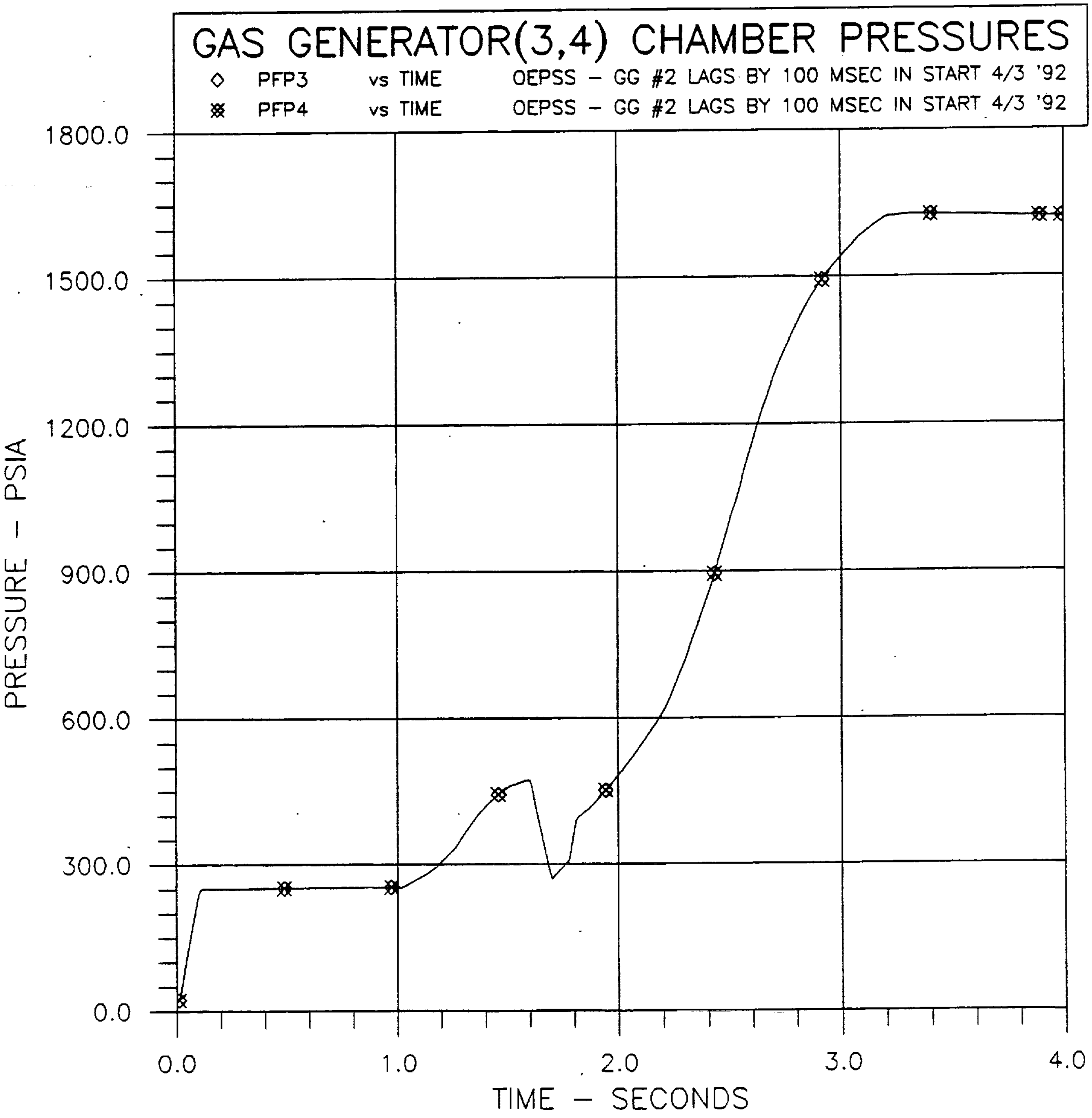

GAS GENERATOR(3,4) CHAMBER PRESSURES
◇ PFP3 vs TIME OEPSS – GG #2 LAGS BY 100 MSEC IN START 4/3 '92
⊗ PFP4 vs TIME OEPSS – GG #2 LAGS BY 100 MSEC IN START 4/3 '92
PRESSURE – PSIA
1800.0
1500.0
1200.0
900.0
600.0
300.0
0.0
0.0
1.0
2.0
3.0
4.0
TIME – SECONDS

Figure A11

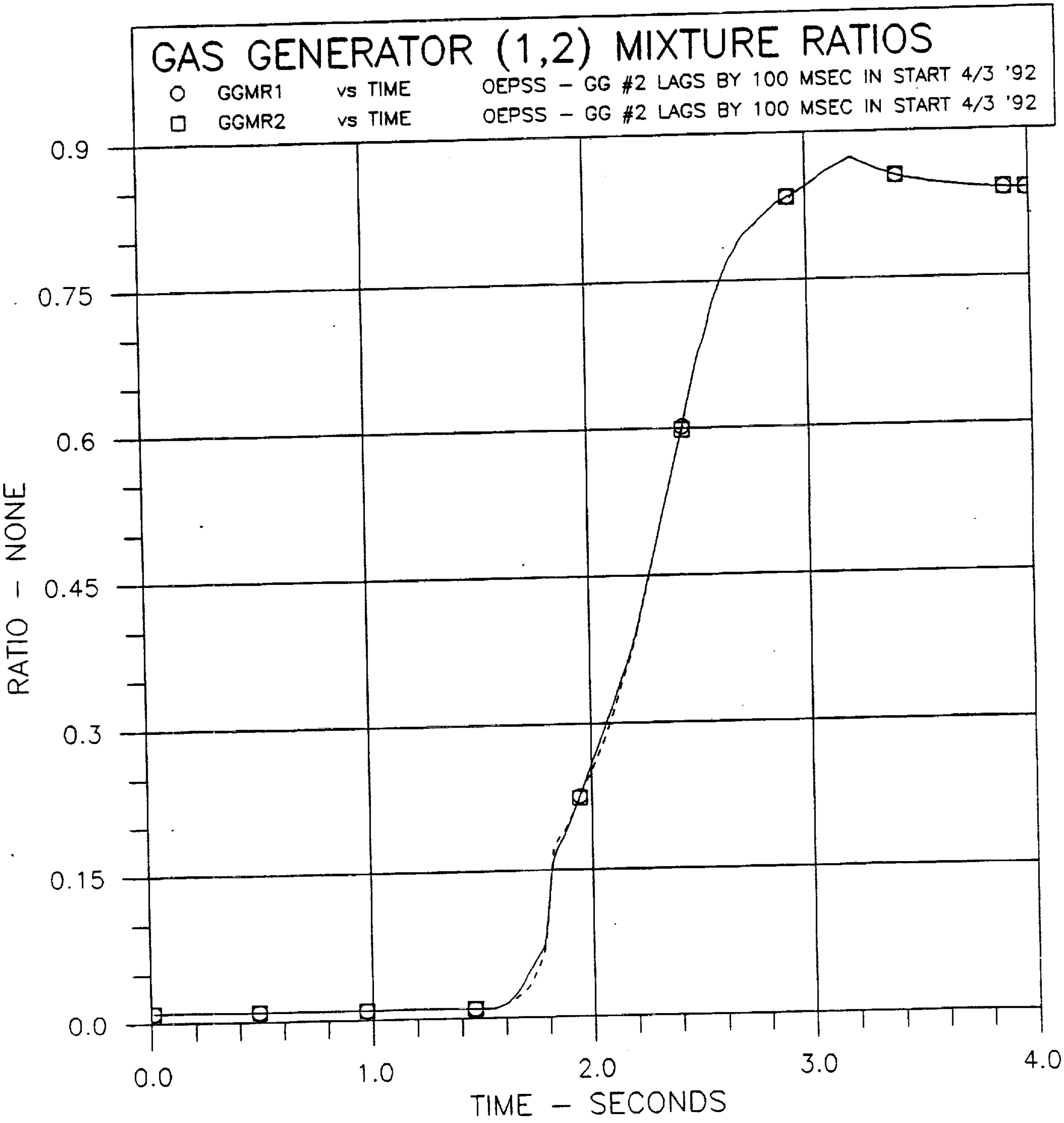

GAS GENERATOR (1,2) MIXTURE RATIOS
○ GGMR1 vs TIME OEPSS – GG #2 LAGS BY 100 MSEC IN START 4/3 '92
□ GGMR2 vs TIME OEPSS – GG #2 LAGS BY 100 MSEC IN START 4/3 '92
0.9
0.75
0.6
0.45
0.3
0.15
0.0
RATIO – NONE
0.0
1.0
2.0
3.0
4.0
TIME – SECONDS

Figure A12

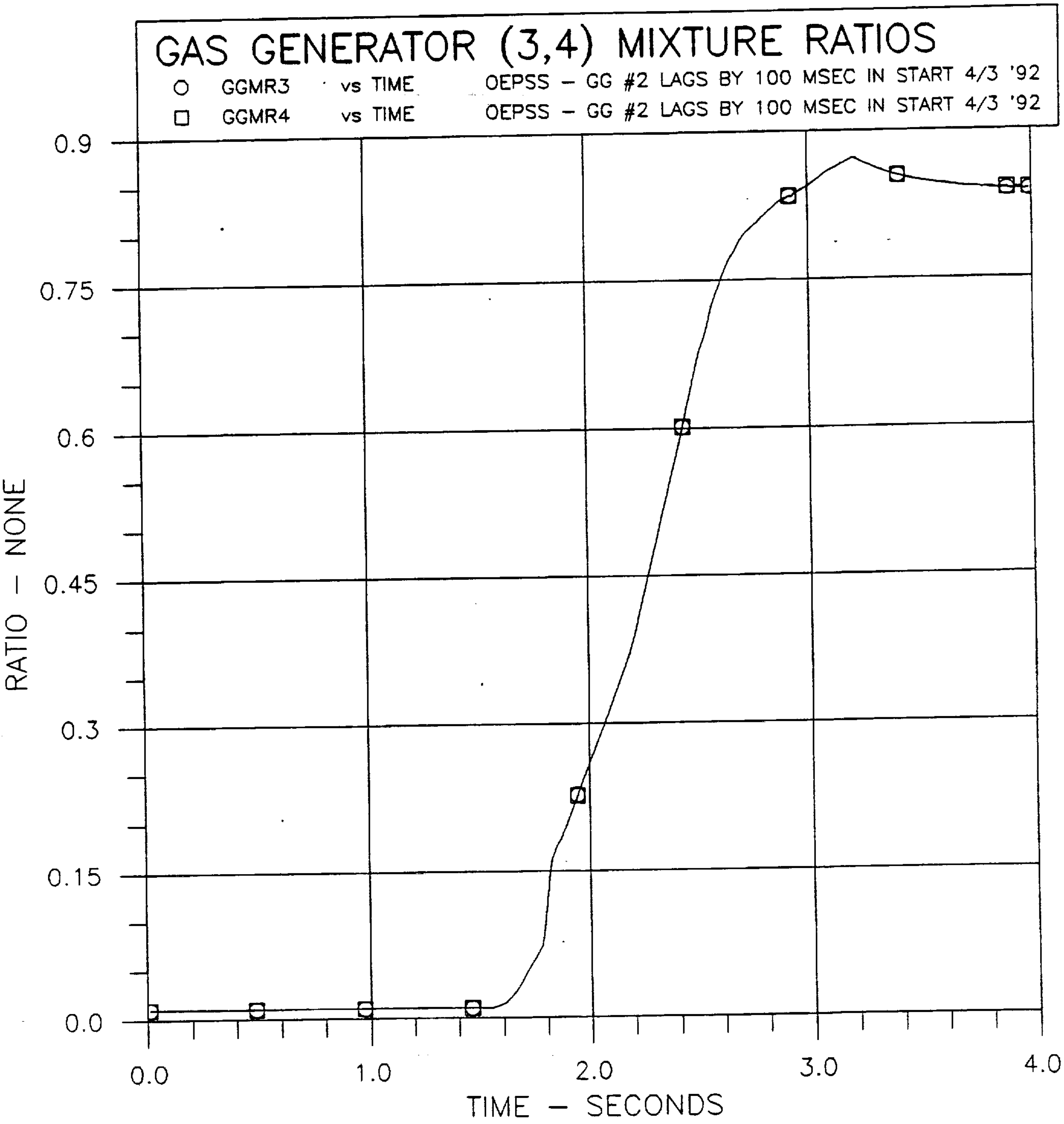

GAS GENERATOR (3,4) MIXTURE RATIOS
○ GGMR3 vs TIME OEPSS – GG #2 LAGS BY 100 MSEC IN START 4/3 '92
□ GGMR4 vs TIME OEPSS – GG #2 LAGS BY 100 MSEC IN START 4/3 '92
0.9
0.75
0.6
0.45
0.3
0.15
0.0
RATIO – NONE
0.0
1.0
2.0
3.0
4.0
TIME – SECONDS

Figure A13

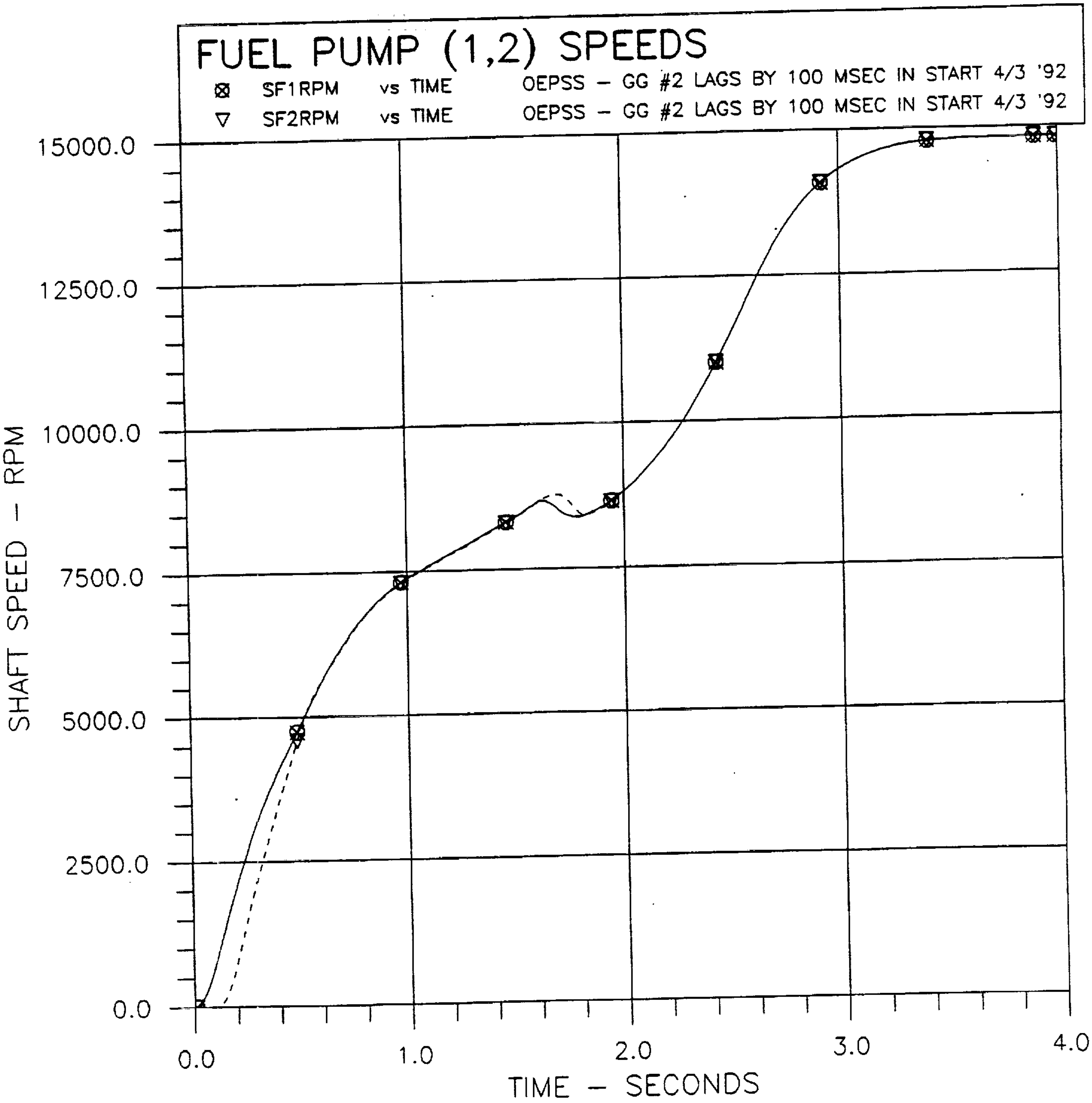

FUEL PUMP (1,2) SPEEDS
⊗ SF1RPM vs TIME OEPSS – GG #2 LAGS BY 100 MSEC IN START 4/3 '92
▽ SF2RPM vs TIME OEPSS – GG #2 LAGS BY 100 MSEC IN START 4/3 '92
SHAFT SPEED – RPM
15000.0
12500.0
10000.0
7500.0
5000.0
2500.0
0.0
0.0
1.0
2.0
3.0
4.0
TIME – SECONDS

Figure A14

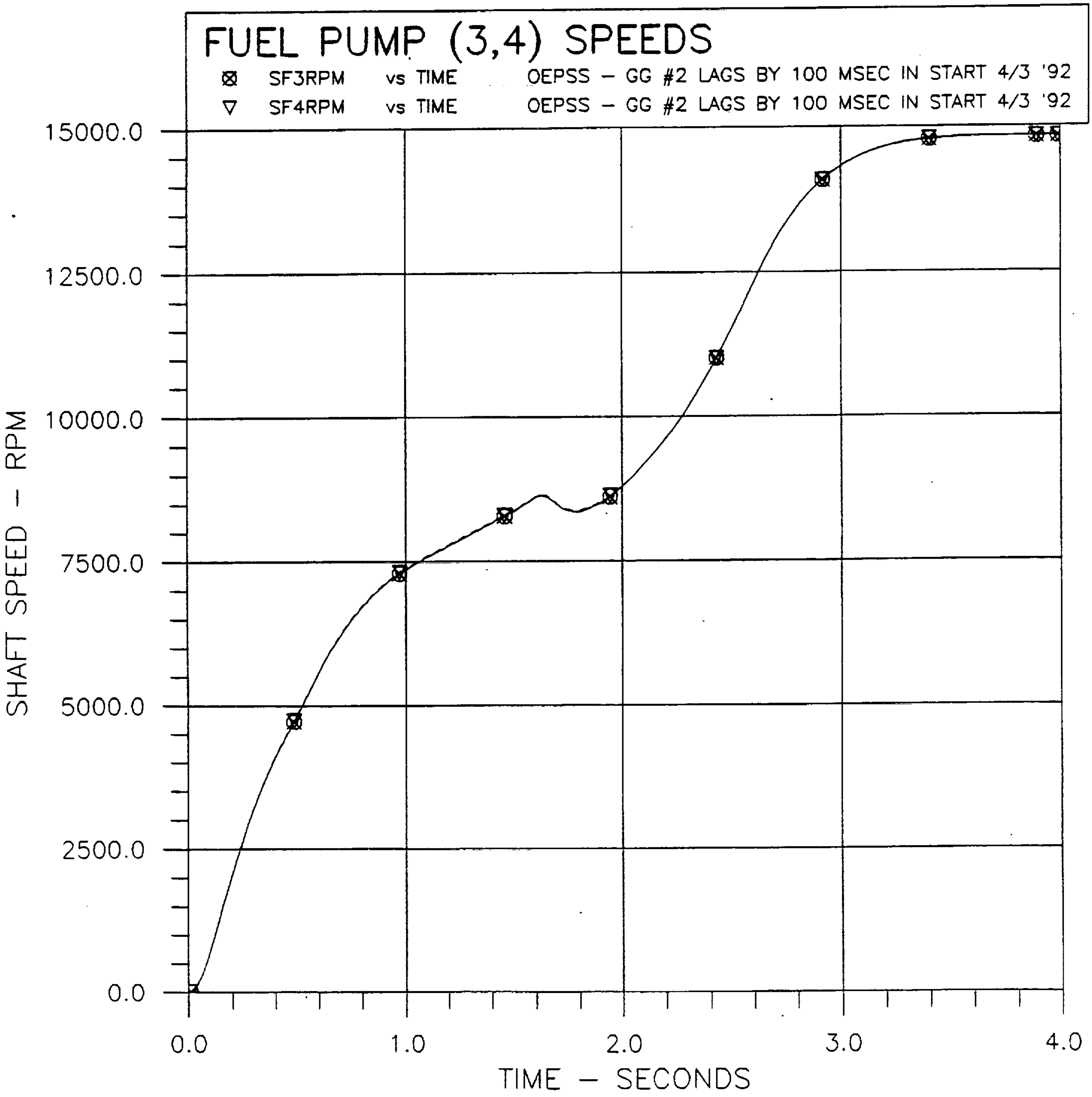

FUEL PUMP (3,4) SPEEDS
⊠ SF3RPM vs TIME OEPSS – GG #2 LAGS BY 100 MSEC IN START 4/3 '92
▽ SF4RPM vs TIME OEPSS – GG #2 LAGS BY 100 MSEC IN START 4/3 '92
15000.0
12500.0
10000.0
7500.0
5000.0
2500.0
0.0
SHAFT SPEED – RPM
0.0
1.0
2.0
3.0
4.0
TIME – SECONDS

Figure A15

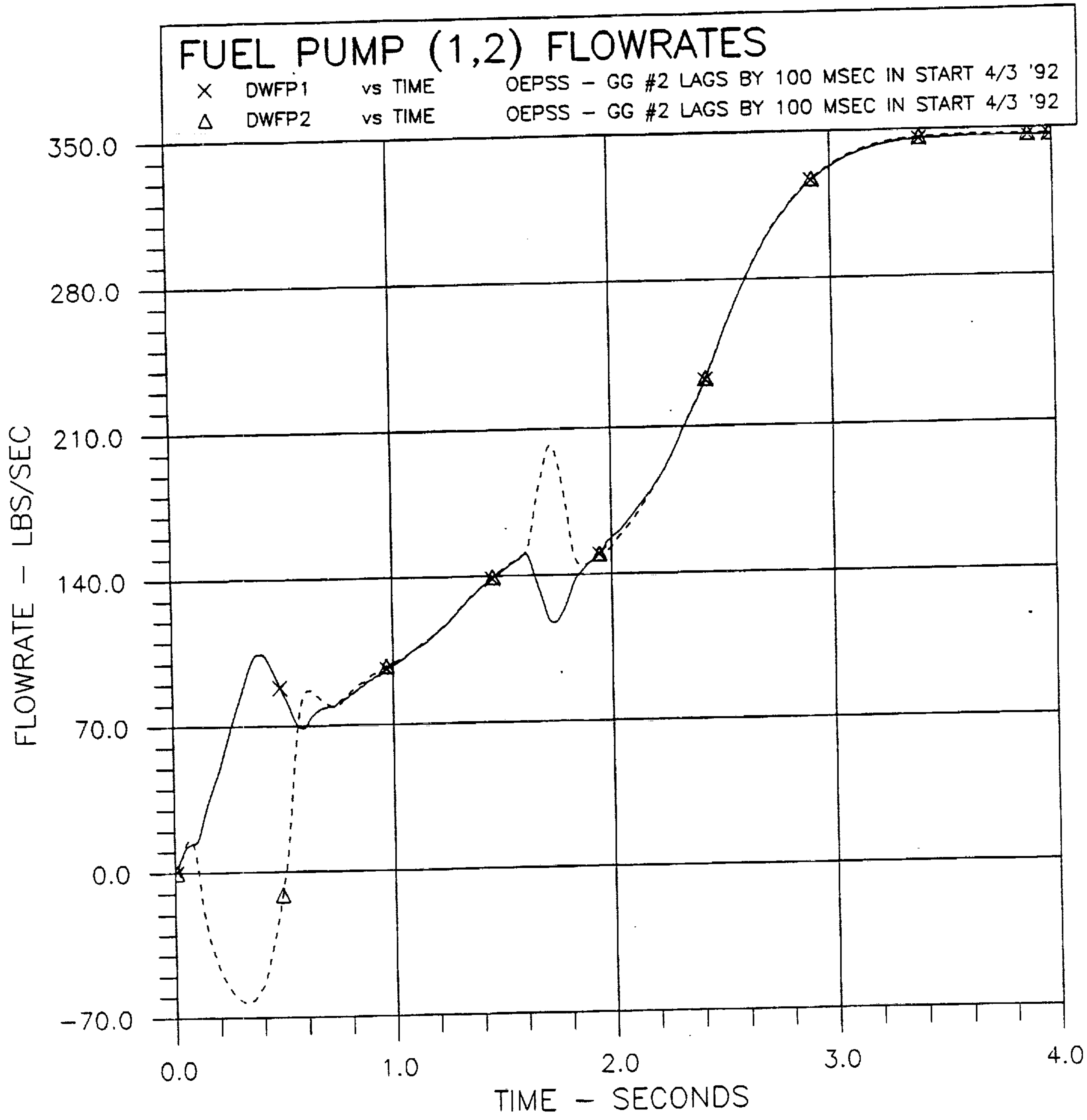

FUEL PUMP (1,2) FLOWRATES
× DWFP1 vs TIME OEPSS - GG #2 LAGS BY 100 MSEC IN START 4/3 '92
△ DWFP2 vs TIME OEPSS - GG #2 LAGS BY 100 MSEC IN START 4/3 '92
350.0
280.0
210.0
140.0
70.0
0.0
-70.0
FLOWRATE - LBS/SEC
0.0
1.0
2.0
3.0
4.0
TIME - SECONDS

Figure A16

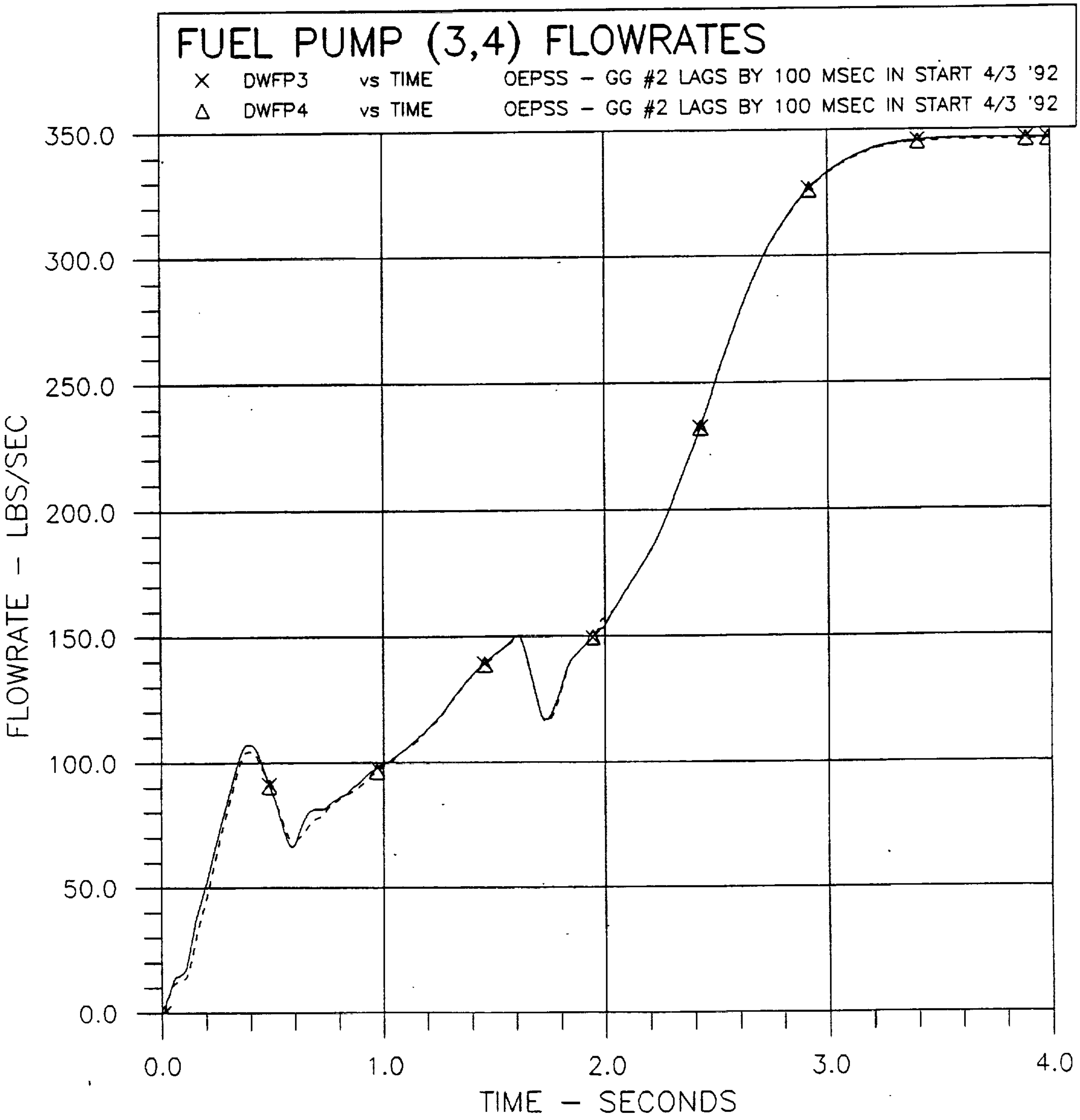

FUEL PUMP (3,4) FLOWRATES
× DWFP3 vs TIME OEPSS – GG #2 LAGS BY 100 MSEC IN START 4/3 '92
△ DWFP4 vs TIME OEPSS – GG #2 LAGS BY 100 MSEC IN START 4/3 '92
FLOWRATE – LBS/SEC
350.0
300.0
250.0
200.0
150.0
100.0
50.0
0.0
0.0
1.0
2.0
3.0
4.0
TIME – SECONDS

