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PRELIMINARY FLIGHT RATING TESTS OF THE HAST PROPULSION SYSTEM

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JANUARY 1975

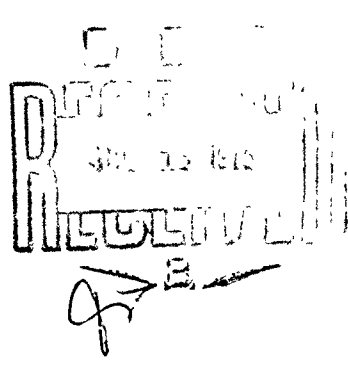
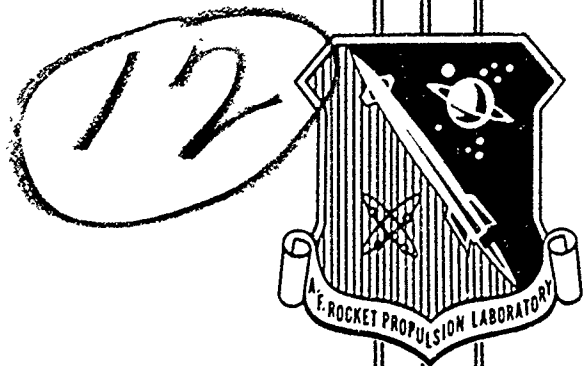
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FOREWORD

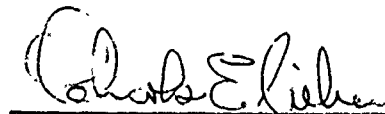
The work reported herein was accomplished by the Air Force Rocket Propulsion Laboratory (AFRPL) in response to a request by the Air Force Armament Laboratory (AFATL). The work supported the High Altitude Supersonic Target advanced development program being conducted by the AFATL under Project 469A. Funds required for the AFRPL test program were provided by the AFATL, with all manpower and facilities provided by the AFRPL under in-house project 314811RA. Test hardware and technical support were provided by Beech Aircraft Corporation (BAC) under Contract F08635-70-C-0100 with the AFATL, and by the United Technology Center (UTC) and the Marquardt Corporation (TMC) under sub-contracts to BAC. The AFATL project engineer for propulsion was Mr. Fred Hewitt. Contractor personnel providing support included Messrs. William Bryne, James Auiler, Gary Peterson, and Frank Chenoweth of BAC; Richard Jones and Bill Hunter of UTC, and Ed Wecker of TMC. The AFRPL project engineers were Capt Donald Grimes and Mr. Carlton D. Penn. Test engineers were Capt M. Fleiszar and Mr. Richard McQuown. Other AFRPL personnel making contributions to this effort included Messrs. John Branigan, Bernard Bornhorst and Herman Martens, and Capts J. Bon and Robert Jamieson. This document is unclassified and suitable for public release.

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) Preliminary Flight Rating Tests of the hybrid rocket propulsion system for the HAST target missile were accomplished by the Air Force Rocket Propulsion Laboratory. Nine tests of the flight configuration system were conducted at simulated altitude. Overall operating characteristics and performance were shown to be satisfactory for missile flight tests. The only test failure was the result of collapse of the oxidizer expulsion device, and a subsequent modification performed satisfactorily. Other problems included erratic pressure regulation, susceptibility of the oxidizer system to corrosion during (over)		

Item 20 (continued)
storage, and damage to the oxidizer pump bearings due to the lack of a static seal. Recommendations are made for component improvements in a future production vehicle.

SUMMARY

A limited Preliminary Flight Rating Test (PFRT) program for the High Altitude Supersonic Target (HAST) propulsion system was conducted by the Air Force Rocket Propulsion Laboratory, using an existing altitude test facility. The HAST propulsion system is based on a hybrid rocket engine, with a liquid oxidizer (inhibited red fuming nitric acid), and a solid fuel (80 wt. percent polybutadiene/20 wt. percent polymethylmethacrylate). The propulsion system is made up of two major sub-assemblies, the Oxidizer Management Assembly (OMA) and the Controlled Thrust Assembly (CTA). The OMA consists of the components required for the storage and pressurization of the oxidizer. These include a compartmented oxidizer storage tank, a start valve, and a pump which is driven by a ram air turbine. Tank pressurization is accomplished by a regulated nitrogen gas supply. A continuous oxidizer supply to the pump during vehicle maneuvers is assured by a tension screen which retains propellant in the aft tank compartment, and by a flexible propellant pickup device, called the free siphon, which moves in response to the local acceleration vector. The ram air turbine also drives an alternator for vehicle electrical power, and this assembly, including the oxidizer pump, is called the Ducted Power Unit (DPU). For the PFRT tests, the DPU was driven by gaseous nitrogen in a connected-pipe mode. The CTA includes the thrust chamber containing the solid fuel grain, oxidizer injectors, and an electromechanical throttle valve. The system produces a maximum boost thrust of 1200 lb_f, and is capable of on-command continuous throttling down to 120 lb_f.

