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SSME

TECHNOLOGY TEST BED

FAST SHUTDOWN ASSESSMENT

FINAL REPORT

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SSME ENGINEERING

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FOREWARD

This report was prepared by Rockwell International, Rocketdyne Division, under Contract NAS8-40000 to satisfy the Fast Shutdown Sequence Assessment portion of WBS 4.4.10.

ABSTRACT

This study develops the fastest practical shutdown sequence for the Technology Test Bed Engine. A sequence is defined and key issues are addressed. The conclusion of the study is that a fastest shutdown sequence within the existing SSME design capability is practical and can cut oxidizer consumption by 50%. However, the revised sequence would not have prevented any of the prior experienced SSME incidents and would introduce development risk to the program.

CONTENTS

INTRODUCTION

The purpose of this study was to develop the fastest practical engine shutdown sequence for use with redline initiated cutoffs. The specified goal was to reduce the amount of oxygen available to an engine during an incident. Practicality of a sequence was determined by existing system limitations, most confining of which was the maximum valve closing rate of 200%/second.

Areas of concern were identified and significant items were addressed. Also, included are implementation issues and recommendations concerning future efforts.

RESULTS SUMMARY

Prior to looking at the sequencing question, it was necessary to adjust the digital transient model system resistances to reflect changes in the hardware made to accommodate additional Technology Test Bed engine (TTB) instrumentation and to match steady state operating levels defined in the Steady State Power Balance for the TTB.

The shutdown sequence developed in the study is depicted at RPL and compared to the Phase II sequence at RPL, as shown in Figures 1 through 10. In all the plots presented in this report, the cutoff signal is at 31 seconds. The time 31 seconds is arbitrary and has no special significance. The changes in valve sequencing and rates are depicted in Figure 1 and can be compared to the

RESULTS SUMMARY (CONTINUED)

nominal sequence in Figure 2. Note that in the fast shutdown sequence, the oxidizer preburner valve and main oxidizer valves close at the maximum rate, whereas the fuel preburner valve closes at a slower than maximum rate. This FPOV sequencing was found to be necessary to provide a smooth transient and will be discussed in subsequent paragraphs.

The fast shutdown sequence developed in this study results in a decay of main combustion chamber pressure to 10% in about 0.5 second compared to about 1.5 seconds for the Phase II nominal shutdown as shown in Figure 3. The accumulated oxidizer flow during the shutdown transient is approximately one half, 352 lbs. vs. 716 lbs., and is depicted in Figure 11. The comparative oxidizer total flowrates are shown in Figure 12. The total oxidizer flow is defined as the sum of the oxidizer flows to the fuel and oxidizer preburners and the flow through the main oxidizer valve.

The study included simulation of engine shutdown at full power level (FPL), rated power level (RPL), and minimum power level (MPL). These transients are presented in Figures 13 through 23. In the process of assessing different power levels, it was found that the MPL was the most stability sensitive, and required several iterations on the fuel preburner valve closing rate. If the fuel preburner oxidizer valve is closed at the maximum rate, 200 percent/second, as shown in Figure 24, the decay is oscillatory, as shown in Figure 25. Slowing the valve closing rate to 50 percent/second resulted in a smooth, non-oscillatory shutdown transient.

RESULTS SUMMARY (CONTINUED)

The main combustion chamber and high pressure turbine temperatures (Figures 4, 5, 6, 17, 18, and 19) show good behavior decaying smoothly and rapidly. The high pressure pump speeds (Figures 7, 8, 20 and 21) decay smoothly except for the effect of preburner shutdown purges which cause temporary speed increases. The pressure surges in the low pressure oxidizer pump inlet and discharge ducts (Figures 9, 10, 22, and 23) are below 200 psia and 600 psia, respectively. The surge pressures are higher than in a nominal shutdown sequence, but well within structural limits. The discharge duct pressure limit with the operating loads in effect is 695 psia.

The effect of an early purge is seen in Figures 7 and 8. In this case, the preburner purges are activated at the cutoff signal, but do not become effective until the system pressures drop below the purge supply pressure of 750 psia. For the nominal shutdown, the purges are set to go on at 1.8 seconds after the cutoff signal. For the fast shutdown, the purges will be set at 0.0 to 0.8 seconds because it results in a faster decay in high pressure pump speeds.

An analysis of the High Pressure Fuel Pump (HPFP) head ($\Delta P/pN^2$)[1] and flow (W/pN)[1] parameters depicted in Figure 28 shows that the points lie on the negative slope of the design curve except at the end of the shutdown transient when flows drop below the 10 percent level. This characteristic is required to maintain stable pump operation and to preclude premature pump stall. All pumps show stable operation with the fast shutdown.

1) ΔP = pump pressure rise

p = fuel density

N = pump speed

W = pump weight flowrate

VALVE SEQUENCING

The valve shutdown sequence developed in this study is depicted in Figure 1. The OPB oxidizer valve closes at a rate of 200 percent/second. The FPB oxidizer valve closes at a rate of 50 percent/second. The MOV also closes at 200 percent/second with a first order lag built into the control loop. The MFV begins to close at 31.5 seconds at a rate of 75 percent per second to 75 percent open, held at that position for about 2.25 seconds and then closed at a rate of 100 percent per second. The CCV closes at about 0.7 seconds after the MFV to about 62 percent open and then closes again as the MFV closes and at a rate of 200 percent per second.

It was found in earlier runs that when the FPB oxidizer valve was closed at the maximum rate (200 percent/second), the shutdown transient was oscillatory, as shown in Figure 25. It was found that the main combustion chamber flowrates and instantaneous accumulated gas weights were driving this oscillation. With the slower closing rate (50 percent per second), the fuel flowrate remains higher relative to the oxidizer flowrate resulting in a smooth decay of pressures and flows. Note that once this developed, the closing to zero position of the MFV and CCV was begun about 1.25 seconds sooner than that shown in Figure 2, the current shutdown sequence.

Shutdowns with the fast shutdown sequence are environmentally benign at all three power levels examined, as indicated in Figures 13 through 23. Note that at different power levels, the preburner valves and CCV begin the shutdown from different initial positions.

VALVE SEQUENCING (CONTINUED)

The changes in sequencing are more conspicuous when the sequencing is compared to that of the Phase II model, as shown in Figure 2. The net result is illustrated in the comparison of chamber pressures in Figure 3 where the TTB shutdown gets to 10 percent in about 0.5 second compared to about 1.5 seconds. The objective of the study was to reduce accumulated oxidizer flow and this is shown in Figure 11 indicating a 50 percent reduction from the Phase II shutdown sequence.

The resulting main chamber and high pressure turbine temperatures all remain below that of the Phase II transients, as shown in Figures 4, 5, and 6. The high pressure pump speeds appear well behaved, as shown in Figures 7 and 8, decreasing smoothly to below the 10,000 rpm level. The rise in speed just after the initial drop results from the onset of purges.

It was observed that the oxidizer preburner chamber pressure decay to 750 psia (the purge pressure level) follows Oxidizer Preburner Oxidizer Valve (OPOV) closure by about 0.9 second for shutdowns from FPL and RPL and by about 0.4 second for MPL. Test experience indicates that this condition provides the potential for burning of OPOV ball seal. An attempt was made to avoid this condition by delaying the closing of the OPOV, as shown in Figure 26. This, however, resulted in a surge in High Pressure Oxidizer Pump (HPOP) discharge pressure, as shown in Figure 27 and the preburner pump discharge pressure as well. It was thought that the sequence should remain as it was and that

VALVE SEQUENCING (CONTINUED)

following any emergency shutdown, the OPOV ball seal would be replaced. This procedure is presently in practice with the SSME for shutdowns between 1.5 and 5.0 seconds.

STEADY STATE BALANCE AND RESISTANCES

The steady state balance for the Phase II TTB engine was used to model fluid resistances between points on the System Dynamics Model schematic where changes in the hardware had been made. Resistances were computed using the pressures, flow rates, and temperatures. These were then input into the system dynamic computer model for this study.

CONCLUSIONS AND RECOMMENDATIONS

The results of this study indicate that a fast shutdown is possible. Decay of main chamber pressure to 10 percent RPL can be reduced from 1.5 seconds to 0.5 seconds. Oxygen consumption during the shutdown transient can be cut in half. This sequence represents the fastest practical shutdown since it utilizes the maximum closing rate of both the OPOV and MOV.

CONCLUSIONS AND RECOMMENDATIONS (CONTINUED)

Several adverse effects to engine hardware have been identified. The OPOV ball seal requires inspection for burning after each fast shutdown. Also, a reduction in turbine component life will be experienced due to accelerated quenching by the shutdown. The magnitude of the life reduction was not quantified as part of this study. An additional concern exists with preburner pops, which may increase due to the rapidly changing environments within the preburners.

Selection of redlines initiating the fast shutdown was limited to the five existing controller redlines and the facility initiated cutoff. Only the HPOTP secondary seal cavity pressure and intermediate seal purge pressure redlines potentially benefited from the fast shutdown in all cases. Any oxidizer reduction to these failure modes was beneficial; however, even the fast shutdown is much too slow to adequately respond to these failure modes. The other four redlines could all be caused by failures which may be exacerbated by the fast shutdown.

CONCLUSIONS AND RECOMMENDATIONS (CONTINUED)

The final measurement of the effectiveness of the fast shutdown was to examine its potential benefit to the 26 major failures experienced in the SSME program to date. The failures examined are listed in Table 1. The speed and nature of each failure was examined in this review. In each case, the significant engine damage occurred prior to the cutoff signal. It was inconclusive whether the fast shutdown would have prevented further hardware damage by reducing engine oxidizer flow, or caused additional damage by increasing the magnitude of pressure surges. Damage done to the test facility would not have been significantly reduced, due to the large volume of oxygen available downstream of the facility prevalves. Facility repairs have been relatively minor in nature and have not been the pacing item in the return to testing.

The overall evidence produced in this study indicates even the fastest TTB engine shutdown sequence may not benefit to the program. The engine's control system response capability is the limiting factor and increases in surge pressures would prevent significantly faster shutdowns.

TABLE I

SSME FAILURE SUMMARY

ENGINE	DATE	FAILURE MODE	TYPE CUTOFF	DAMAGE CONT.	FLT SHUT-DOWN	IN-FLIGHT DATA DETECT
0003	3-24-77 (901-110)	HPOTP PRIMARY LOX SEAL RUB – IGNITION	OBSERVER – FIRE	N	Y	Y
0004	8-27-77 (901-133)	FUEL PREBURNER WALL BURNTHROUGH	OBSERVER – FIRE	N	N	N
0004	9-8-77 (901-136)	HPOTP BEARING FAILURE	OBSERVER – FIRE	N	N	Y
0103	12-1-77 (901-147)	HPFTP TURBINE BLADE FAILURE	HPOTP VIBRATION	Y	N	Y
0002	3-31-78 (901-173)	MAIN INJECTOR LOX POST FATIGUE CRACK	HPFTP TURBINE TEMPERATURE	Y	Y	Y
0101	6-10-78 (902-112)	ENGINE FUEL SUPPLY BLOCKAGE – SOLID N_2	HPFTP SPEED	Y	Y	Y
0005	8-5-78 (901-185)	MAIN INJECTOR LOX POST FATIGUE CRACK	HPFTP VIBRATION (UNRELATED TO FAILURE)	Y	Y	Y
0101	7-18-78 (902-120)	HPOTP EXPERIMENTAL INST. DEVICE RUB–IGNITION	HPOTP VIBRATION	N	N	Y

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TABLE I (CONTINUED)

SSME FAILURE SUMMARY

ENGINE	DATE	FAILURE MODE	TYPE CUTOFF	DAMAGE CONT.	FLT SHUT-DOWN	IN-FLIGHT DATA DETECT
0006	10-3-78 (902-132)	ABNORMAL START – MOV CLOCKING	LOW CHAMBER PRESSURE	Y	Y	Y
0007	12-6-78 (901-222)	HEAT EXCHANGER COIL LEAK	HEAT EXCHANGER OUTLET PRESSURE	N	N	Y
2001	12-27-78 (901-225)	MAIN OXID. VALVE SLEEVE IGNITION	HPFTP TURBINE TEMPERATURE	N	N	Y
0201	5-14-79 (750-041)	STEERHORN RUPTURE	FAILURE OCCURRED AFTER CUTOFF	Y	Y	Y
2002	7-2-79 (SF6-01)	MAIN FUEL VALVE HOUSING FAILURE	HPFTP TURBINE TEMPERATURE	N	Y	Y
2002	11-4-79 (SF6-03)	STEERHORN RUPTURE	FAILURE OCCURRED AFTER CUTOFF	Y	Y	Y
0006	7-12-80 (SF10-01)	FUEL PREBURNER WALL BURNTHROUGH	OBSERVER – FIRE	N	N	Y
2004	7-23-80 (902-198)	MAIN INJECTOR LOX POST FATIGUE CRACK	HPOTP TURBINE TEMPERATURE	Y	Y	Y
0010	7-30-80 (901-284)	MAIN Pc SENSING LEE JET FAILURE	HPOTP VIBRATION	N	Y	Y

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TABLE I (CONTINUED)

SSME FAILURE SUMMARY

ENGINE	DATE	FAILURE MODE	TYPE CUTOFF	DAMAGE CONT.	FLT SHUT-DOWN	IN-FLIGHT DATA DETECT
2108	7-15-81 (901-331)	MAIN INJECTOR LOX POST FATIGUE CRACK	HPOTP TURBINE TEMPERATURE	Y	Y	Y
0110	9-2-81 (750-148)	MAIN INJECTOR LOX POST FATIGUE CRACK	HPOTP TURBINE TEMPERATURE	Y	Y	Y
0204	9-21-81 (902-249)	HPFTP TURBINE BLADE FAILURE	HPFTP VIBRATION	N	N	Y
0110F	2-12-82 (750-160)	FUEL PREBURNER FUEL FLOW BLOCKAGE(ICE)	HPFTP TURBINE TEMPERATURE	N	Y	Y
2013	4-7-82 (901-364)	HPFTP TURBINE RETAINER NUT LEAK	HPOTP VIBRATION	N	N	Y
2208	8-27-82 (750-175)	HPOTP DISCHARGE DUCT RUPTURE	HPOTP VIBRATION	N	N	Y
0108	2-14-84 (901-436)	TURBOPUMP COOLANT LINER BULGE	HPFTP VIBRATION	N	Y	Y
0207	2-4-85 (901-468)	FUEL PREBURNER INST. PORT CRACK	OBSERVER – FIRE	N	N	N
2308	3-27-85 (750-259)	MAIN COMBUSTION CHAMBER OUTLET NECK RUPTURE	HPFTP VIBRATION	N	N	Y

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FAST SHUTDOWN CONTROL VALVE POSITIONS