Figure A17

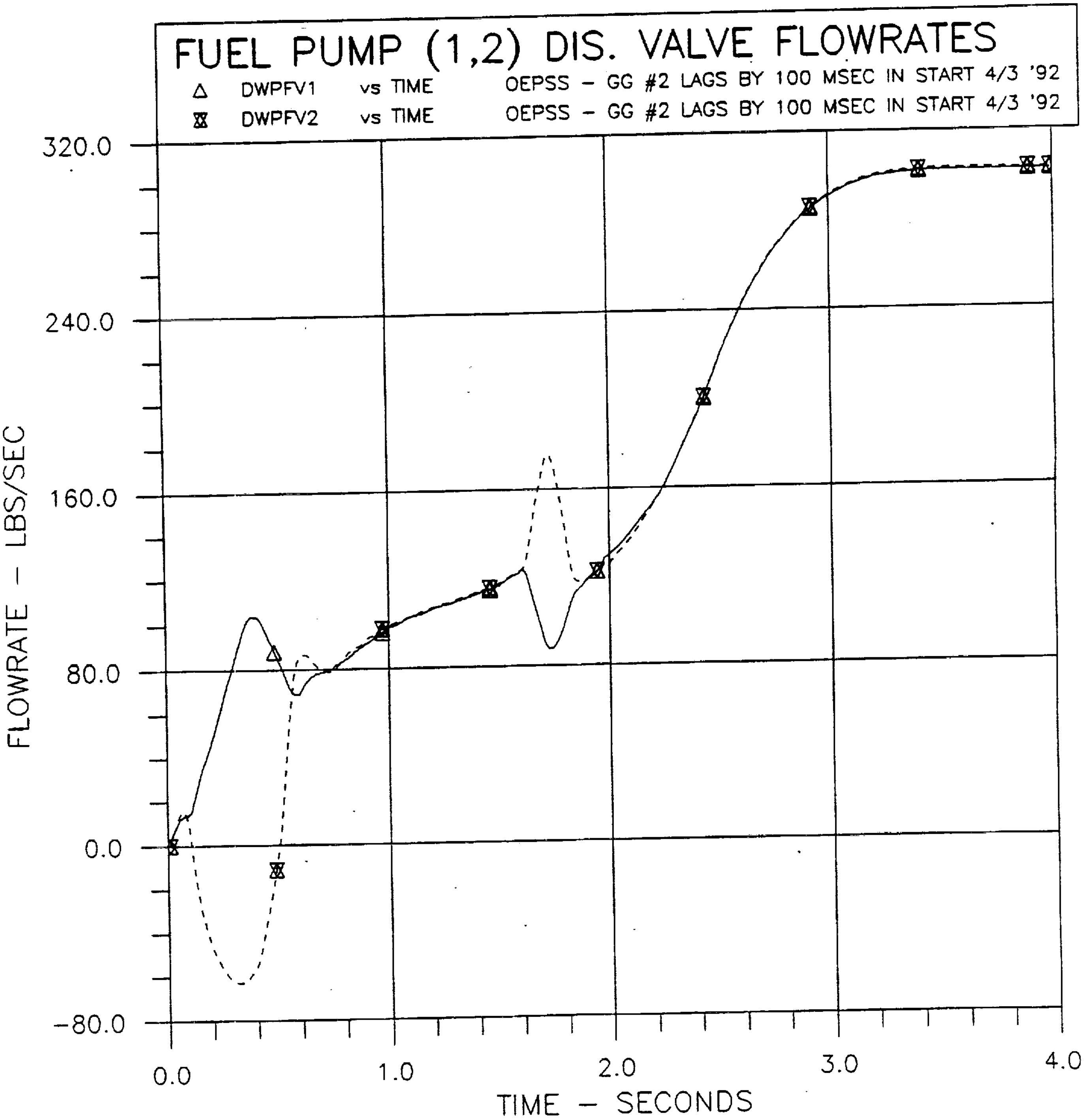

FUEL PUMP (1,2) DIS. VALVE FLOWRATES
△ DWPFV1 vs TIME OEPSS - GG #2 LAGS BY 100 MSEC IN START 4/3 '92
⧖ DWPFV2 vs TIME OEPSS - GG #2 LAGS BY 100 MSEC IN START 4/3 '92
320.0
240.0
160.0
80.0
0.0
-80.0
FLOWRATE - LBS/SEC
0.0
1.0
2.0
3.0
4.0
TIME - SECONDS

Figure A18

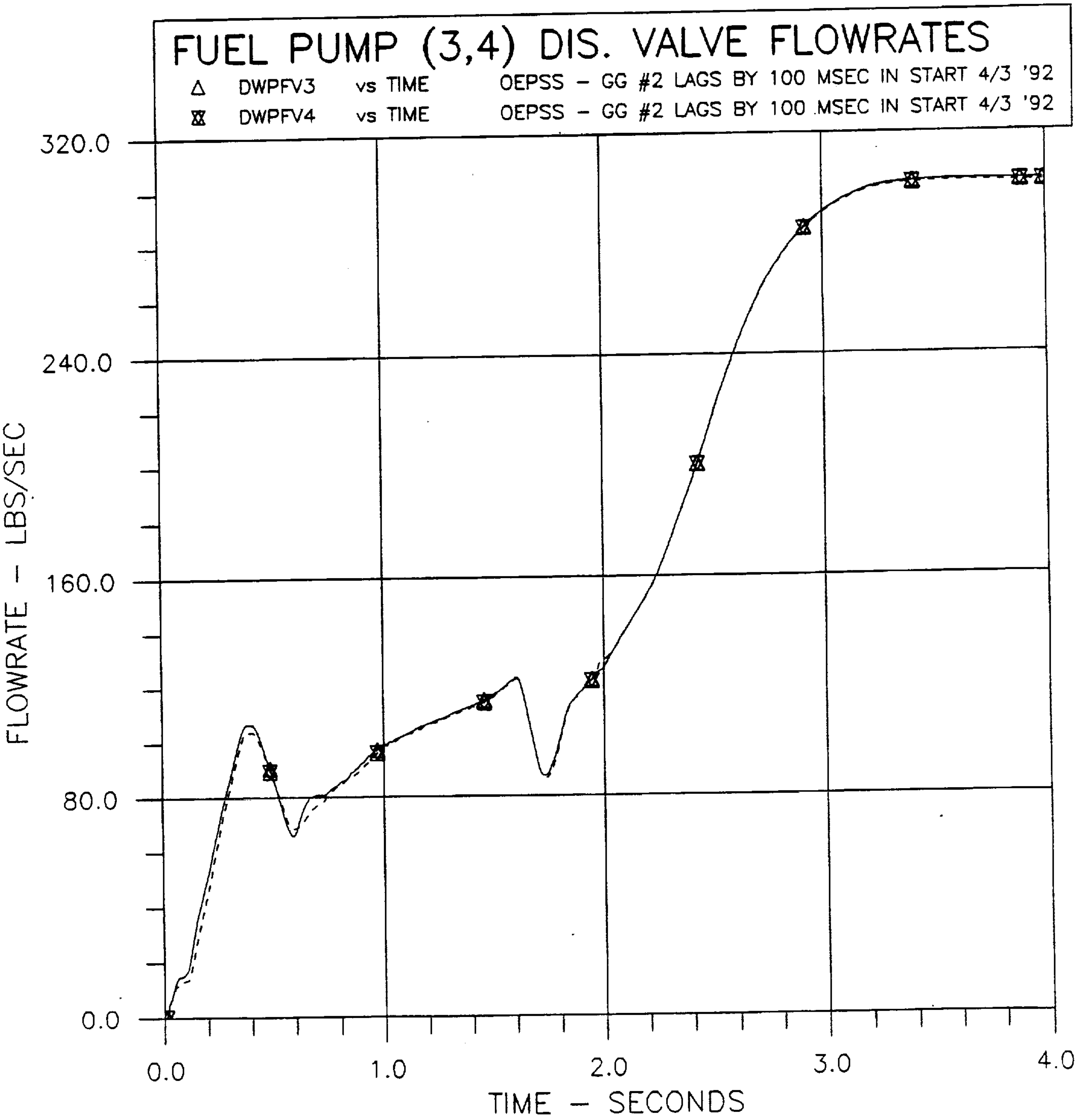

FUEL PUMP (3,4) DIS. VALVE FLOWRATES
△ DWPFV3 vs TIME OEPSS - GG #2 LAGS BY 100 MSEC IN START 4/3 '92
⧖ DWPFV4 vs TIME OEPSS - GG #2 LAGS BY 100 MSEC IN START 4/3 '92
320.0
240.0
160.0
80.0
0.0
FLOWRATE - LBS/SEC
0.0
1.0
2.0
3.0
4.0
TIME - SECONDS

Figure A19

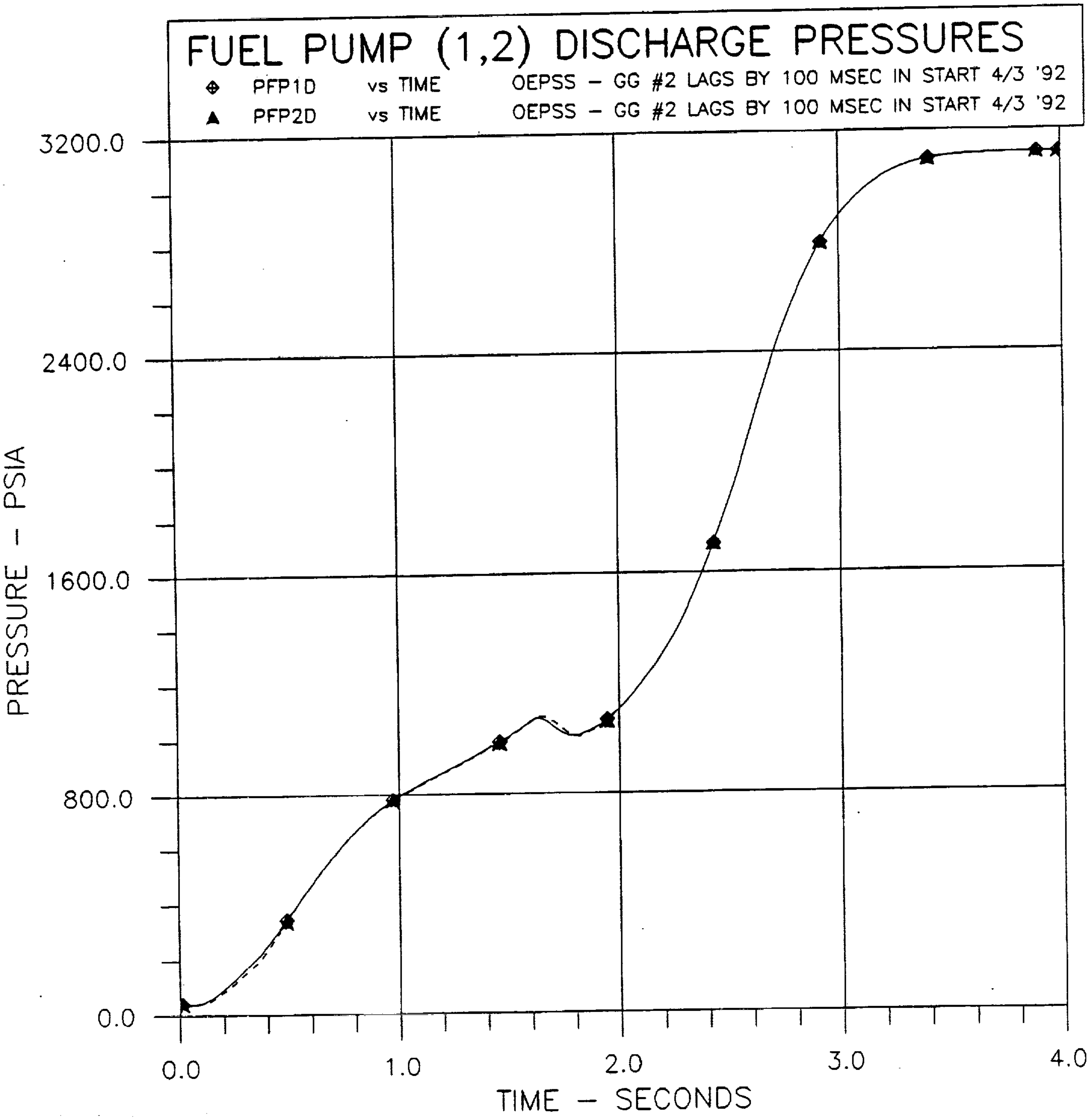

FUEL PUMP (1,2) DISCHARGE PRESSURES
⊕ PFP1D vs TIME OEPSS – GG #2 LAGS BY 100 MSEC IN START 4/3 '92
▲ PFP2D vs TIME OEPSS – GG #2 LAGS BY 100 MSEC IN START 4/3 '92
3200.0
2400.0
1600.0
800.0
0.0
PRESSURE – PSIA
0.0
1.0
2.0
3.0
4.0
TIME – SECONDS

Figure A20

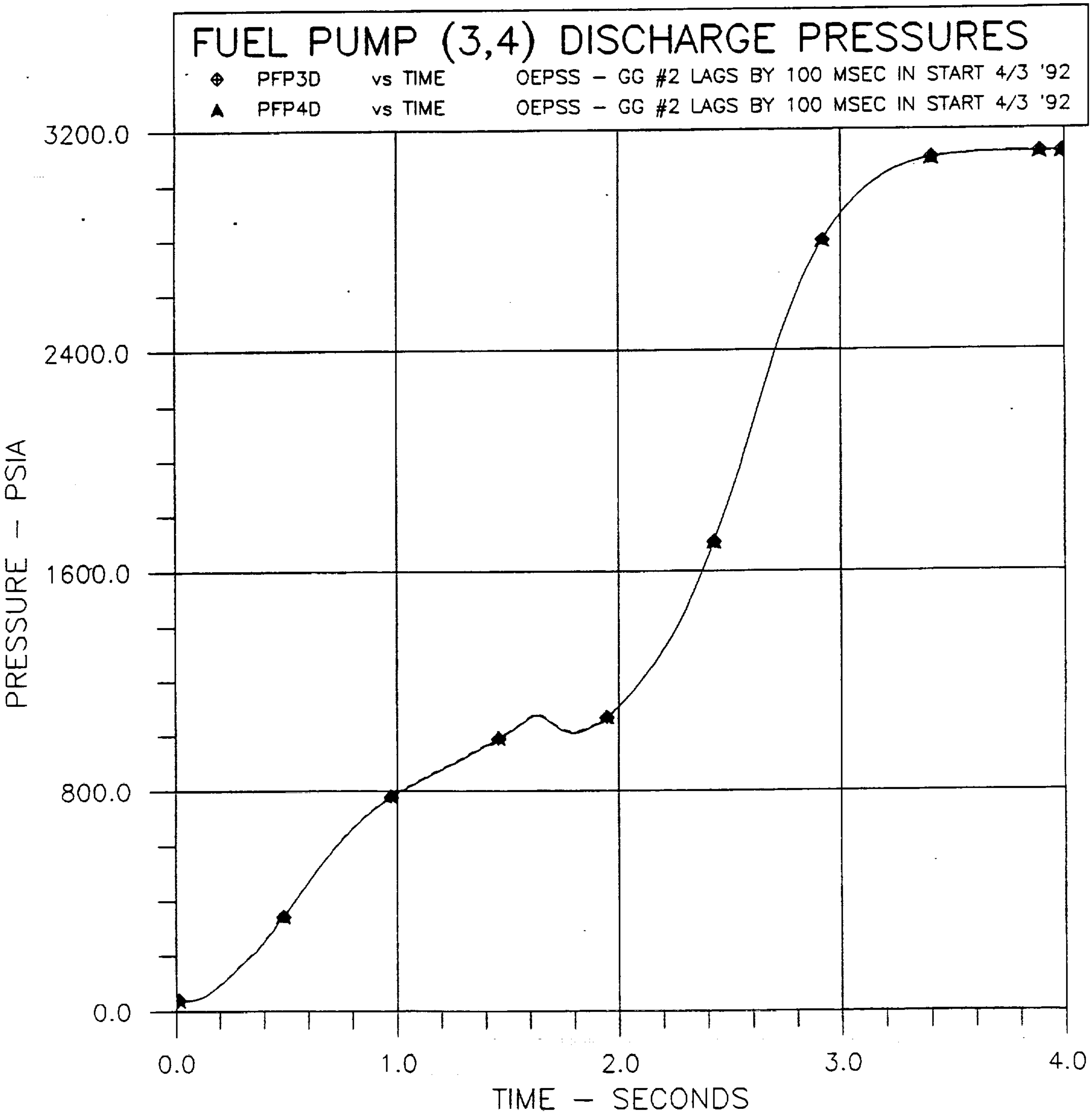

FUEL PUMP (3,4) DISCHARGE PRESSURES
⊕ PFP3D vs TIME OEPSS – GG #2 LAGS BY 100 MSEC IN START 4/3 '92
▲ PFP4D vs TIME OEPSS – GG #2 LAGS BY 100 MSEC IN START 4/3 '92
PRESSURE – PSIA
3200.0
2400.0
1600.0
800.0
0.0
0.0
1.0
2.0
3.0
4.0
TIME – SECONDS

Figure A21

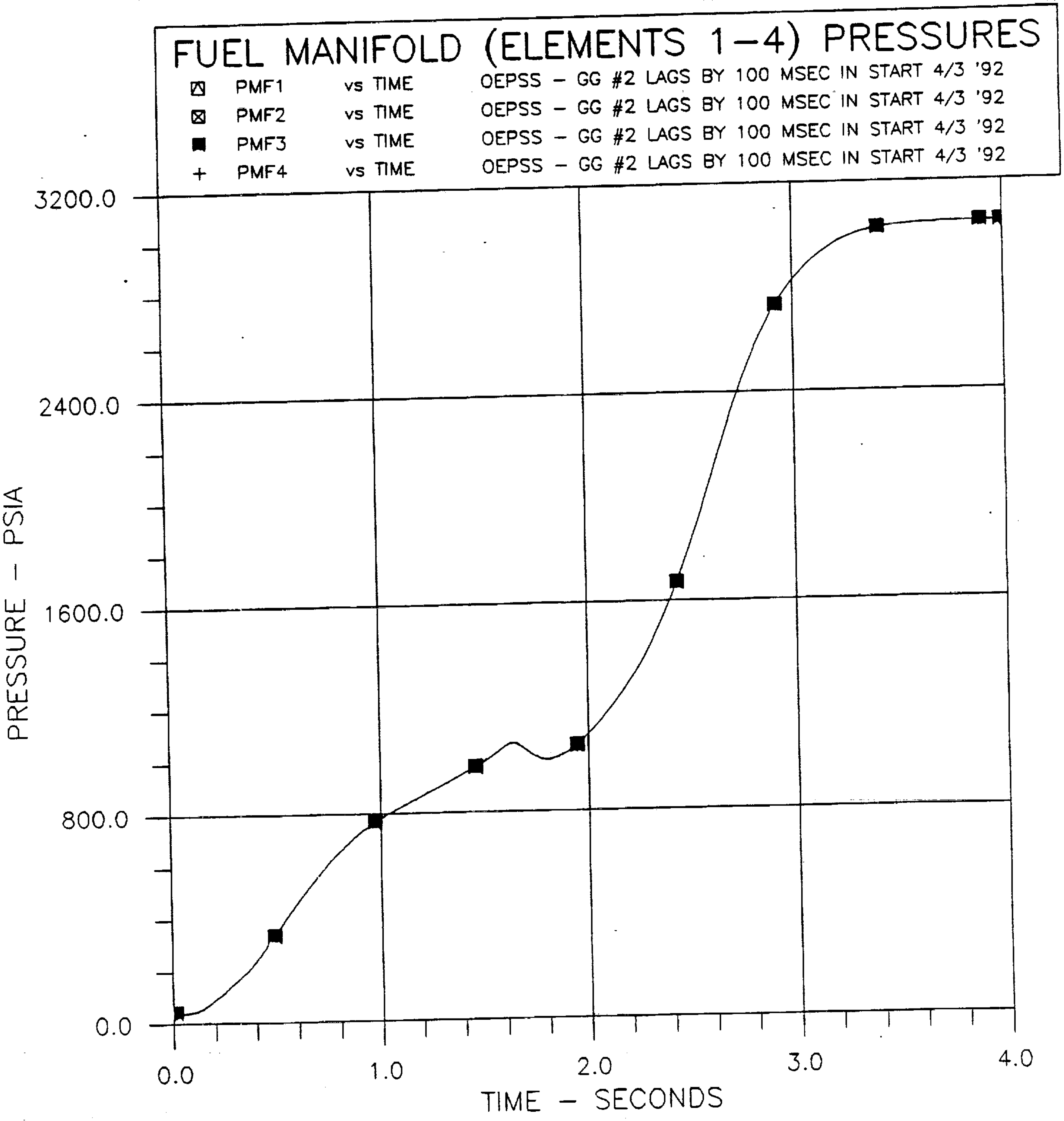

FUEL MANIFOLD (ELEMENTS 1–4) PRESSURES
☒ PMF1 vs TIME OEPSS – GG #2 LAGS BY 100 MSEC IN START 4/3 '92
☒ PMF2 vs TIME OEPSS – GG #2 LAGS BY 100 MSEC IN START 4/3 '92
■ PMF3 vs TIME OEPSS – GG #2 LAGS BY 100 MSEC IN START 4/3 '92
+ PMF4 vs TIME OEPSS – GG #2 LAGS BY 100 MSEC IN START 4/3 '92
3200.0
2400.0
1600.0
800.0
0.0
PRESSURE – PSIA
0.0
1.0
2.0
3.0
4.0
TIME – SECONDS

Figure A22

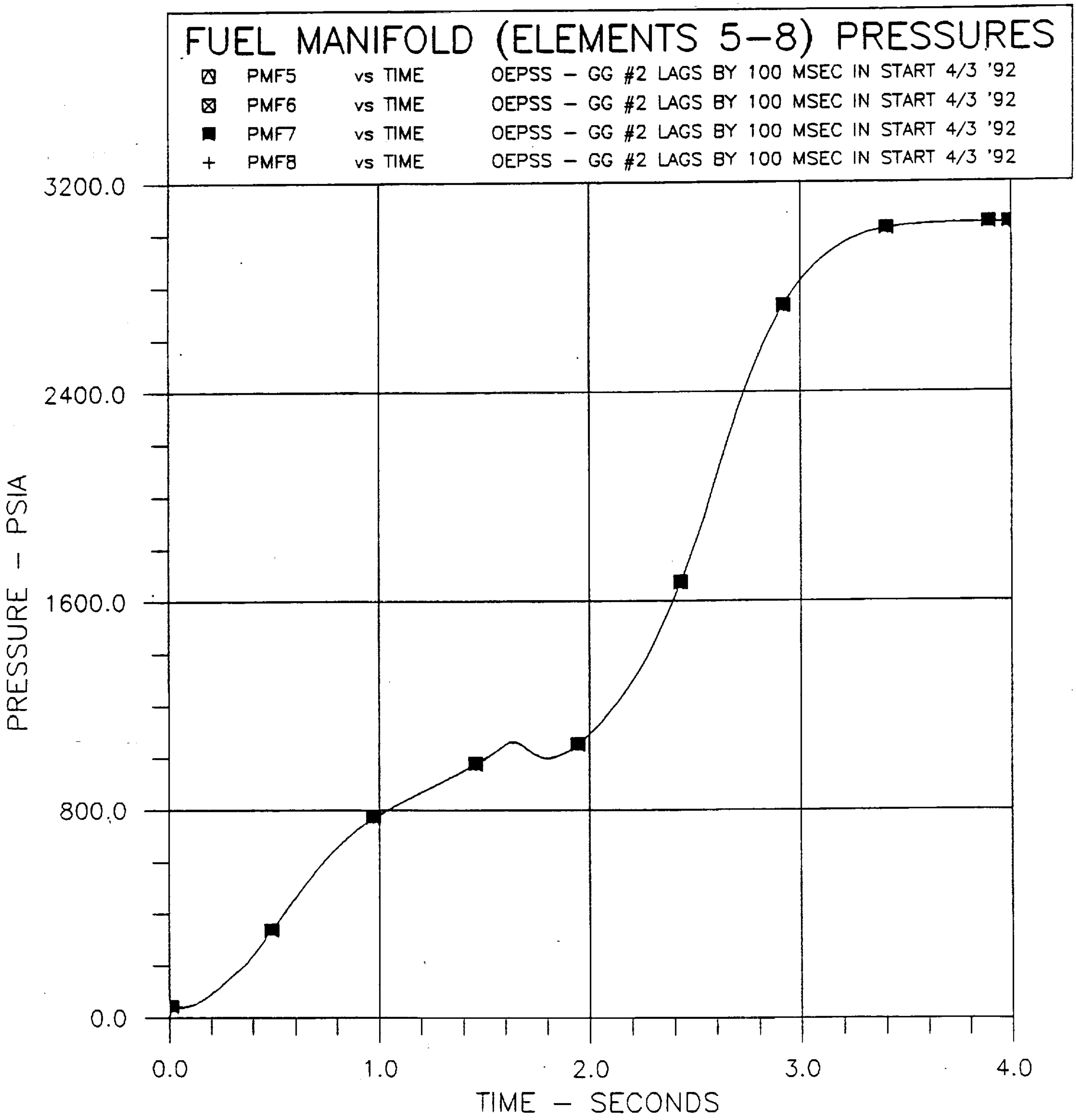

FUEL MANIFOLD (ELEMENTS 5–8) PRESSURES
▨ PMF5 vs TIME OEPSS – GG #2 LAGS BY 100 MSEC IN START 4/3 '92
☒ PMF6 vs TIME OEPSS – GG #2 LAGS BY 100 MSEC IN START 4/3 '92
■ PMF7 vs TIME OEPSS – GG #2 LAGS BY 100 MSEC IN START 4/3 '92
+ PMF8 vs TIME OEPSS – GG #2 LAGS BY 100 MSEC IN START 4/3 '92
3200.0
2400.0
1600.0
800.0
0.0
PRESSURE – PSIA
0.0
1.0
2.0
3.0
4.0
TIME – SECONDS

Figure A23

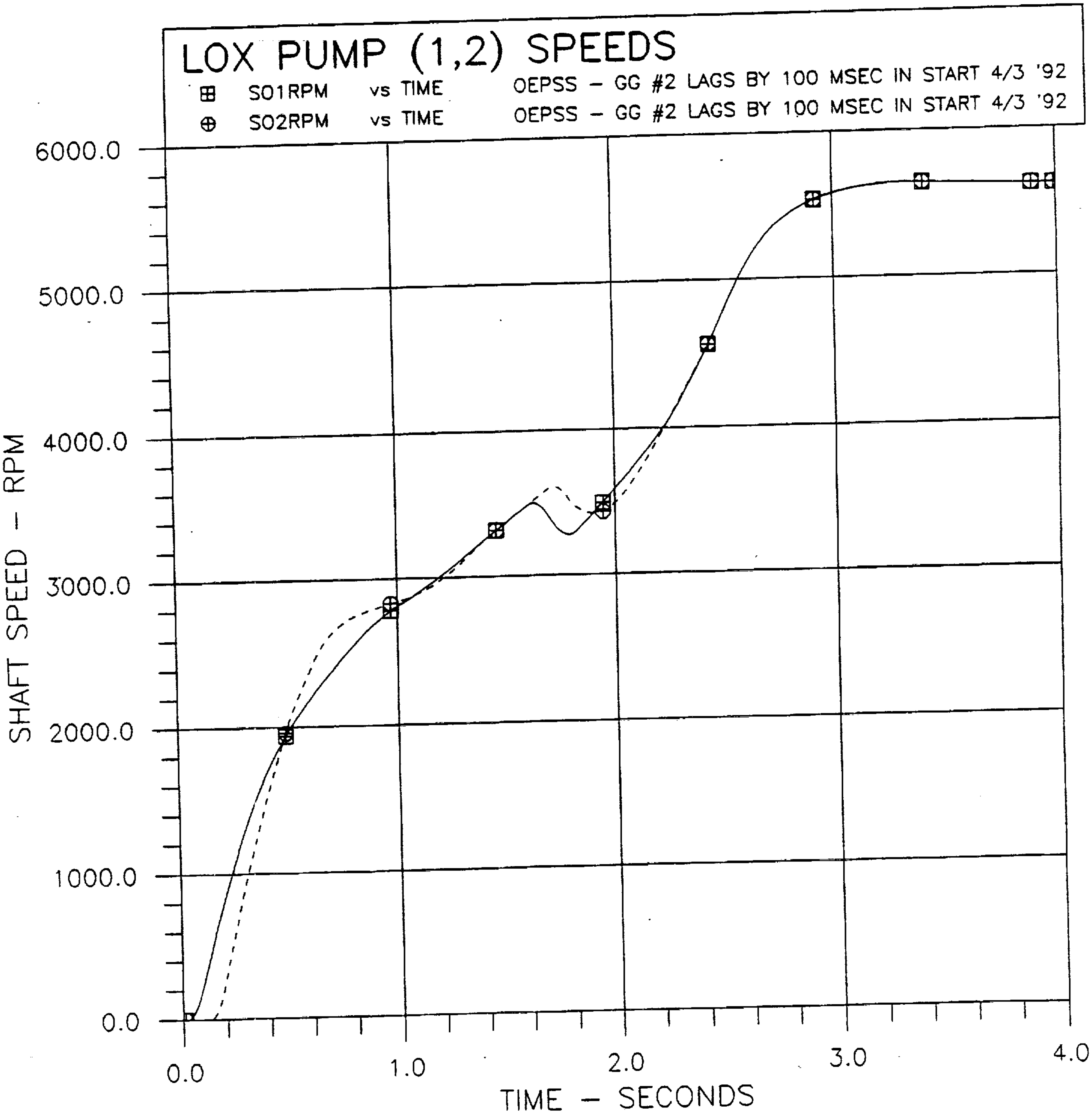
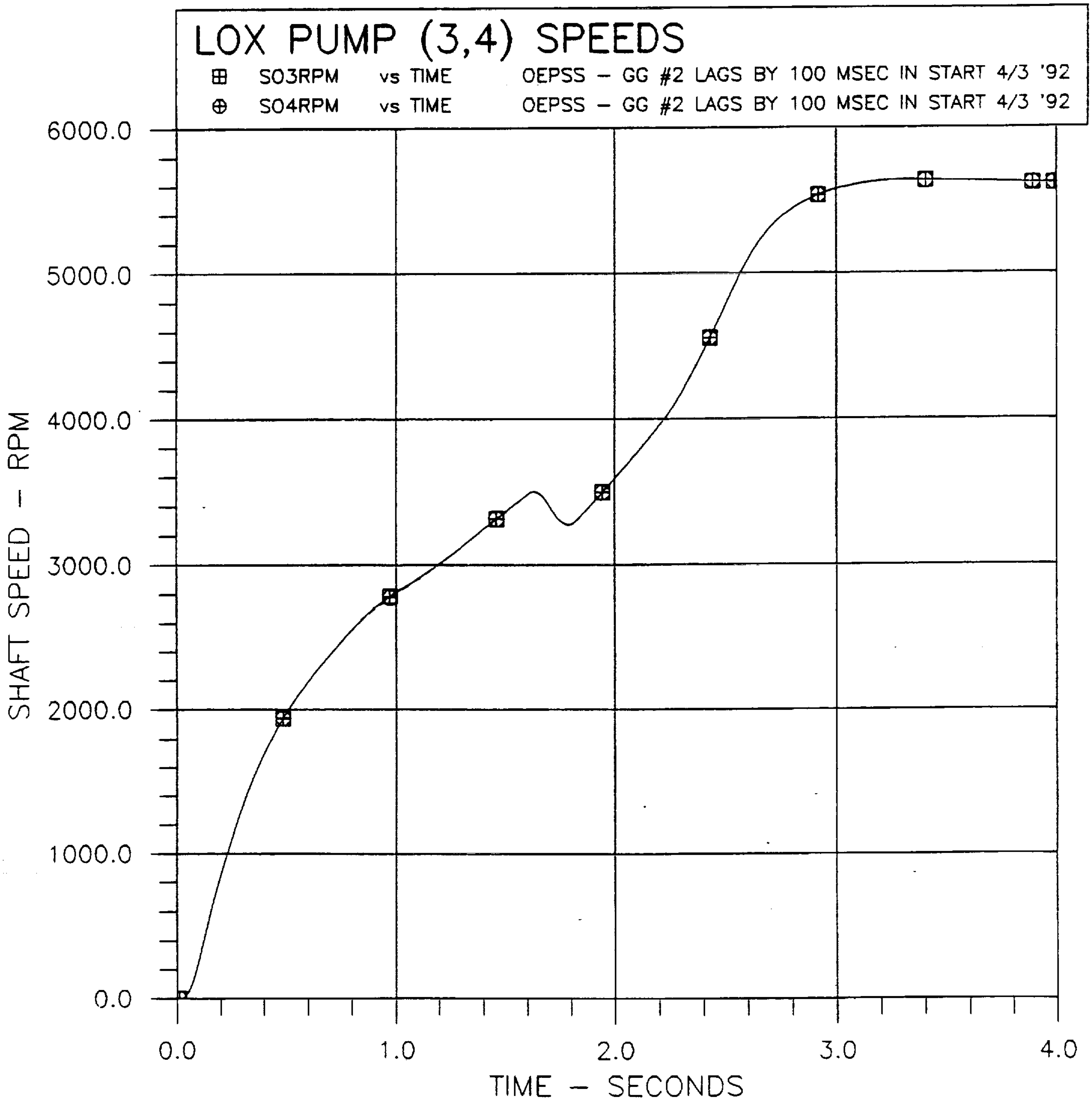