A series of checkout tests of the DPU drive system and expulsion tests of the OMA were conducted prior to initiating the actual PFRT tests. These tests identified some component problems which were corrected. It was found that, at turbine inlet pressures representative of much of the planned HAST flight envelope, the DPU speed control was unstable. Speed control was by means of a butterfly throttle valve in the inlet duct, and the instability was manifested in oscillations of the butterfly. AFRPL controls analyses indicated unduly high gain in the speed control feedback circuitry could create instabilities at high inlet duct pressures. Most of the PFRT test program was intentionally conducted with duct pressures low enough, below 5 psia, that the oscillations did not occur. A reduced-gain speed control circuit was installed for the last two tests, and stability was demonstrated at higher duct pressures.

The OMA expulsion tests showed that the regulated tank pressure was too low to prevent pump cavitation. This problem did not occur until the system was tested at altitude because the regulator is a gage pressure device, using ambient pressure as a reference, and thus provides a higher absolute pressure output when in a one-atmosphere environment than in a vacuum. The regulator set point was increased by 10 psia, and a successful demonstration of the complete OMA was obtained. Prior to the

definition and solution of this regulator problem, two other problems had occurred during the OMA tests. On the first test, the free siphon had collapsed, severely restricting the oxidizer flow. This was caused by the siphon inlet not having adequate initial clearance to the tank bottom, and then being sucked down to the bottom when the flow was being accelerated. This problem was corrected by providing adequate clearance. There was also an instance of flow restriction caused by plugging of the tension screen. The plugging was due to accumulation of corrosion products from previous exposure to oxidizer, and was corrected by limiting the exposure time.

A total of nine PFRT tests were conducted, simulating mission duty cycles planned for the flight test program. Eight of these tests were successful. The one failure, on the second test, was caused by another collapse of the free siphon. A special series of water expulsion tests in a transparent tank showed that the collapse was due to pressure and flow transients induced by the rapid opening of the oxidizer start valve. While the siphon was being redesigned to resist this failure mode, the test program continued with a rigid standpipe replacing the siphon. The modified free siphon design was utilized successfully on the last two tests.

During the PFRT tests, there was also a repetition of the tension screen plugging problem, although less severe and due to a somewhat different basic cause than on the OMA tests. Repetitive cleaning of the oxidizer tank had etched the grain boundaries in the wall and increased the surface area available for corrosion. The corrosion products created after a relatively short time of exposure to IRFNA partially plugged the screen, but in no instance did this restrict the flow. The problem was corrected by a revision in the cleaning procedure to eliminate a final nitric acid pickling.

The pressure regulators showed somewhat erratic operation, with several instances of low pressure output from the first stage regulator. The second stage regulator was generally satisfactory but there was one instance where it failed closed. Since this was late in the test, with a large tank ullage volume, the pressure during the ensuing blowdown stayed well above the minimum to prevent pump cavitation.

Static seals between the oxidizer pump and the alternator were shown to be incapable of preventing residual oxidizer from entering the bearings and alternator windings. There were several instances of damage to these components because of the resulting corrosion. The problem was largely alleviated by a shutdown procedure which permitted the residual oxidizer to be vented while the dynamic seal was still operative. This procedure more closely simulated in-flight shutdown conditions expected with the HAST at high altitude.

There were no problems with the CTA. Fuel utilization was generally good, with typically at least 95 percent of the initial fuel loading being consumed, and in some instances nearly 100 percent. The delivered total impulse was typically near 150,000 lbf-sec.

The conclusion was that, despite the component problems, the operation of the total propulsion system was generally satisfactory and the system is ready for flight tests. Failure of a flight test is not anticipated because of component deficiencies, but there could be performance degradation, particularly as related to the regulator operation.

Recommendations are made for improvements of the HAST propulsion system if it is to be put into production. A more reliable pressure regulator is needed, and an alternate pulse-modulated, or "bang-bang", approach is suggested. There is also a need for a more effective pump seal, and provision should be made for isolation of the oxidizer tank after shutdown. The tension screen should be replaced by a propellant retention device which is not susceptible to plugging from corrosion products expected after long term storage.

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SECTION I

INTRODUCTION

The High Altitude Supersonic Target (HAST) is a reusable target missile capable of cruise at speeds up to Mach 4.0 at altitudes of 100,000 ft after air launch at Mach 1.5 at 50,000 ft. The target is intended for tri-service use for training and weapon systems evaluation. A unique feature of this vehicle is the hybrid rocket propulsion system, which uses a liquid oxidizer (inhibited red fuming nitric acid) and a solid fuel (80 wt. percent polybutadiene/20 wt. percent polymethylmethacrylate). The current vehicle development was preceded by the Sandpiper Target Missile demonstration in 1968, with three successful flights of a hybrid rocket powered expendable vehicle.

The Sandpiper program was jointly sponsored by the Air Force Armament Laboratory (AFATL) and the Air Force Rocket Propulsion Laboratory (AFRPL) through respective contracts with Beech Aircraft Corporation (BAC) for the vehicle development and system integration, and United Technology Center (UTC) for the hybrid propulsion development. The current phase of the HAST program is being conducted by the AFATL as an Advanced Development Program, with the AFRPL providing technical and management consultation for the propulsion system. BAC is the prime contractor, with UTC a subcontractor responsible for the hybrid thrust chamber and throttling valve. Other major subcontractors for the propulsion system are The Marquardt Company (TMC), which provides the ducted power unit (oxidizer pump and electrical supply), and Futurecraft Corporation, which provides the nitrogen pressure regulators.