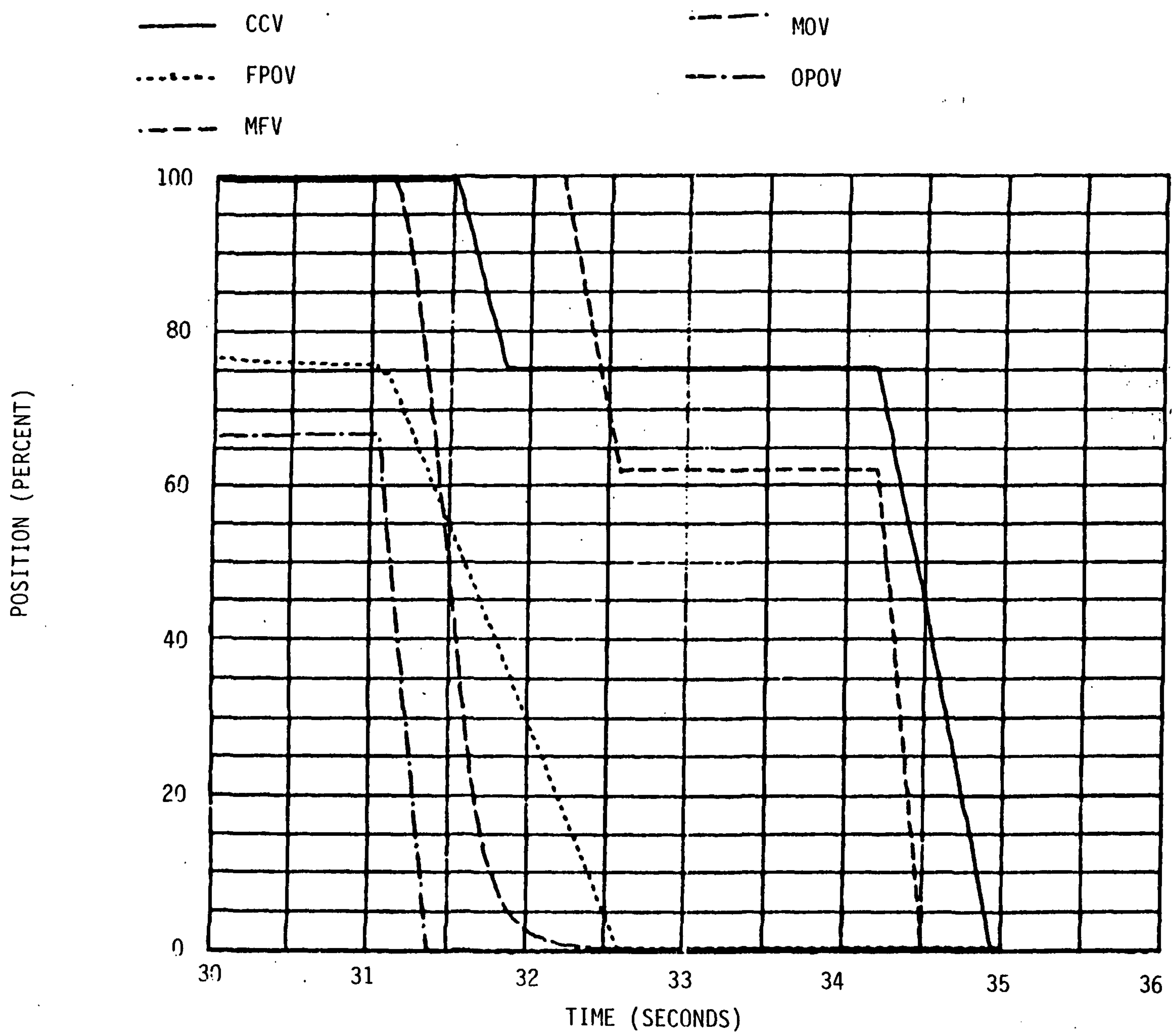

FIGURE 1

CURRENT SHUTDOWN CONT[illegible] VALVE POSITIONS

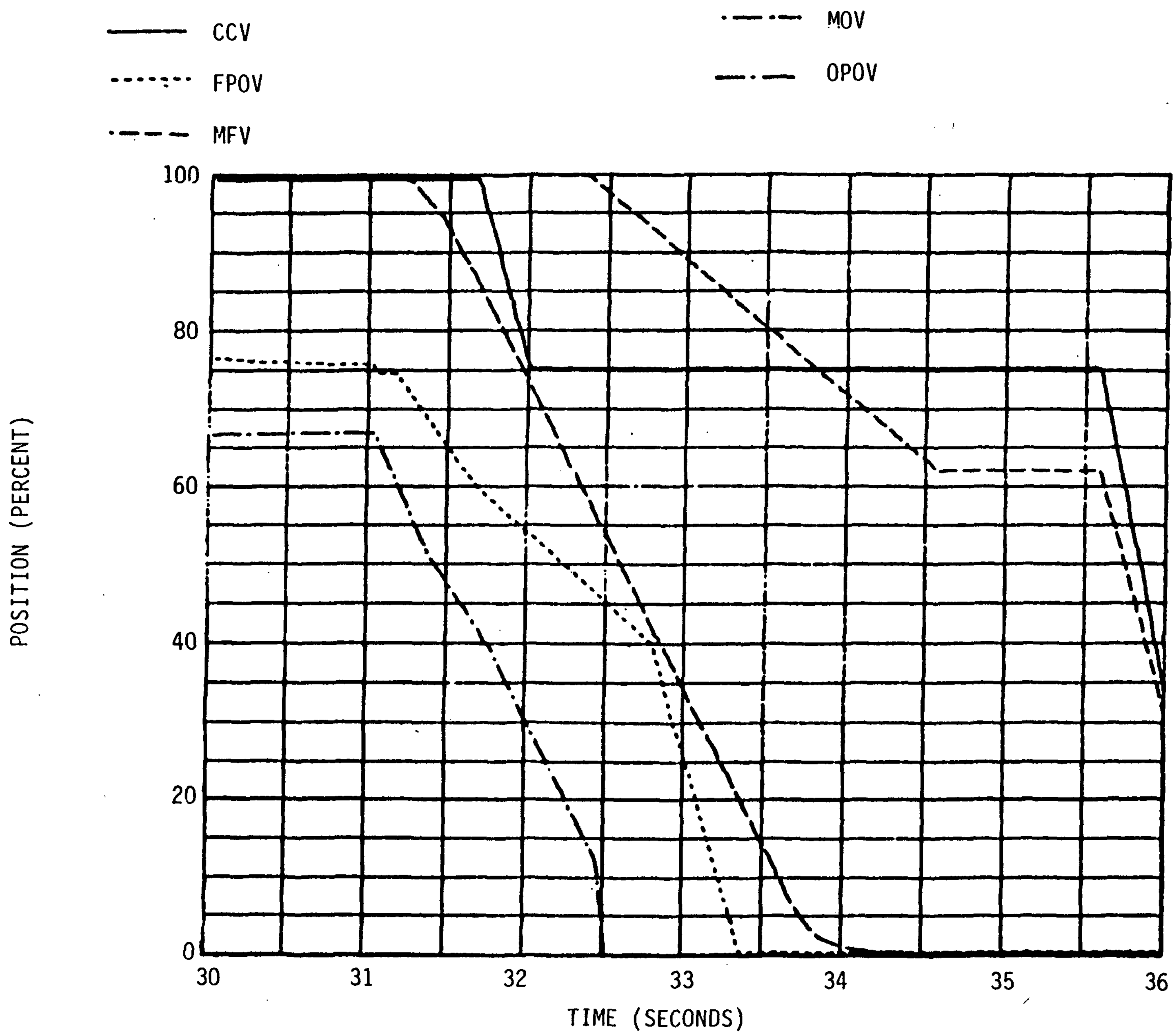

FIGURE 2

MAIN COMBUSTION CHAMBER PRESSURE

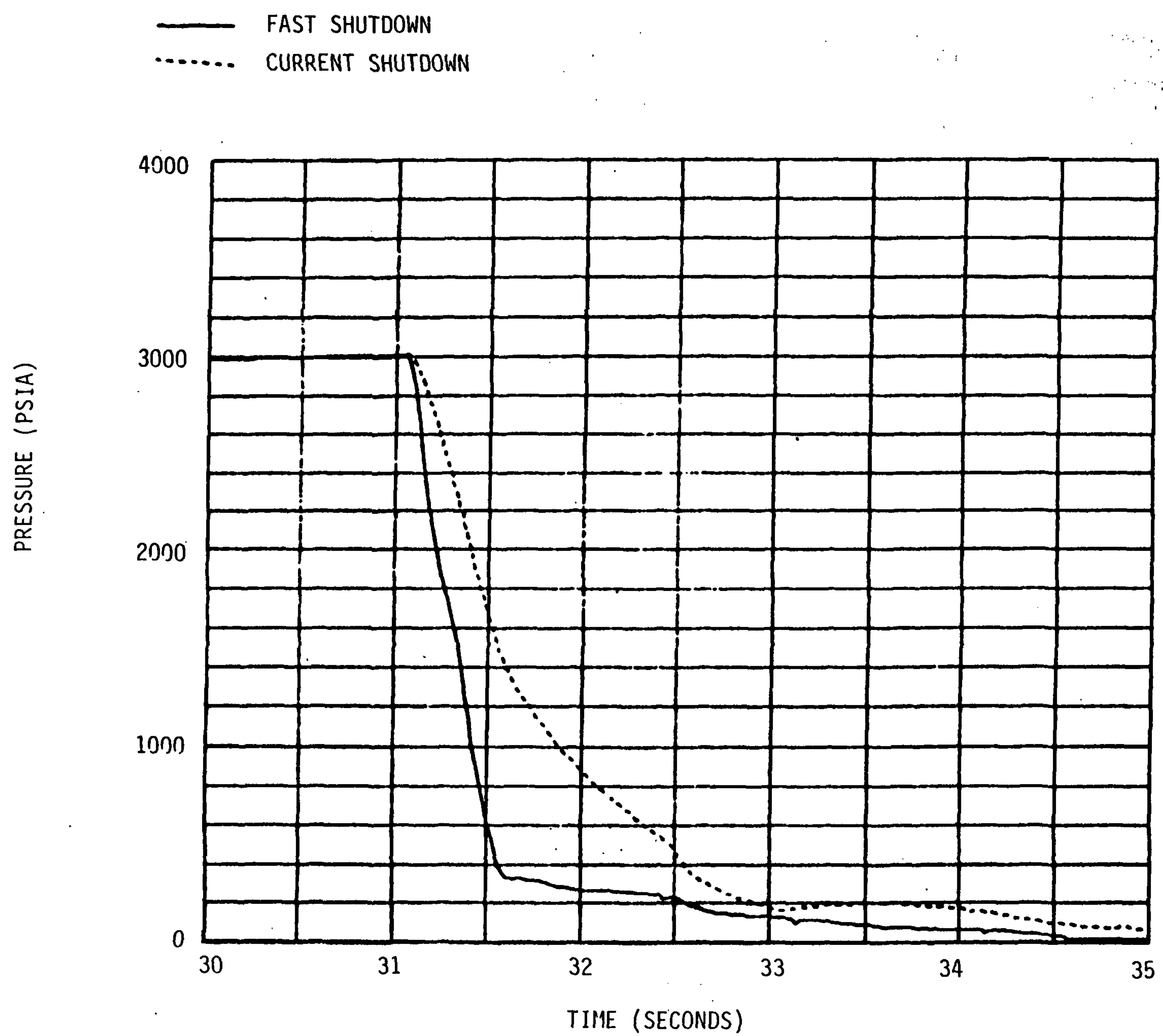

FIGURE 3

MAIN COMBUSTION CHAMBER TEMPERATURE

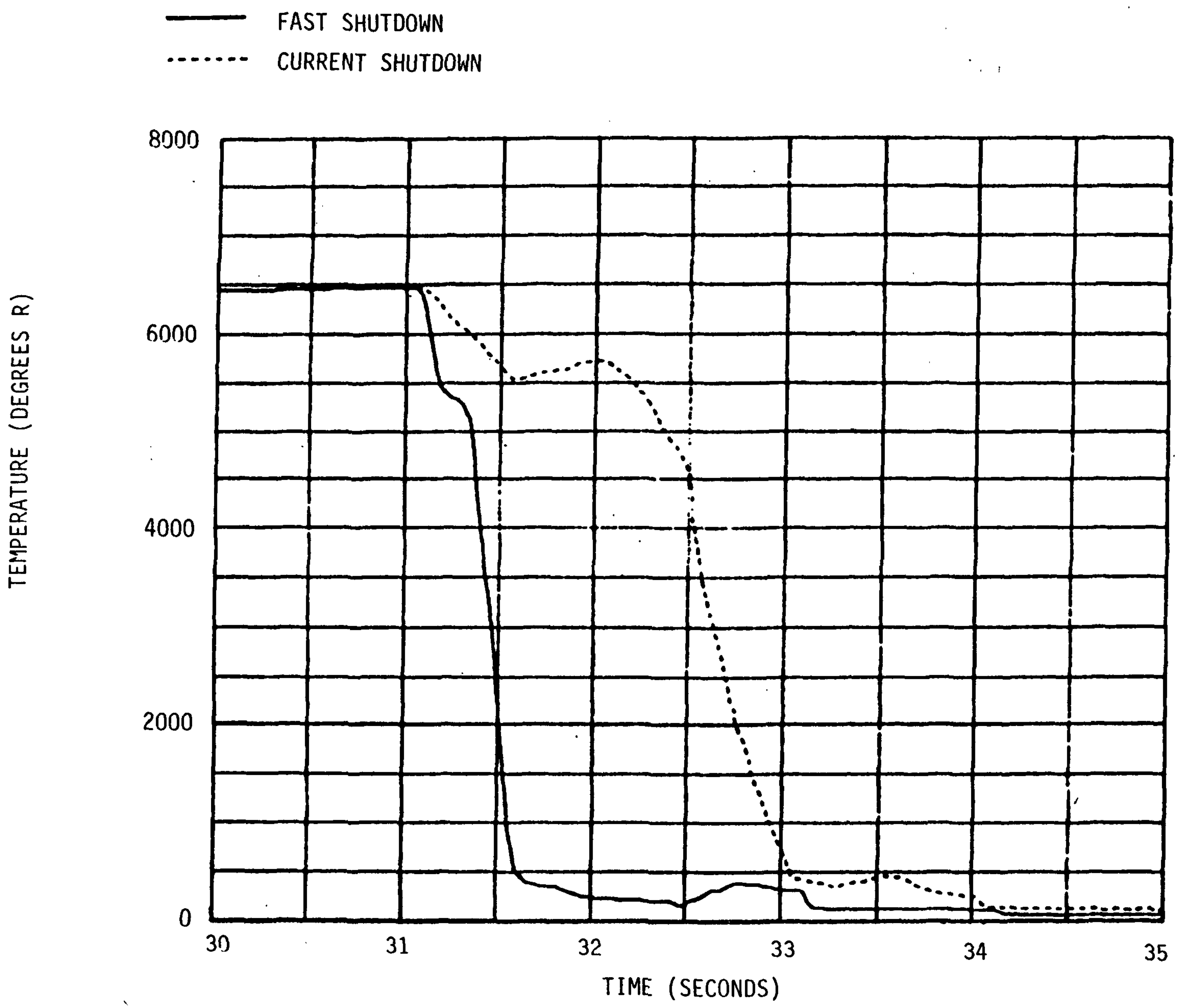

FIGURE 4

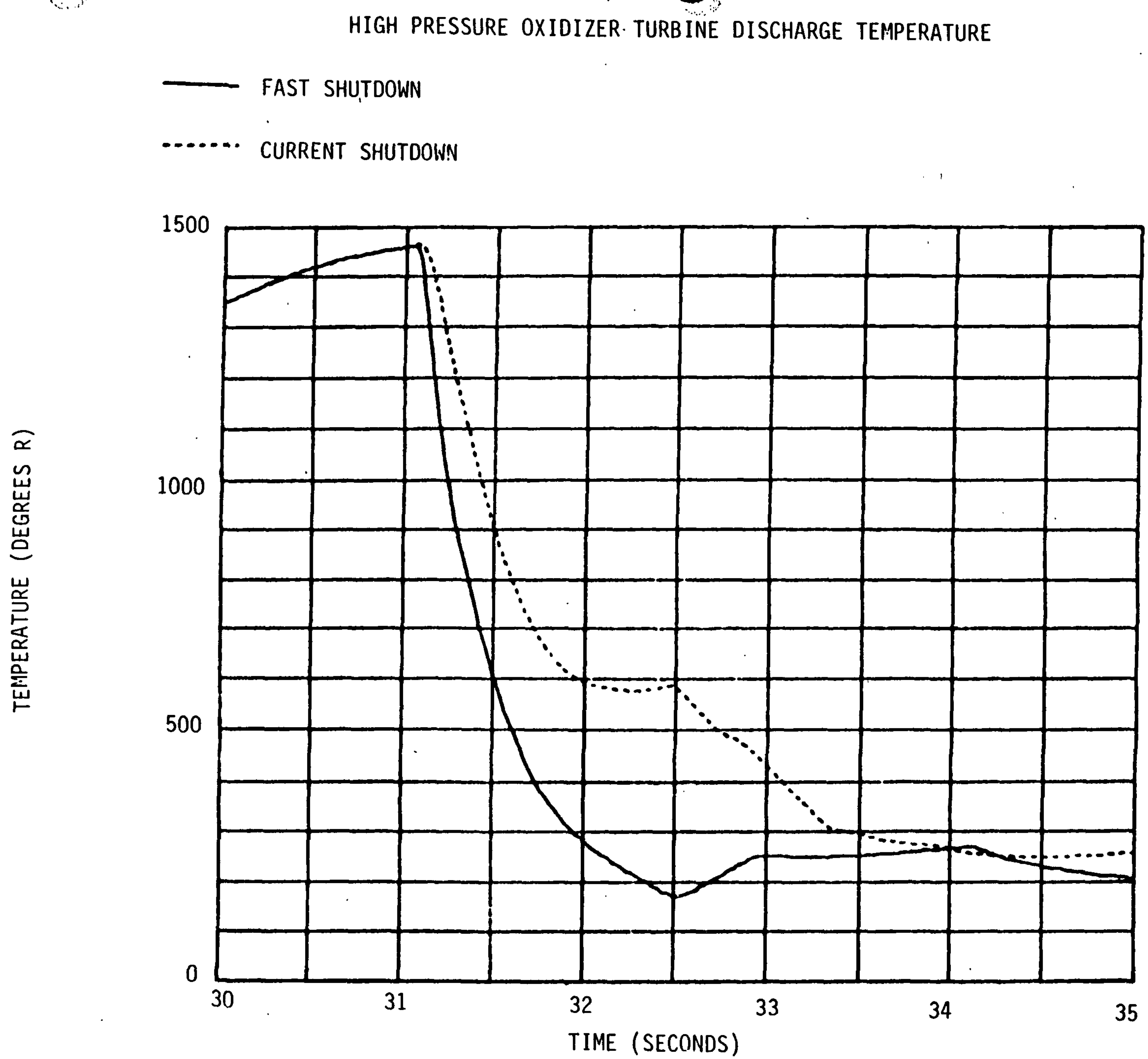
HIGH PRESSURE OXIDIZER TURBINE DISCHARGE TEMPERATURE