LOX PUMP (1,2) SPEEDS
⊞ SO1RPM vs TIME OEPSS – GG #2 LAGS BY 100 MSEC IN START 4/3 '92
⊕ SO2RPM vs TIME OEPSS – GG #2 LAGS BY 100 MSEC IN START 4/3 '92
6000.0
5000.0
4000.0
3000.0
2000.0
1000.0
0.0
SHAFT SPEED – RPM
0.0
1.0
2.0
3.0
4.0
TIME – SECONDS

Figure A24



LOX PUMP (3,4) SPEEDS
⊞ S03RPM vs TIME OEPSS – GG #2 LAGS BY 100 MSEC IN START 4/3 '92
⊕ S04RPM vs TIME OEPSS – GG #2 LAGS BY 100 MSEC IN START 4/3 '92
6000.0
5000.0
4000.0
3000.0
2000.0
1000.0
0.0
SHAFT SPEED – RPM
0.0
1.0
2.0
3.0
4.0
TIME – SECONDS

~~Figure~~ A25

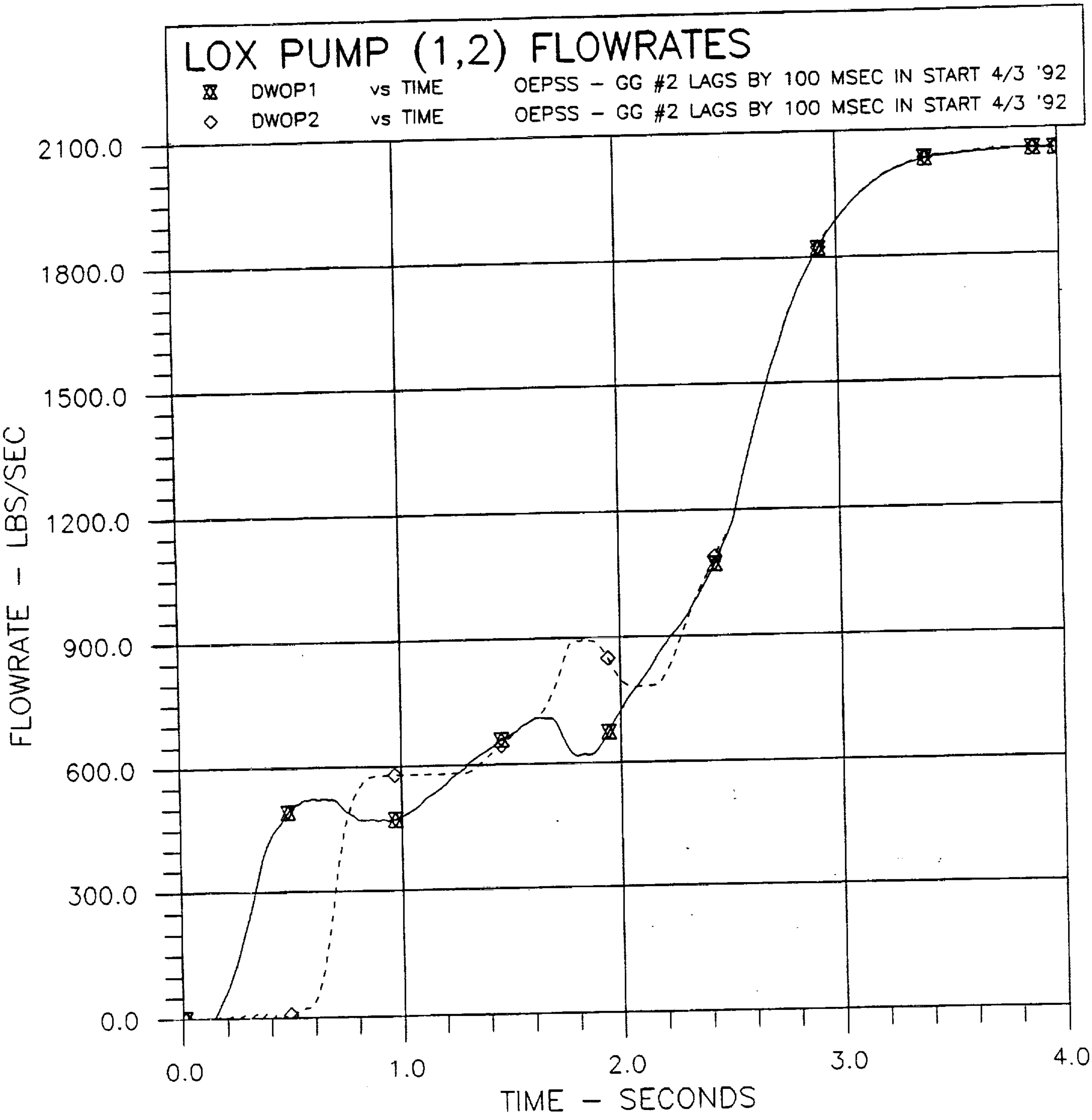

LOX PUMP (1,2) FLOWRATES
⧖ DWOP1 vs TIME OEPSS - GG #2 LAGS BY 100 MSEC IN START 4/3 '92
◇ DWOP2 vs TIME OEPSS - GG #2 LAGS BY 100 MSEC IN START 4/3 '92
2100.0
1800.0
1500.0
1200.0
900.0
600.0
300.0
0.0
FLOWRATE - LBS/SEC
0.0
1.0
2.0
3.0
4.0
TIME - SECONDS

Figure A26

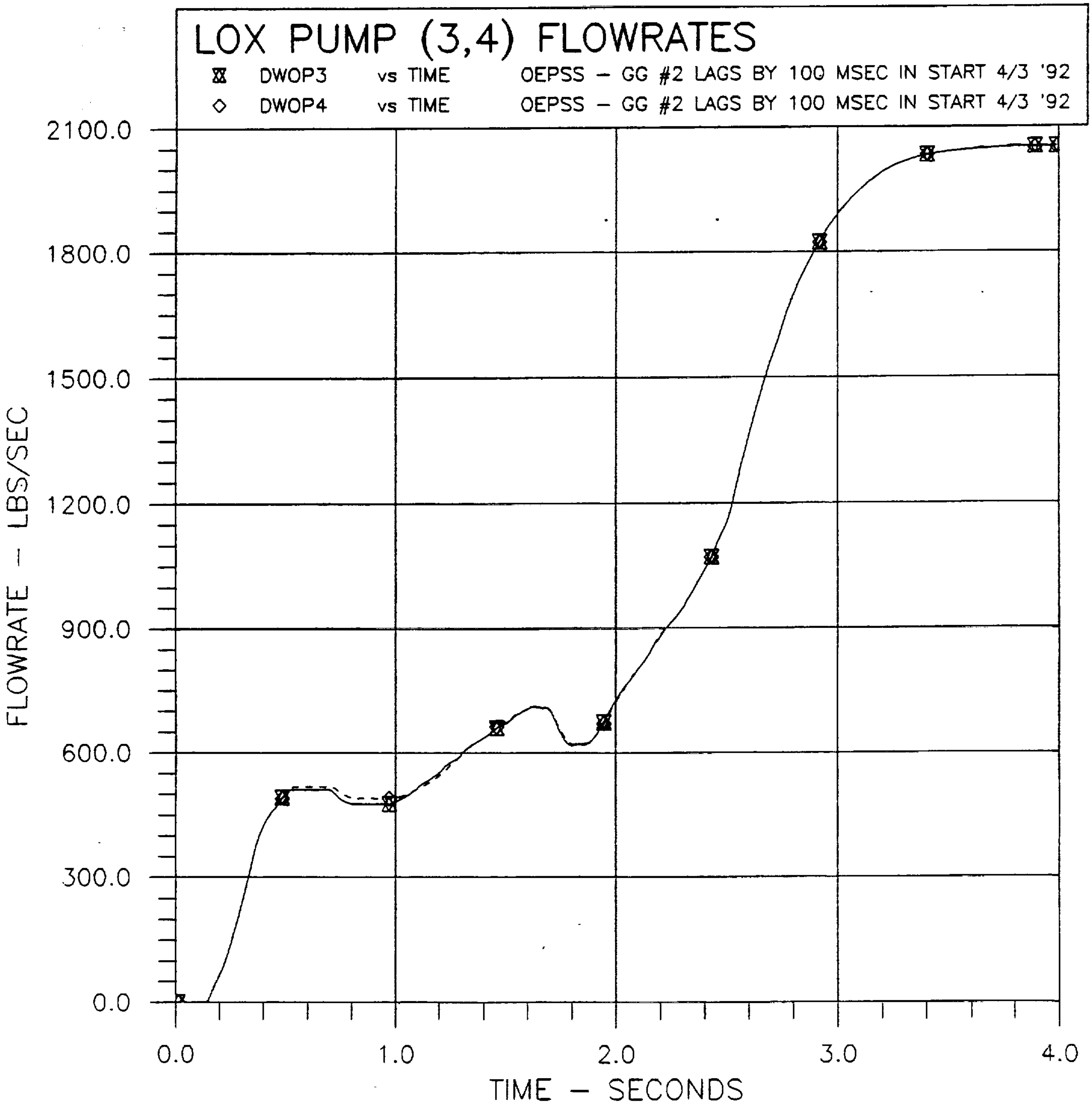

LOX PUMP (3,4) FLOWRATES
DWOP3 vs TIME OEPSS – GG #2 LAGS BY 100 MSEC IN START 4/3 '92
◇ DWOP4 vs TIME OEPSS – GG #2 LAGS BY 100 MSEC IN START 4/3 '92
FLOWRATE – LBS/SEC
2100.0
1800.0
1500.0
1200.0
900.0
600.0
300.0
0.0
0.0
1.0
2.0
3.0
4.0
TIME – SECONDS

Figure A27

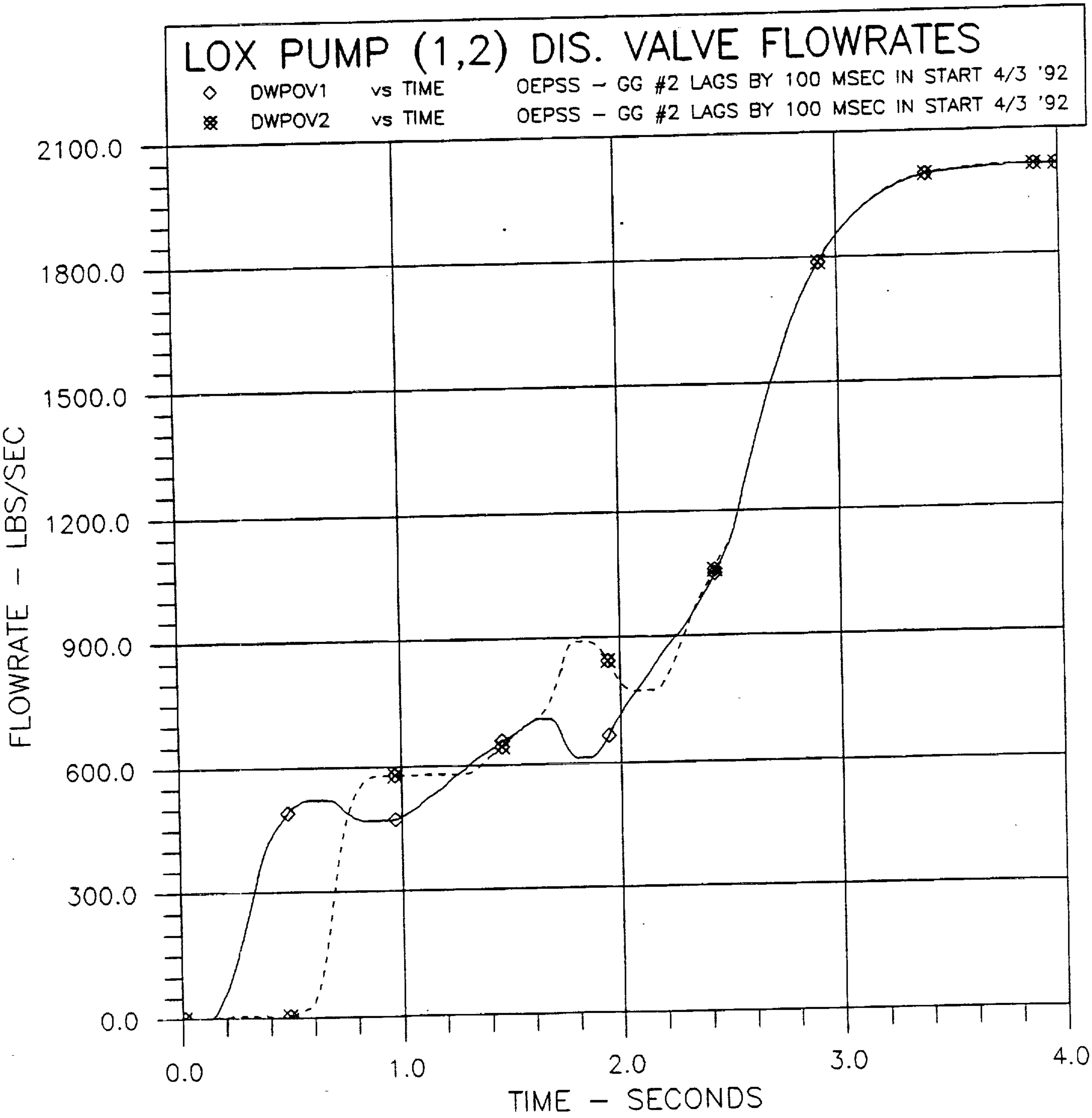

LOX PUMP (1,2) DIS. VALVE FLOWRATES
◇ DWPOV1 vs TIME OEPSS – GG #2 LAGS BY 100 MSEC IN START 4/3 '92
⊗ DWPOV2 vs TIME OEPSS – GG #2 LAGS BY 100 MSEC IN START 4/3 '92
2100.0
1800.0
1500.0
1200.0
900.0
600.0
300.0
0.0
FLOWRATE – LBS/SEC
0.0
1.0
2.0
3.0
4.0
TIME – SECONDS

Figure A28

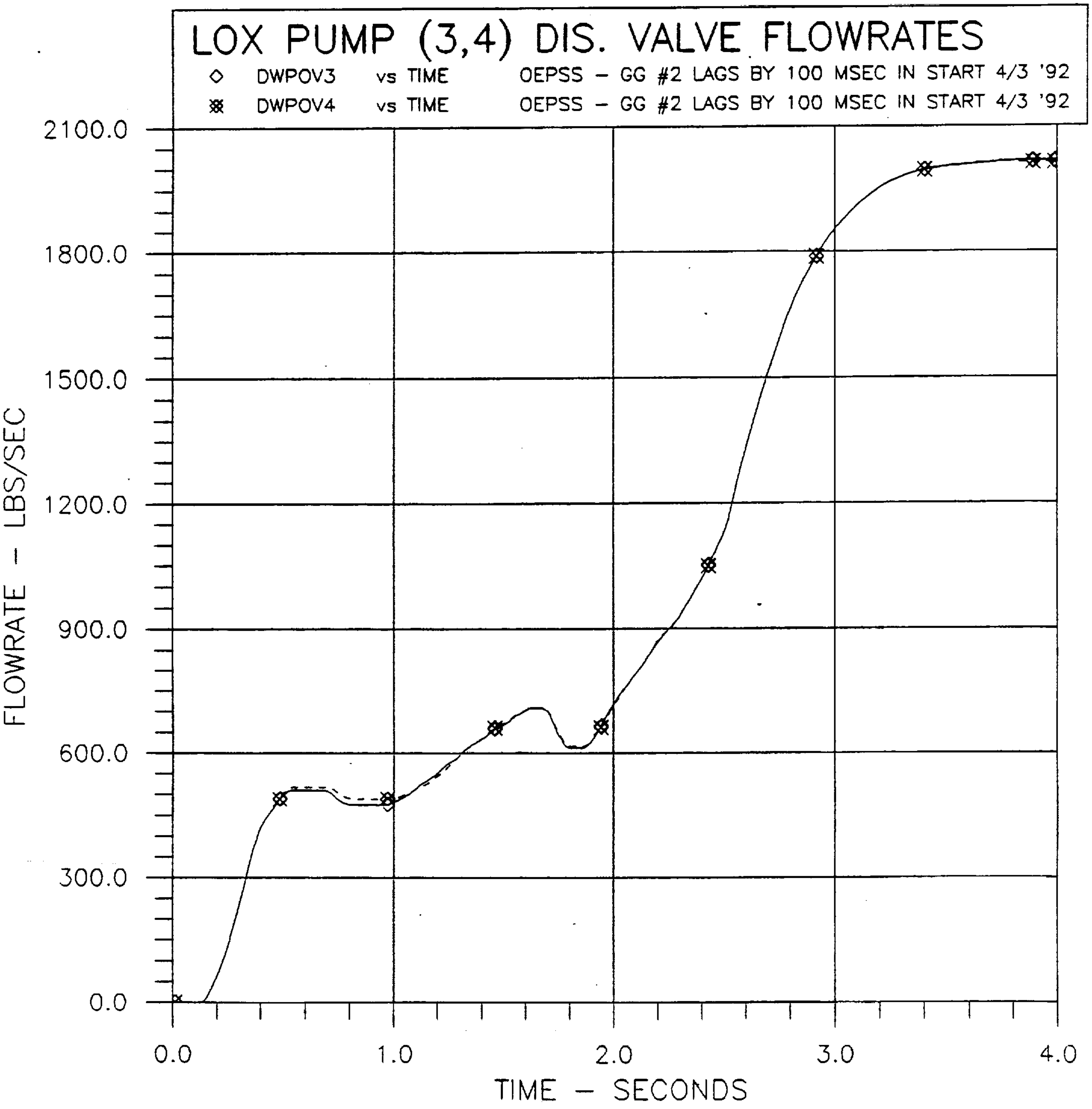

LOX PUMP (3,4) DIS. VALVE FLOWRATES
◇ DWPOV3 vs TIME OEPSS – GG #2 LAGS BY 100 MSEC IN START 4/3 '92
⊗ DWPOV4 vs TIME OEPSS – GG #2 LAGS BY 100 MSEC IN START 4/3 '92
2100.0
1800.0
1500.0
1200.0
900.0
600.0
300.0
0.0
FLOWRATE – LBS/SEC
0.0
1.0
2.0
3.0
4.0
TIME – SECONDS

Figure A29

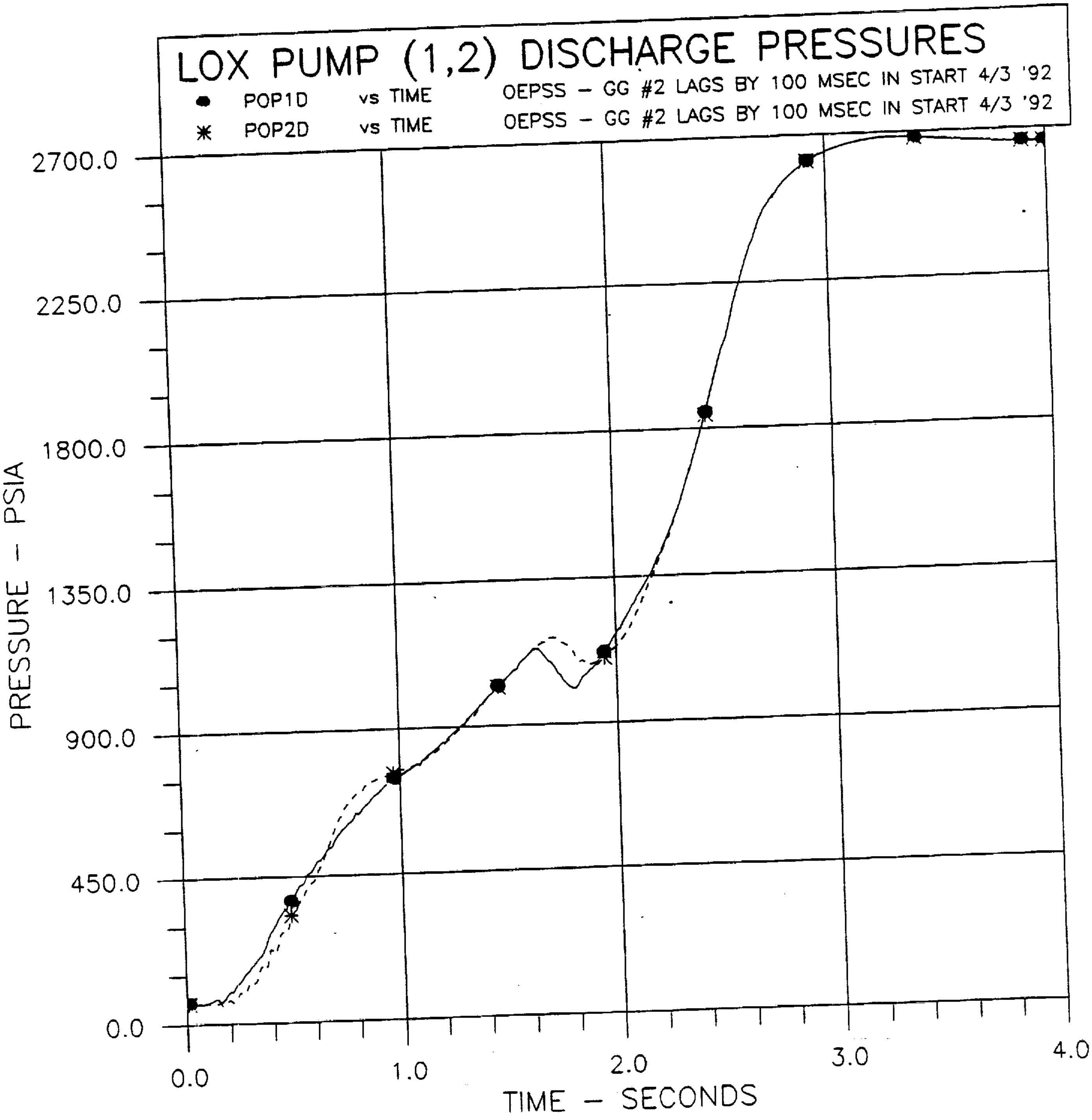

LOX PUMP (1,2) DISCHARGE PRESSURES
● POP1D vs TIME OEPSS - GG #2 LAGS BY 100 MSEC IN START 4/3 '92
✳ POP2D vs TIME OEPSS - GG #2 LAGS BY 100 MSEC IN START 4/3 '92
2700.0
2250.0
1800.0
1350.0
900.0
450.0
0.0
PRESSURE - PSIA
0.0
1.0
2.0
3.0
4.0
TIME - SECONDS