In addition to the propulsion consultation role, the AFRPL was requested by the AFATL to conduct a limited Preliminary Flight Rating Test (PFRT) program for the HAST propulsion system, using an existing altitude test facility at the AFRPL. The objectives of the PFRT were

to: (1) demonstrate that the propulsion system will reliably perform the intended flight test missions, (2) verify safe altitude ignition and operation so as to be able to certify flight safety, and (3) obtain performance data at simulated altitudes for selected flight test missions.

SECTION II

HAST PROPULSION SYSTEM

The inboard profile of the HAST target missile is shown in Figure 1. The components of the propulsion system that were tested in the PFRT program may be seen in the drawing. These components are part of two sub-assemblies of the propulsion system, identified as the Oxidizer Management Assembly (OMA) and the Controlled Thrust Assembly (CTA).

The OMA includes all components for the storage and pressurization of the oxidizer (Type III B IRFNA). These include the oxidizer tank, start valve, Ducted Power Unit (DPU-includes the oxidizer pump, alternator, and ram air turbine), nitrogen storage tank, pressure regulators, and associated plumbing. The CTA includes the thrust chamber assembly with the solid fuel grain, oxidizer throttle valve, injectors and associated plumbing. Drawings and photographs of the OMA and CTA are shown in Figures 2 through 5.

Oxidizer Management Assembly

The oxidizer tank is a rolled and welded structure of 17-7 PH stainless steel. The tank volume is 9,465 cubic inches, with a maximum IRFNA loading of 496 pounds. The tank is divided into four compartments so as to control the location of the vehicle center of gravity as oxidizer is consumed. The forward three compartments are connected by transfer ports at the bottom of the bulkheads. Provisions are made to retain propellant in the aft compartment during vehicle maneuvers and to insure propellant flow through the outlet port.

Propellant retention is accomplished by a surface tension screen in the forward bulkhead of the aft compartment. Sufficient pressure differential is available to allow propellant to flow into the aft compartment,