FAST SHUTDOWN
CURRENT SHUTDOWN
TEMPERATURE (DEGREES R)
1500
1000
500
0
30
31
32
33
34
35
TIME (SECONDS)

FIGURE 5

HIGH PRESSURE FUEL TURBINE DISCHARGE TEMPERATURE

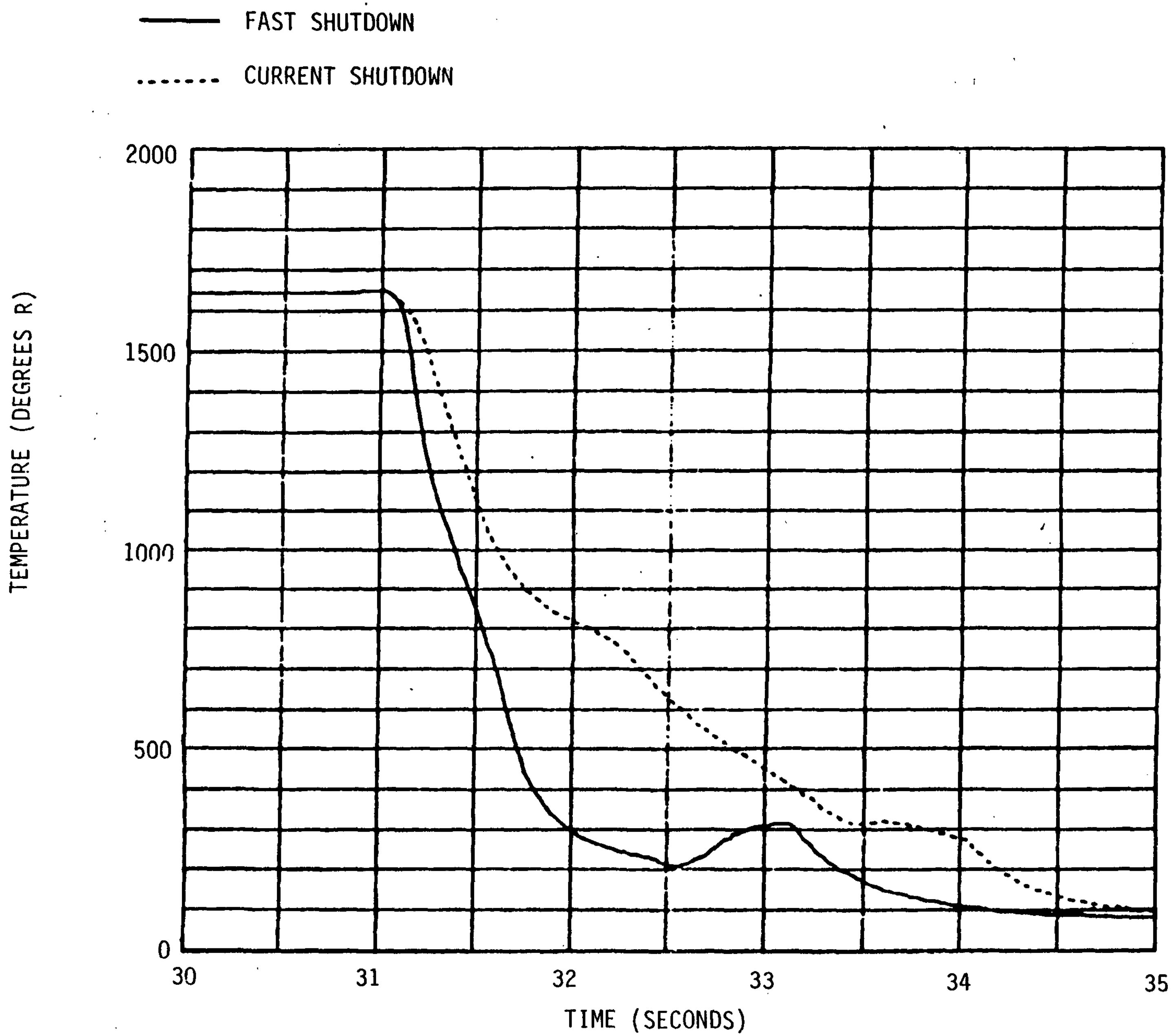

FIGURE 6

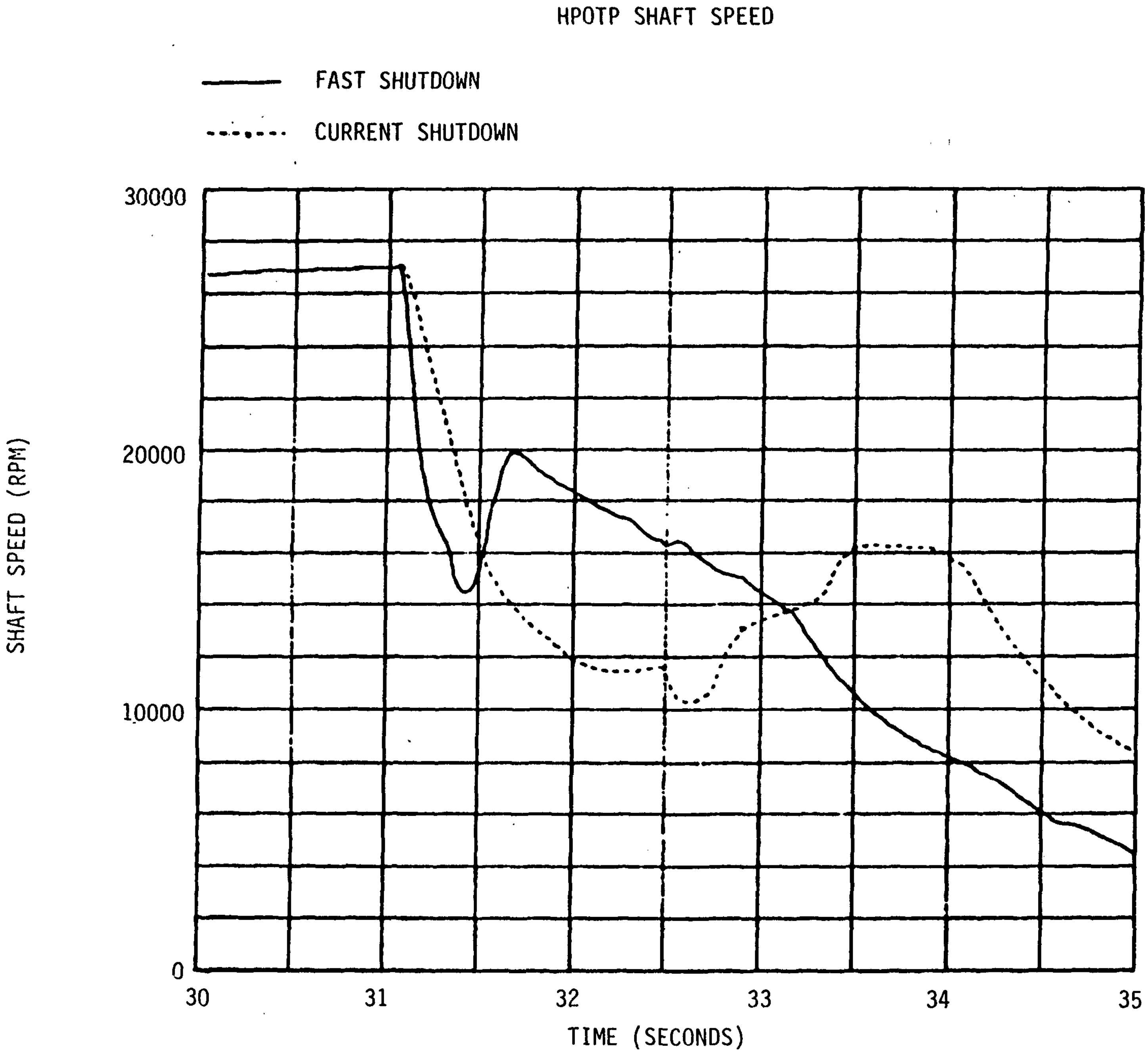
HPOTP SHAFT SPEED
FAST SHUTDOWN
CURRENT SHUTDOWN
SHAFT SPEED (RPM)
30000
20000
10000
0
30
31
32
33
34
35
TIME (SECONDS)