Figure A30

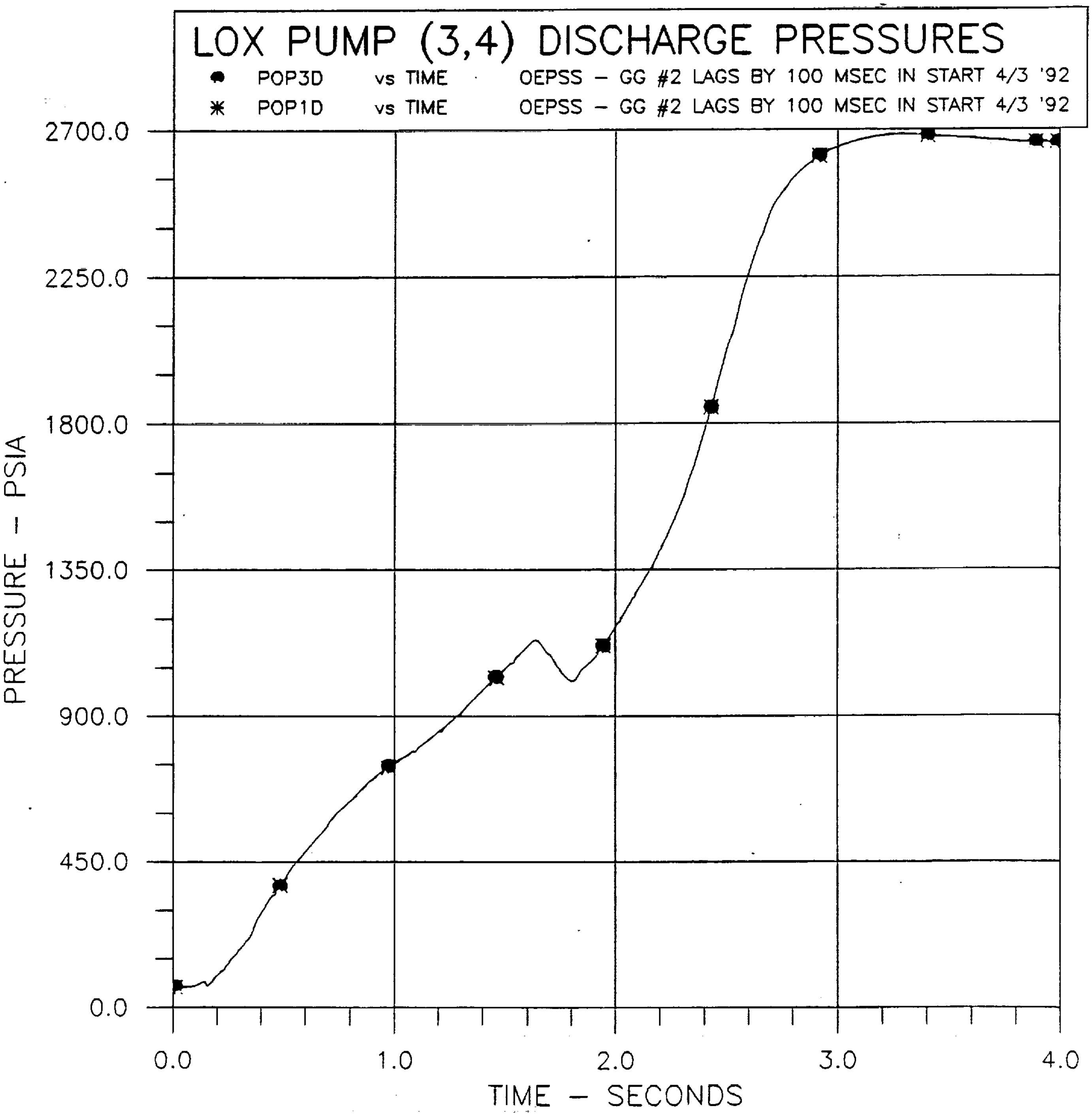
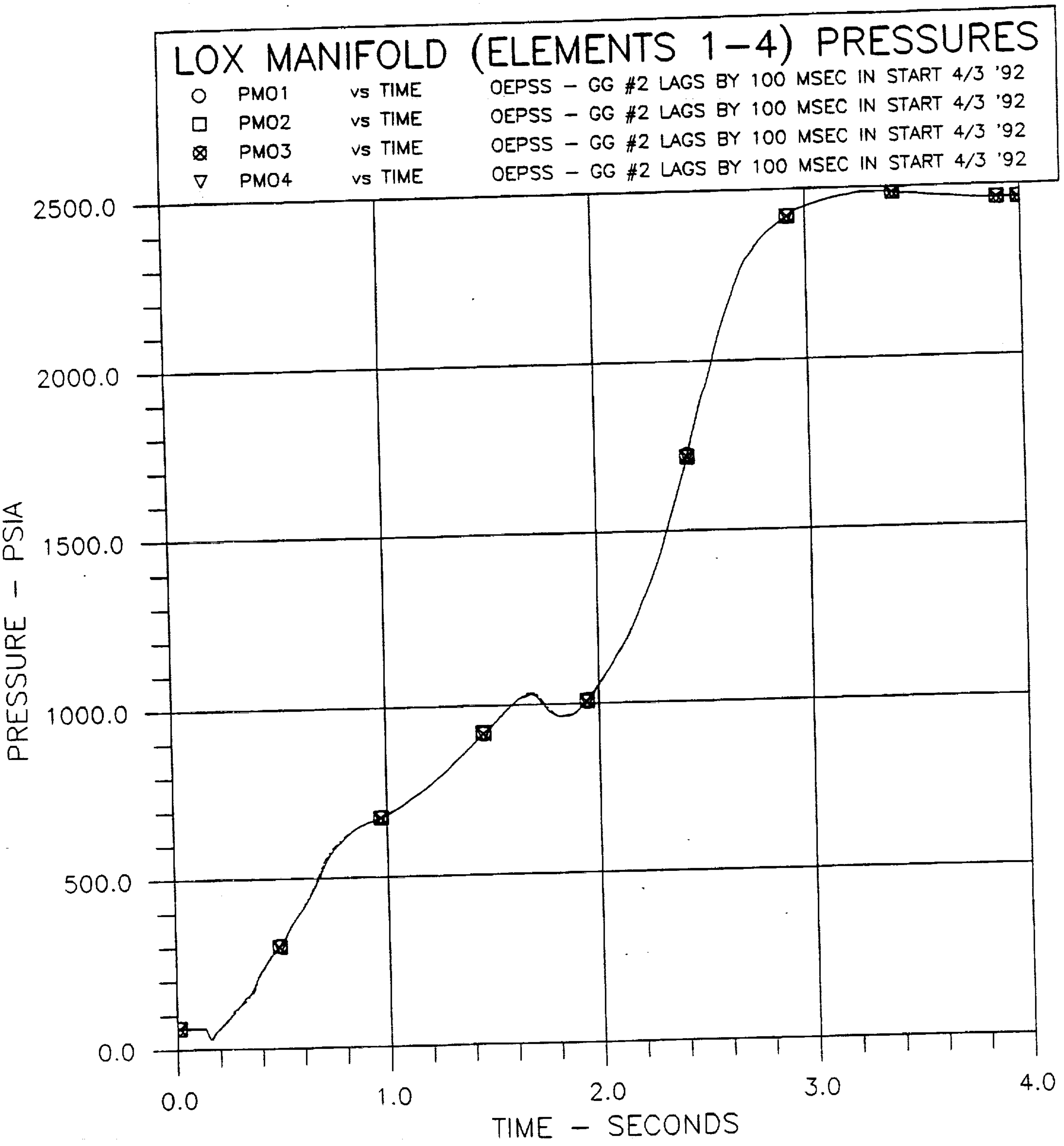

LOX PUMP (3,4) DISCHARGE PRESSURES
● POP3D vs TIME OEPSS – GG #2 LAGS BY 100 MSEC IN START 4/3 '92
✳ POP1D vs TIME OEPSS – GG #2 LAGS BY 100 MSEC IN START 4/3 '92
2700.0
2250.0
1800.0
1350.0
900.0
450.0
0.0
PRESSURE – PSIA
0.0
1.0
2.0
3.0
4.0
TIME – SECONDS

Figure A31



LOX MANIFOLD (ELEMENTS 1−4) PRESSURES
○ PM01 vs TIME OEPSS − GG #2 LAGS BY 100 MSEC IN START 4/3 '92
□ PM02 vs TIME OEPSS − GG #2 LAGS BY 100 MSEC IN START 4/3 '92
⊠ PM03 vs TIME OEPSS − GG #2 LAGS BY 100 MSEC IN START 4/3 '92
▽ PM04 vs TIME OEPSS − GG #2 LAGS BY 100 MSEC IN START 4/3 '92
PRESSURE − PSIA
2500.0
2000.0
1500.0
1000.0
500.0
0.0
TIME − SECONDS
0.0
1.0
2.0
3.0
4.0

Figure A32

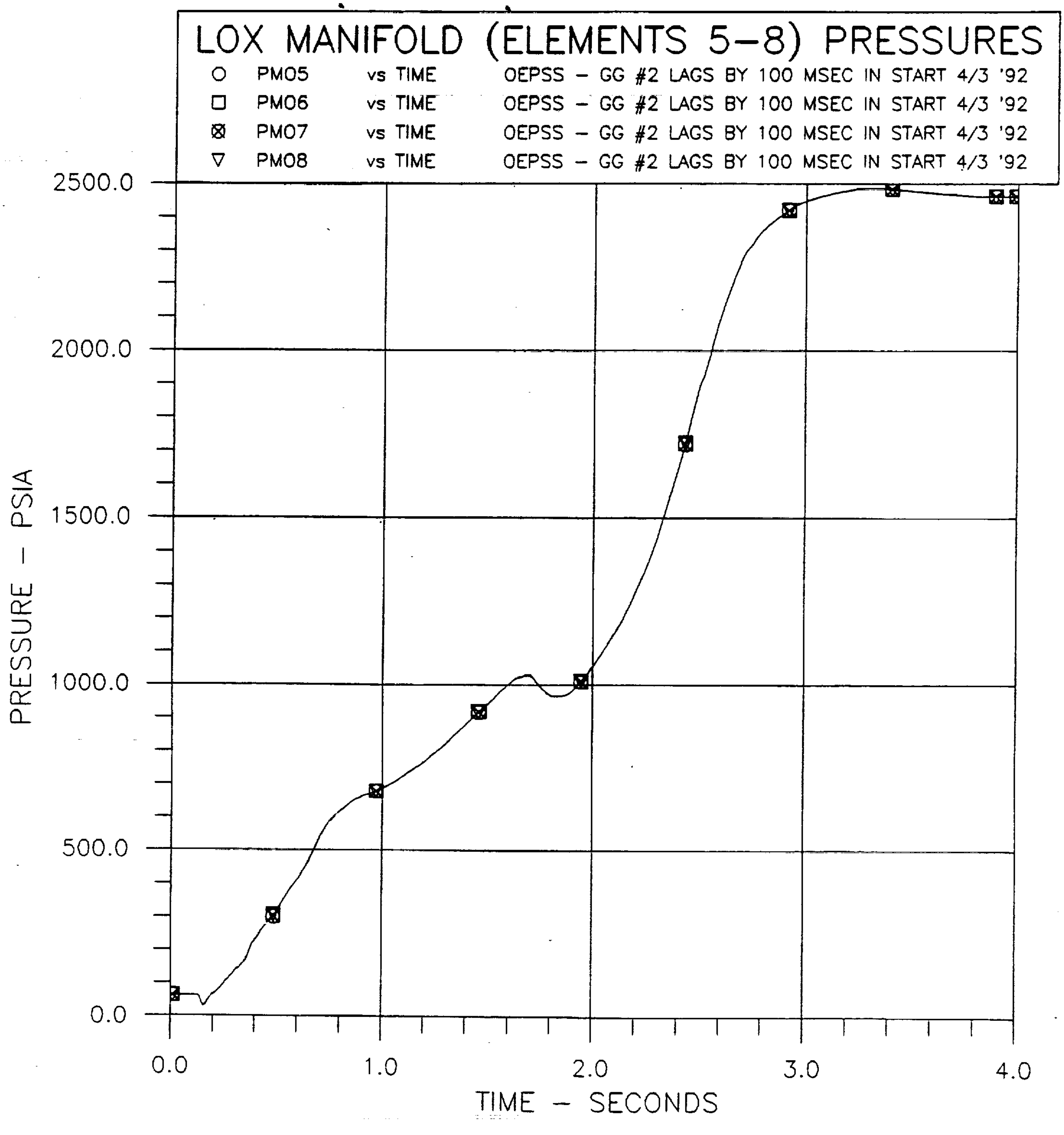

LOX MANIFOLD (ELEMENTS 5-8) PRESSURES
○ PM05 vs TIME OEPSS - GG #2 LAGS BY 100 MSEC IN START 4/3 '92
□ PM06 vs TIME OEPSS - GG #2 LAGS BY 100 MSEC IN START 4/3 '92
⊠ PM07 vs TIME OEPSS - GG #2 LAGS BY 100 MSEC IN START 4/3 '92
▽ PM08 vs TIME OEPSS - GG #2 LAGS BY 100 MSEC IN START 4/3 '92
2500.0
2000.0
1500.0
1000.0
500.0
0.0
PRESSURE - PSIA
0.0
1.0
2.0
3.0
4.0
TIME - SECONDS

Figure A33

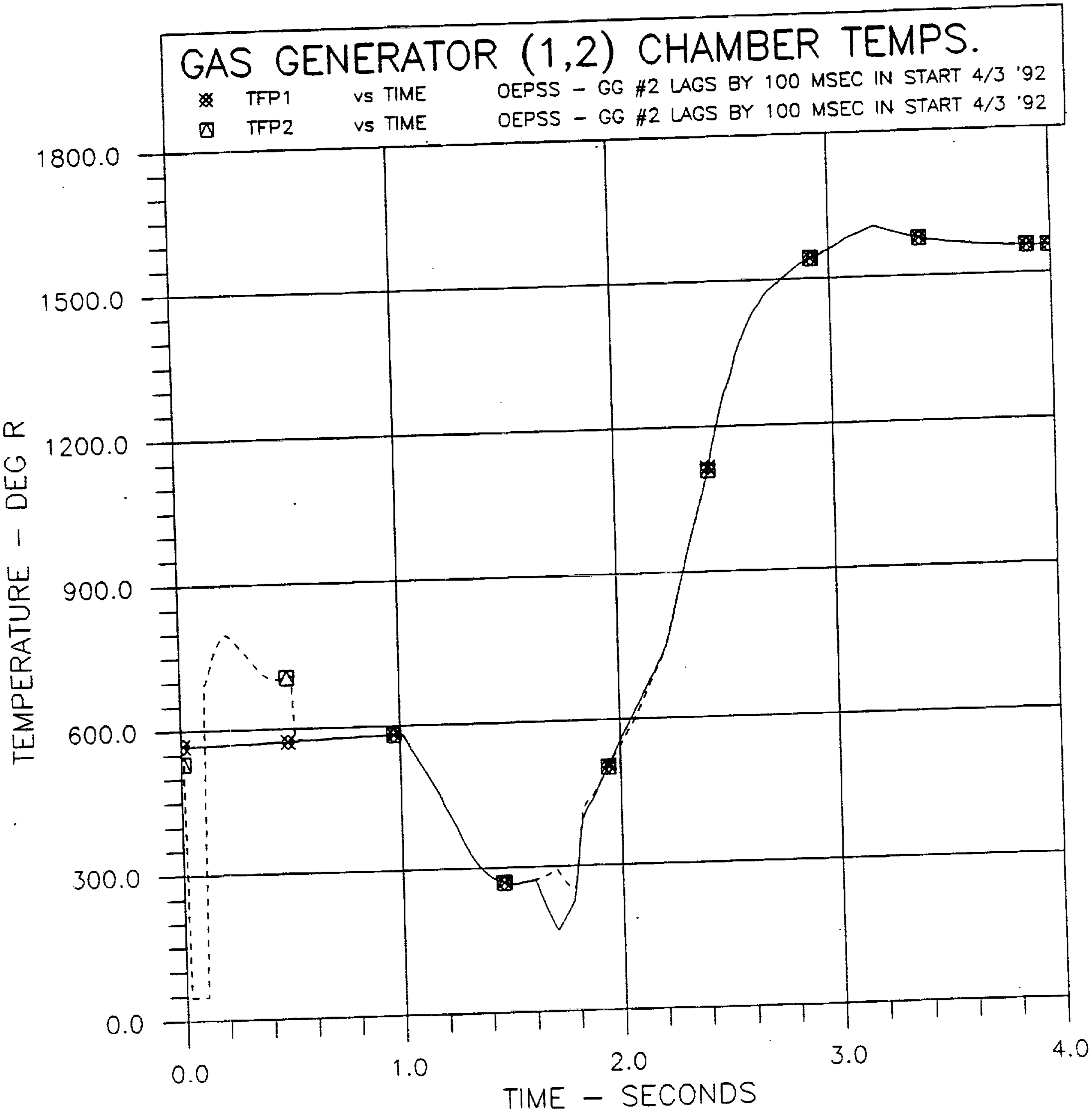

GAS GENERATOR (1,2) CHAMBER TEMPS.
TFP1 vs TIME OEPSS – GG #2 LAGS BY 100 MSEC IN START 4/3 '92
TFP2 vs TIME OEPSS – GG #2 LAGS BY 100 MSEC IN START 4/3 '92
1800.0
1500.0
1200.0
900.0
600.0
300.0
0.0
TEMPERATURE – DEG R
0.0
1.0
2.0
3.0
4.0
TIME – SECONDS

Figure A34

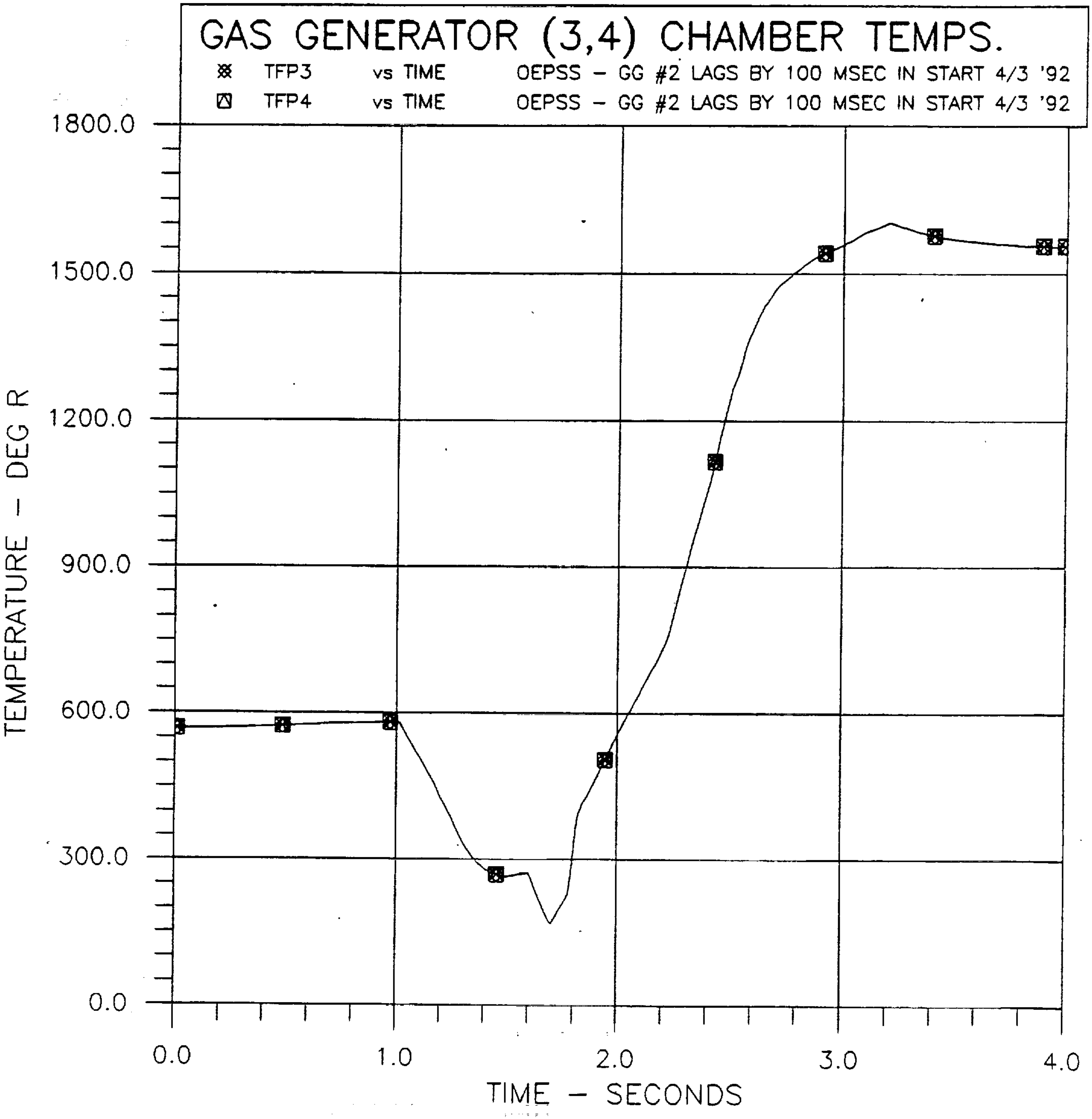
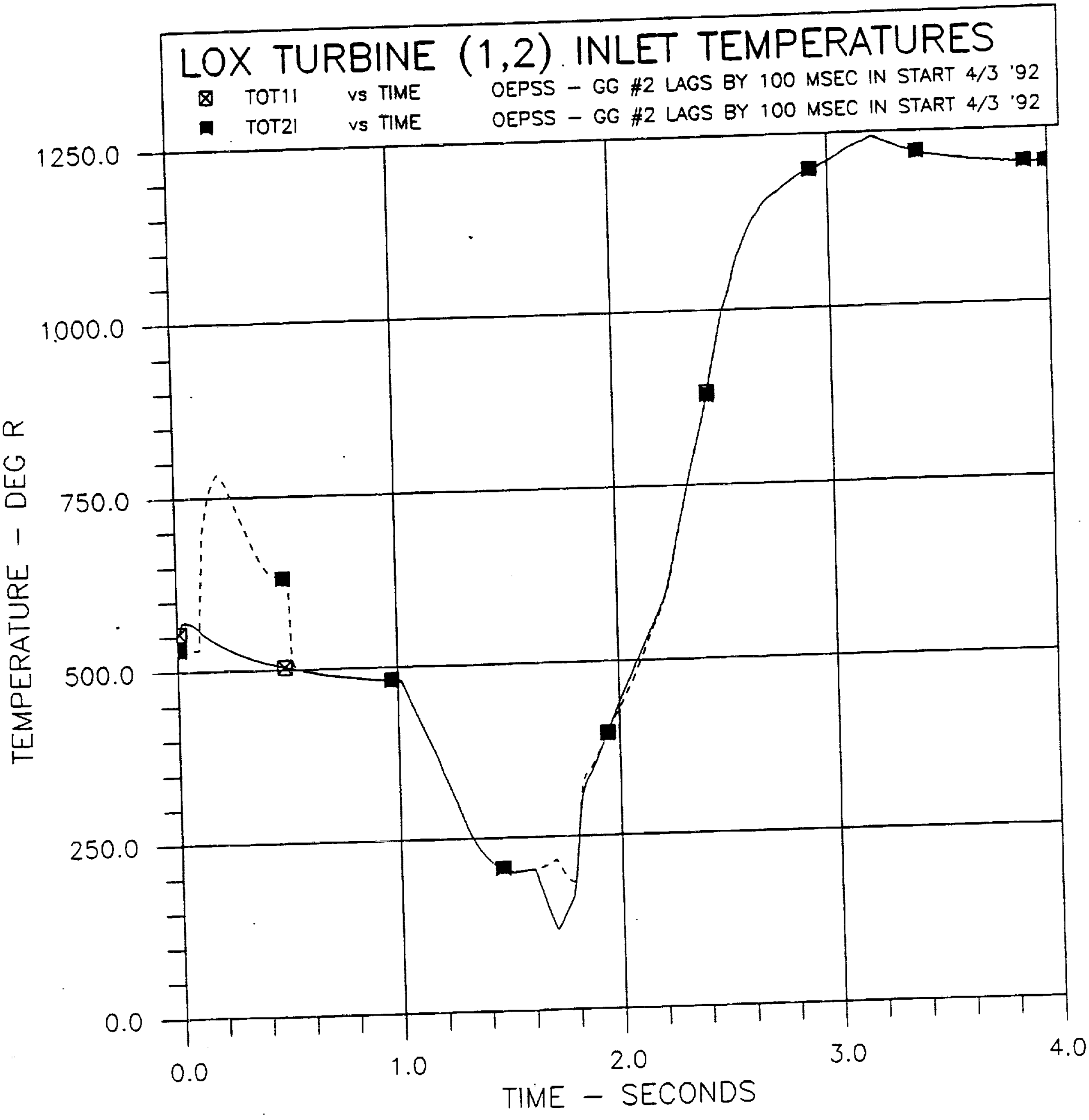

GAS GENERATOR (3,4) CHAMBER TEMPS.
⊠ TFP3 vs TIME OEPSS – GG #2 LAGS BY 100 MSEC IN START 4/3 '92
⊠ TFP4 vs TIME OEPSS – GG #2 LAGS BY 100 MSEC IN START 4/3 '92
1800.0
1500.0
1200.0
900.0
600.0
300.0
0.0
TEMPERATURE – DEG R
0.0
1.0
2.0
3.0
4.0
TIME – SECONDS

Figure A35



LOX TURBINE (1,2) INLET TEMPERATURES
☒ TOT1I vs TIME OEPSS – GG #2 LAGS BY 100 MSEC IN START 4/3 '92
■ TOT2I vs TIME OEPSS – GG #2 LAGS BY 100 MSEC IN START 4/3 '92
1250.0
1000.0
750.0
500.0
250.0
0.0
TEMPERATURE – DEG R
0.0
1.0
2.0
3.0
4.0
TIME – SECONDS

Figure A36

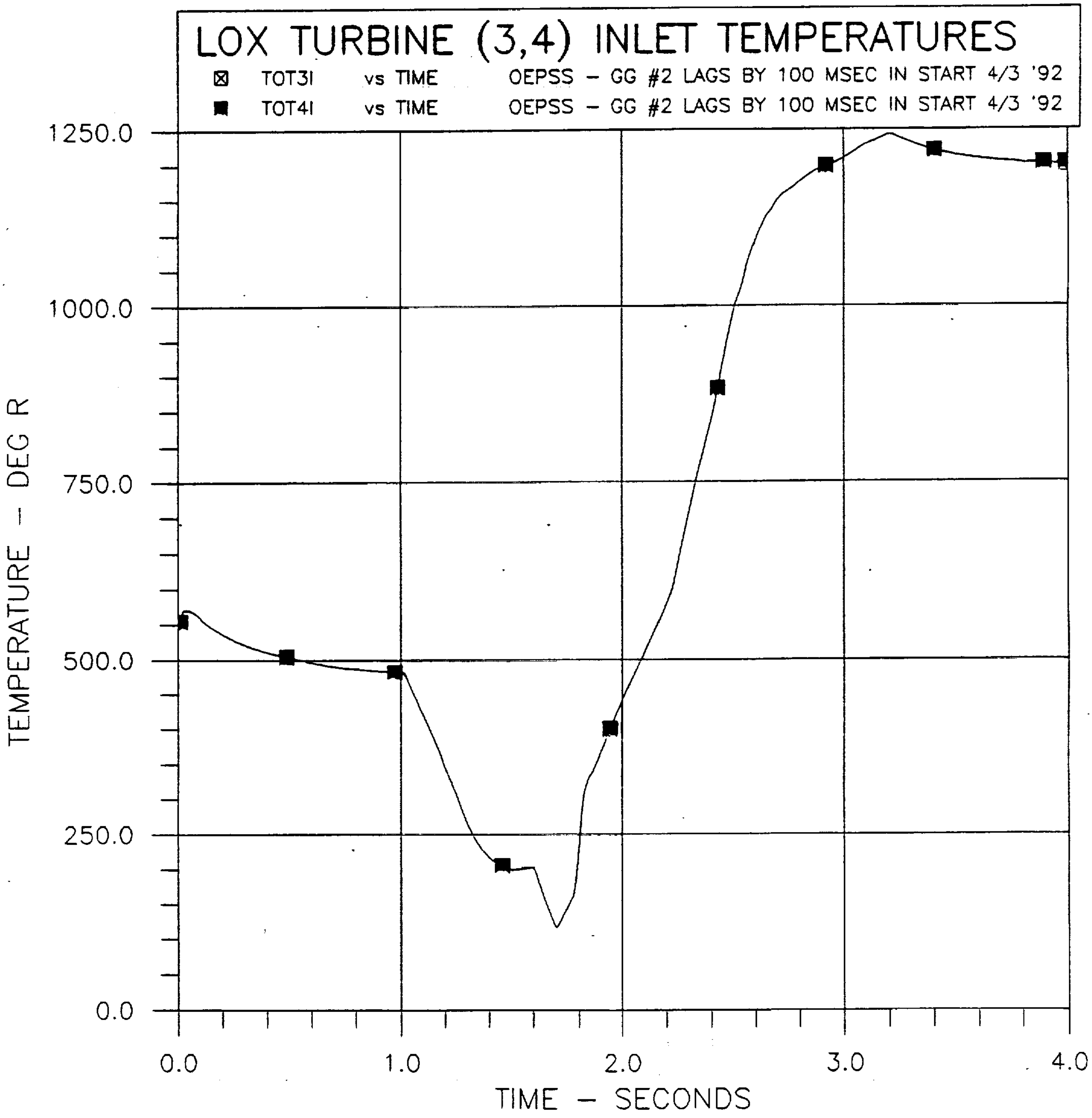

LOX TURBINE (3,4) INLET TEMPERATURES
⊠ TOT3I vs TIME OEPSS - GG #2 LAGS BY 100 MSEC IN START 4/3 '92
■ TOT4I vs TIME OEPSS - GG #2 LAGS BY 100 MSEC IN START 4/3 '92
1250.0
1000.0
750.0
500.0
250.0
0.0
TEMPERATURE - DEG R
0.0
1.0
2.0
3.0
4.0
TIME - SECONDS

Figure A37

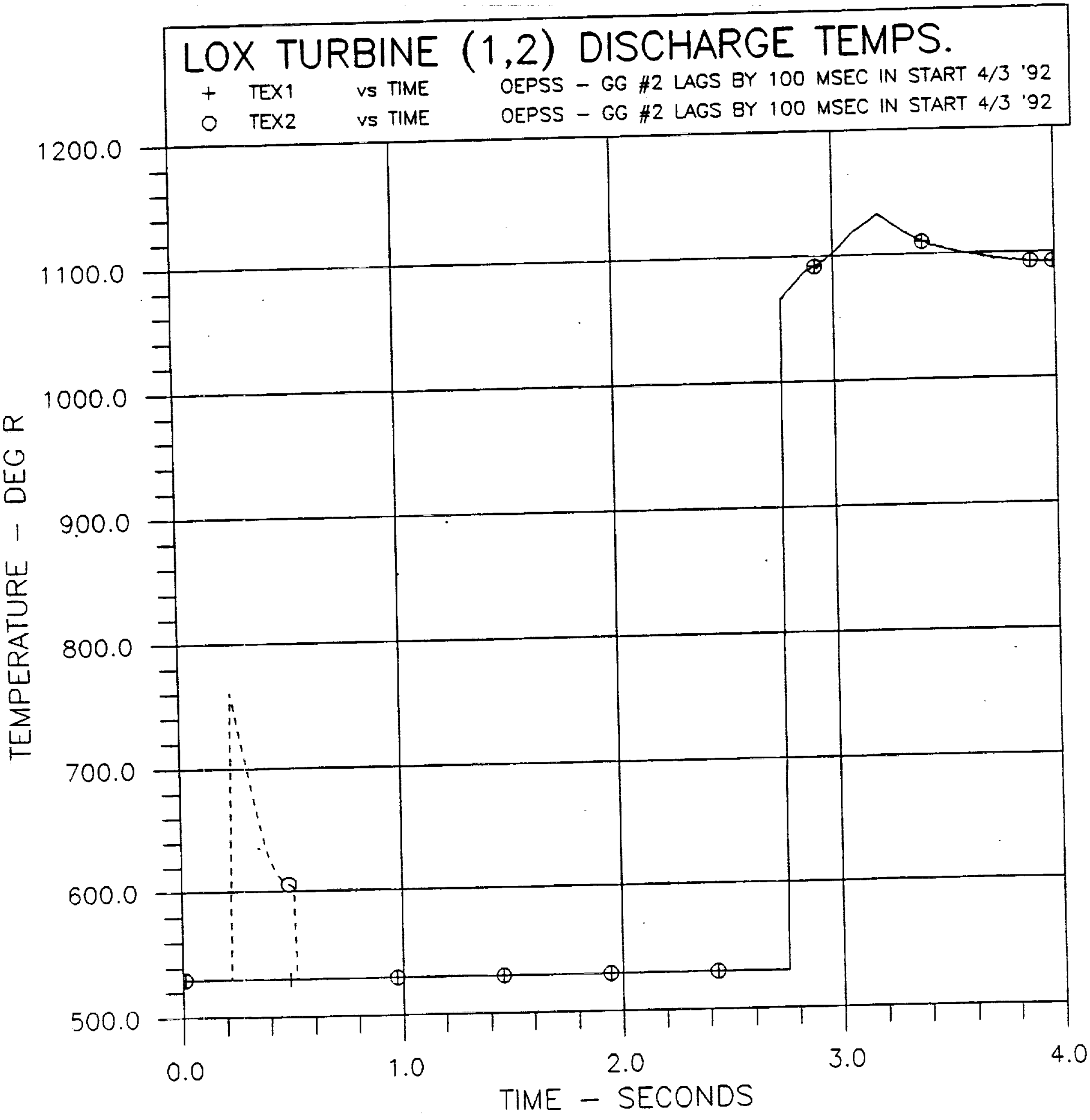

LOX TURBINE (1,2) DISCHARGE TEMPS.
+ TEX1 vs TIME OEPSS - GG #2 LAGS BY 100 MSEC IN START 4/3 '92
○ TEX2 vs TIME OEPSS - GG #2 LAGS BY 100 MSEC IN START 4/3 '92
1200.0
1100.0
1000.0
900.0
800.0
700.0
600.0
500.0
TEMPERATURE - DEG R
0.0
1.0
2.0
3.0
4.0
TIME - SECONDS