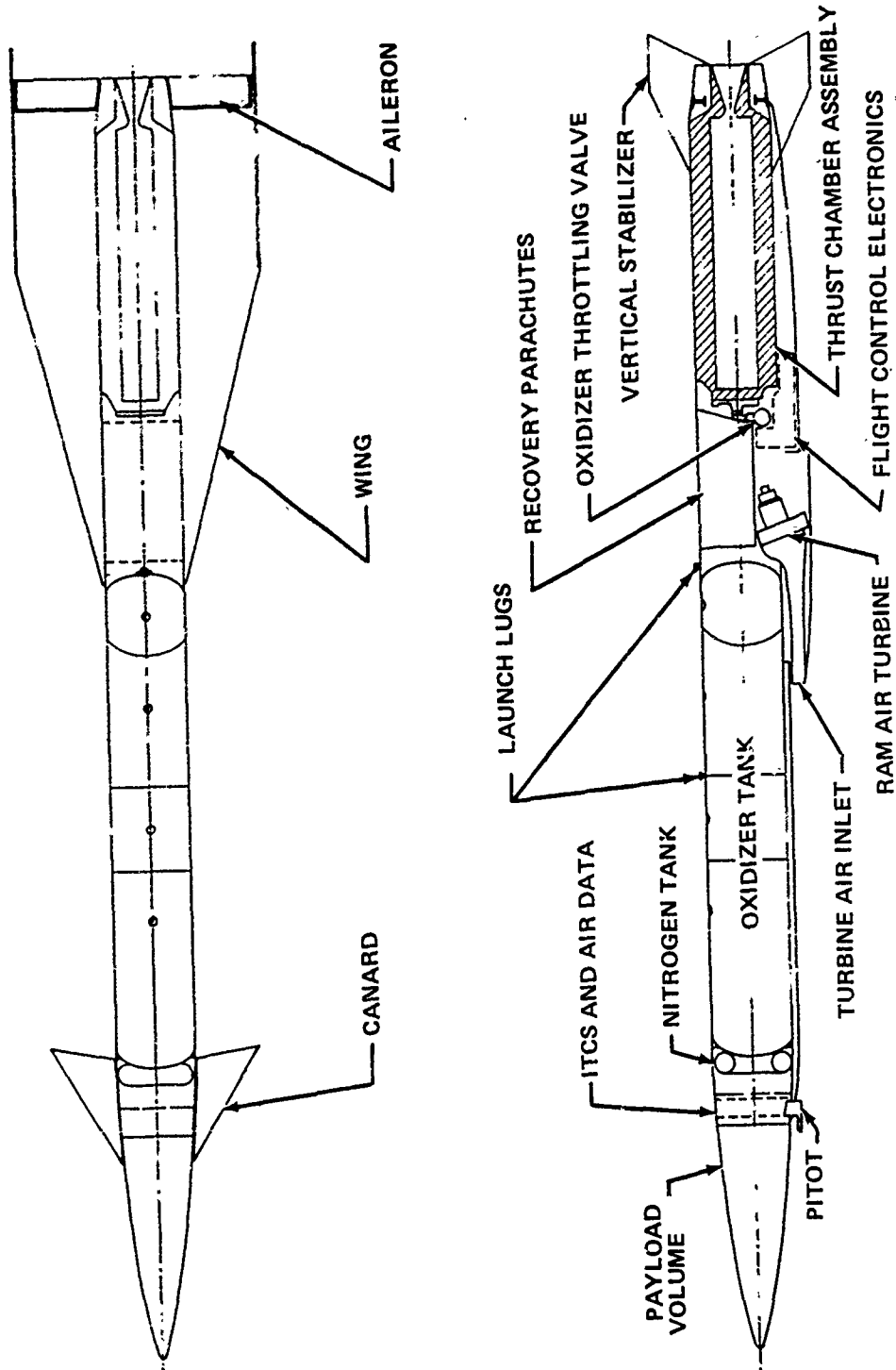


Figure 1. HAST Inboard Profile

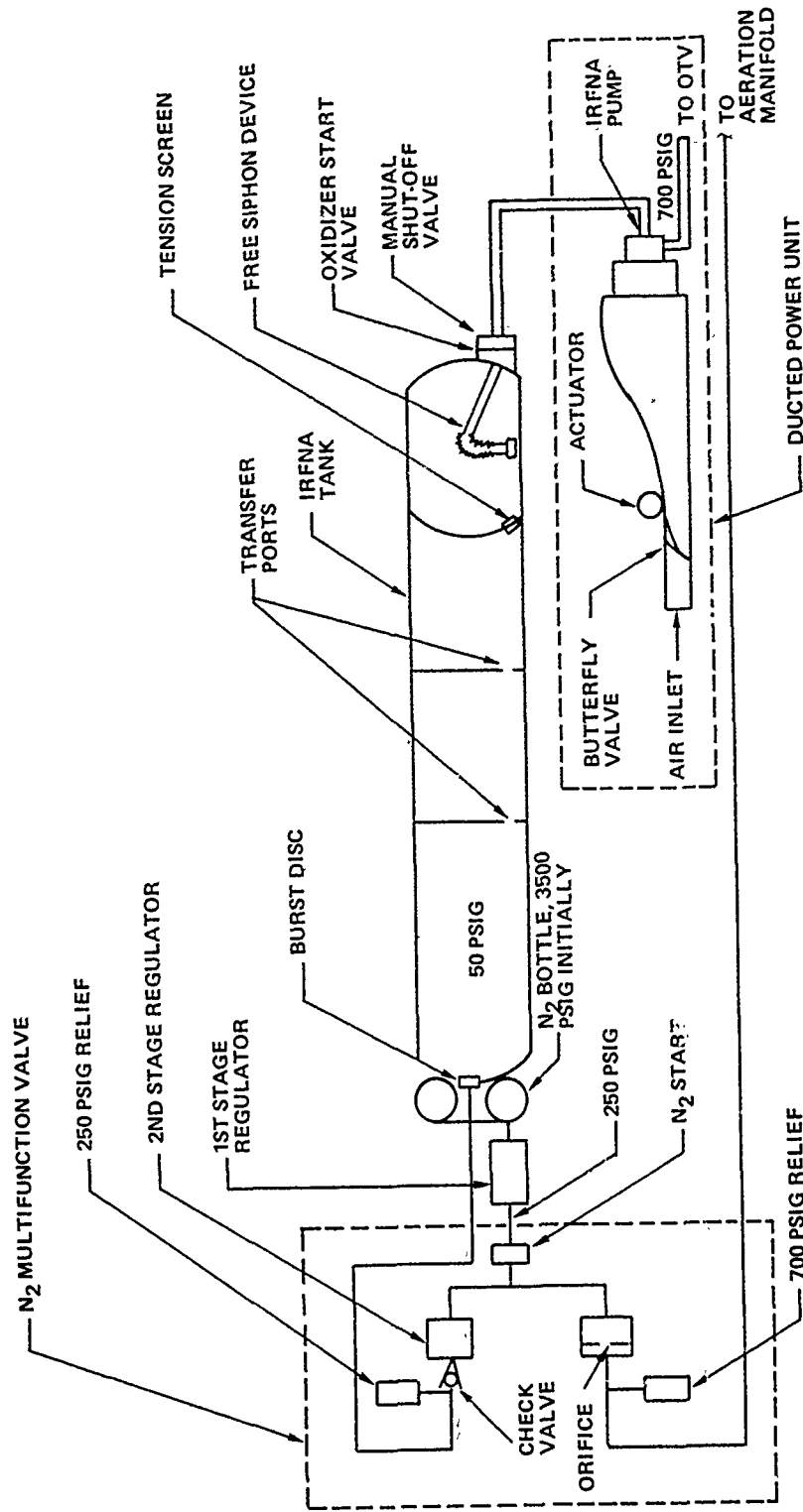


Figure 2. Functional Diagram of Oxidizer Management Assembly



Figure 3. Oxidizer Management Assembly Installed in Test Cell

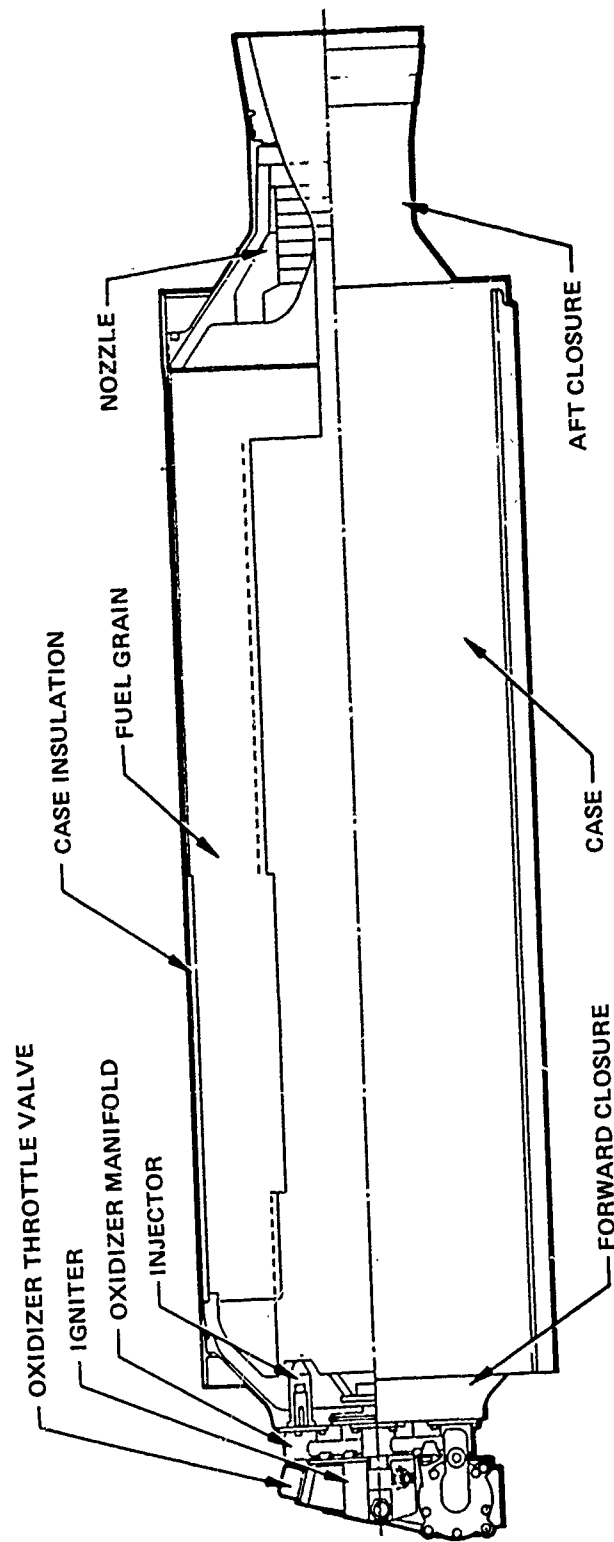


Figure 4. Controlled Thrust Assembly



Figure 5. Controlled Thrust Assembly Installed in Test Cell

but surface tension forces are high enough to prevent back flow of propellant out of the aft compartment under the forces expected to be produced by vehicle maneuvers (not to exceed 5 g's). The nominal pressure differential across the screen at boost flow rates is 7 psid. The screen material is 304L stainless steel.

Outflow from the aft compartment takes place through a flexible tube which is termed a "free siphon". This device is weighted on the free end and is flexible enough to follow the local resultant acceleration vector as the vehicle maneuvers. Thus when the aft compartment is only partially full, the end of the siphon follows the residual propellant as it moves within the almost spherical compartment. The siphon is constructed by heat shrinking a seamless Teflon sleeve over a stainless steel wire helix, and the helix ends are restrained in elongation by a stainless steel chain.

Isolation of the propellant prior to launch is accomplished by an oxidizer start valve located at the tank outlet. This is an explosive actuated valve in which firing of a pressure cartridge activates a piston, shearing a cap in the outlet port. After a test, the tank can again be isolated by manually operating a blade valve which is within the start valve body.

The functions of the Ducted Power Unit (DPU) are to pump the oxidizer to the pressure required by the thrust chamber and to provide electrical power for the vehicle. The unit contains a ram air turbine, an alternator, and a centrifugal oxidizer pump, all mounted in that order on a common shaft which rotates at a nominal speed of 32,000 rpm. The DPU is illustrated in Figures 6 and 7. The turbine is driven by air admitted through a normal shock inlet underneath the vehicle, with air flow throttled by a butterfly valve in the inlet duct. Position of this butterfly is controlled by an electronic speed control circuit and electric actuator. The oxidizer pump impeller is a radial vane type and is unshrouded. The pump produces a pressure rise of 685 psia at an IRFNA flowrate of 3.6 lb/sec at 70°F with a minimum suction pressure of 30 psia. The alternator was required to produce 47 amperes maximum at 28 volt DC.