FIGURE 7

HPFTP SHAFT SPEED

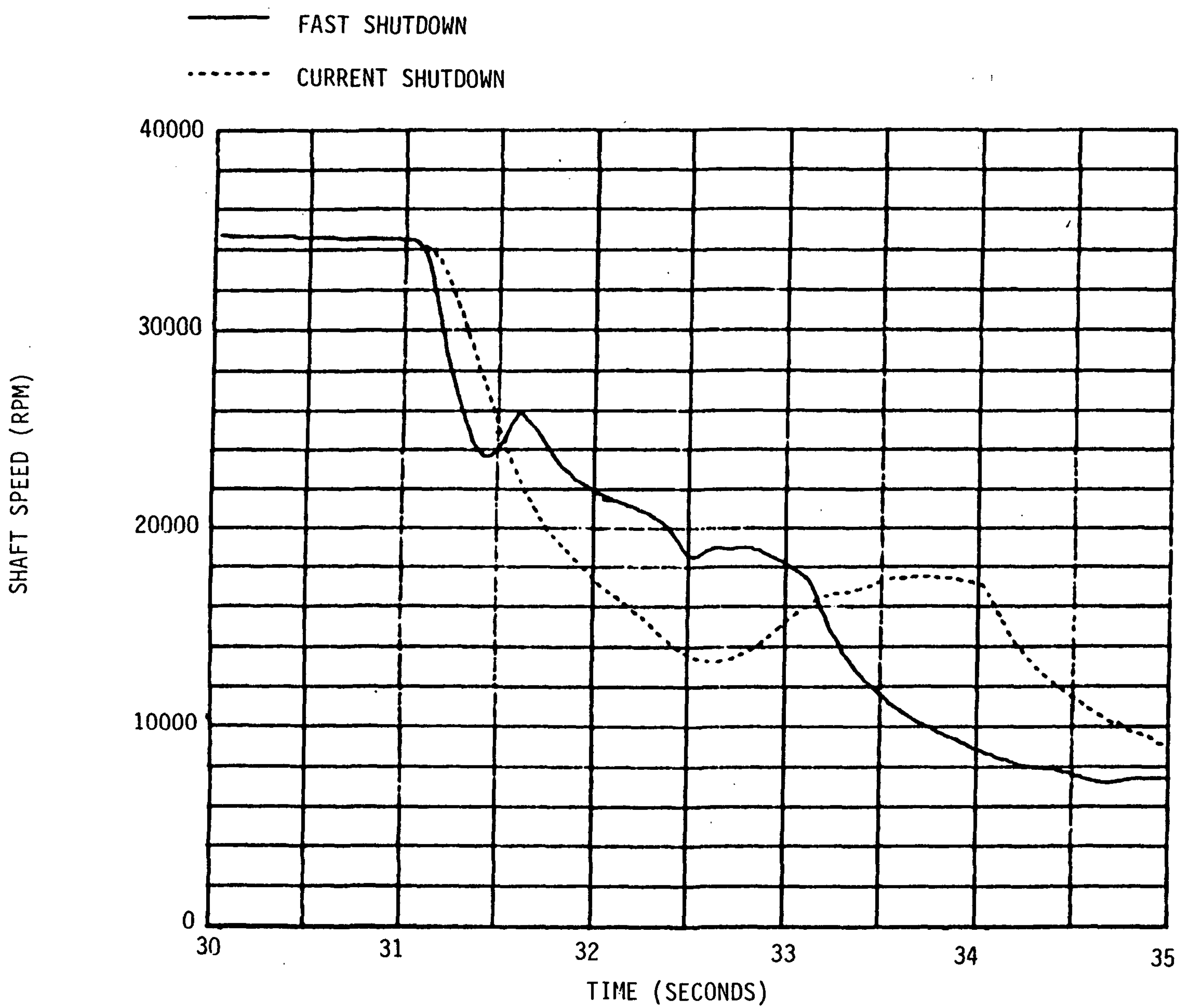

FIGURE 8

LOX SUPPLY PRESSURE

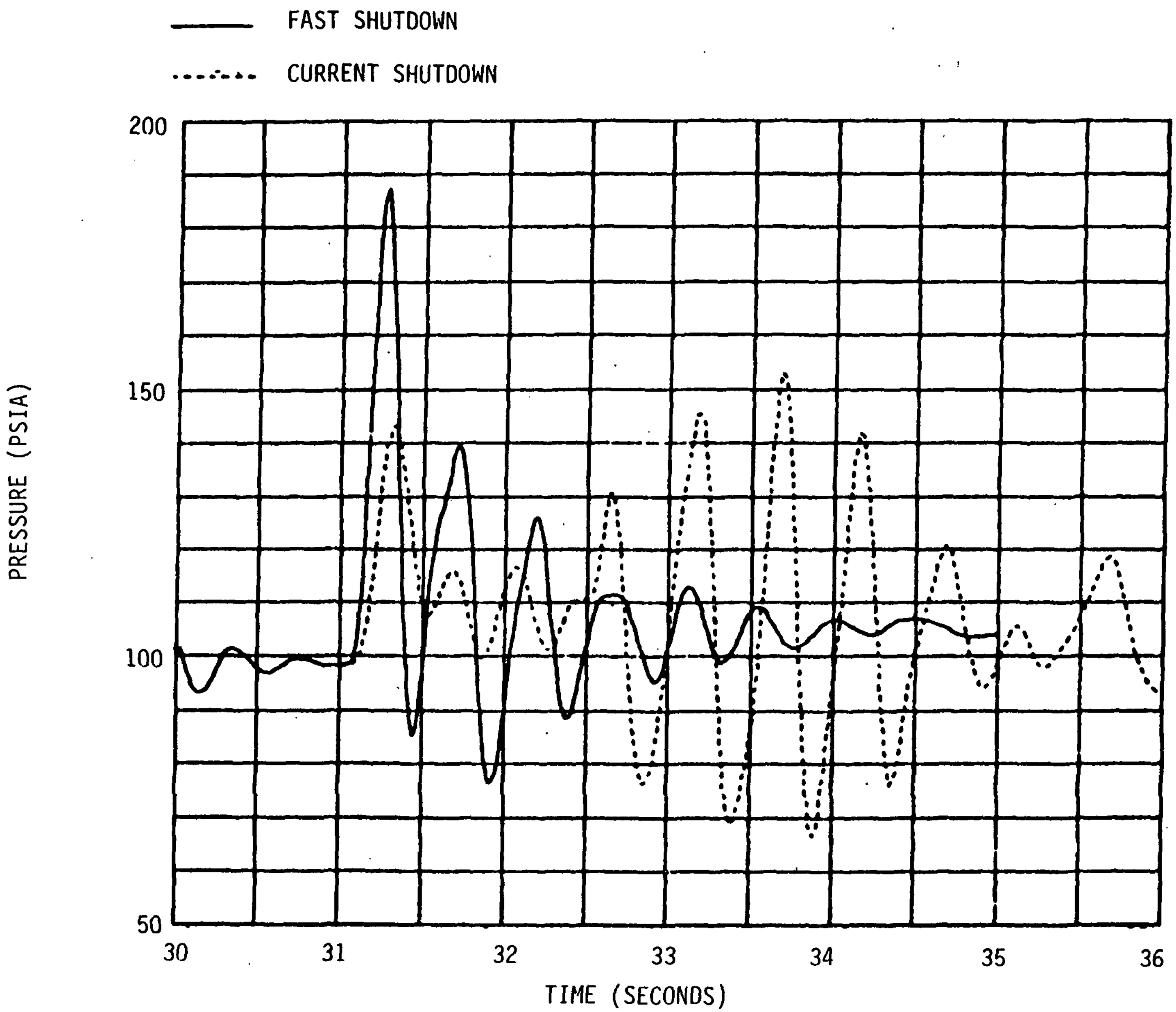

FIGURE 9

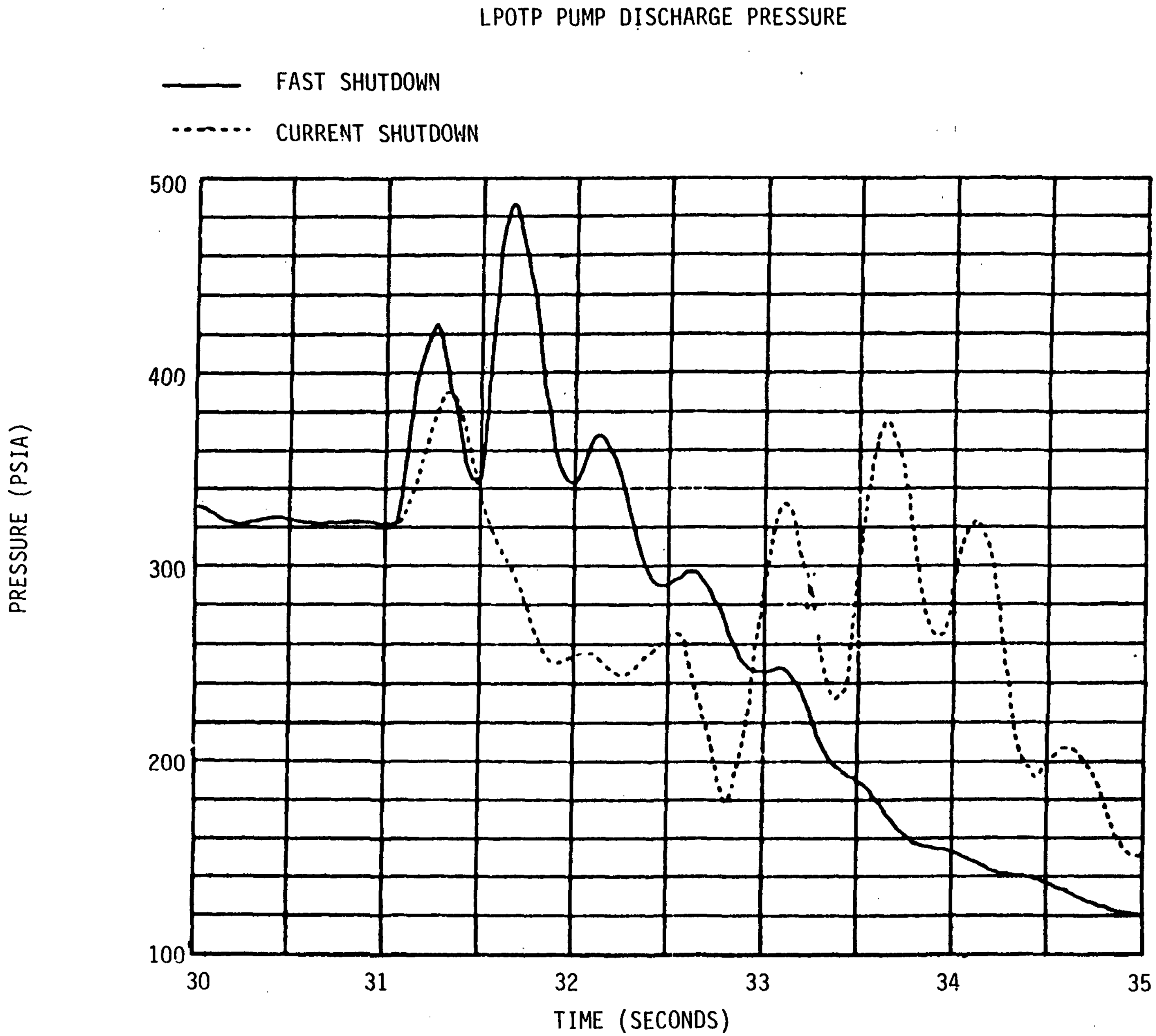
LPOTP PUMP DISCHARGE PRESSURE
FAST SHUTDOWN
CURRENT SHUTDOWN
PRESSURE (PSIA)
500
400
300
200
100
30
31
32
33
34
35
TIME (SECONDS)

FIGURE 10

TOTAL CUTOFF OXIDIZER FLOW

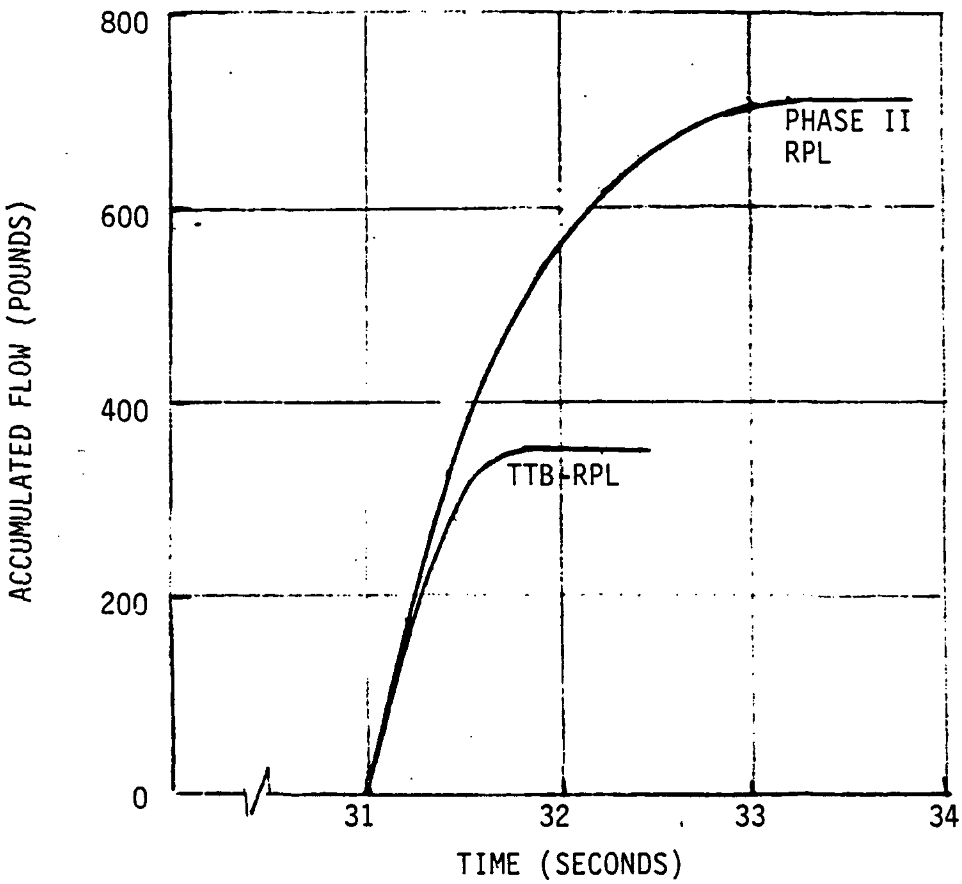

FIGURE 11

OXIDIZER FLOWRATE

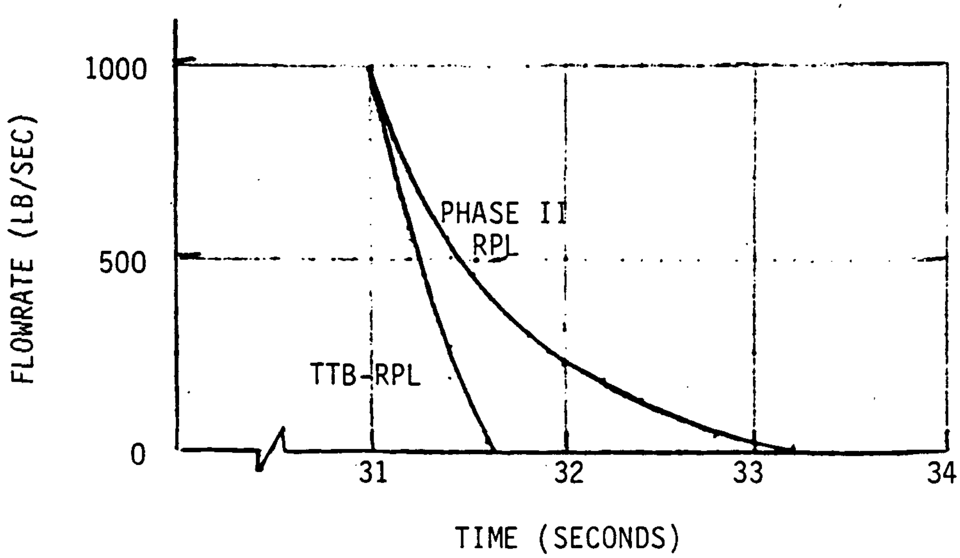

FIGURE 12

FAST SHUTDOWN MCC PRESSURE DECAY

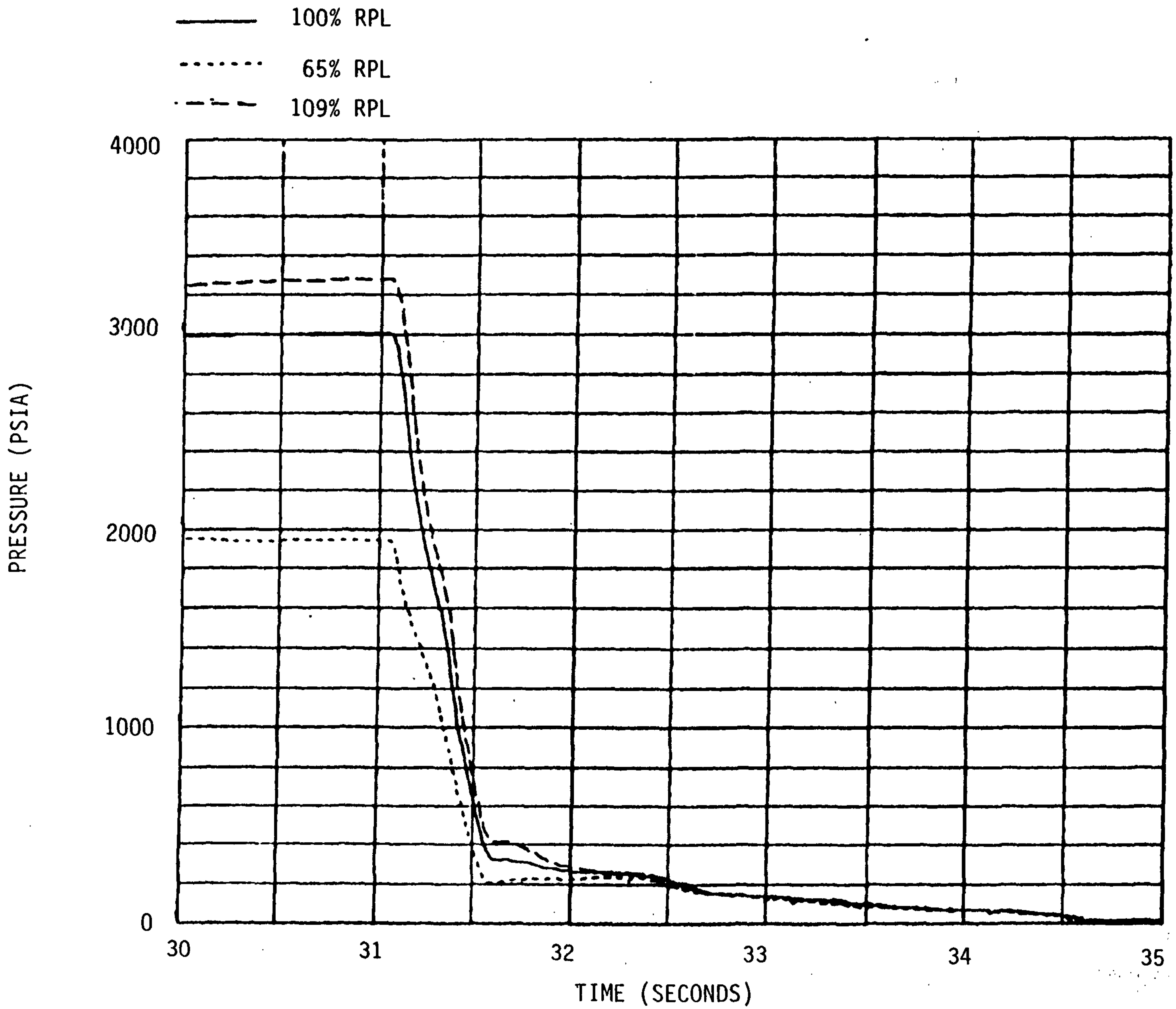

FIGURE 13

FAST SHUTDOWN VALVE POSITIONS (RPL CUTOFF)