Figure A38

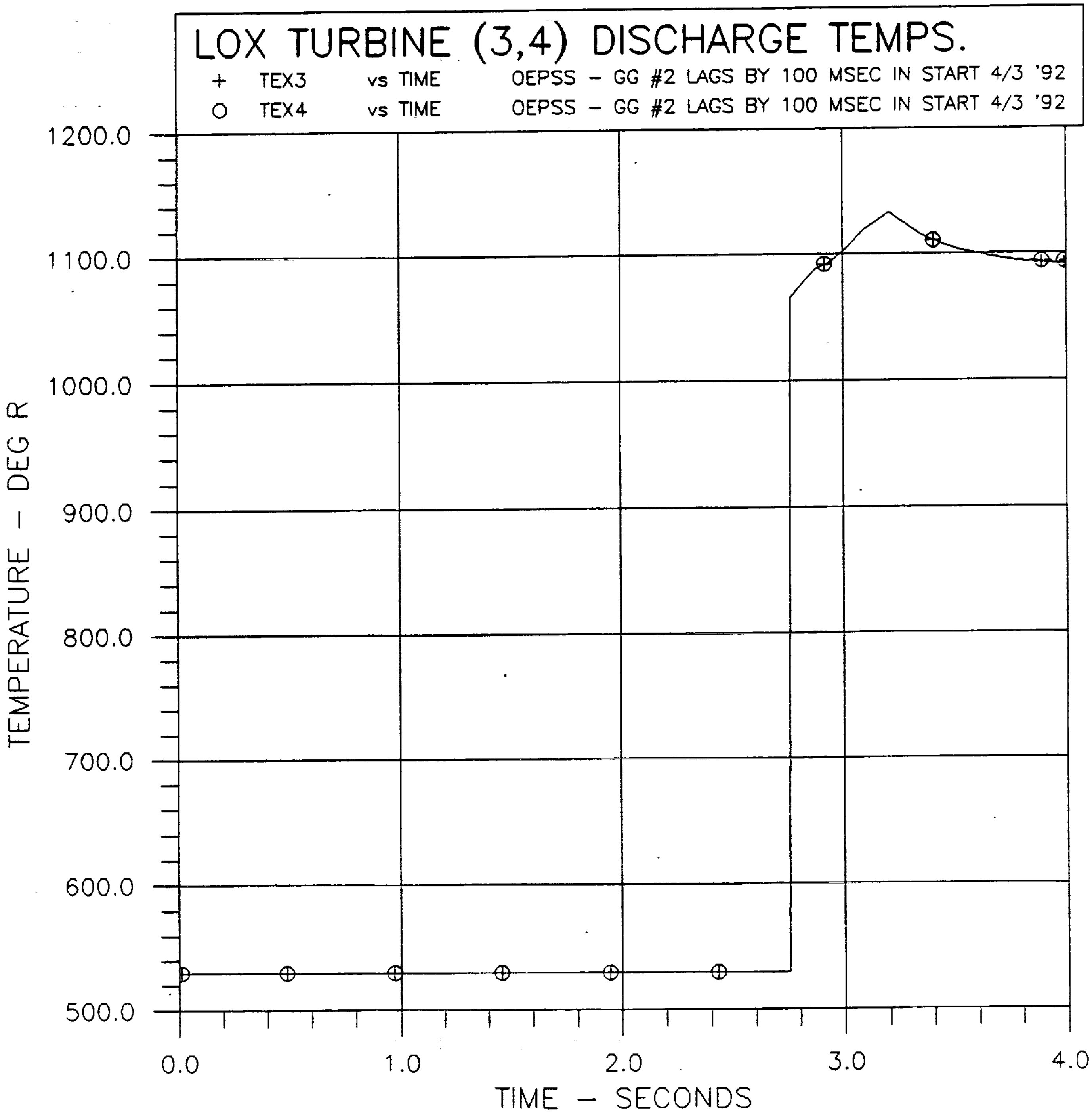
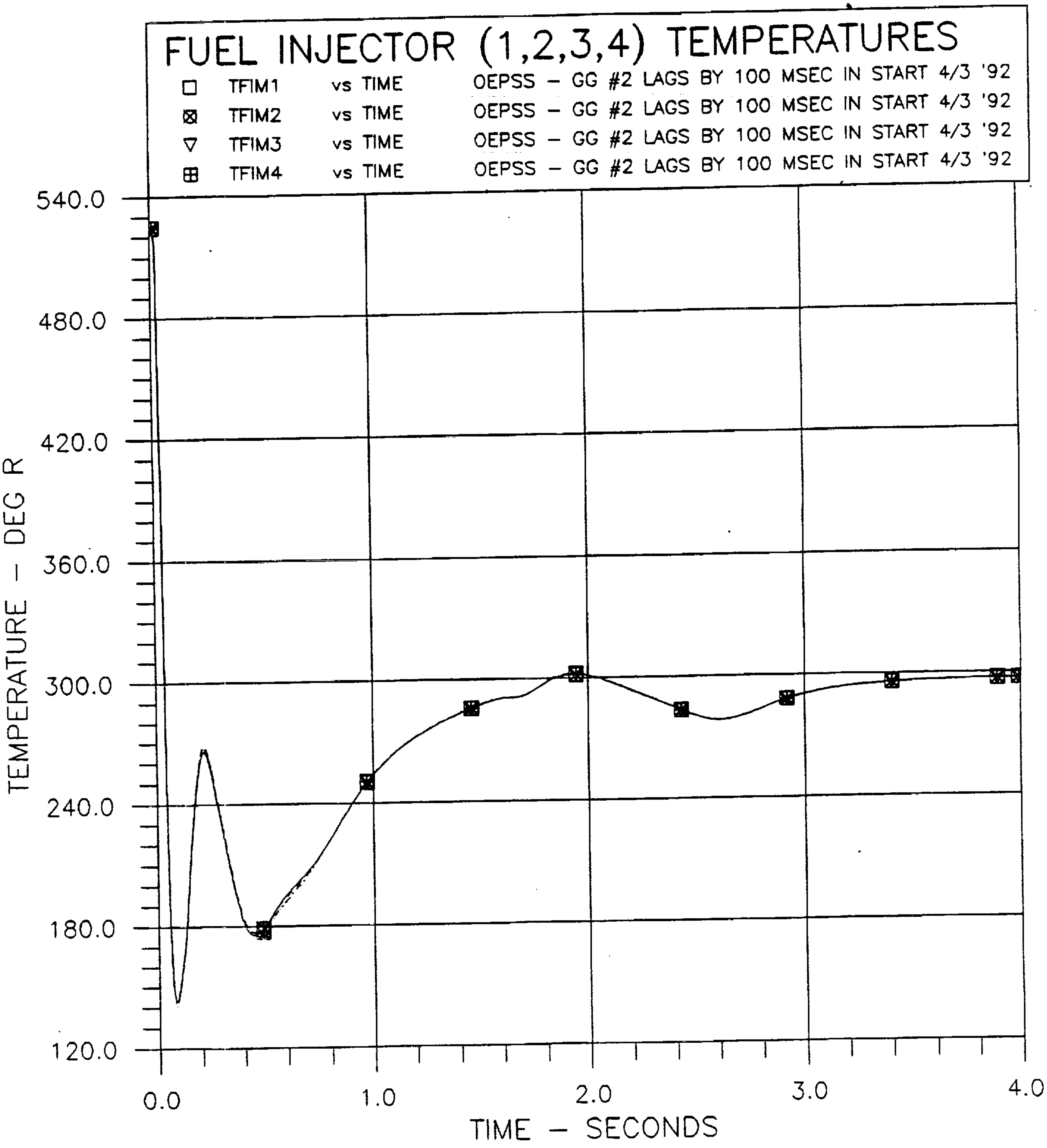

LOX TURBINE (3,4) DISCHARGE TEMPS.
+ TEX3 vs TIME OEPSS – GG #2 LAGS BY 100 MSEC IN START 4/3 '92
○ TEX4 vs TIME OEPSS – GG #2 LAGS BY 100 MSEC IN START 4/3 '92
1200.0
1100.0
1000.0
900.0
800.0
700.0
600.0
500.0
TEMPERATURE – DEG R
0.0
1.0
2.0
3.0
4.0
TIME – SECONDS

Figure A39



FUEL INJECTOR (1,2,3,4) TEMPERATURES
□ TFIM1 vs TIME OEPSS – GG #2 LAGS BY 100 MSEC IN START 4/3 '92
⊠ TFIM2 vs TIME OEPSS – GG #2 LAGS BY 100 MSEC IN START 4/3 '92
▽ TFIM3 vs TIME OEPSS – GG #2 LAGS BY 100 MSEC IN START 4/3 '92
⊞ TFIM4 vs TIME OEPSS – GG #2 LAGS BY 100 MSEC IN START 4/3 '92
540.0
480.0
420.0
360.0
300.0
240.0
180.0
120.0
TEMPERATURE – DEG R
0.0
1.0
2.0
3.0
4.0
TIME – SECONDS

Figure A40

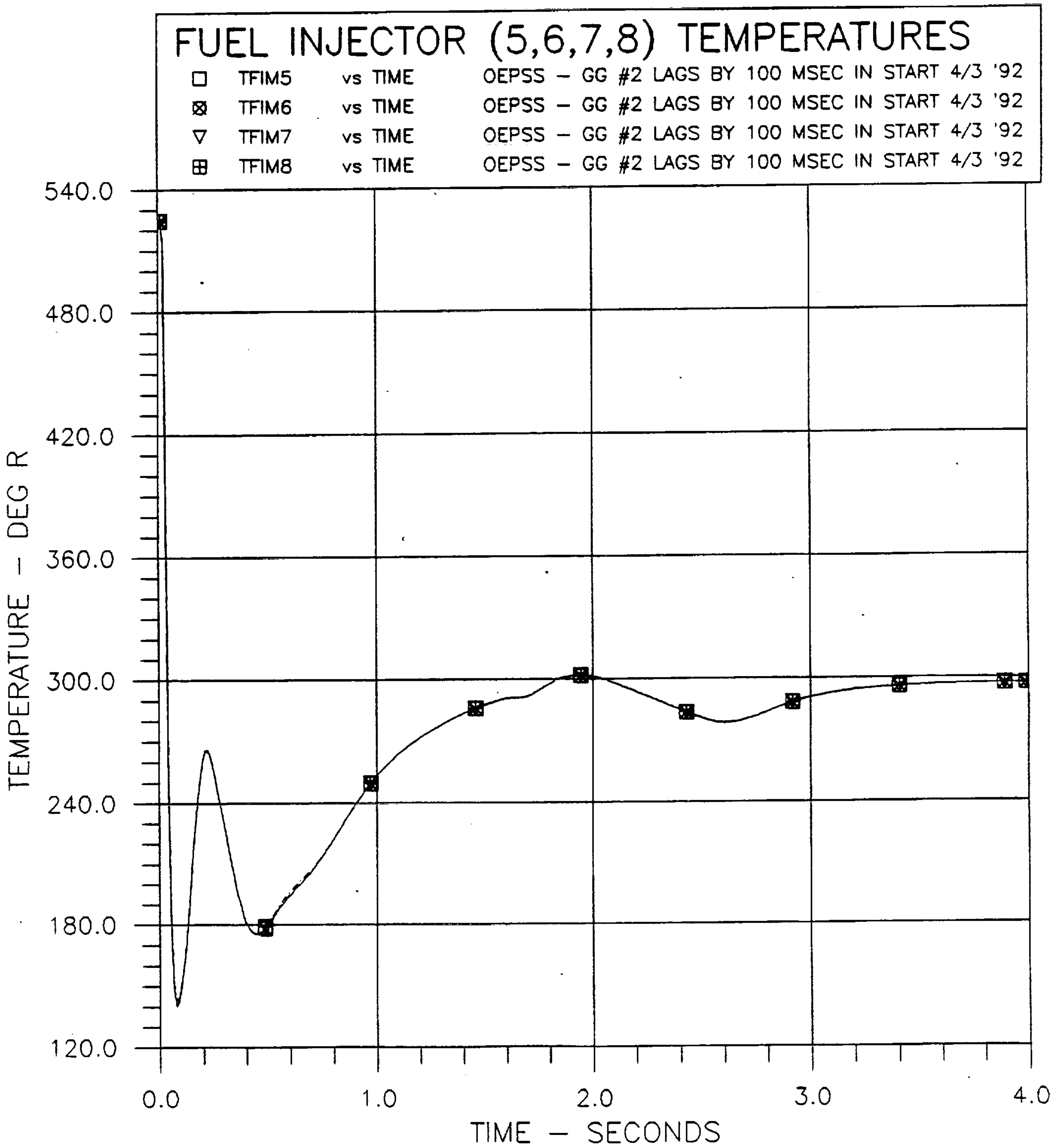
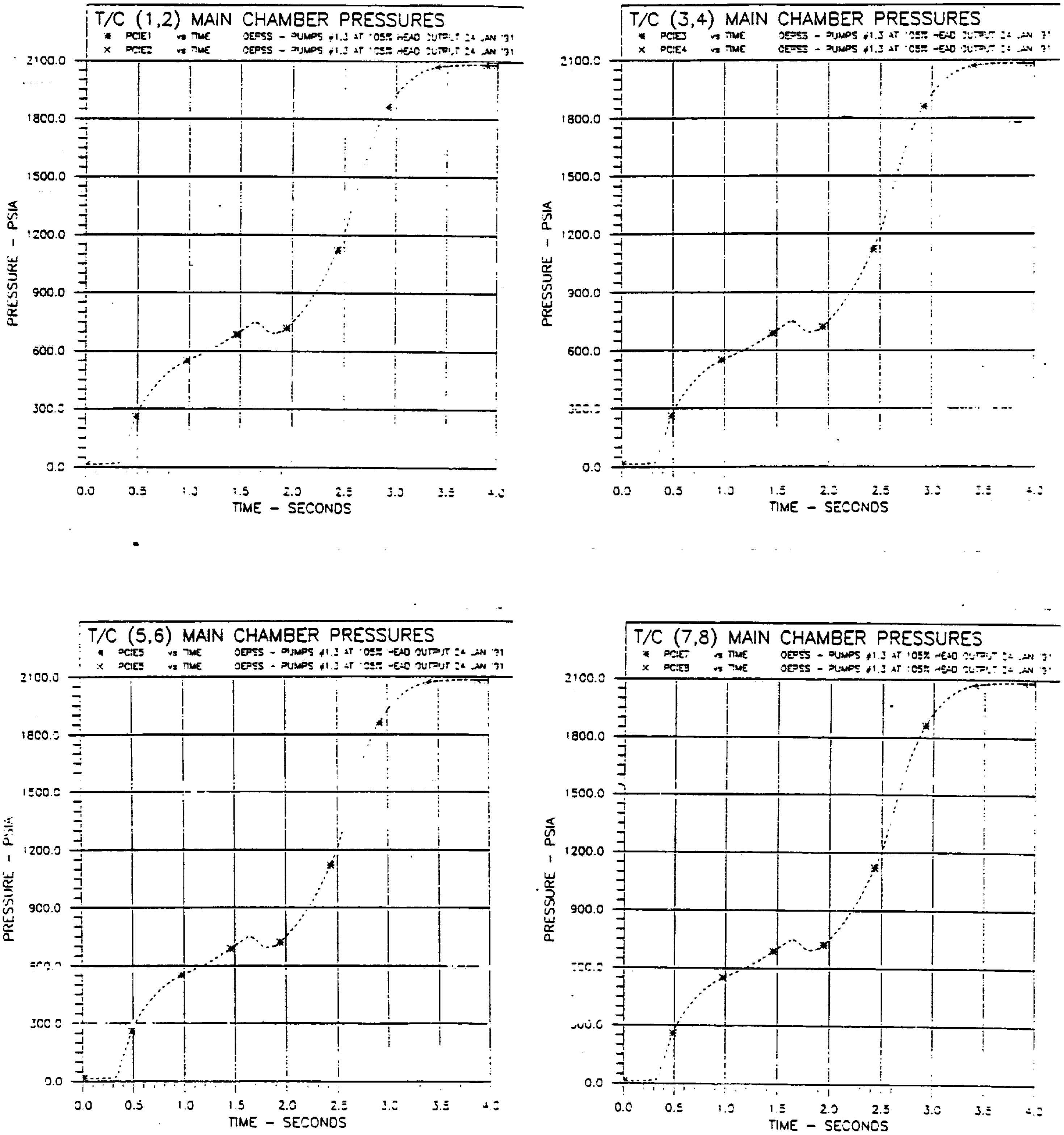
FUEL INJECTOR (5,6,7,8) TEMPERATURES
☐ TFIM5 vs TIME OEPSS – GG #2 LAGS BY 100 MSEC IN START 4/3 '92
⊠ TFIM6 vs TIME OEPSS – GG #2 LAGS BY 100 MSEC IN START 4/3 '92
▽ TFIM7 vs TIME OEPSS – GG #2 LAGS BY 100 MSEC IN START 4/3 '92
⊞ TFIM8 vs TIME OEPSS – GG #2 LAGS BY 100 MSEC IN START 4/3 '92
540.0
480.0
420.0
360.0
300.0
240.0
180.0
120.0
TEMPERATURE – DEG R
0.0
1.0
2.0
3.0
4.0
TIME – SECONDS

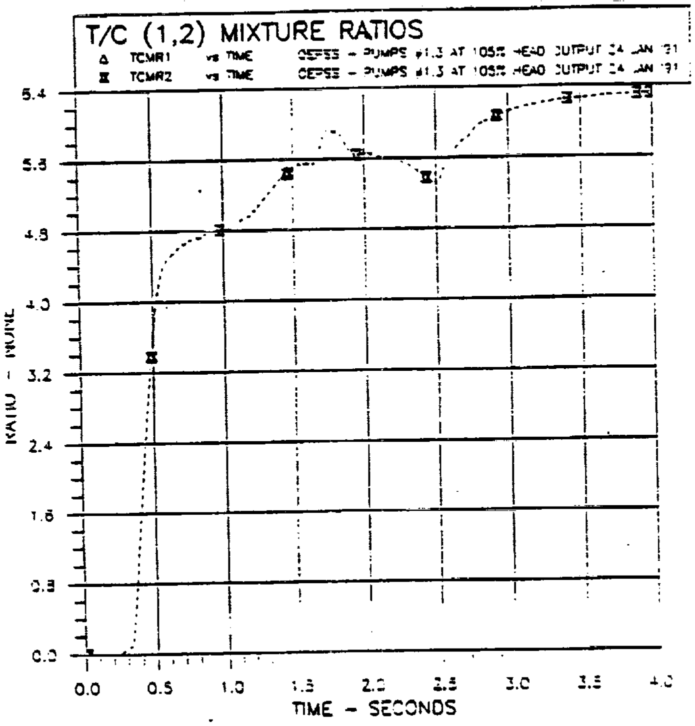
Figure A41

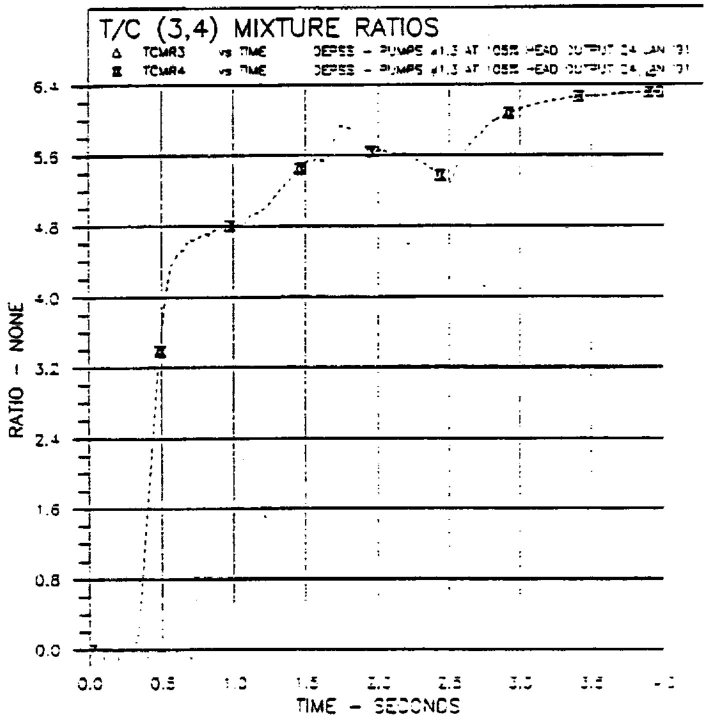
APPENDIX B

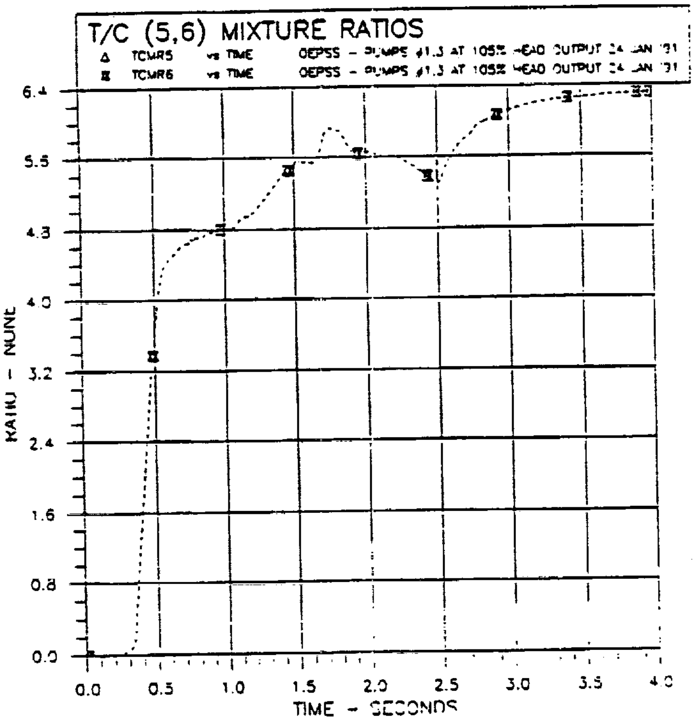
TRANSIENT ANALYTICAL RESULTS
CASE I: INCREASED HEAD PERFORMANCE BY 5% FOR PUMPS 1 AND 3