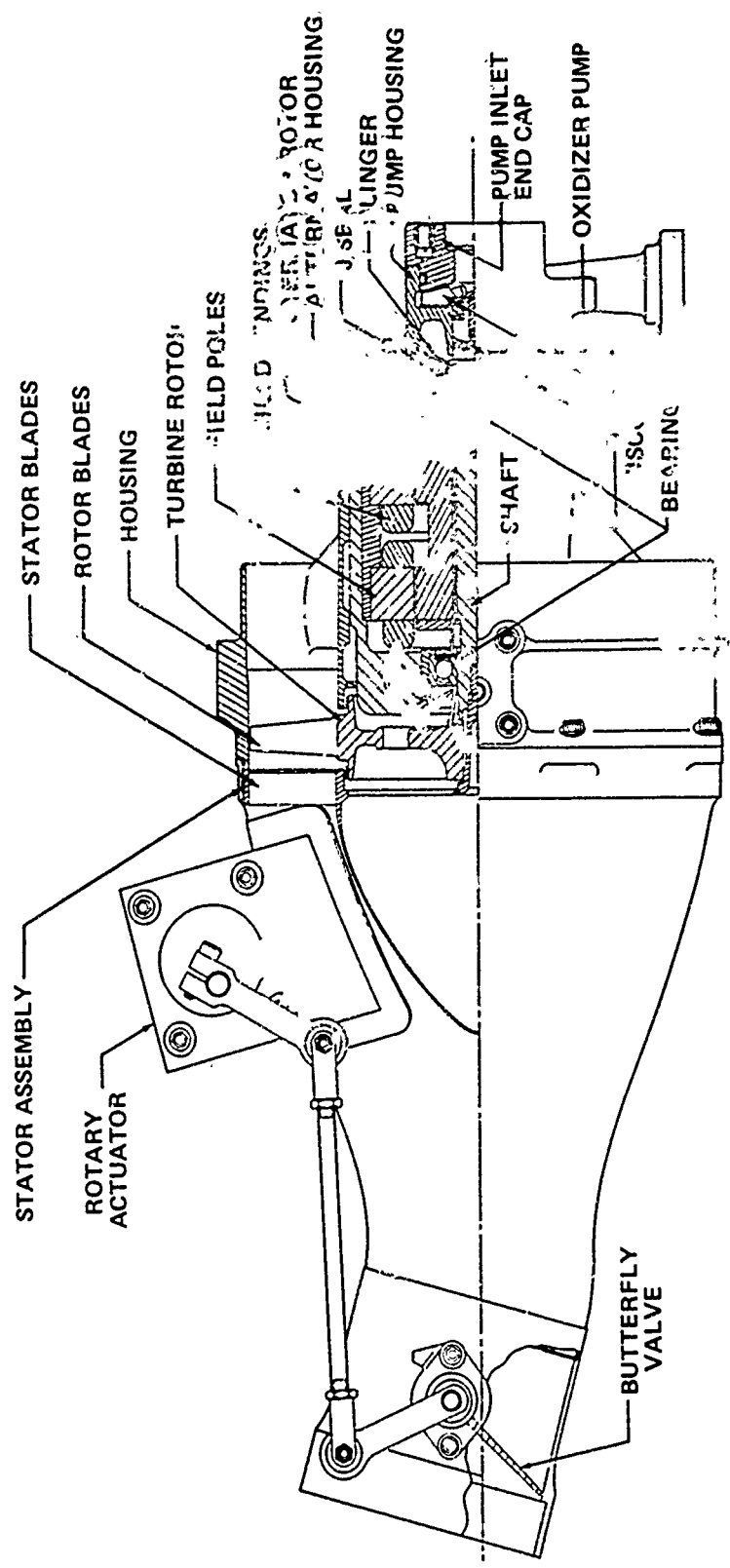


Figure 6. Ducted Power Unit



Figure 7. Test Installation of Ducted Power Unit

The dynamic seal between the pump and the alternator uses the visco-seal concept. Helical grooves are machined into the shaft, and there is a very small clearance between the groove lands and the housing bore (see Figure 6). At speed, the rotating helix resists flow along the shaft from the pump impeller toward the alternator. The seal is designed for zero leakage at a pump inlet pressure of 50 psia. A centrifugal slinger pumps any leakage overboard through the seal cavity drain.

A static seal is provided immediately adjacent to the slinger. This is a Teflon diaphragm with a shape resembling the letter "J", and is thus termed a J-seal. The inner edge rests on the shaft, and the outer edge is fixed to the housing. This seal can withstand a pressure differential of 15 psid in the static condition, thus allowing a low pressure leak check of the oxidizer plumbing between the pump and the OTV. As the shaft rotates, frictional heating causes the curved lip of the J-seal to expand away from the shaft, establishing a running clearance.

Gaseous nitrogen for pressurizing the oxidizer tank is stored in a toroidal tank made of 17-7 PH steel. The tank volume is 317 cu in, containing 3.3 lb of nitrogen at 3500 psia. Two stages of pressure regulation are used to reduce this pressure to the desired tank pressure of approximately 50 psia. The first stage is a spring reference, piston actuated, gage pressure regulator. The outlet pressure regulator band is specified to be 340 to 280 psig over a gas flow range of 1 to 10 SCFM. The second stage regulator is contained within the multifunction valve (MFV) and is supplied directly from the first stage regulator (see Figure 2). This regulator is the same type as the first stage. The required outlet pressure is 68 to 53 psig over a gas flow range of 1 to 8 SCFM. The nitrogen tank and regulators are shown in Figure 8.