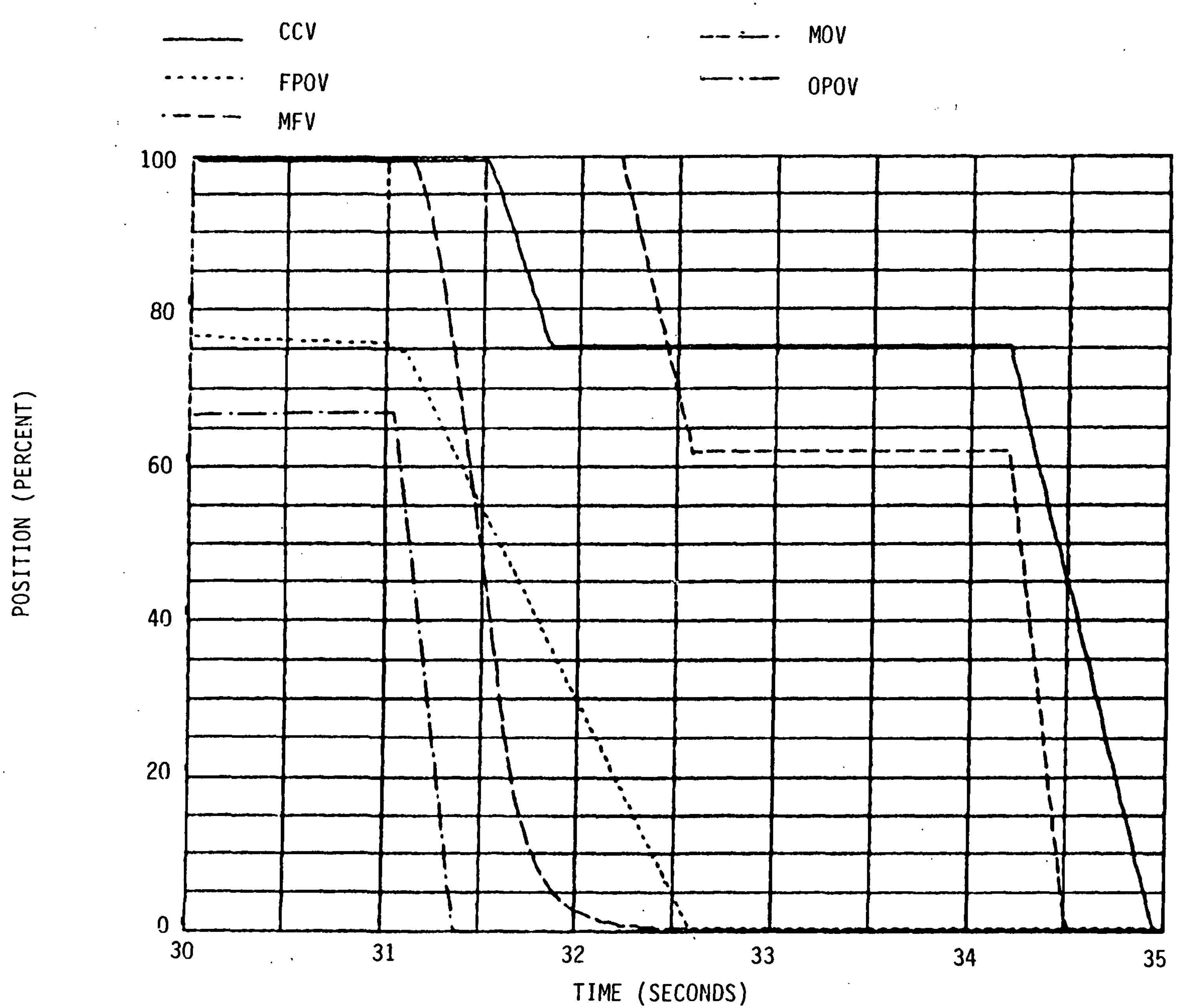

FIGURE 14

FAST SHUTDOWN VALVE POSITIONS (FPL CUTOFF)

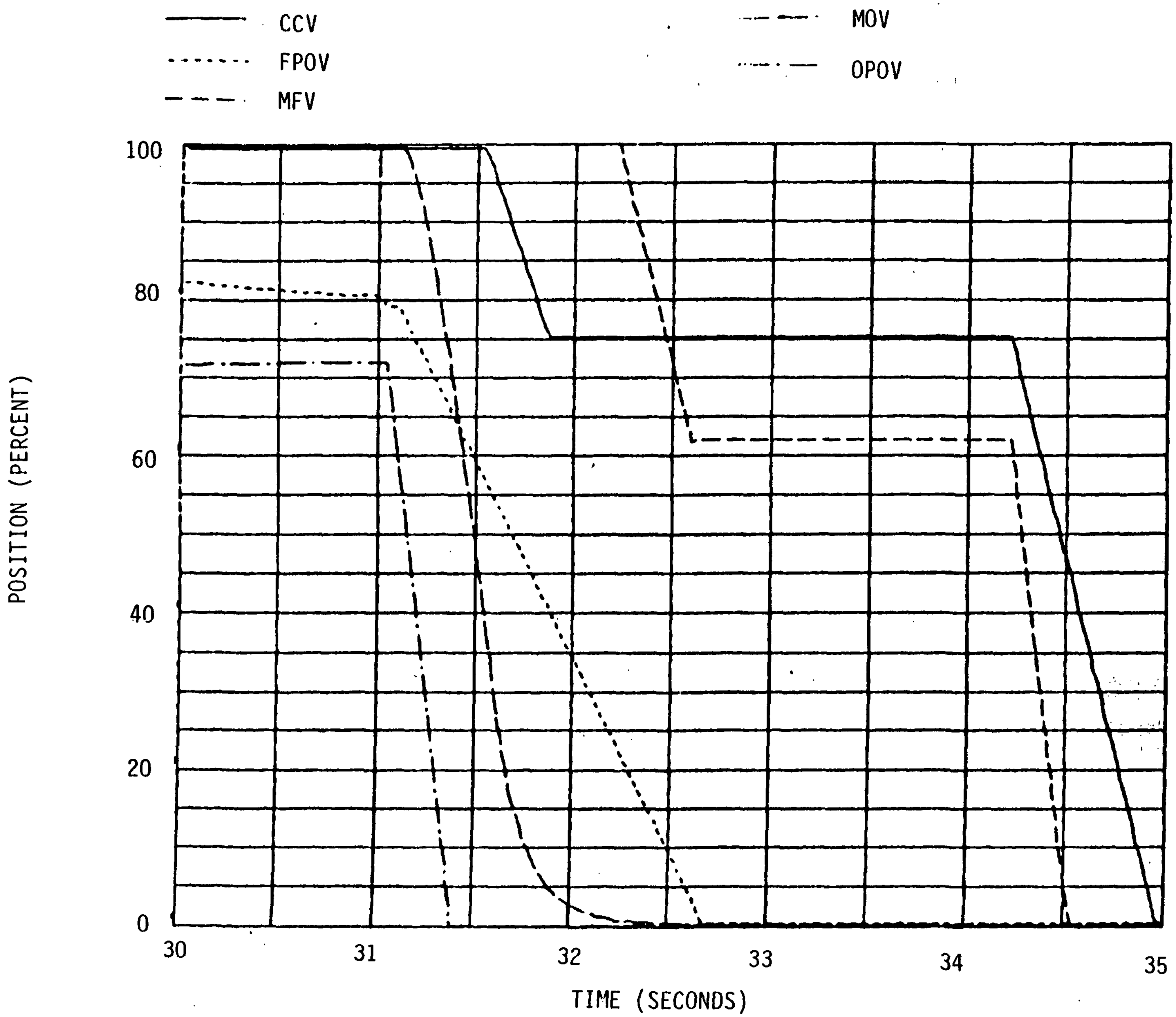

FIGURE 15

FAST SHUTDOWN VALVE POSITIONS (MPL CUTOFF)