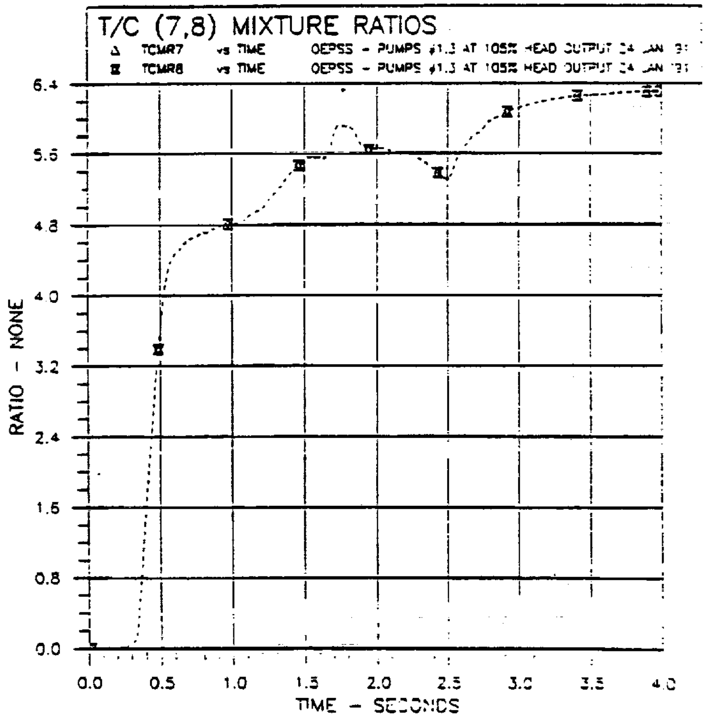


Figures B1-B4

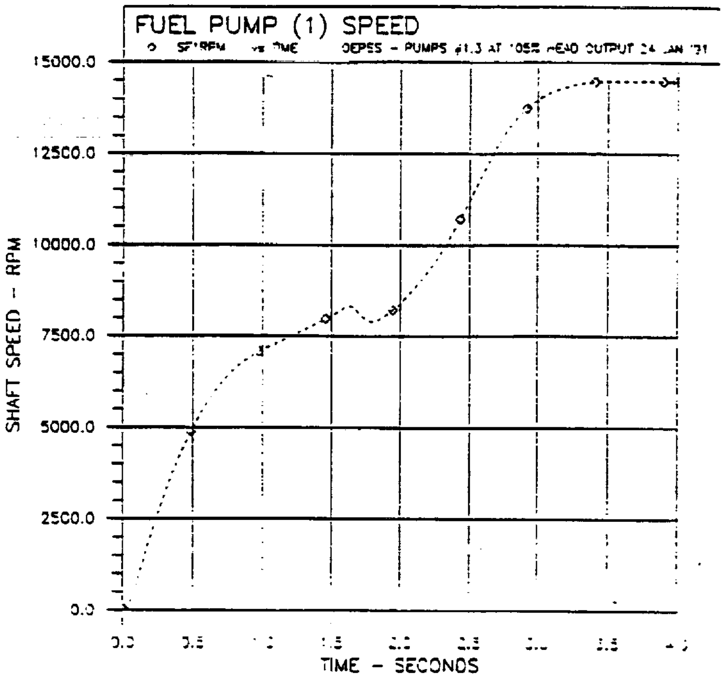


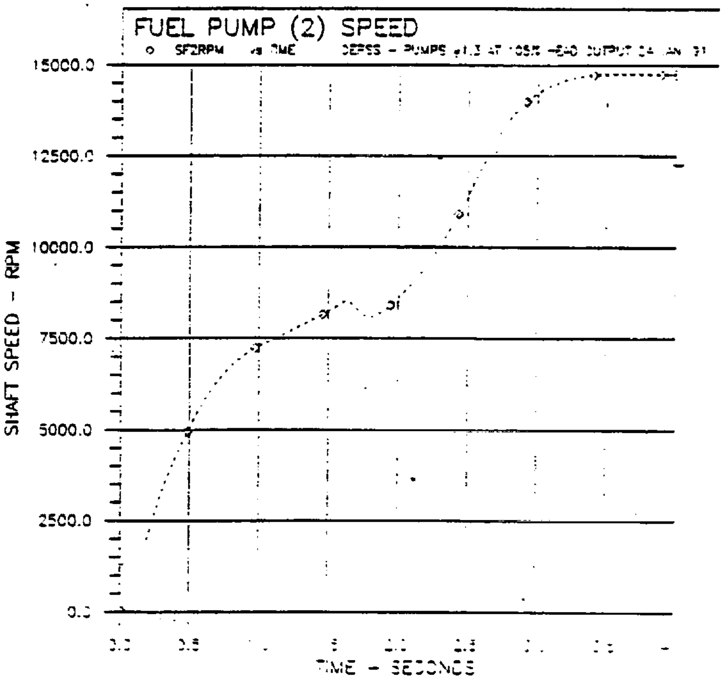


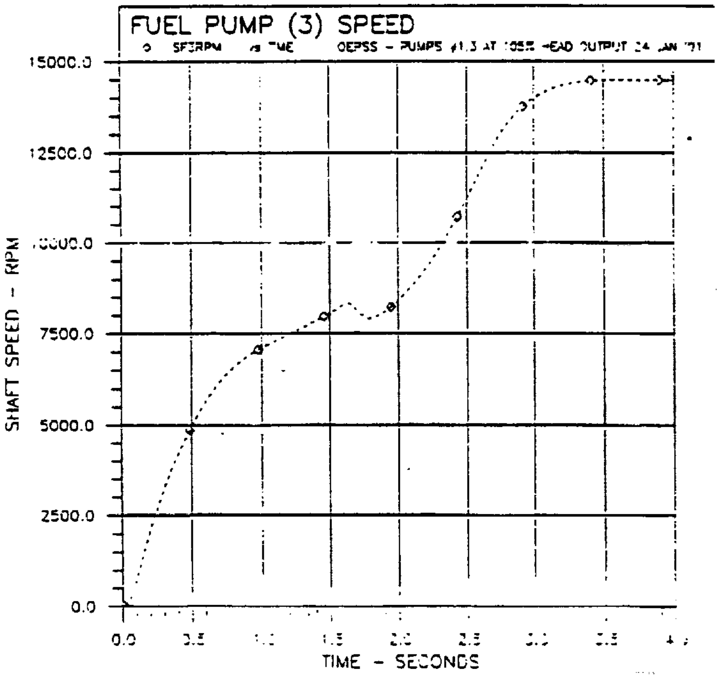


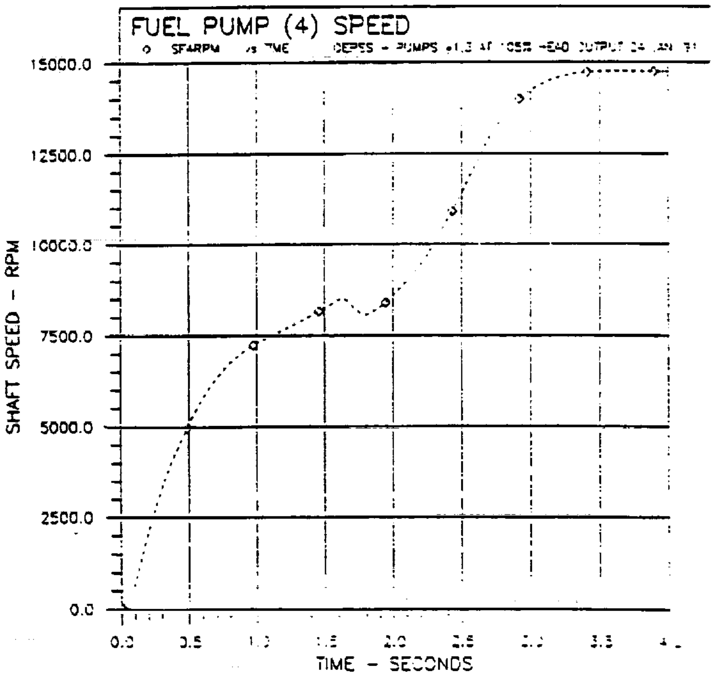


Figures B5-B8

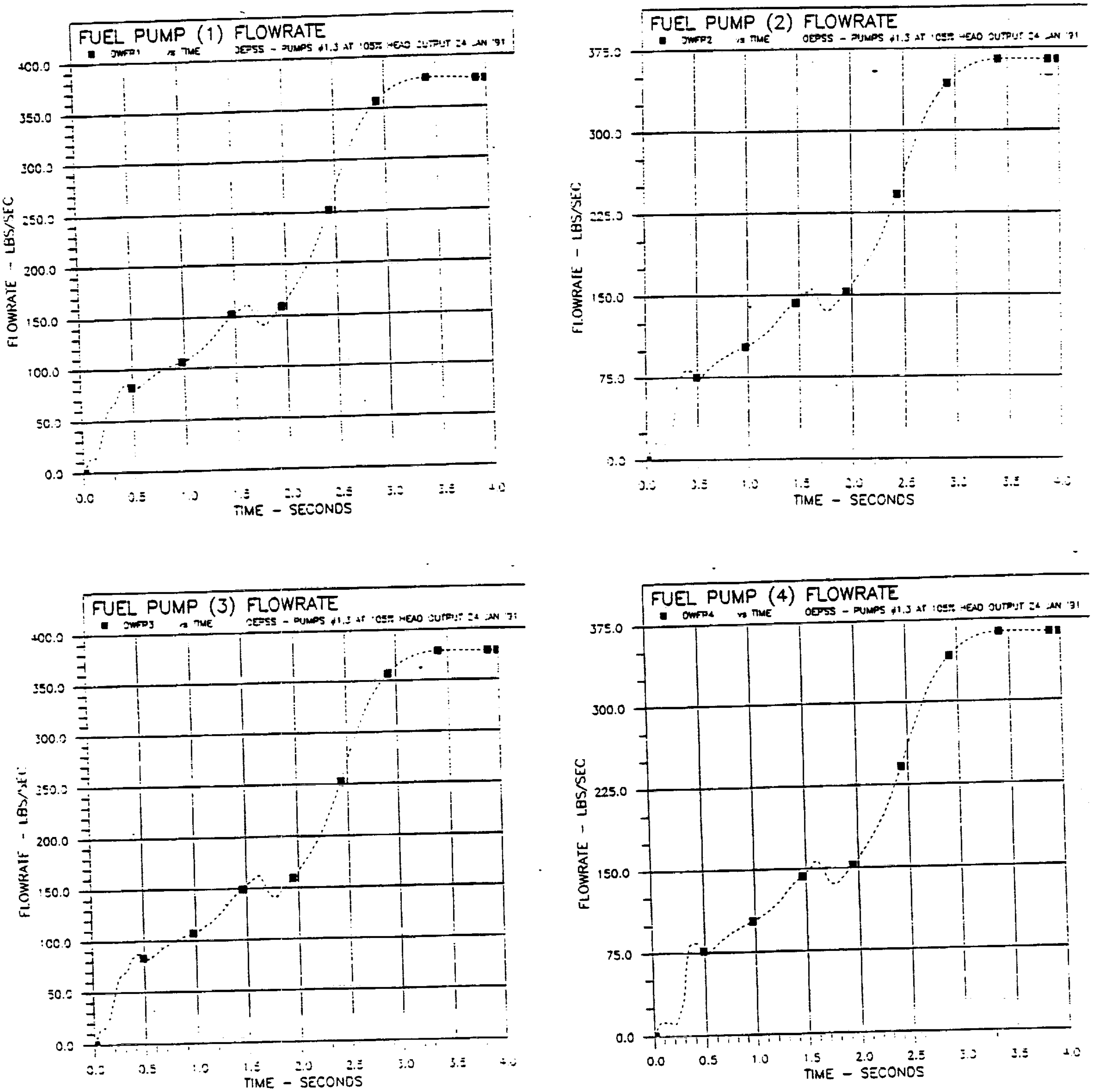




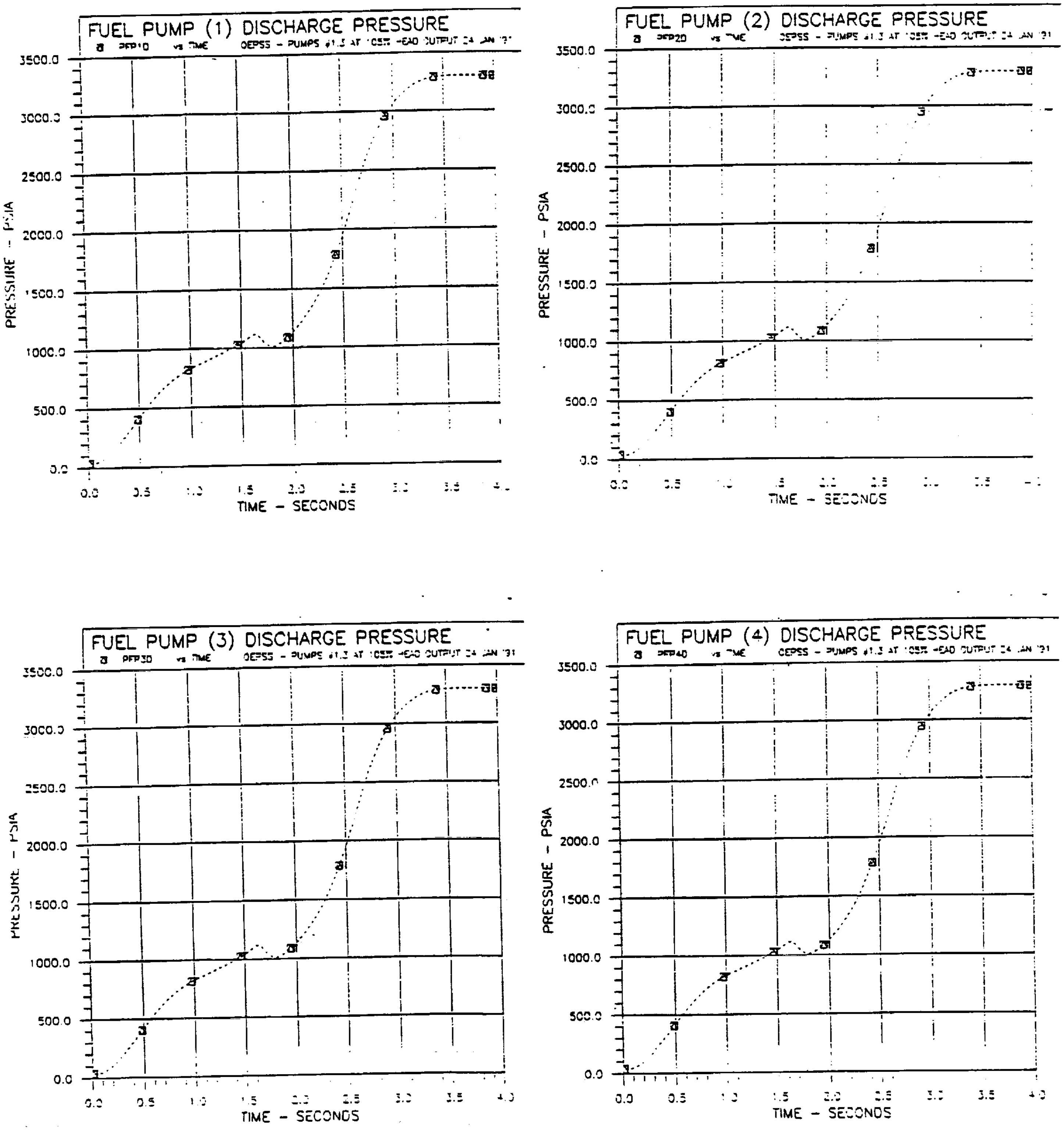




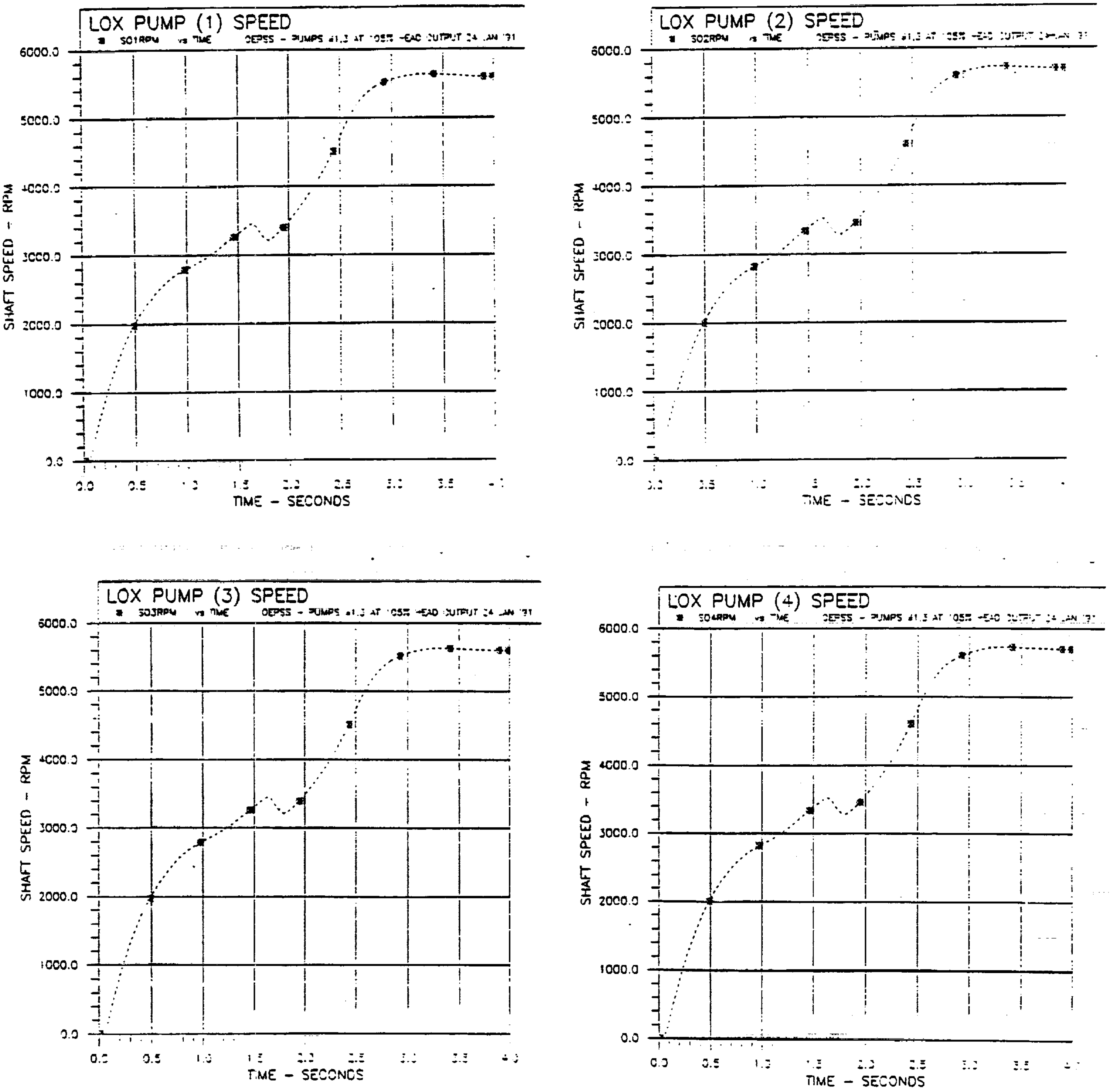
Figures B9-B12



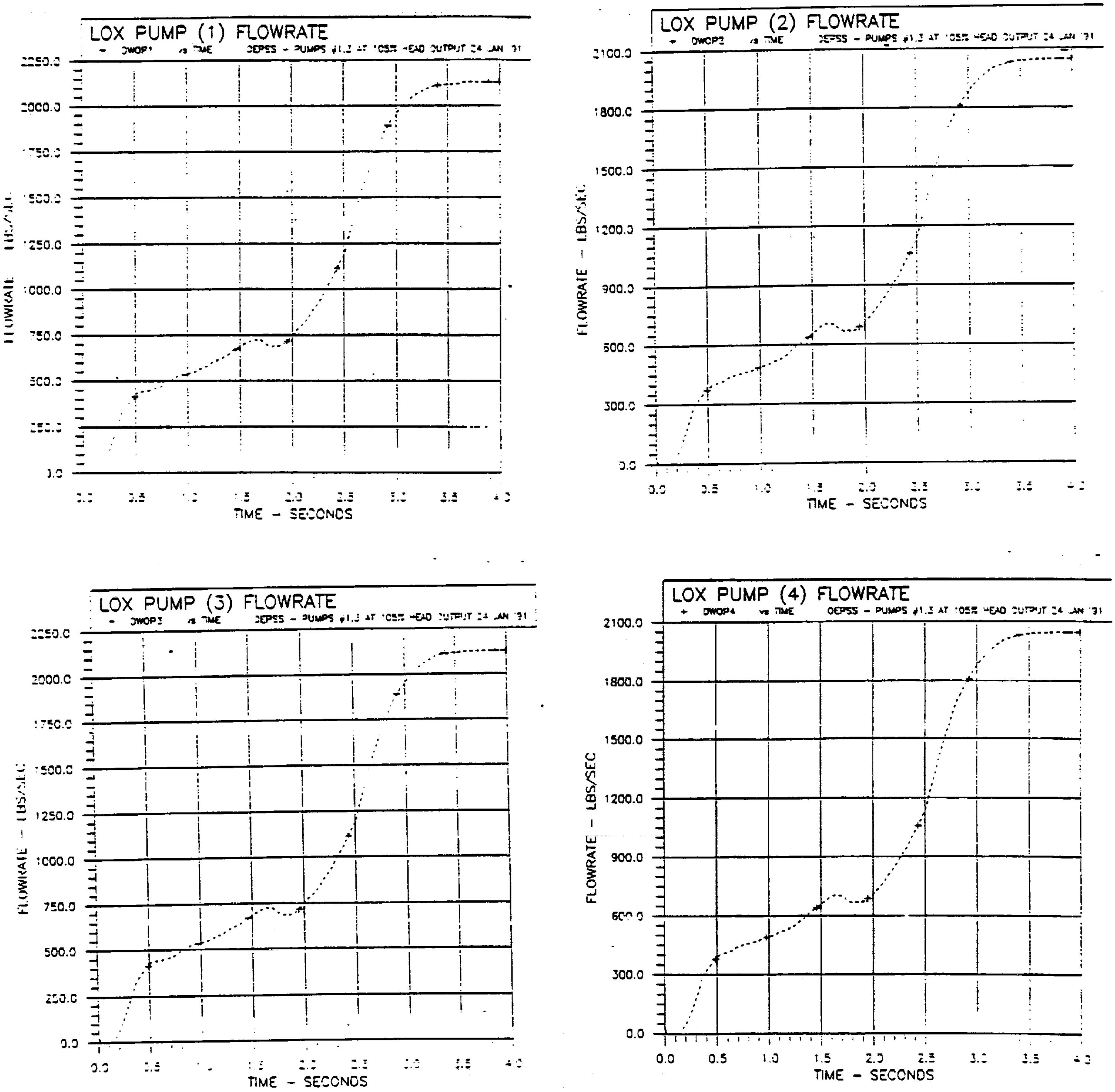
Figures B13-B16



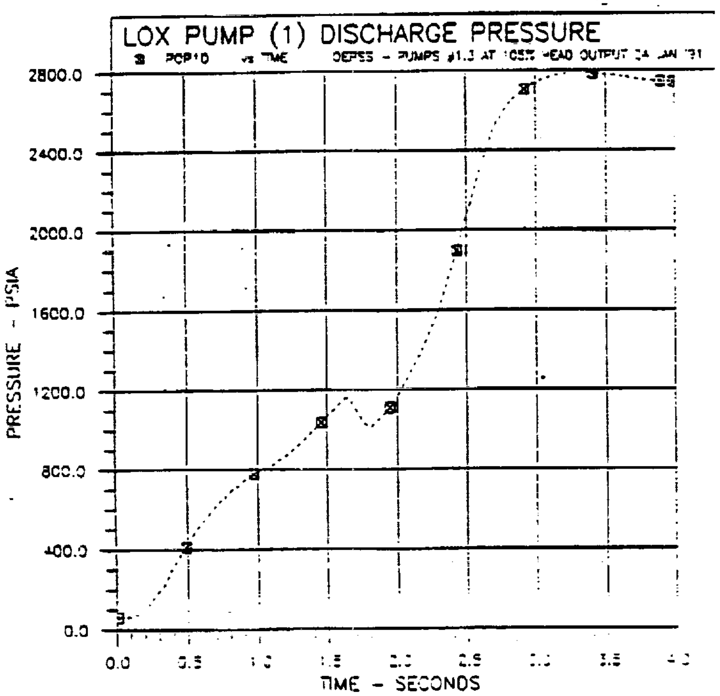
Figures B17-B20

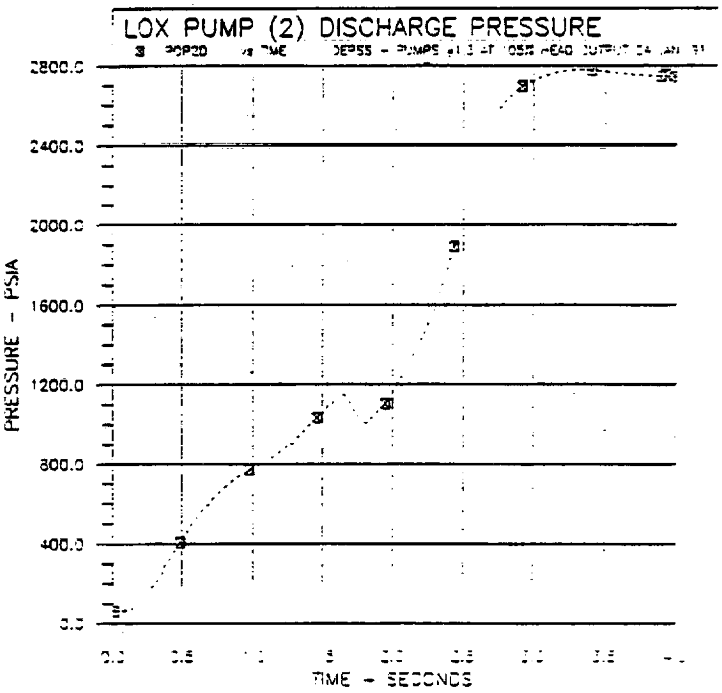


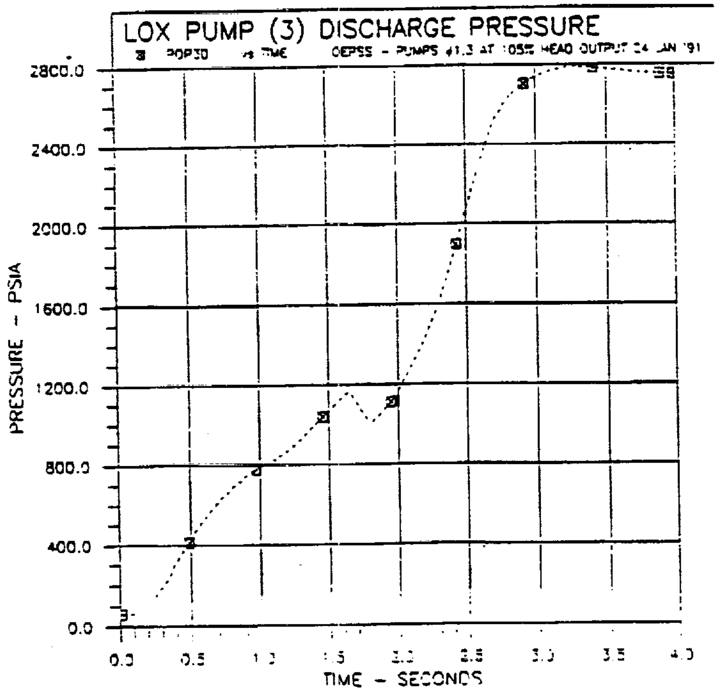
Figures B21-B24

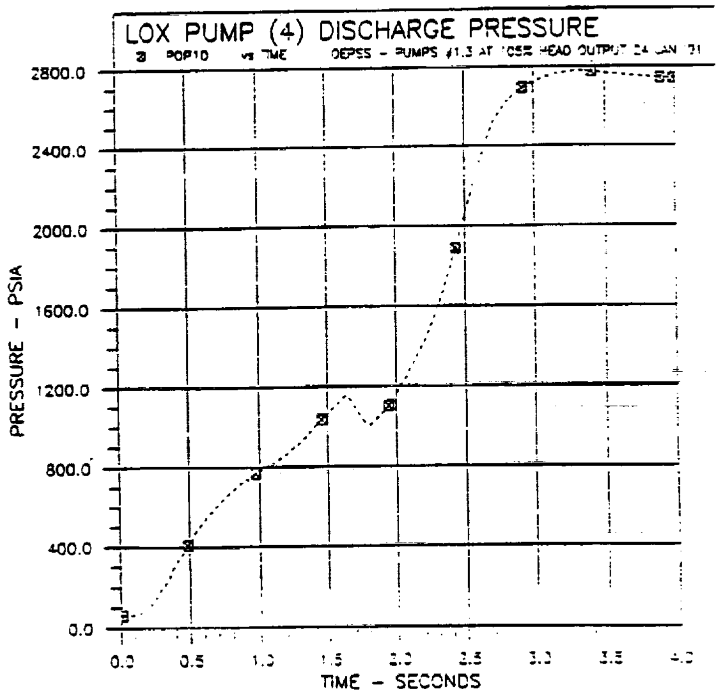


Figures B25-B28





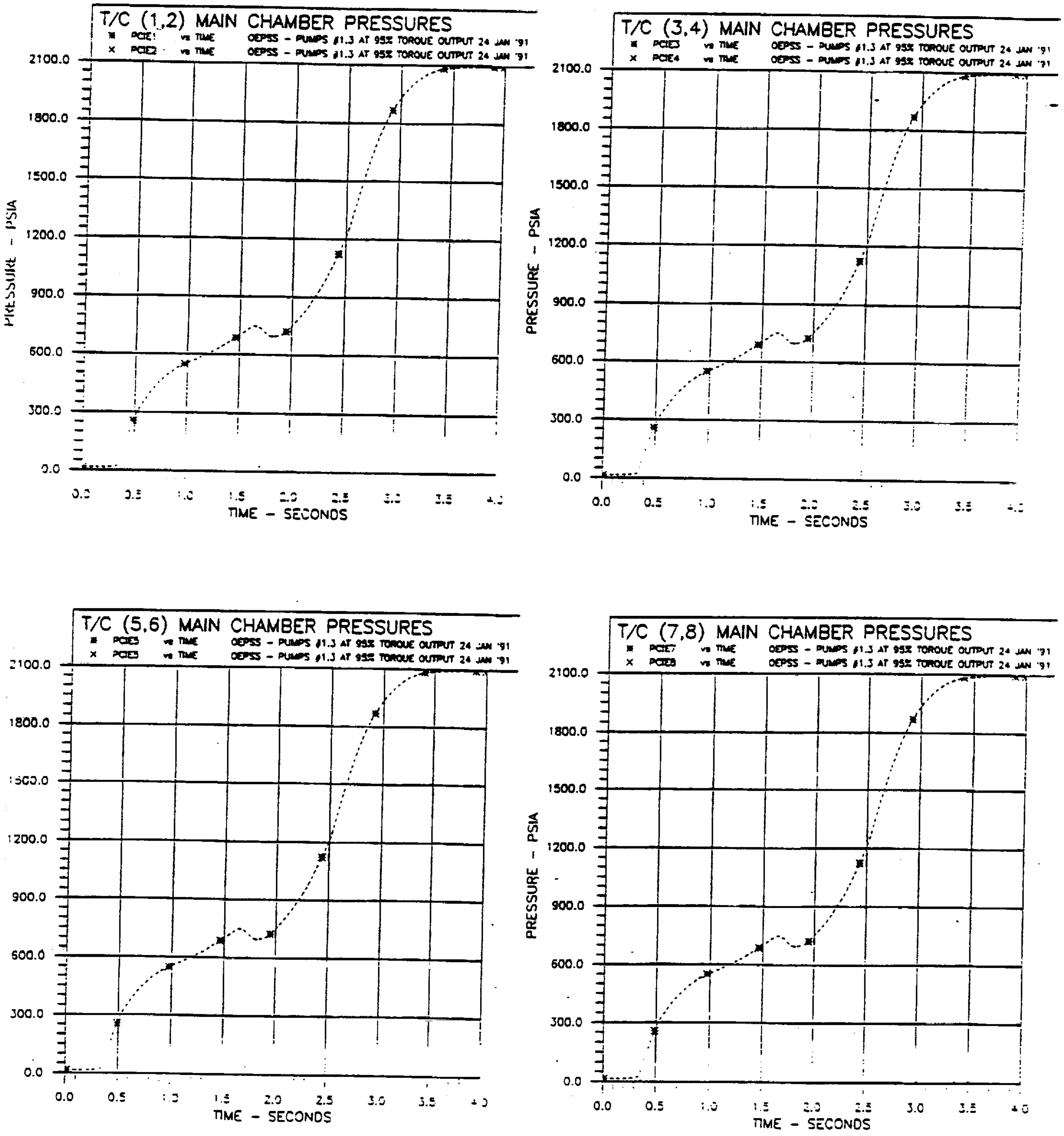




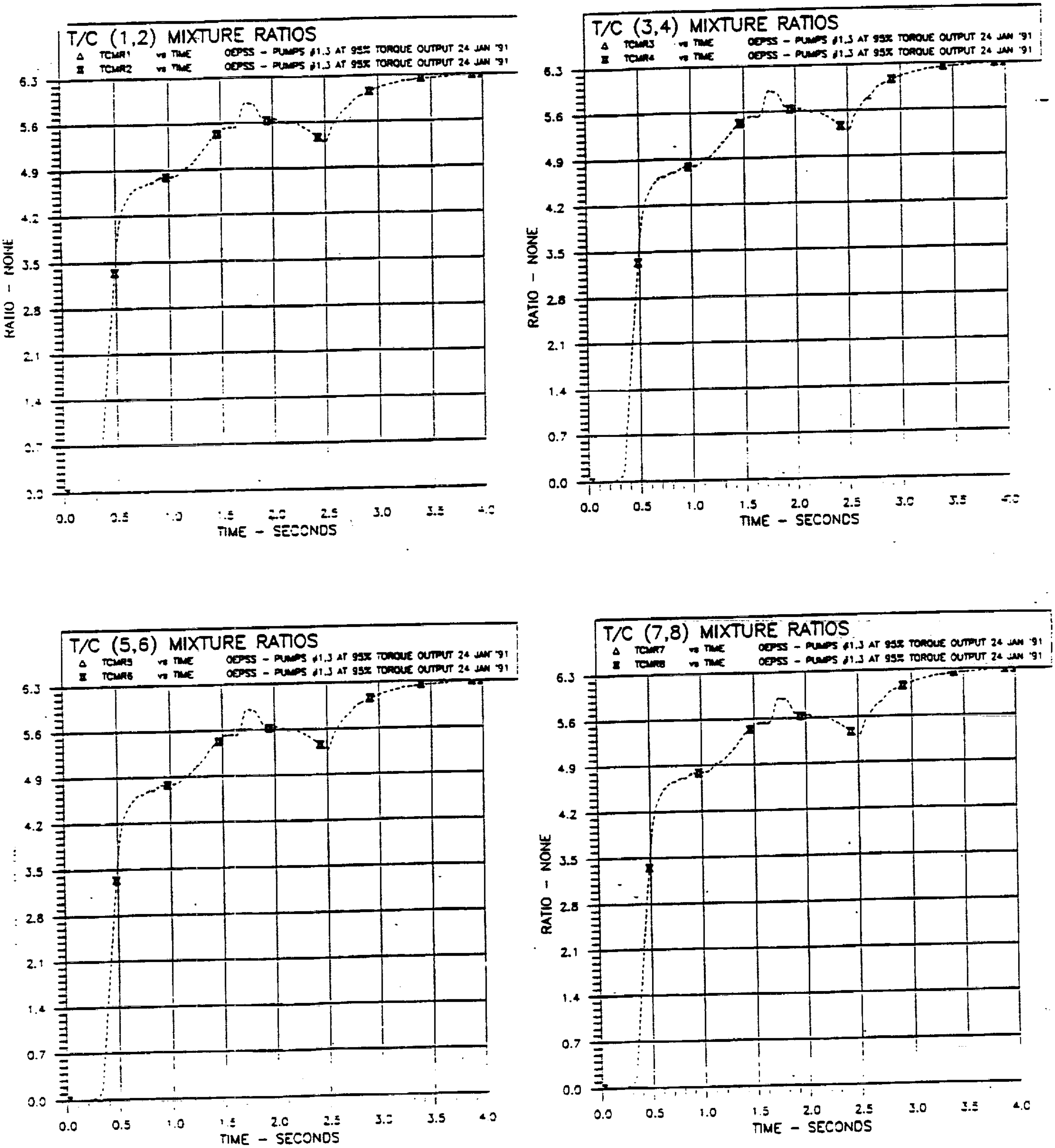
Figures B29-B32

APPENDIX C

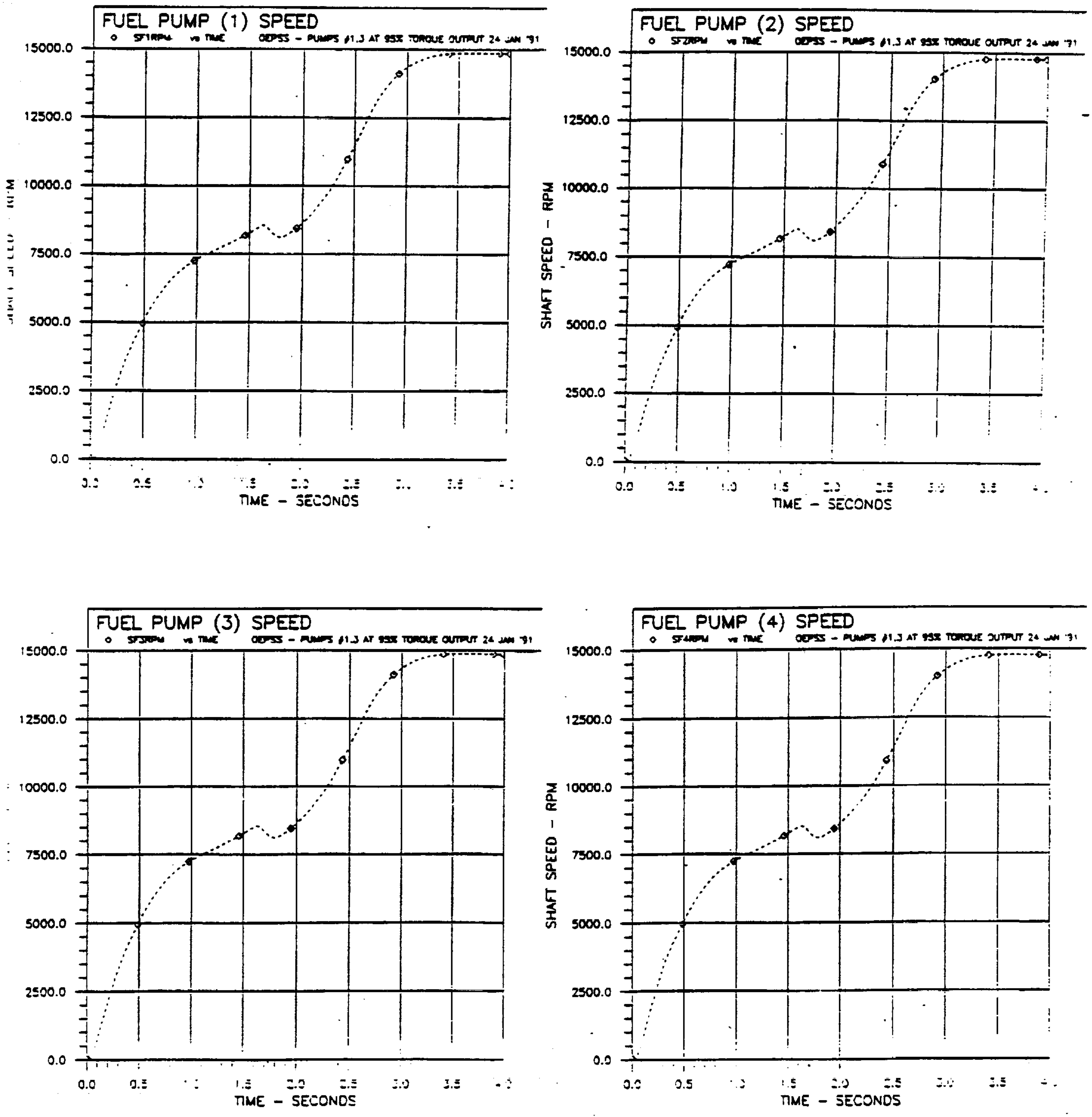
TRANSIENT ANALYTICAL RESULTS CASE II: DECREASED TORQUE PERFORMANCE BY 5% FOR PUMPS 1 AND 3