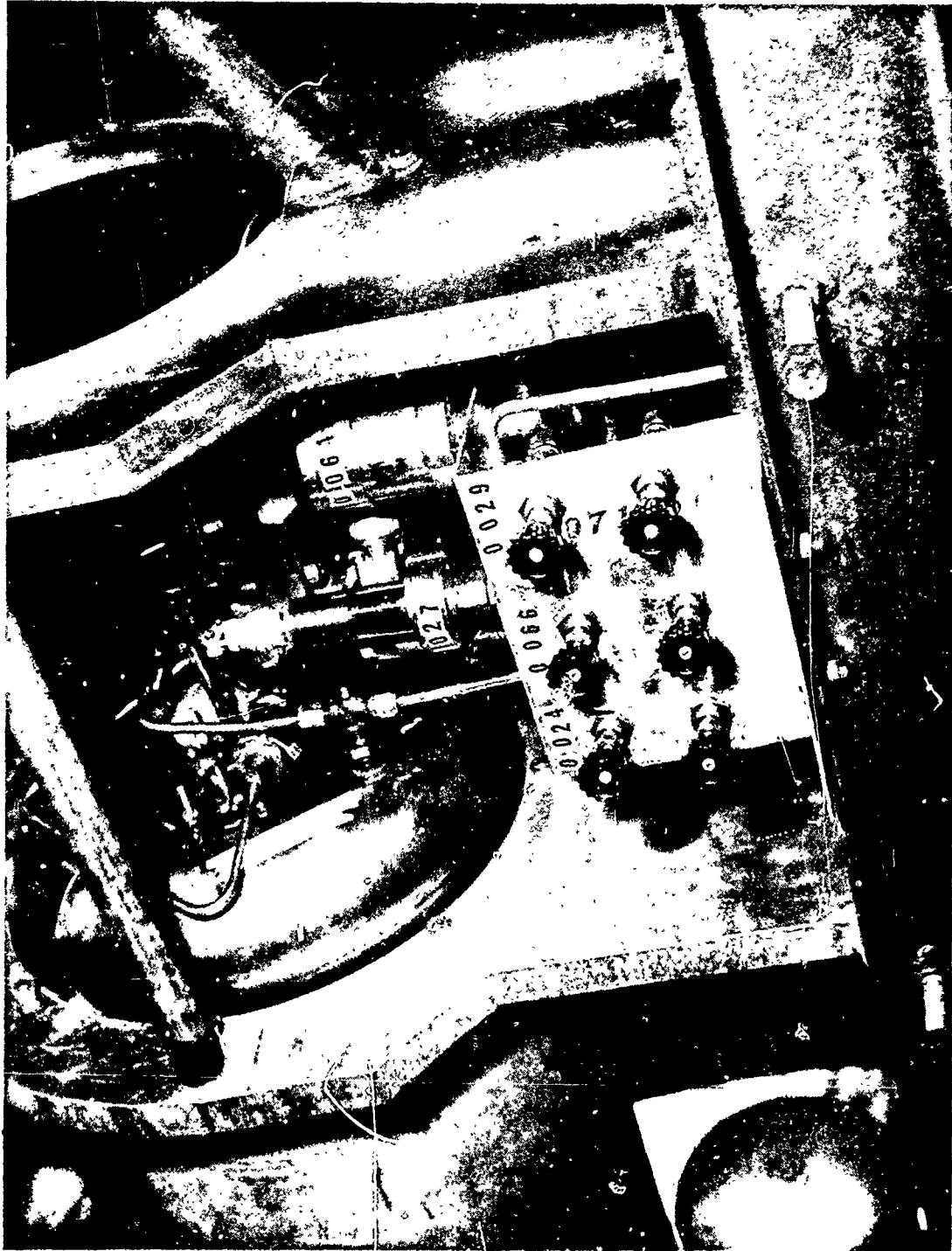


Figure 8. Test Installation of HAST Pressurization System

The first stage regulator also supplies the aeration gas for the thrust chamber injectors. This flow is metered by a sonic orifice in the MFV body, with the first stage regulator pressure applied immediately upstream of the orifice. The aeration flow is approximately 2 SCFM.

The MFV also incorporates two relief valves. One provides a pressure relief for the aeration supply (first stage regulator pressure) at 700 psig. The other is a relief for the oxidizer tank (second stage regulator pressure) at 250 psig. A check valve in the MFV prevents back flow from the oxidizer tank after the propulsion system is shut down and the nitrogen supply depleted.

A shear pin at the MFV inlet isolates the nitrogen tank prior to start of the propulsion system. This pin is sheared by a piston which is driven by an explosive pressure cartridge.

An aluminum burst disc at the oxidizer tank pressurization inlet isolates the regulators from the oxidizer. This disc ruptures when a differential pressure of 20 ± 5 psid is applied in the forward direction, and can withstand a differential pressure of 150 psid in the reverse direction.

Controlled Thrust Assembly

The thrust chamber case is shear spun from 4130 steel. It contains 153 lb of the solid fuel, a mixture of 80 wt. percent polybutadiene and 20 wt. percent polymethylmethacrylate. The fuel is molded into wafers approximately two inches thick. These are then stacked and bonded to the case insulation.

The nozzle throat is a stack of pyrolytic graphite washers. The entrance and exit sections of the throat are made of high density graphite. The nozzle exit section and the throat backup are silica phenolic. The throat diameter is 1.675 in., and the nozzle expansion ratio is 20:1.