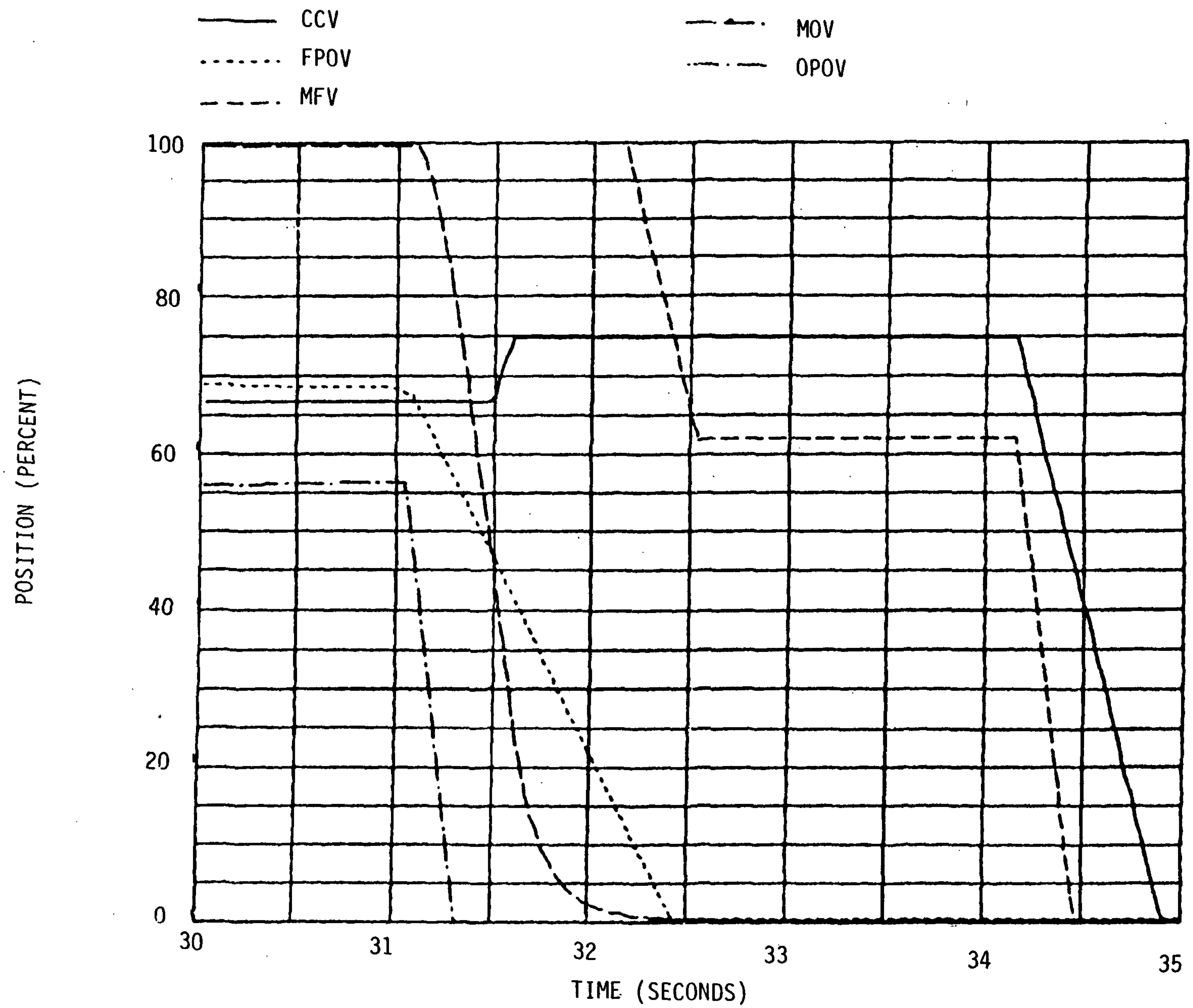

FIGURE 16

FAST SHUTDOWN MCC TEMPERATURE DECAY

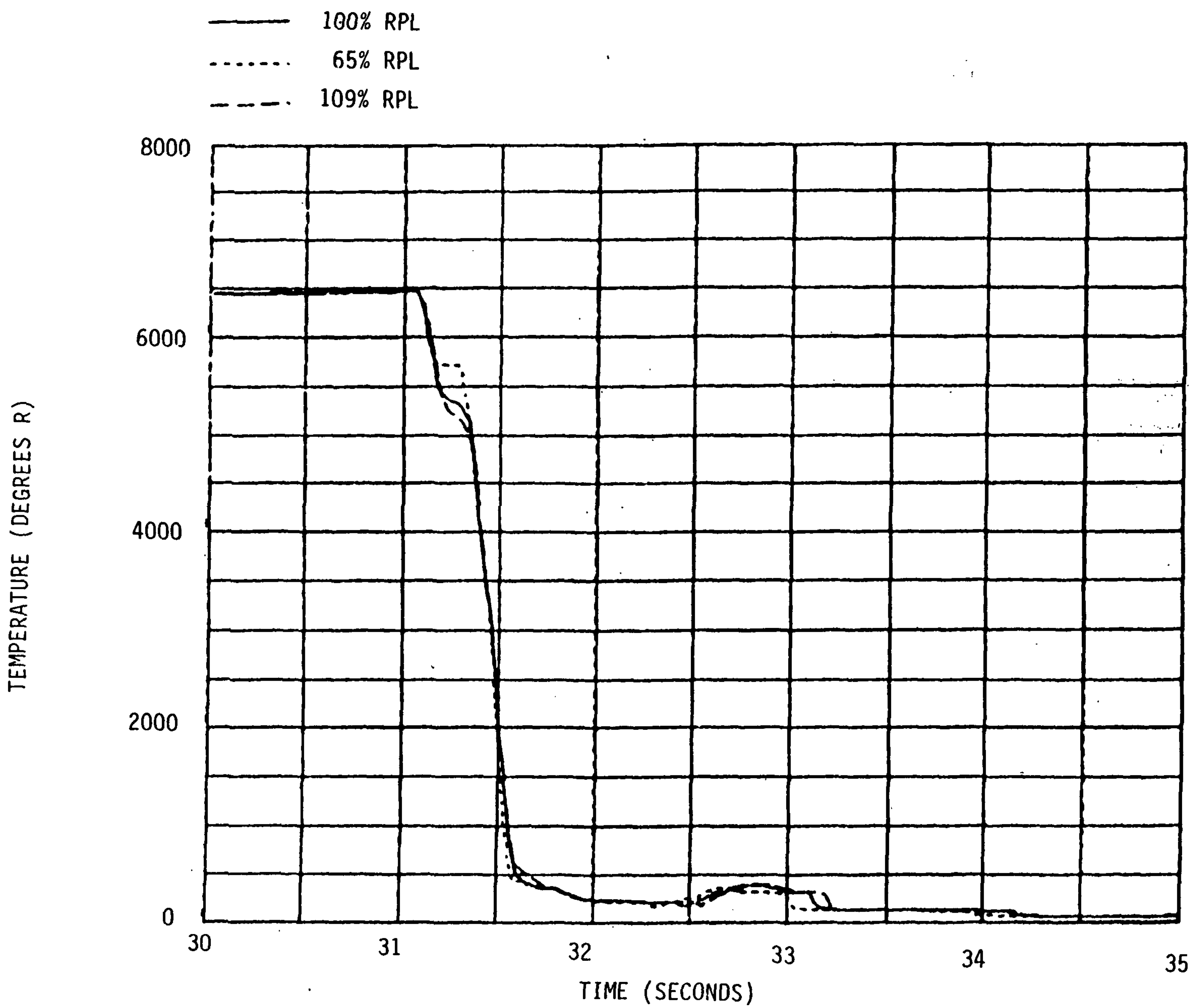

FIGURE 17

FAST SHUTDOWN HPOTP TURBINE DISCHARGE TEMPERATURE

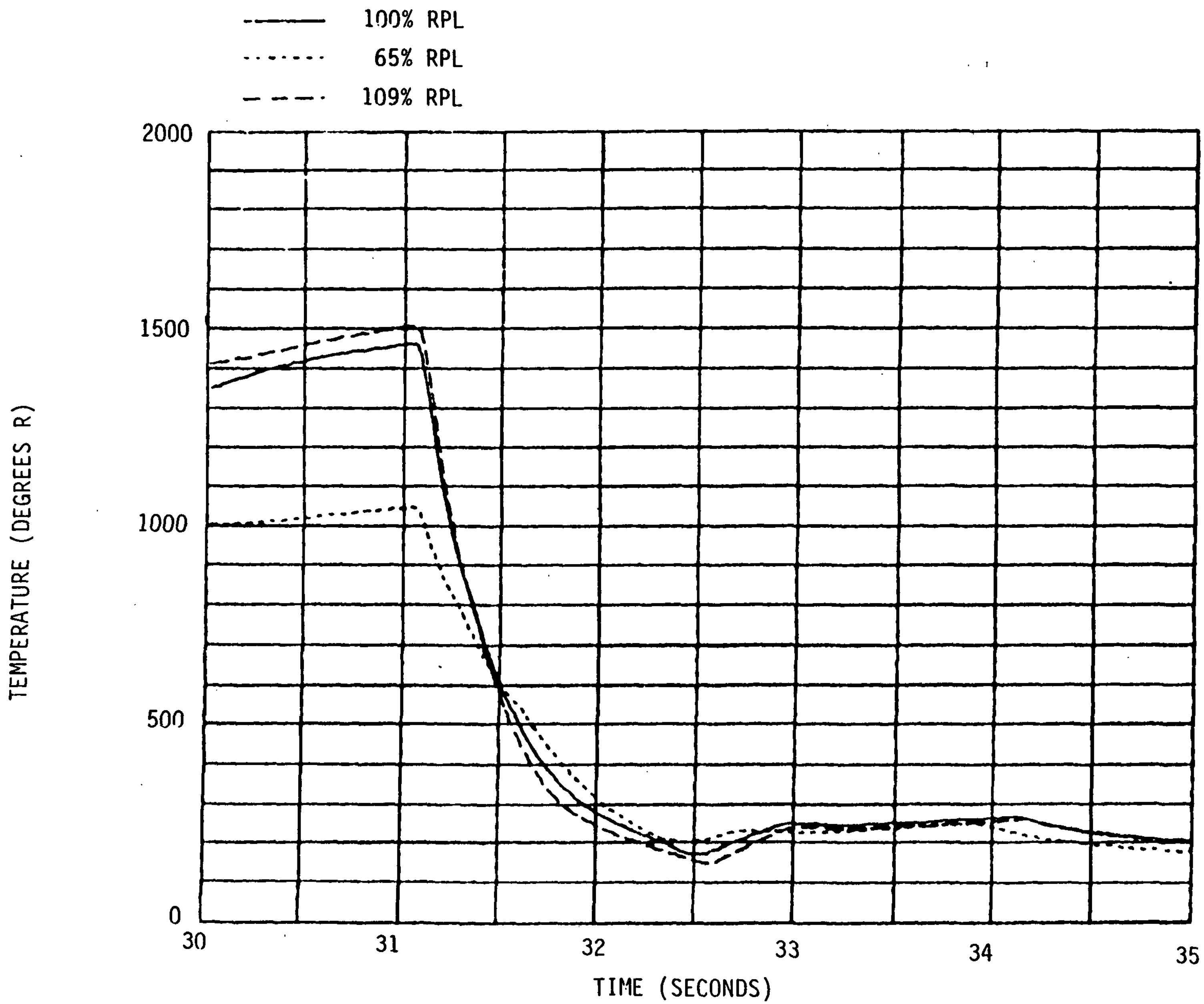

FIGURE 18

FAST SHUTDOWN HPFTP TURBINE DISCHARGE TEMPERATURE

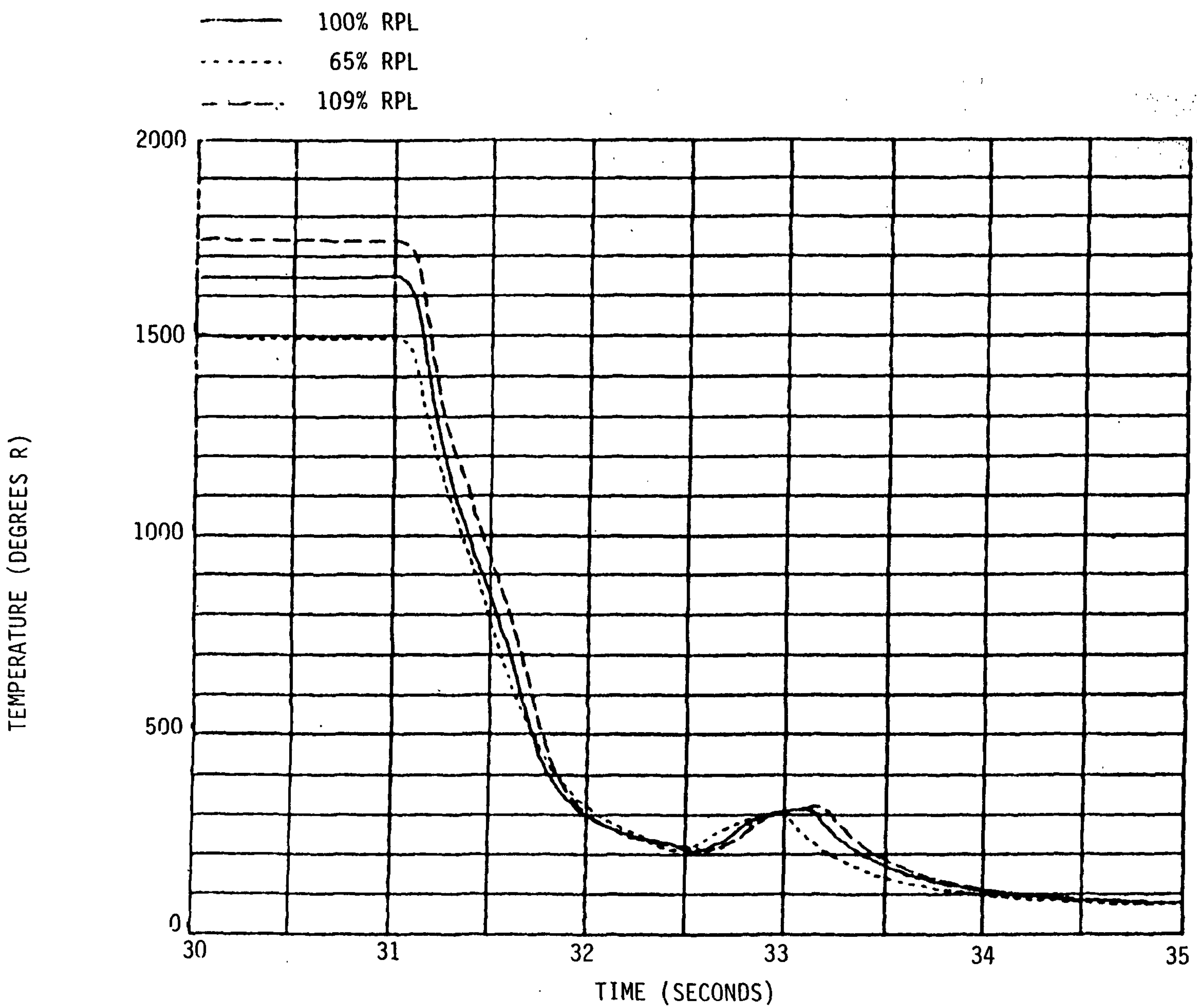

FIGURE 19

FAST SHUTDOWN HPOTP SHAFT SPEED DECAY

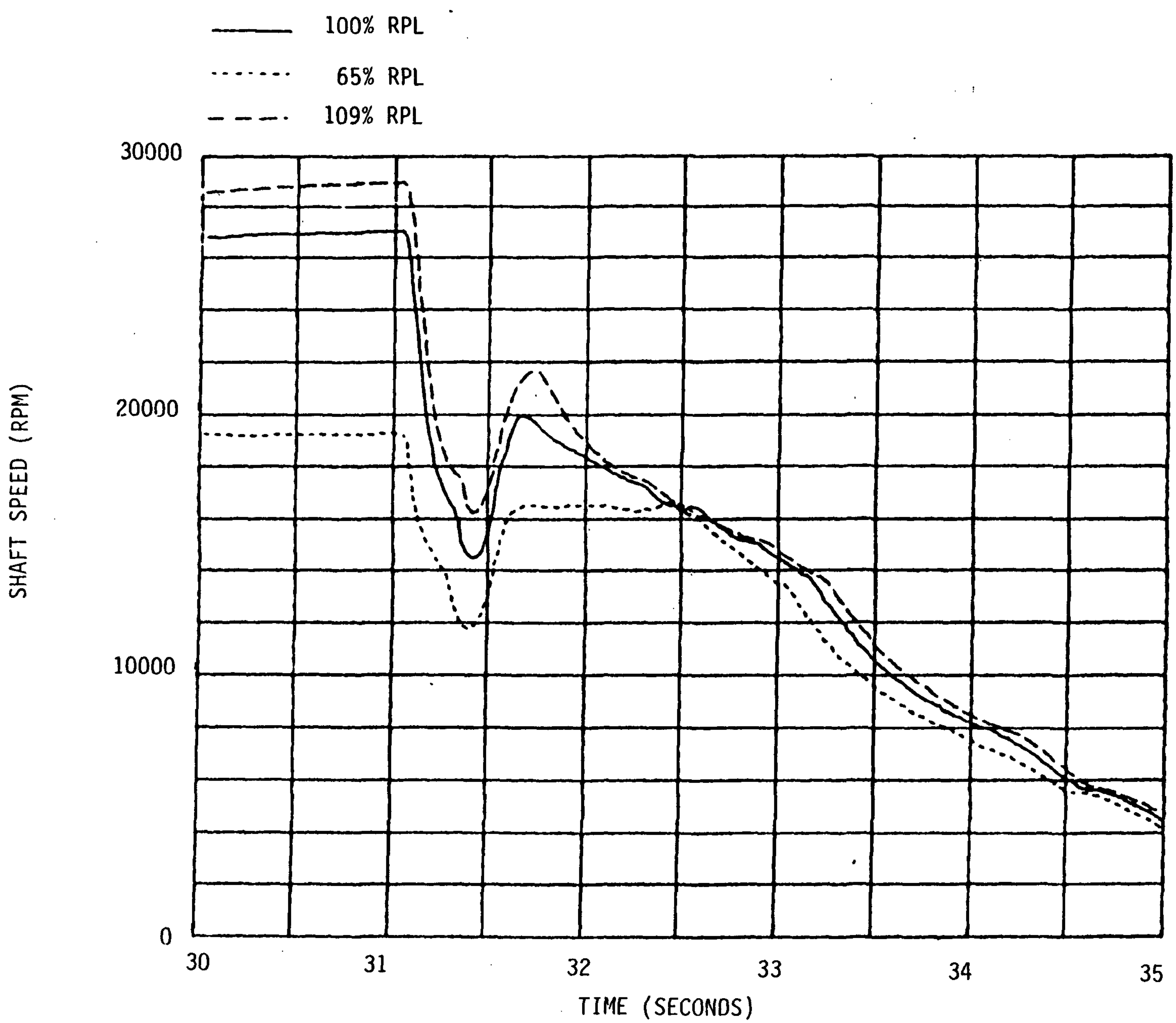

FIGURE 20

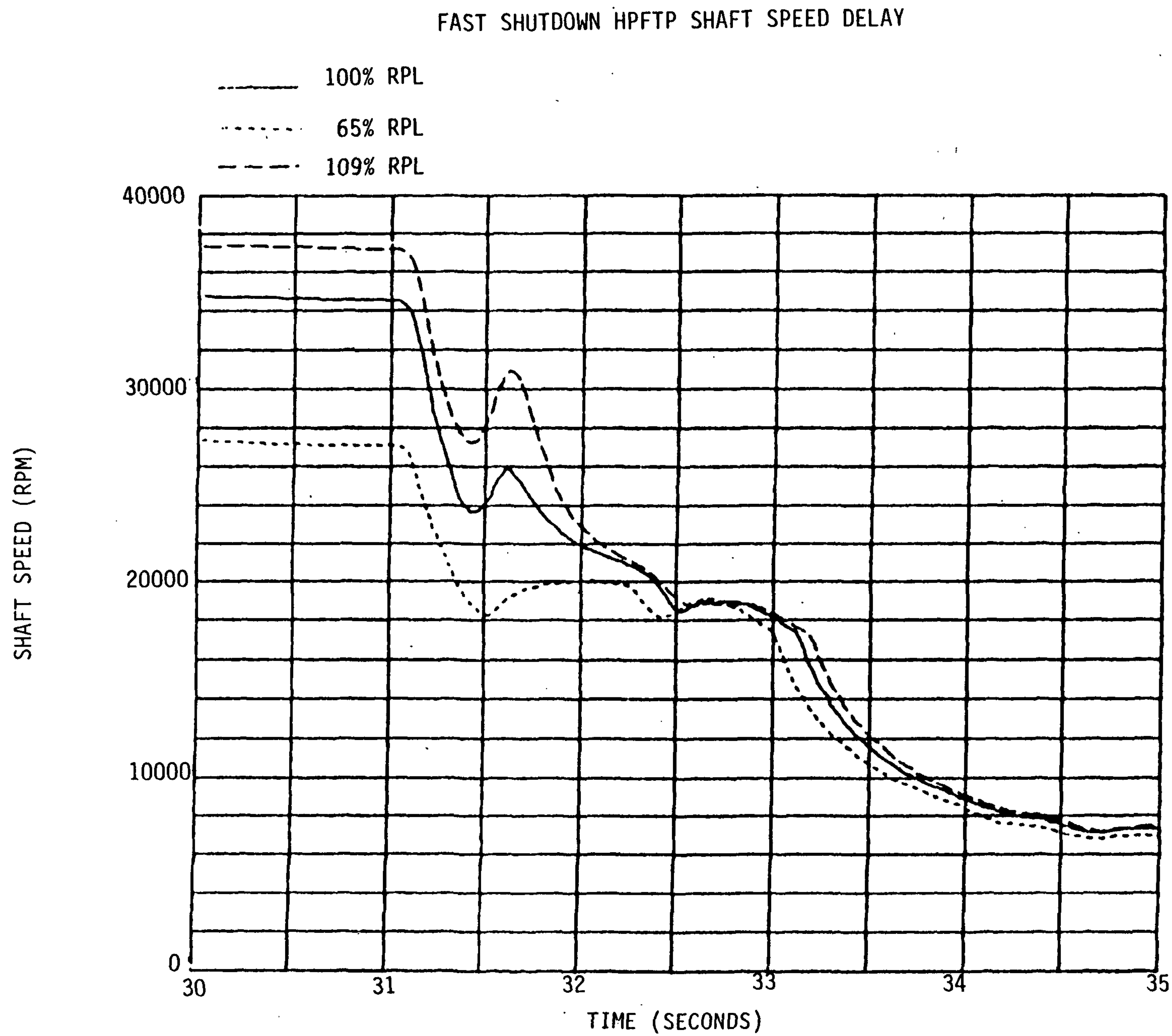
FAST SHUTDOWN HPFTP SHAFT SPEED DELAY
100% RPL
65% RPL
109% RPL
40000
30000
20000
10000
0
SHAFT SPEED (RPM)
30
31
32
33
34
35
TIME (SECONDS)