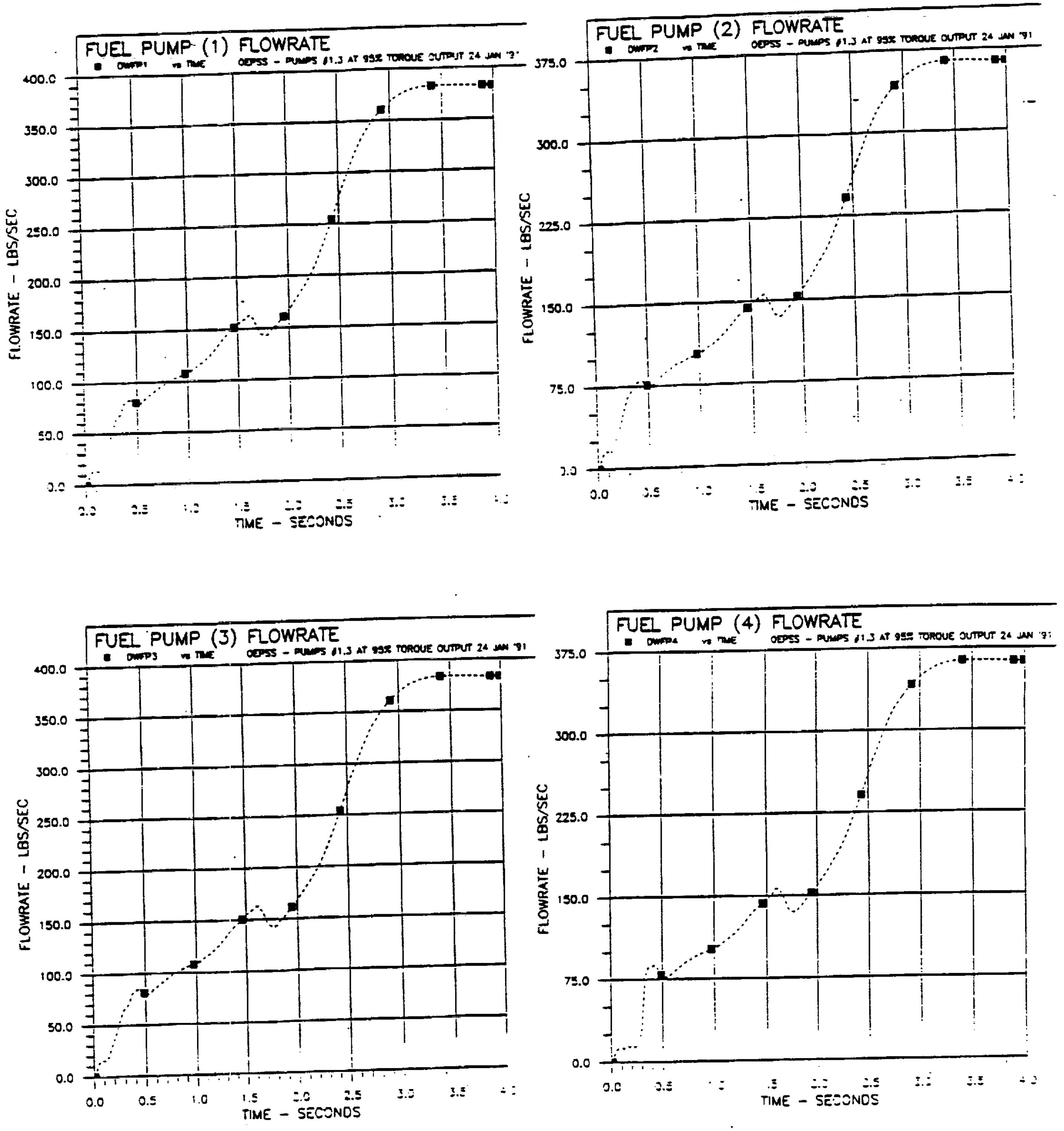
Figures C1-C4



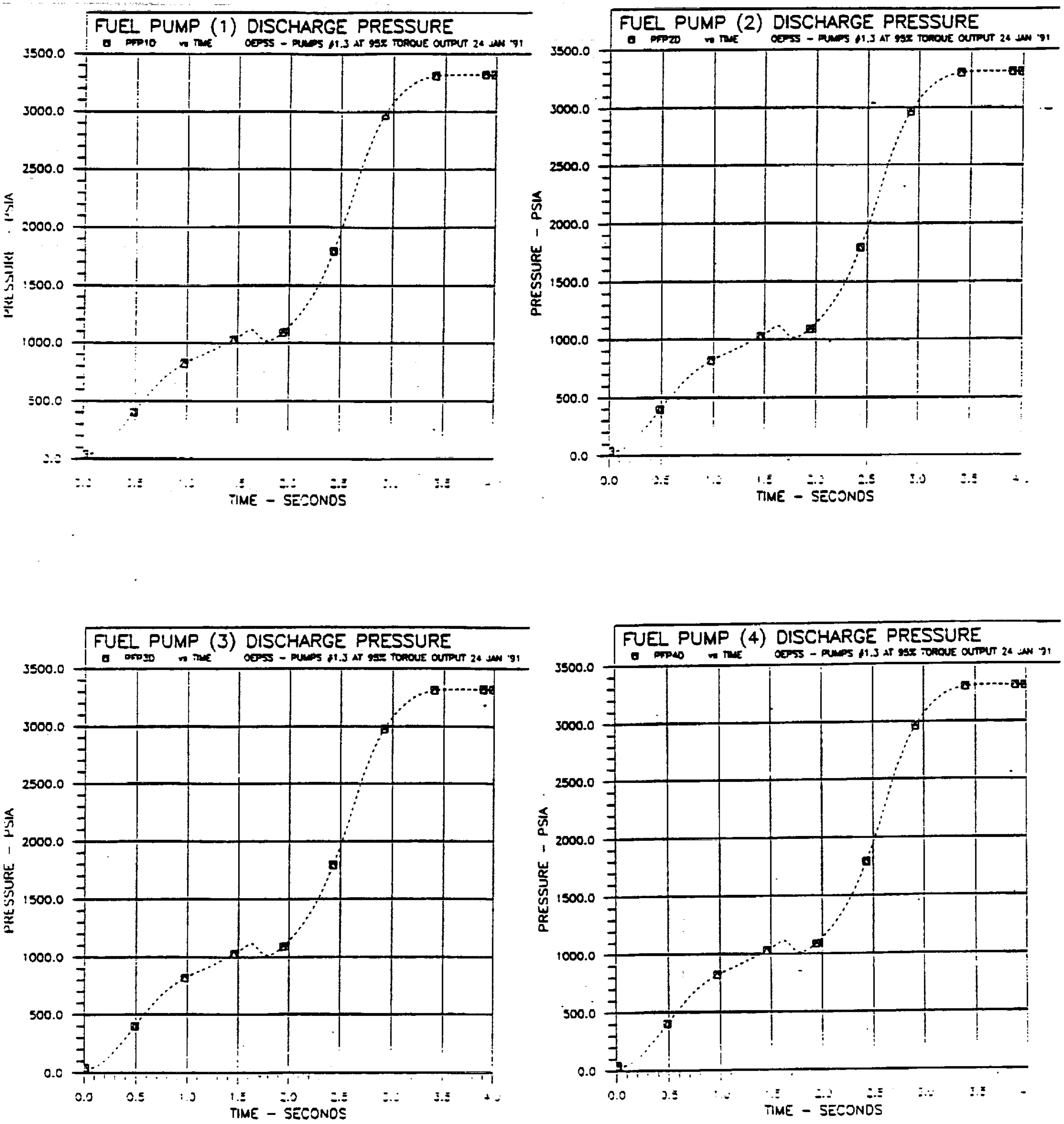
Figures C5-C8



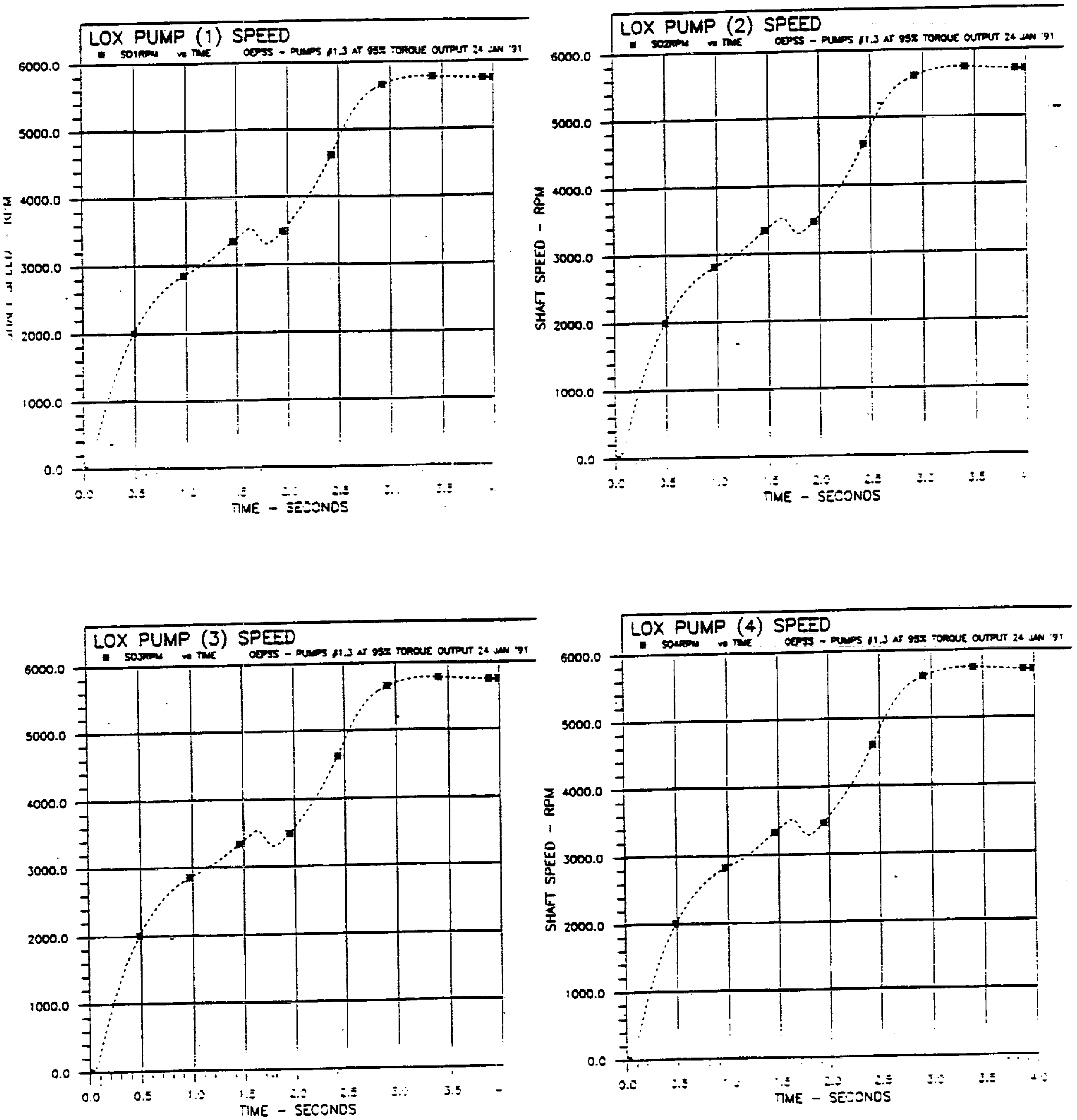
Figures C9-C12



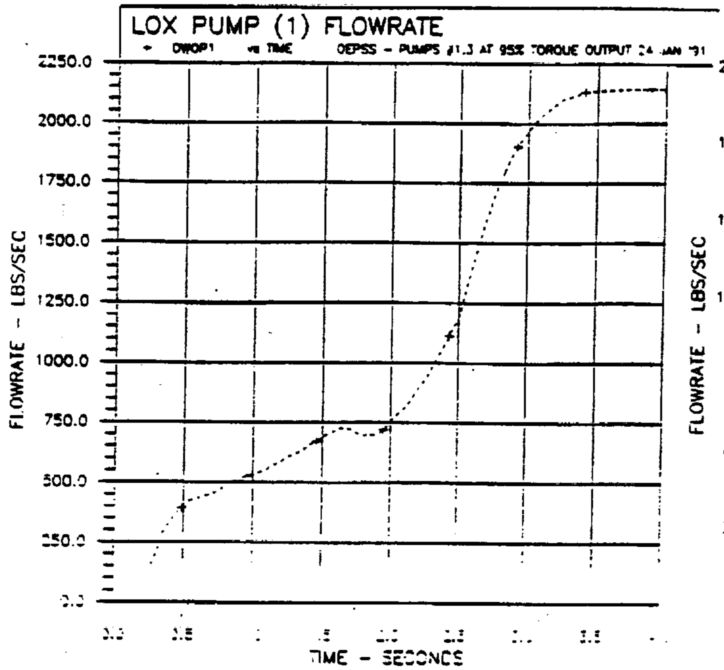
Figures C13-C16

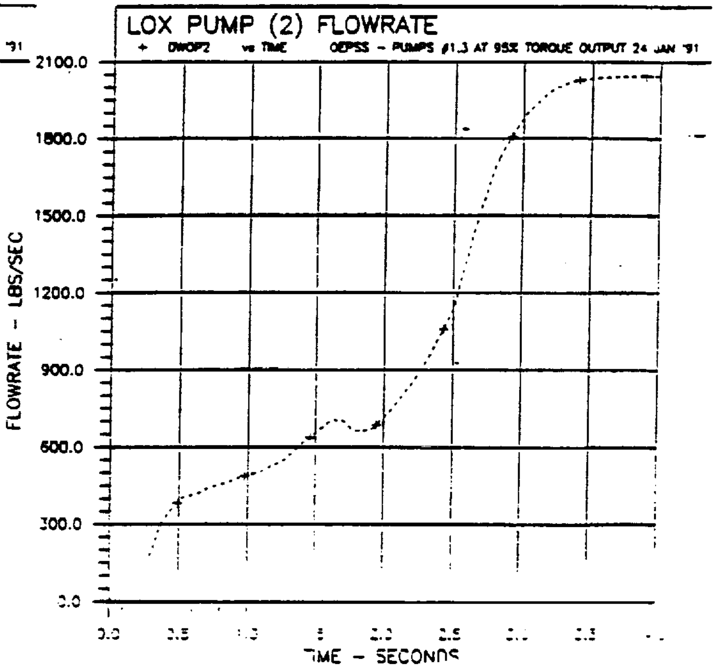


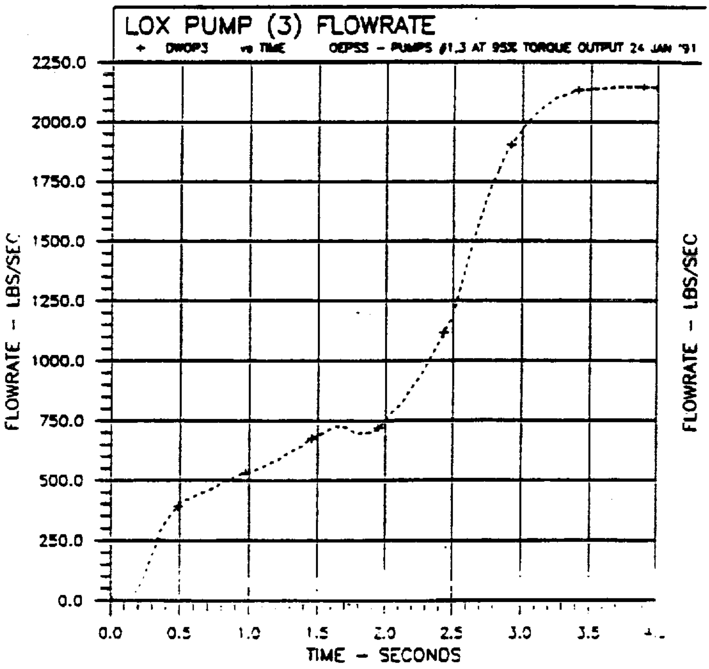
Figures C17-C20

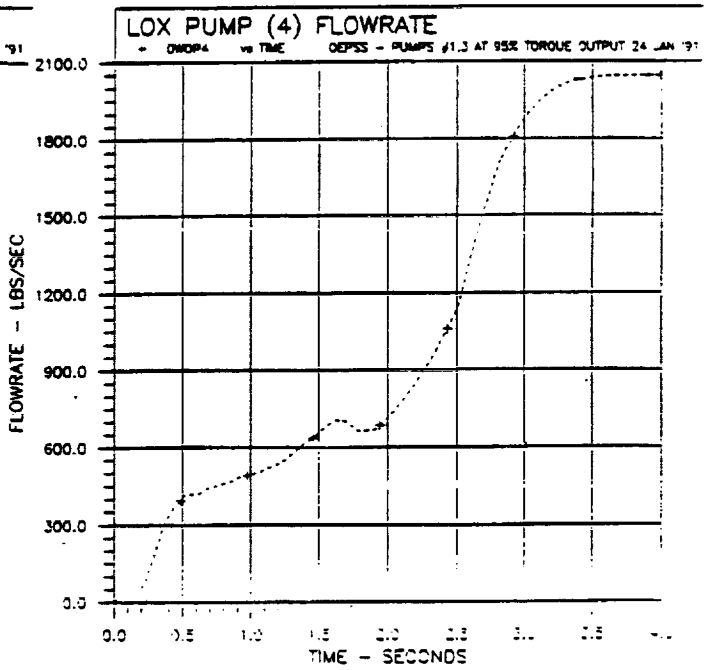


Figures C21-C24

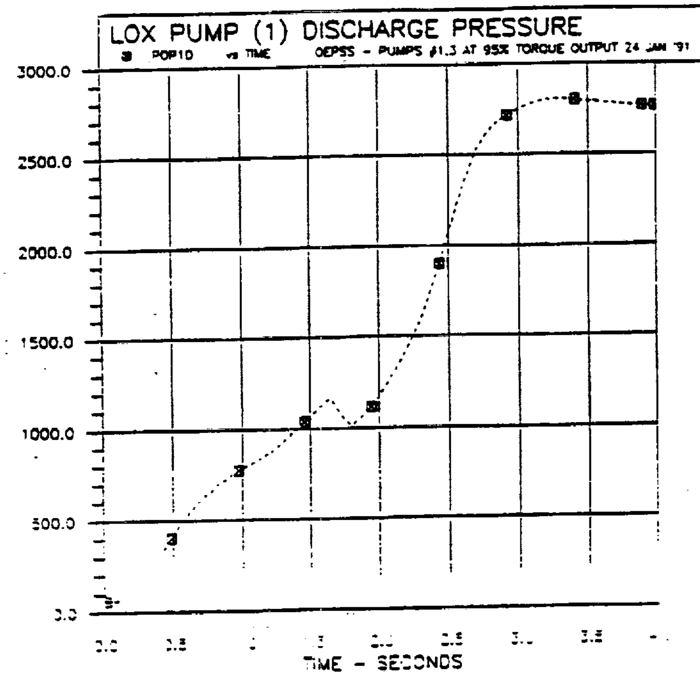


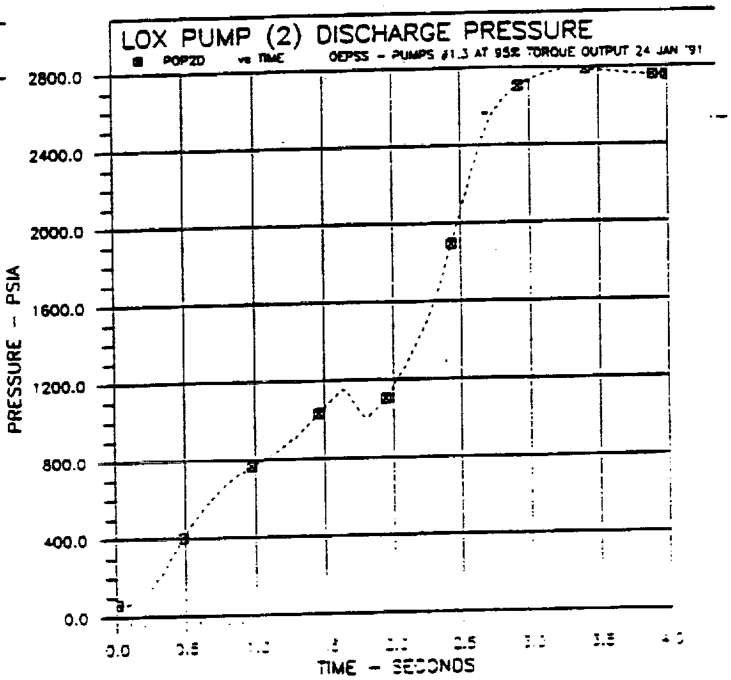


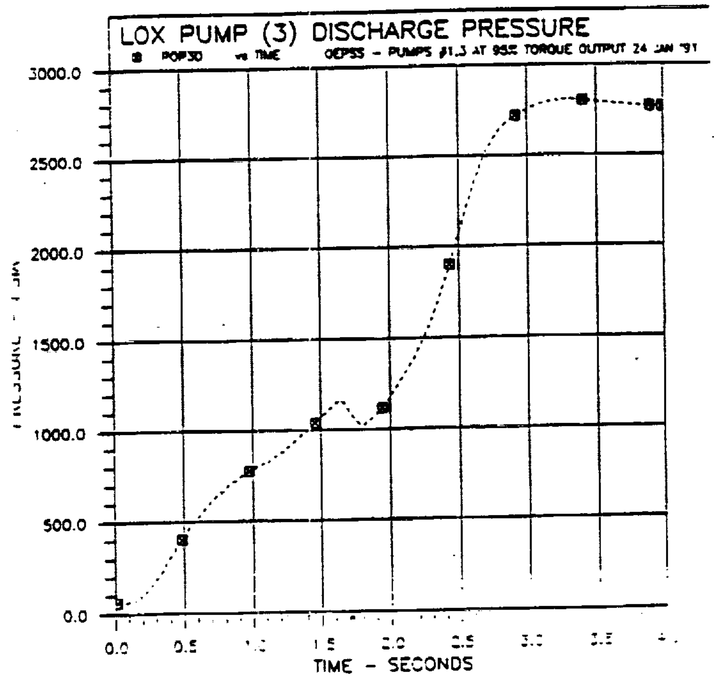


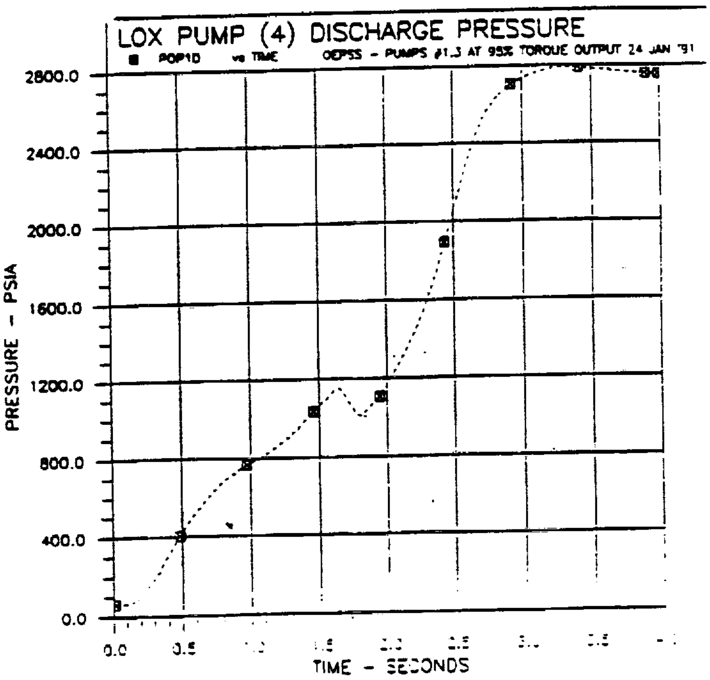


Figures C25-C28





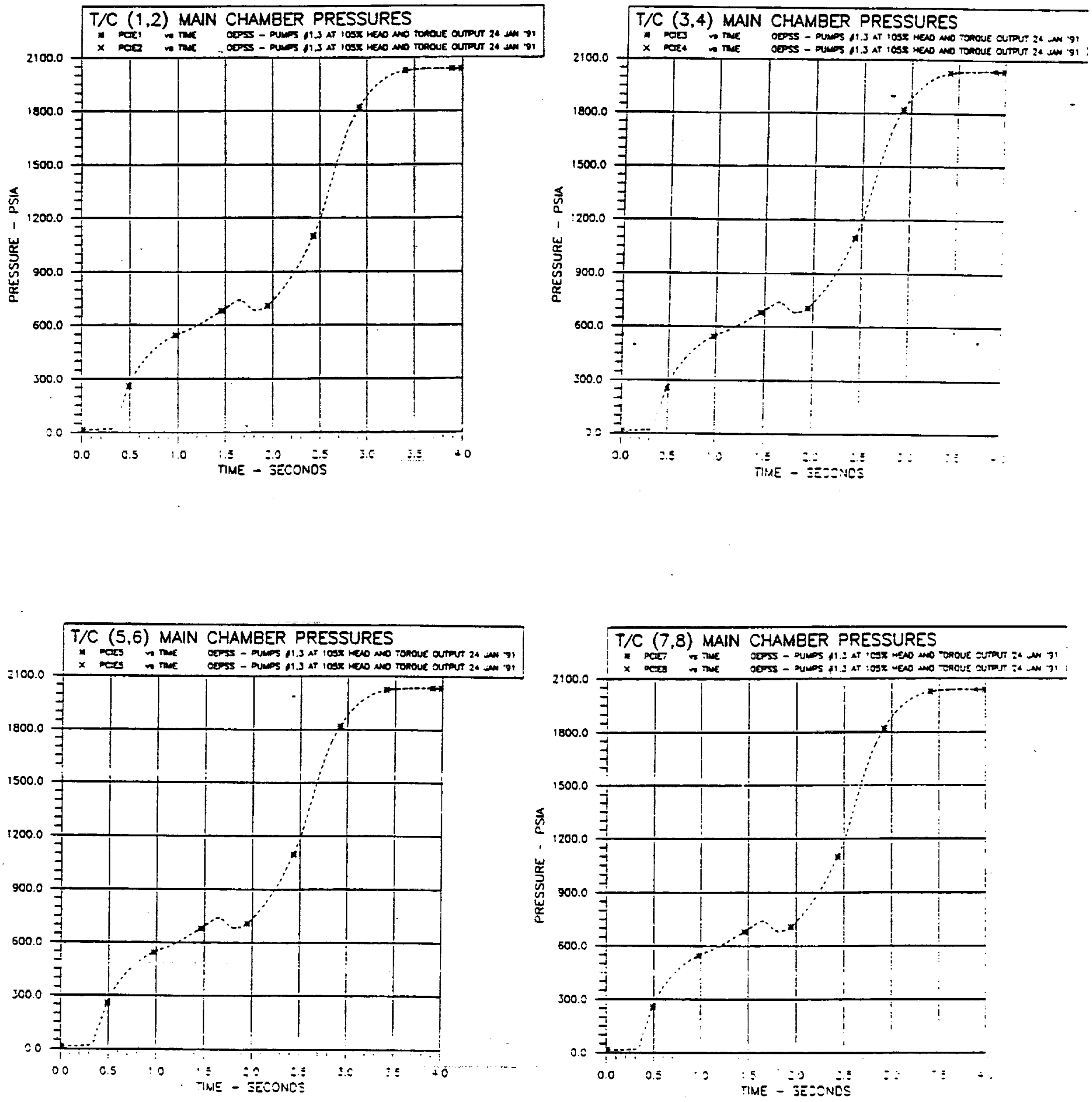




Figures C29-C32

APPENDIX D

TRANSIENT ANALYTICAL RESULTS
CASE III: INCREASED HEAD AND TORQUE PERFORMANCES BY 5% FOR PUMPS 1 AND 3



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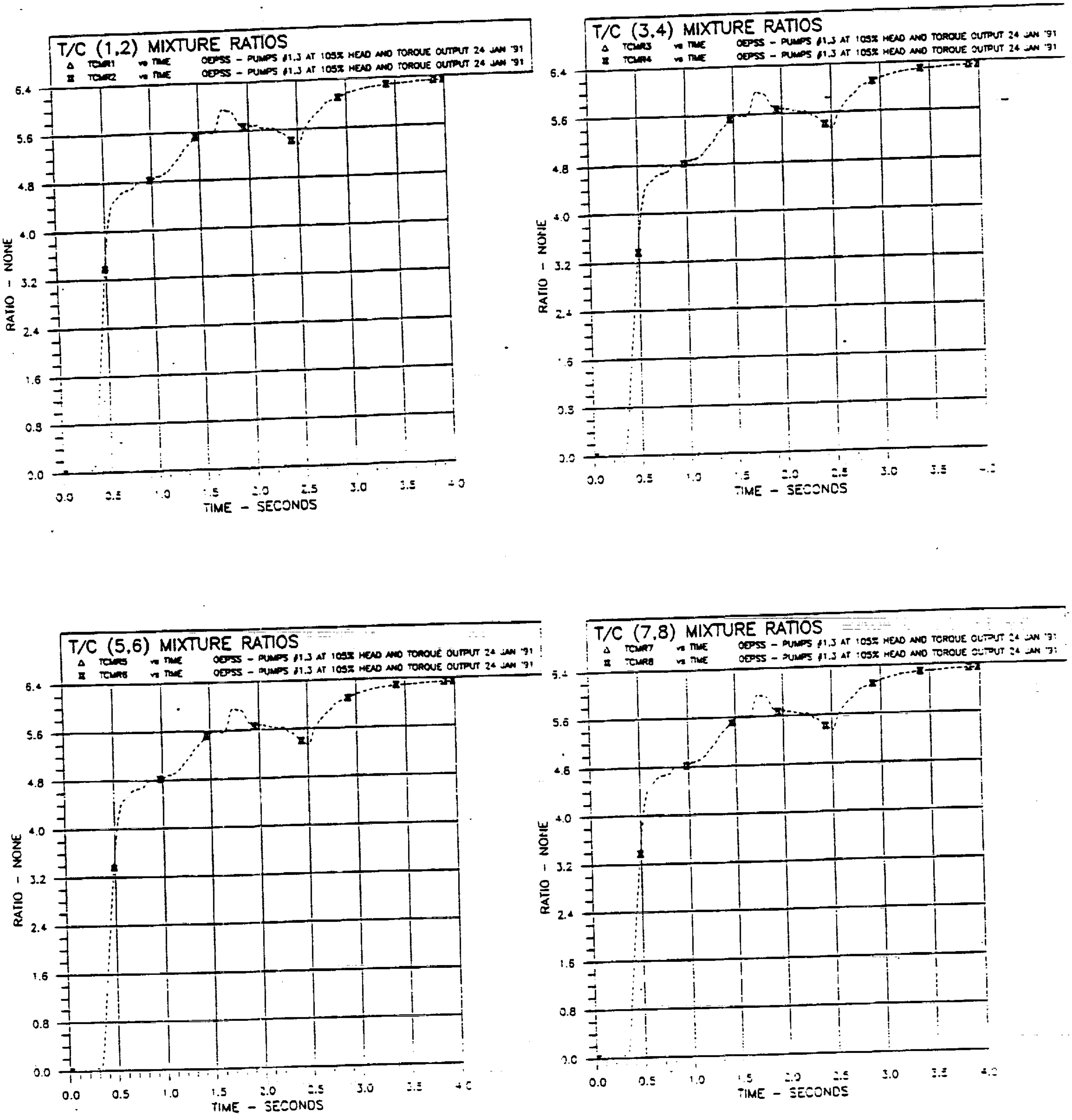

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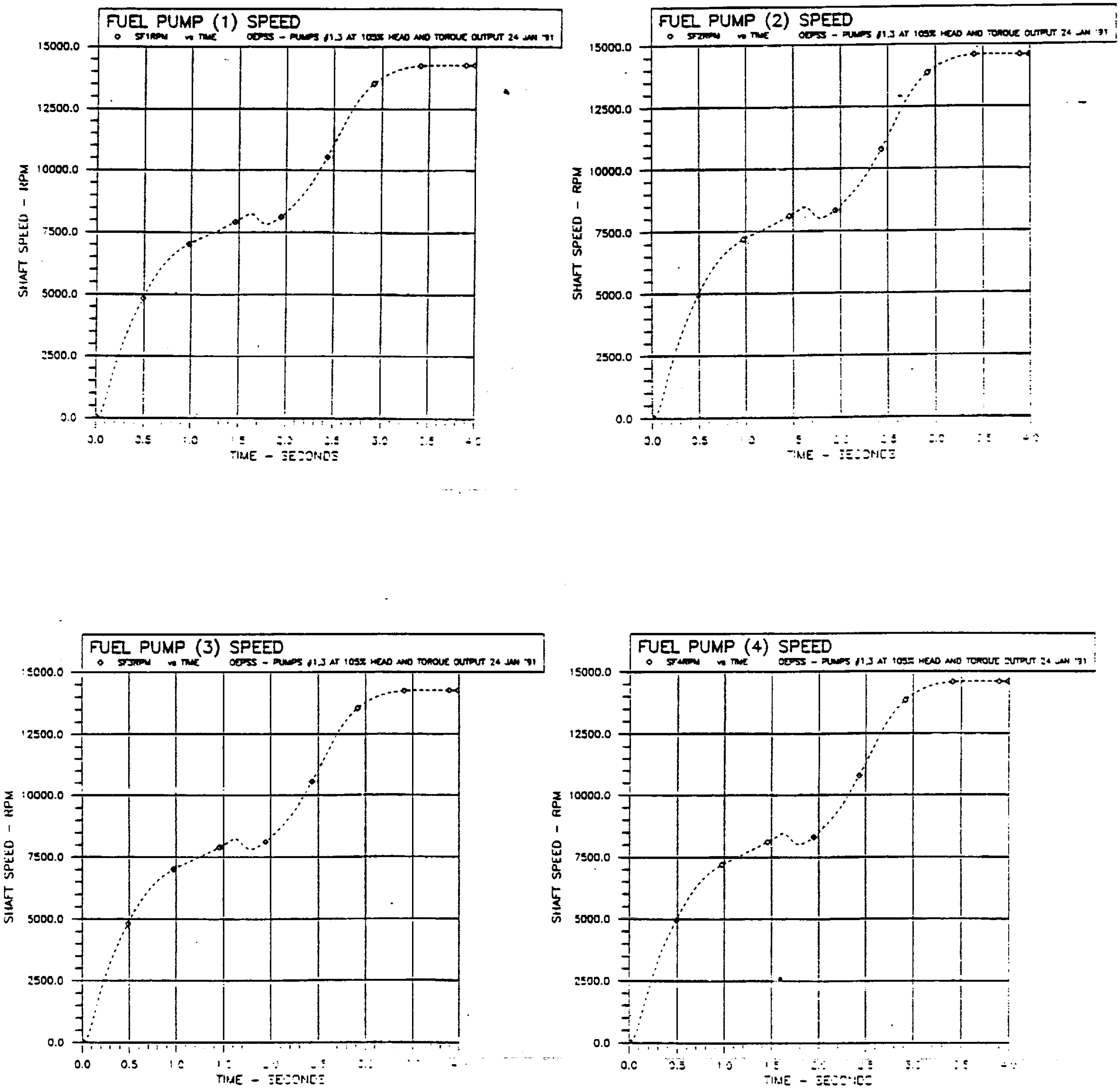

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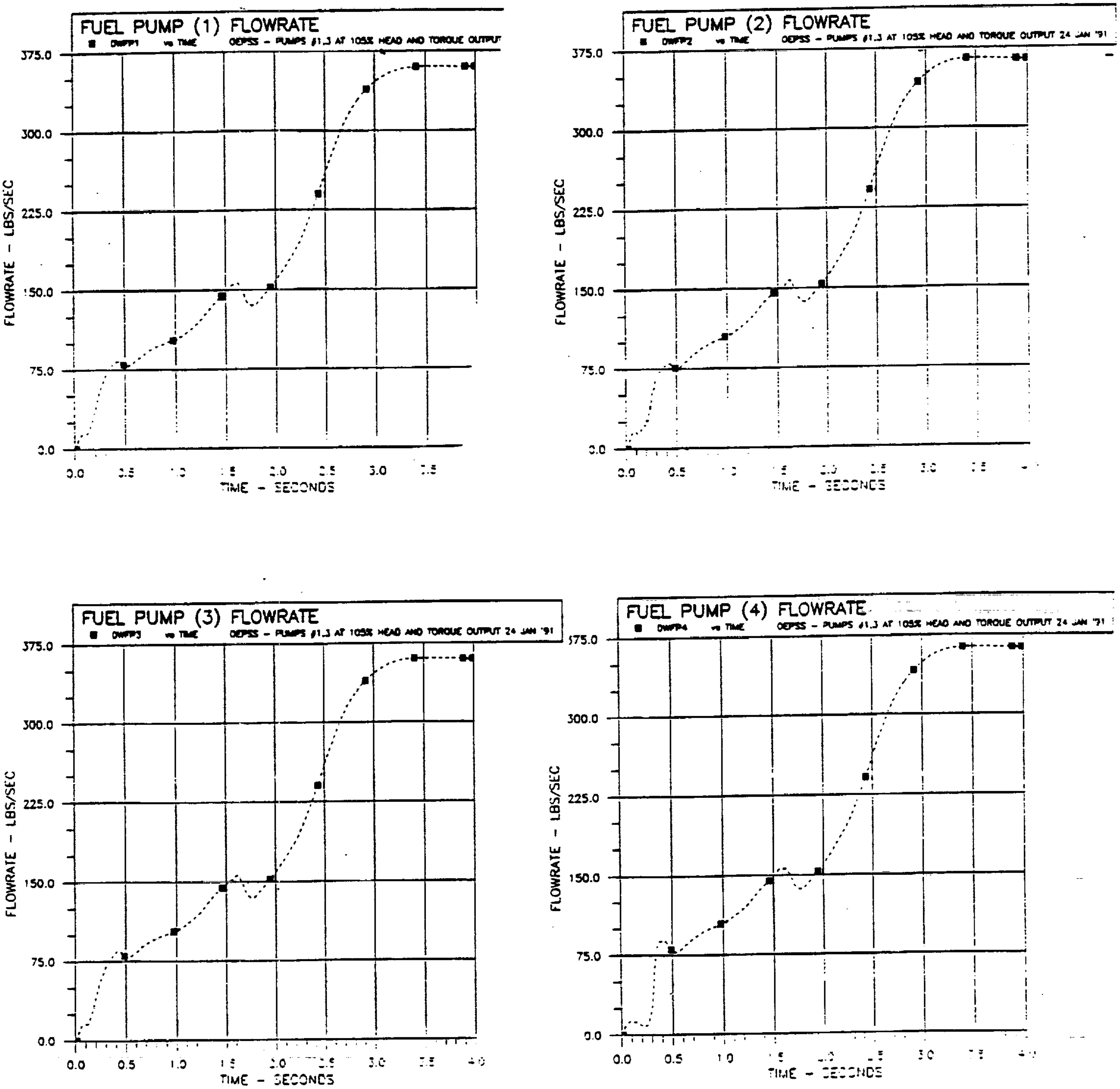

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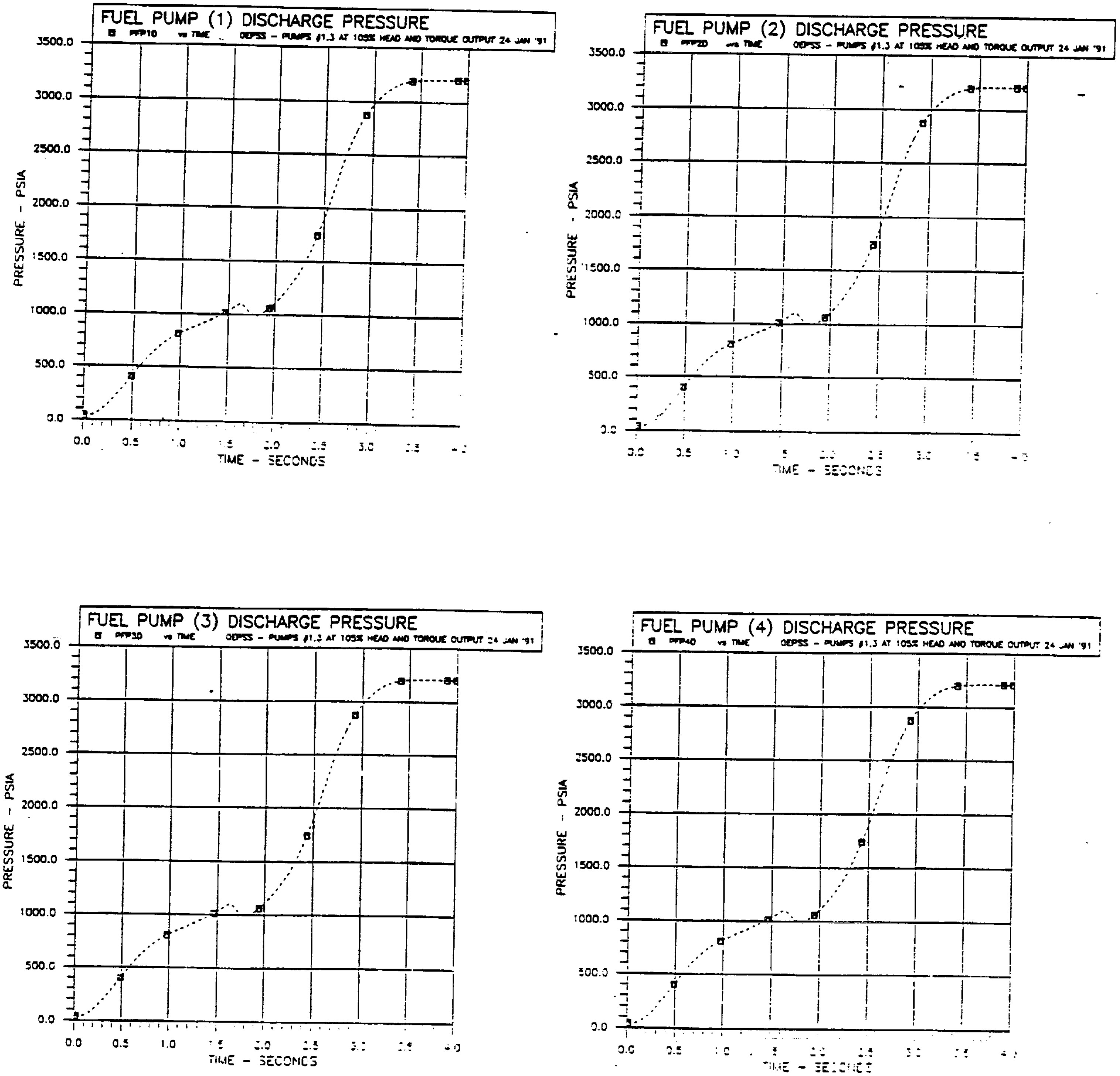