FIGURE 21

FAST SHUTDOWN OXIDIZER INLET PRESSURE SURGE

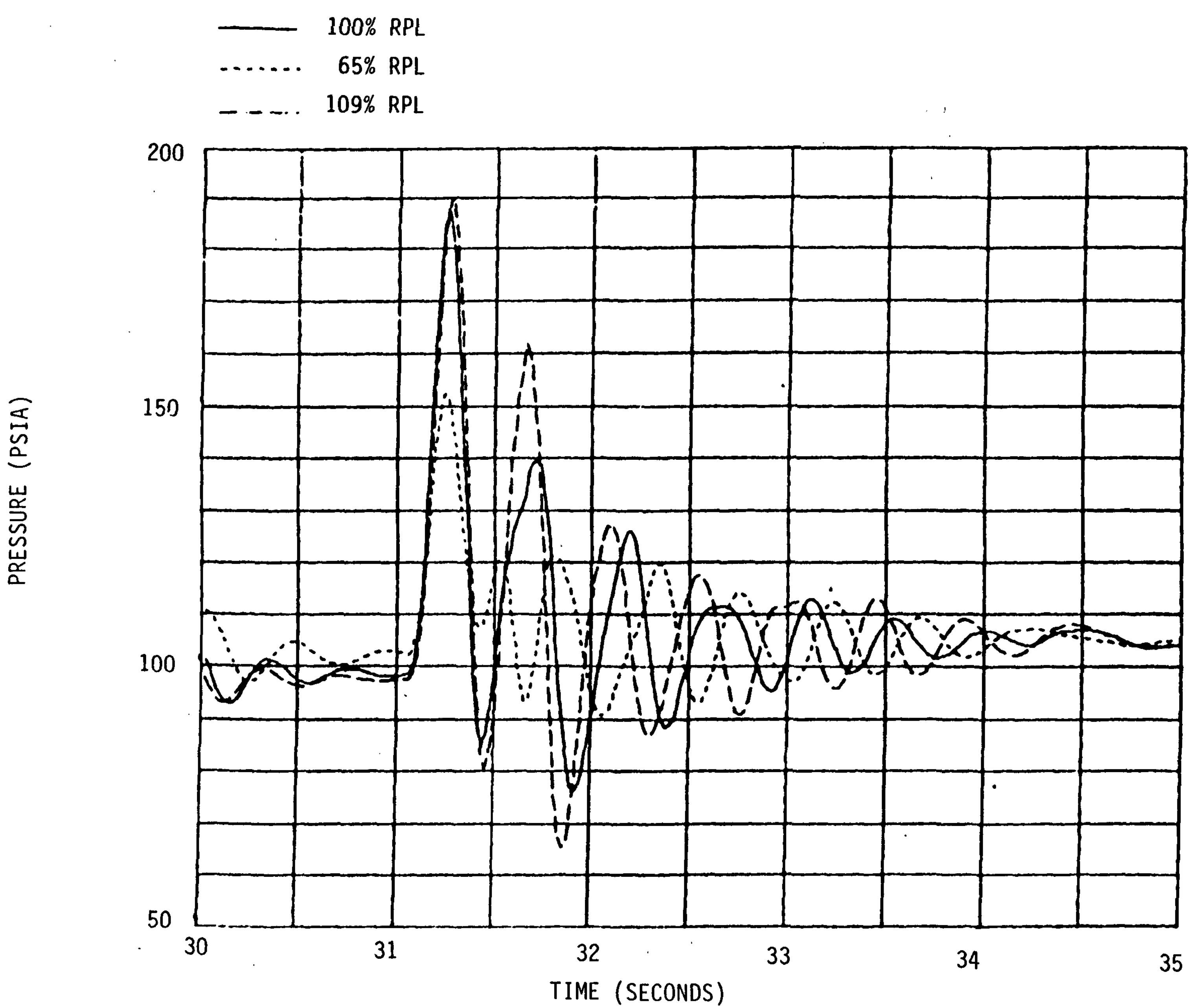

FIGURE 22

FAST SHUTDOWN LPOTP DISCHARGE PRESSURE SURGE

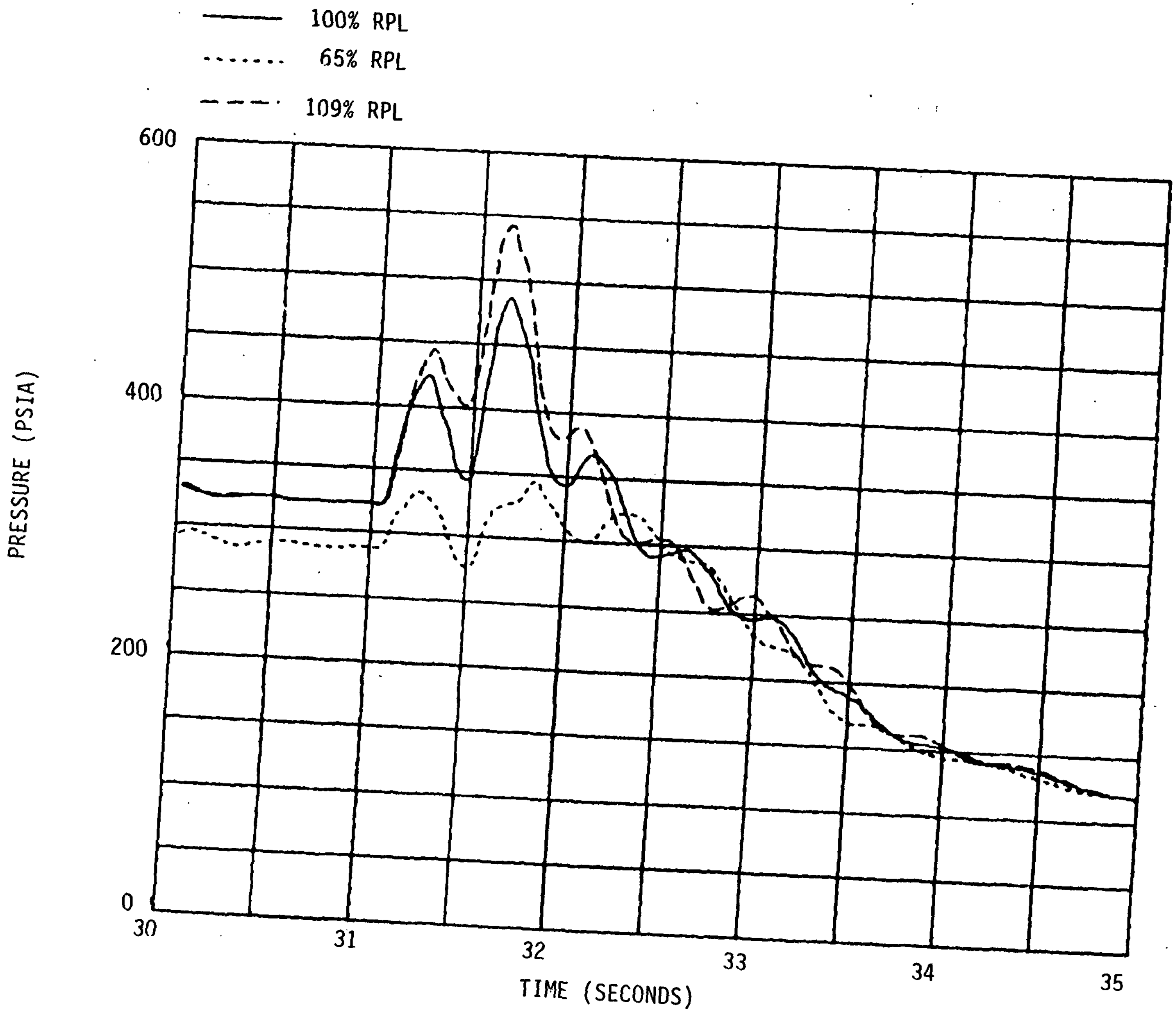

FIGURE 23

FAST SHUTDOWN WITH FPOV CLOSING AT MAXIMUM RATE

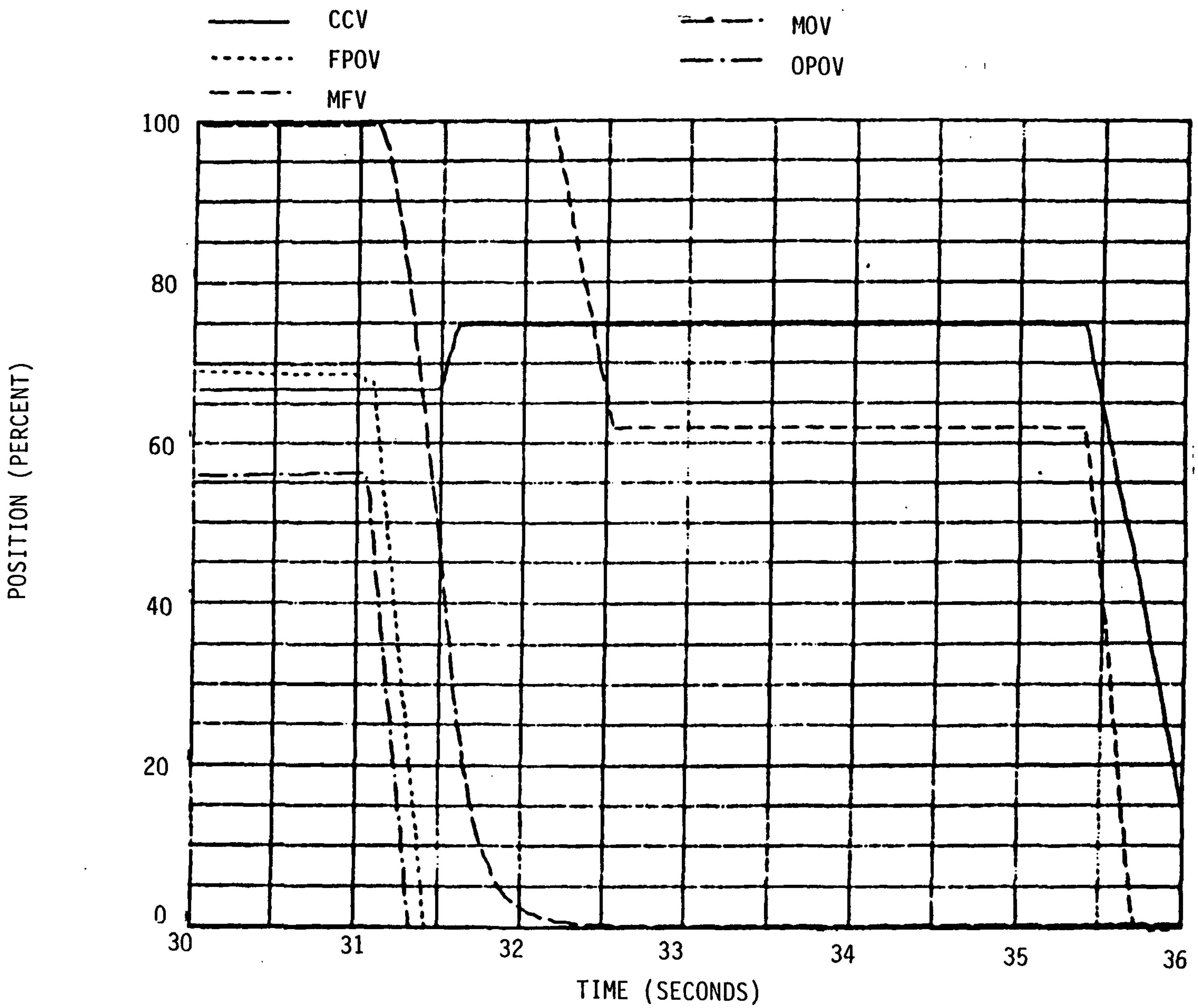

FIGURE 24

MAXIMUM FPOV CLOSING RATE MCC PRESSURE OSCILLATION

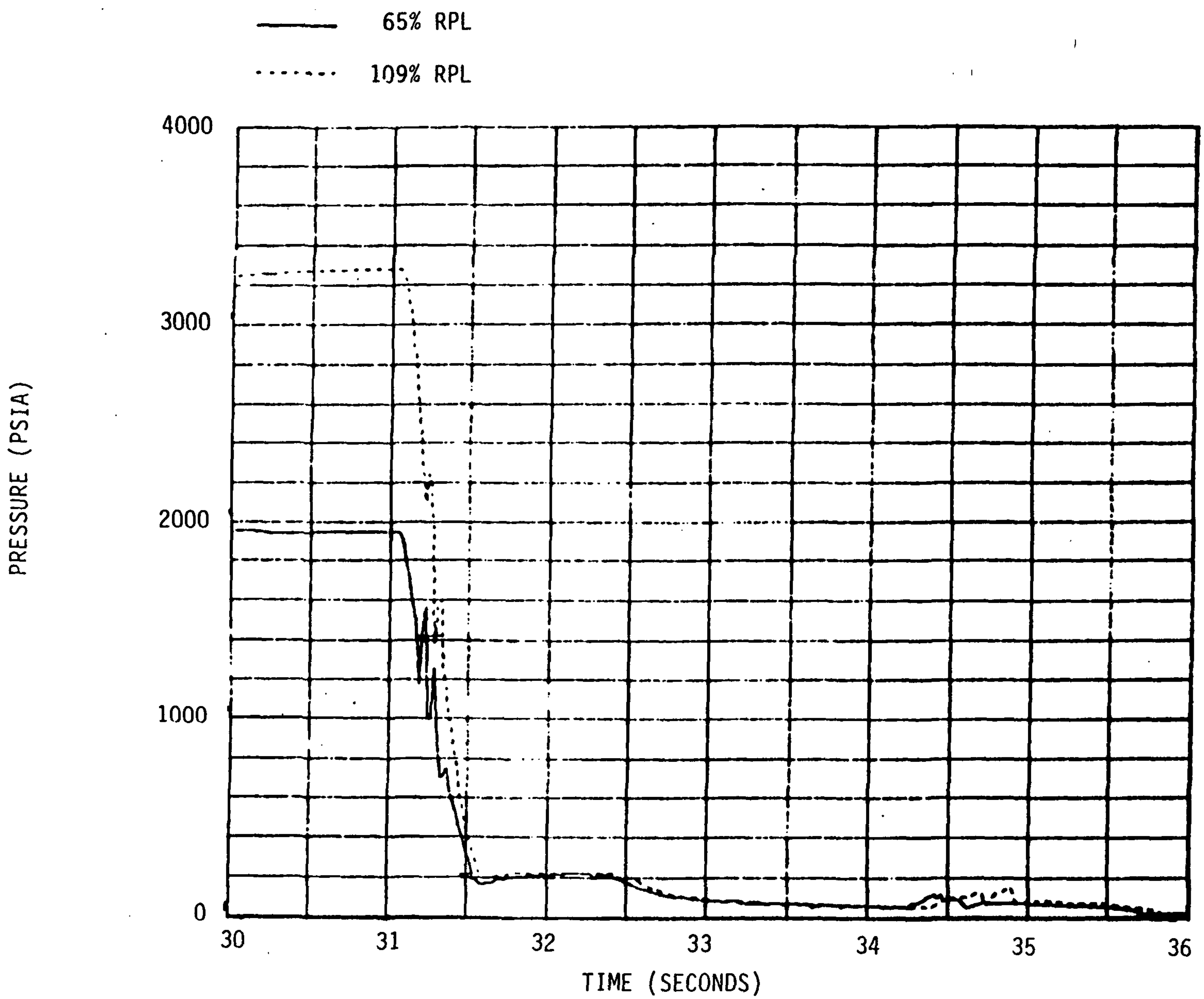

FIGURE 25

FAST SHUTDOWN WITH EXTENDED OPOV CLOSING SCHEDULE

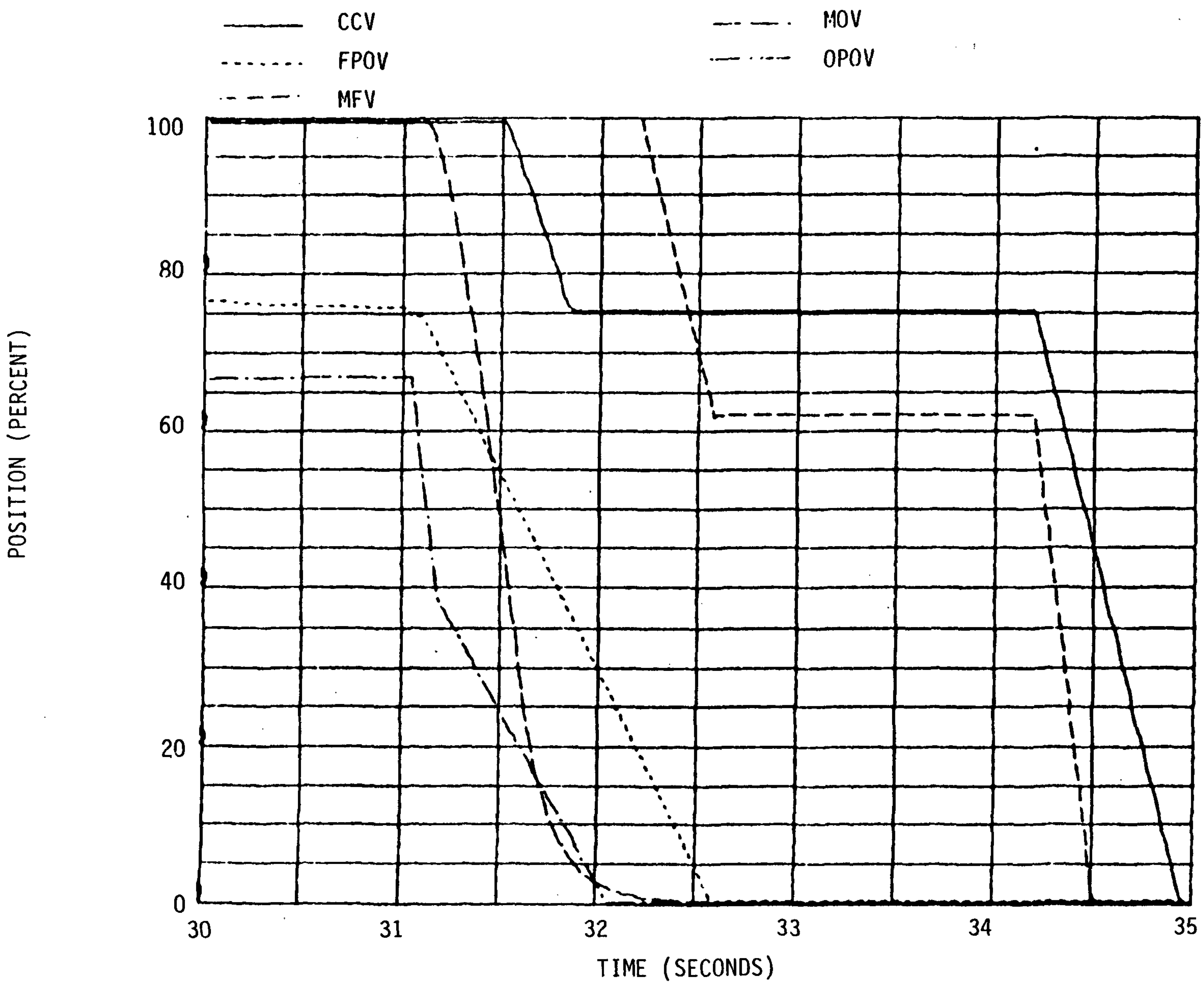

FIGURE 26

HPOTP PUMP DISCHARGE PRESSURE SURGE WITH OPOV DELAY

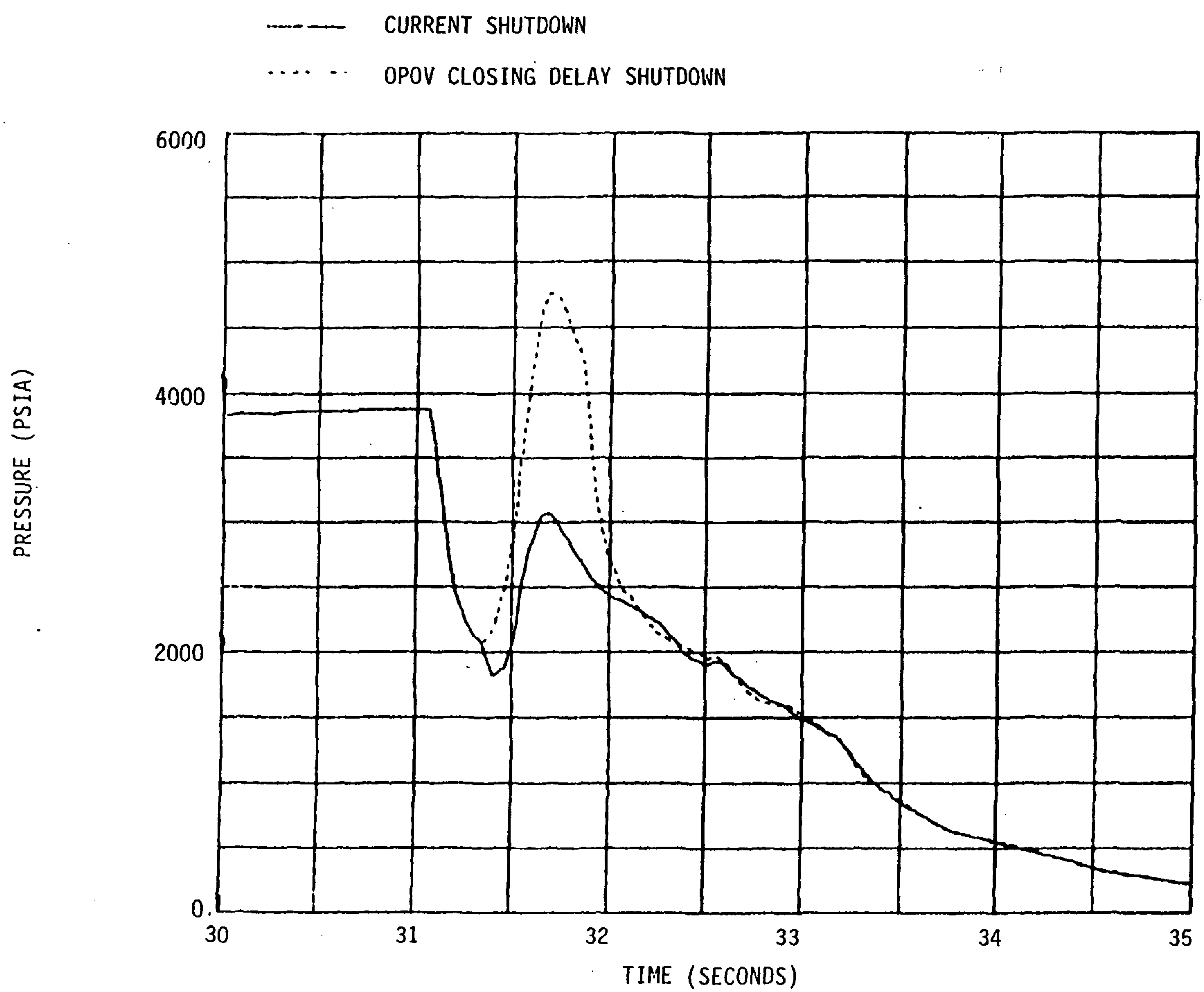

FIGURE 27

HIGH PRESSURE FUEL PUMP HEAD / FLOW PARAMETERS

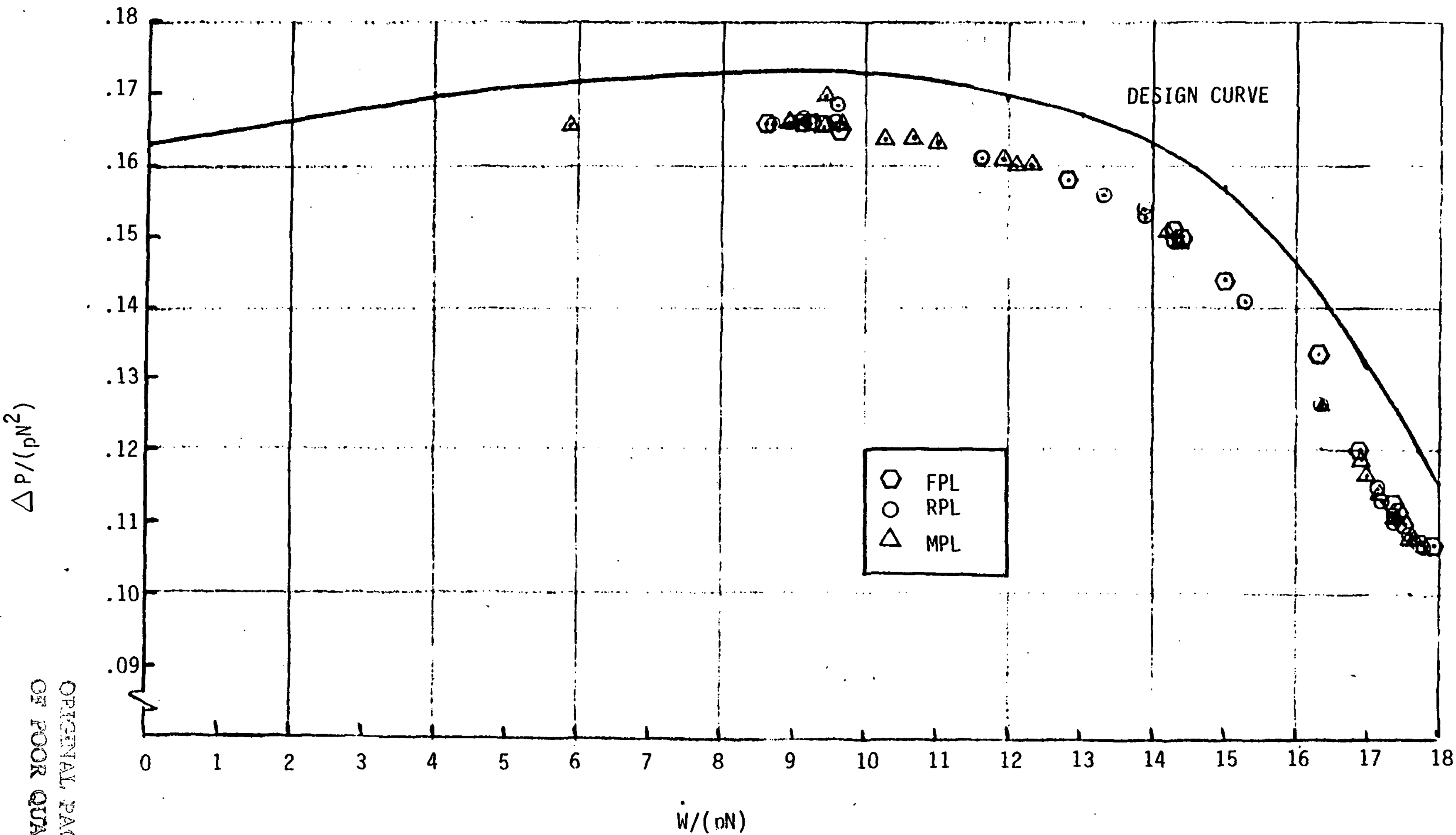

FIGURE 28