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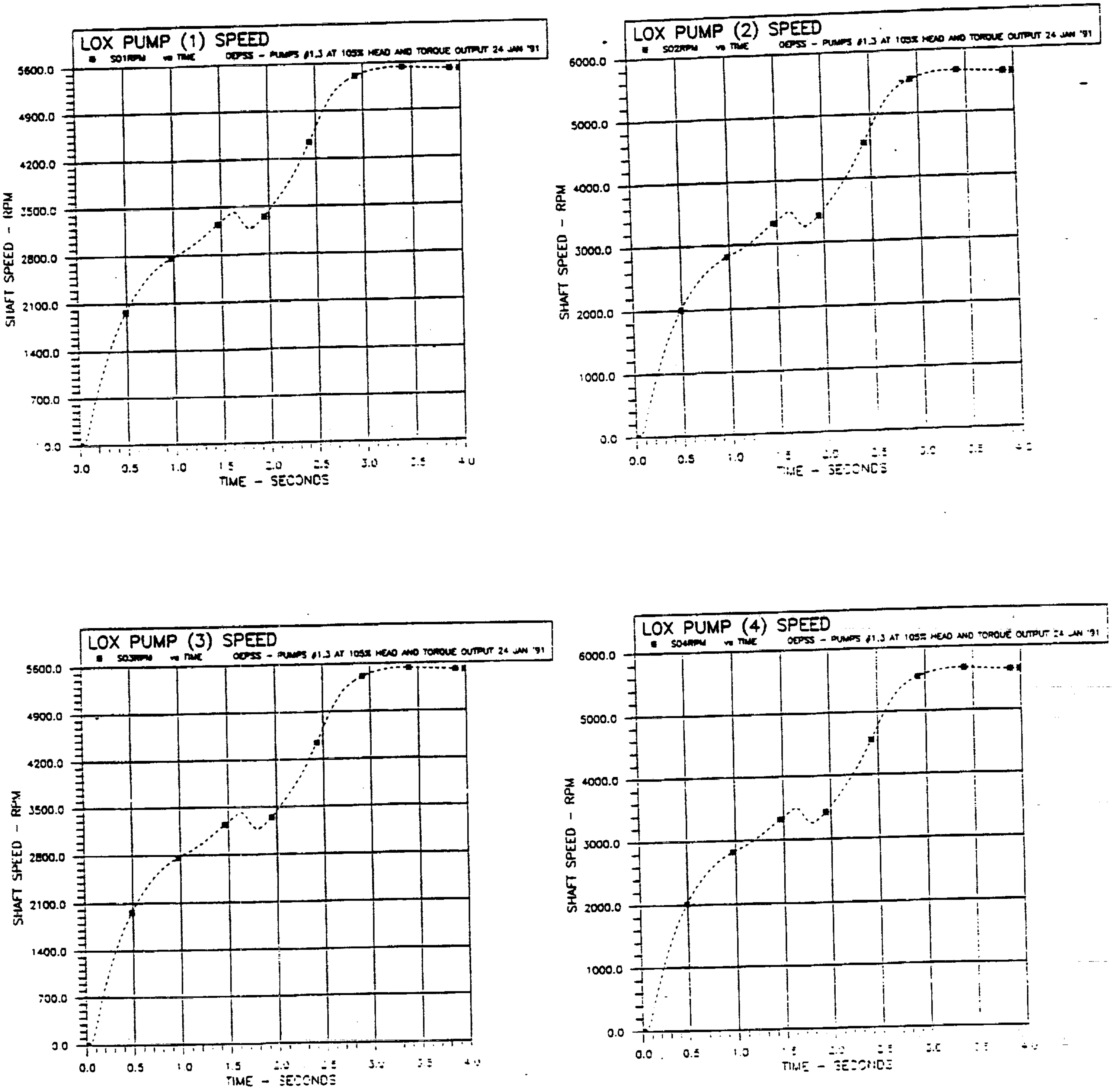

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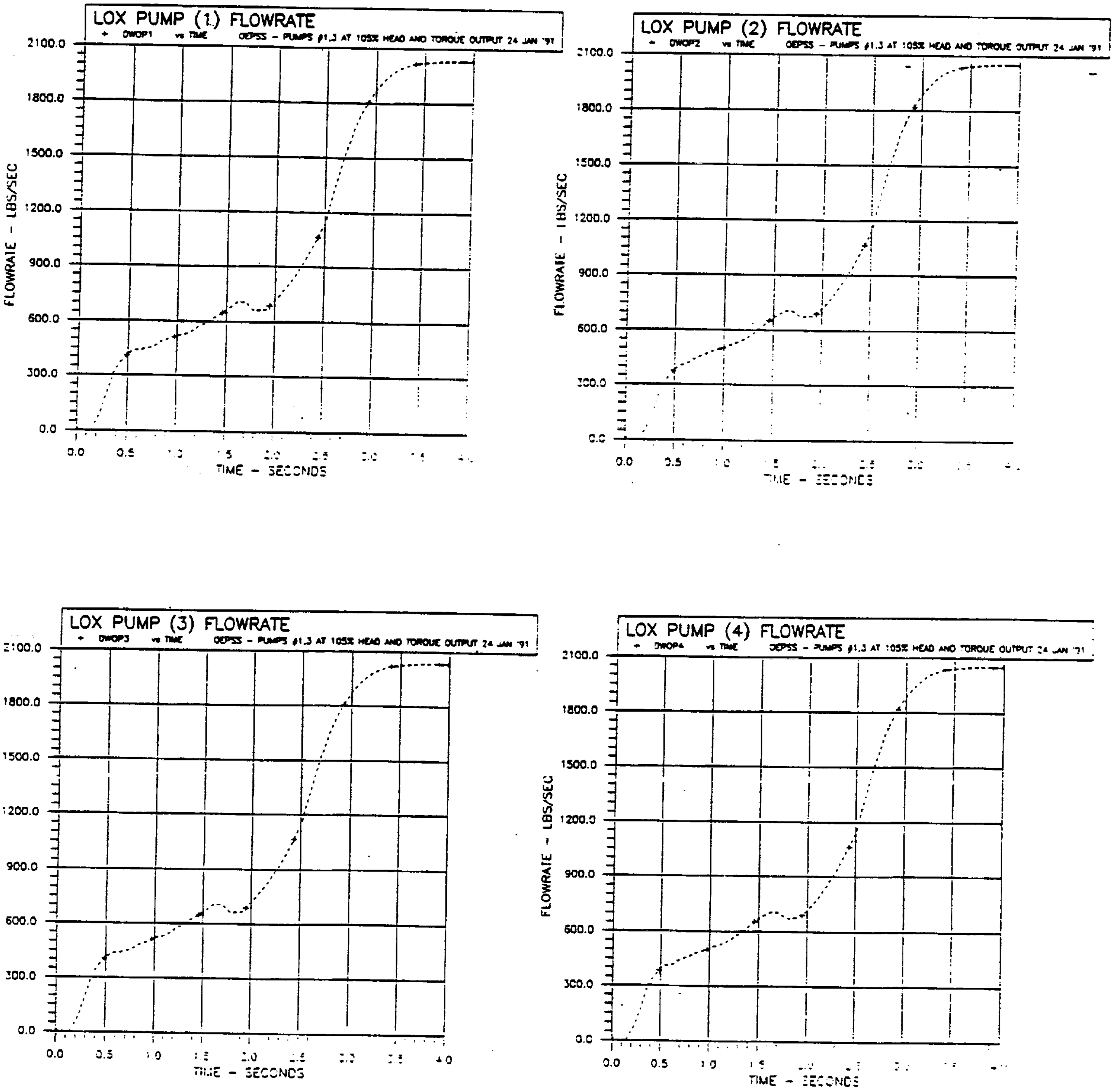

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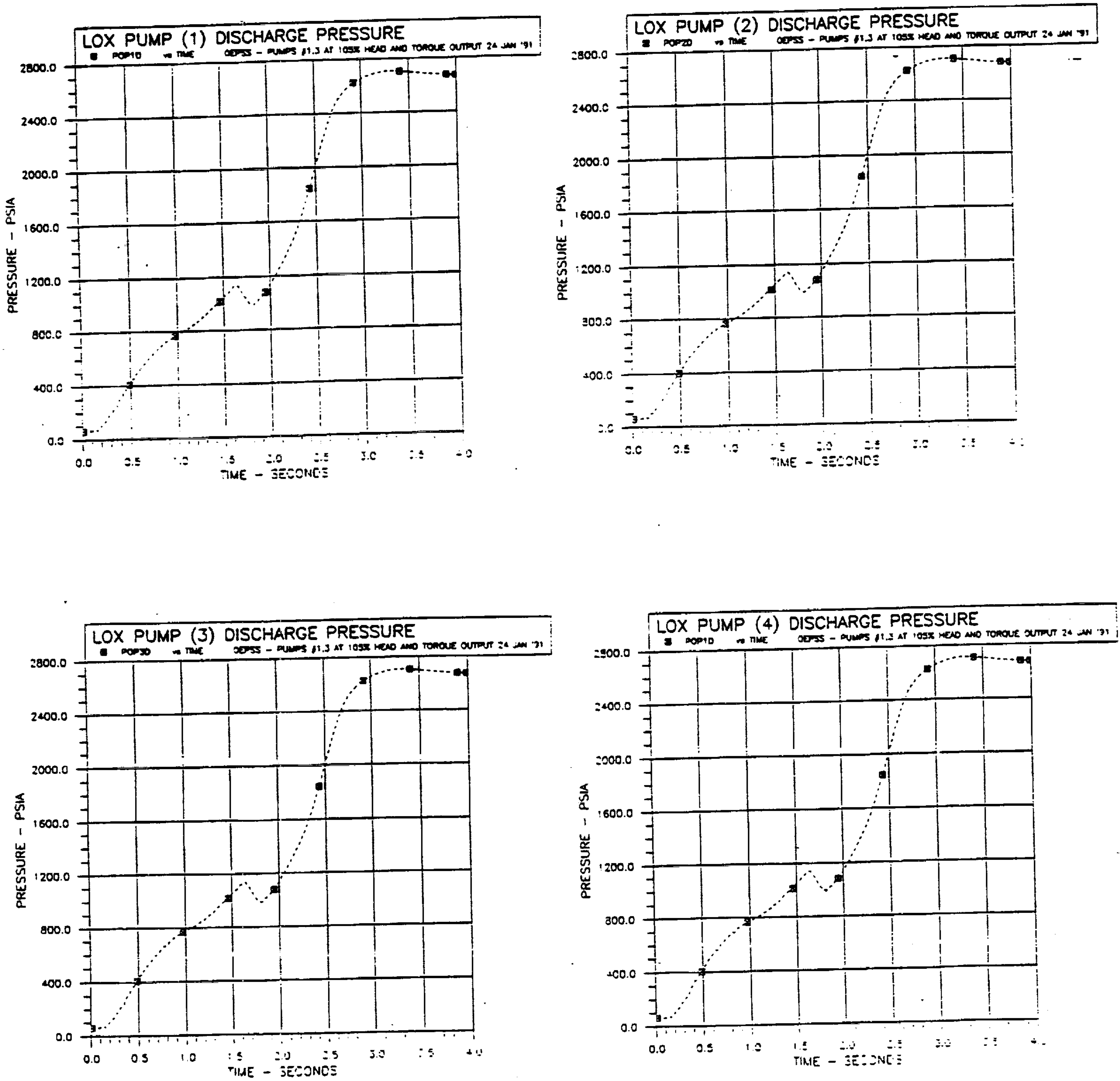

Figures D29-D32

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This document is a collection of technical data books on several tasks of study during a two year extension to the basic Operationally Efficient Propulsion System Study (OEPSS) conducted by Rocketdyne Division, Rockwell International for the NASA at Kennedy Space Center (KSC), Florida. This document is organized in the following data books: Volume VI, Space Transfer Propulsion Operationally Efficient Study Task of OEPSS; Volume VII, Launch Operations Index (LOI) Design Features and Options; Volume VIII, Integrated Booster Propulsion Module (BPM) Engine Start Dynamics; Volume IX, Preliminary Development Plan for an Integrated Booster Propulsion Module; Volume X, Air Augmented Rocket Afterburning; and an OEPSS Final Briefing/Report along with an OEPSS Video Script with Video.

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