The injectors produce a conical spray pattern by means of tangential spinners in the flow passage. There are four injectors, each aligned with a port in the fuel grain. At low flow rates, the spray pattern and oxidizer atomization are maintained by gas aeration, with nitrogen gas introduced just downstream of the spinner. Aeration is not used during the maximum flow rates. A check valve at the inlet to the aeration manifold on the forward closure allows aeration gas to flow when chamber pressure drops below the aeration supply pressure.

Oxidizer flow rate is controlled by the oxidizer throttle valve (OTV). The valve is mounted on the thrust chamber forward closure, and its outlet is connected directly to the injector manifold. The pintle within the OTV is positioned by a torque motor which drives a ball screw actuator. Associated electronic components are housed within the valve package.

Prior to starting the propulsion ignition sequence, the OTV is in the closed position. At the OTV ignition command, the valve opens rapidly to approximately 50 percent open. Ignition in the thrust chamber occurs at this condition (750 lb thrust), and the OTV then ramps linearly to the full open position in 20 seconds. The valve remains full open as long as the boost command is applied. Upon removal of the boost command, the oxidizer flow can be throttled by inputting the desired sustain voltage. In flight, the on-board flight controller removes the boost command when the desired Mach number has been attained, and then throttles the OTV to maintain this Mach number. The OTV can be closed by inputting a shutdown command.

The fuel and oxidizer are not hypergolic, therefore requiring an ignition source. Hot gases for ignition are produced by a solid propellant grain which burns for 2.5 seconds. The igniter grain is contained within a case which is attached to the forward closure.

Event Sequencing

An on-board Digital Logic System (DLS) sequences the propulsion system start events, in addition to performing pre-launch checkout functions. The start sequence is as follows:

<u>Event</u>	<u>Time (Seconds), Cumulative</u>
Launch	0
Nitrogen Start Valve Opens	0.5
Oxidizer Start Valve Opens	0.9
CTA Igniter Fires	1.7
OTV Opens	2.2
Full Thrust	22.2

SECTION III

TEST FACILITY

All tests were performed at simulated altitude in the AFRPL Test Facility 1-42A. The altitude chamber is equipped for test firings in a horizontal position with either liquid or solid propulsion systems having a maximum thrust of 20,000 lbs. The combustion products are exhausted through a 4 ft diameter duct. The duct is water-cooled, and the combustion products are also cooled by a water spray. The test chamber is evacuated for altitude simulation by a two-stage steam ejector system. The system is capable of not only initially evacuating the chamber to a pressure altitude of approximately 100,000 ft but has sufficient pumping capacity to maintain this altitude during the engine firing. Three parallel two-stage ejector systems are available, but the exhaust flow rate of the HAST propulsion system was low enough that only one two-stage system was used to maintain altitude. The ejectors are driven by saturated steam which is obtained by heating water in propane boilers. Three boilers are used, and the hot water is stored in nine 50,000 gallon spherical pressure vessels. The water is then flashed to steam when the altitude simulation is required.

For the HAST OMA tests, it was only necessary to provide a pressure in the test chamber low enough that the ram air turbine could be driven at design speed and power with the low pressure facility nitrogen supply system. Therefore, these tests were conducted at a simulated altitude of 55,000 ft, which was obtained by operating only a single second-stage ejector. The PFRT tests were accomplished at altitudes of 90,000 to 110,000 ft so as to insure that the thrust chamber nozzle was fully expanded at the lowest chamber pressure.

The steam system was modified for the HAST tests so as to have the capability of controlling the pressure in the test chamber at the start of the test. Prior to the simulated launch, with the nitrogen

drive gas for the ram air turbine flowing into the chamber, the ejectors could maintain an altitude of at least 100,000 ft. However, during full boost flow, it was calculated that the altitude would drop to 90,000 ft. This would result in some of the combustion gases being recirculated into the cell rather than being completely exhausted. In order to prevent this recirculation, the altitude at the start of the test was controlled to 90,000 ft so that there would be no increase in pressure during boost. A bleed was installed so that steam could be injected upstream of the first stage ejector, artificially loading the ejector and decreasing its pumping capability. The bleed steam could be throttled to obtain chamber altitudes between 75,000 and 100,000 ft.

Oxidizer System

The facility oxidizer systems provided means for loading the desired amount of IRFNA into the HAST oxidizer tank and for remotely off-loading the oxidizer in the event of an emergency. Both these systems are shown schematically in Figure 9.

The IRFNA was loaded from 55 gallon drums through fill and vent devices which attached to the oxidizer tank fill ports, with control by appropriate valving on a fill console. This system was provided by BAC. The fill console is shown in Figure 10, and Figure 11 shows the fill and vent components in place on the HAST oxidizer tank. The tank was filled through the port on the forward compartment, while the other compartments were vented through the individual vent valves. All four compartments were filled and then liquid was extracted from the forward compartment to provide the desired ullage volume. The volume of ullage to be extracted was determined by the temperature of the liquid so that the required mass of IRFNA would remain in the tank. In most cases the loaded weight of IRFNA was 496 lb. The volume being extracted was measured by a sight gage on the accumulator which was part of the fill console.

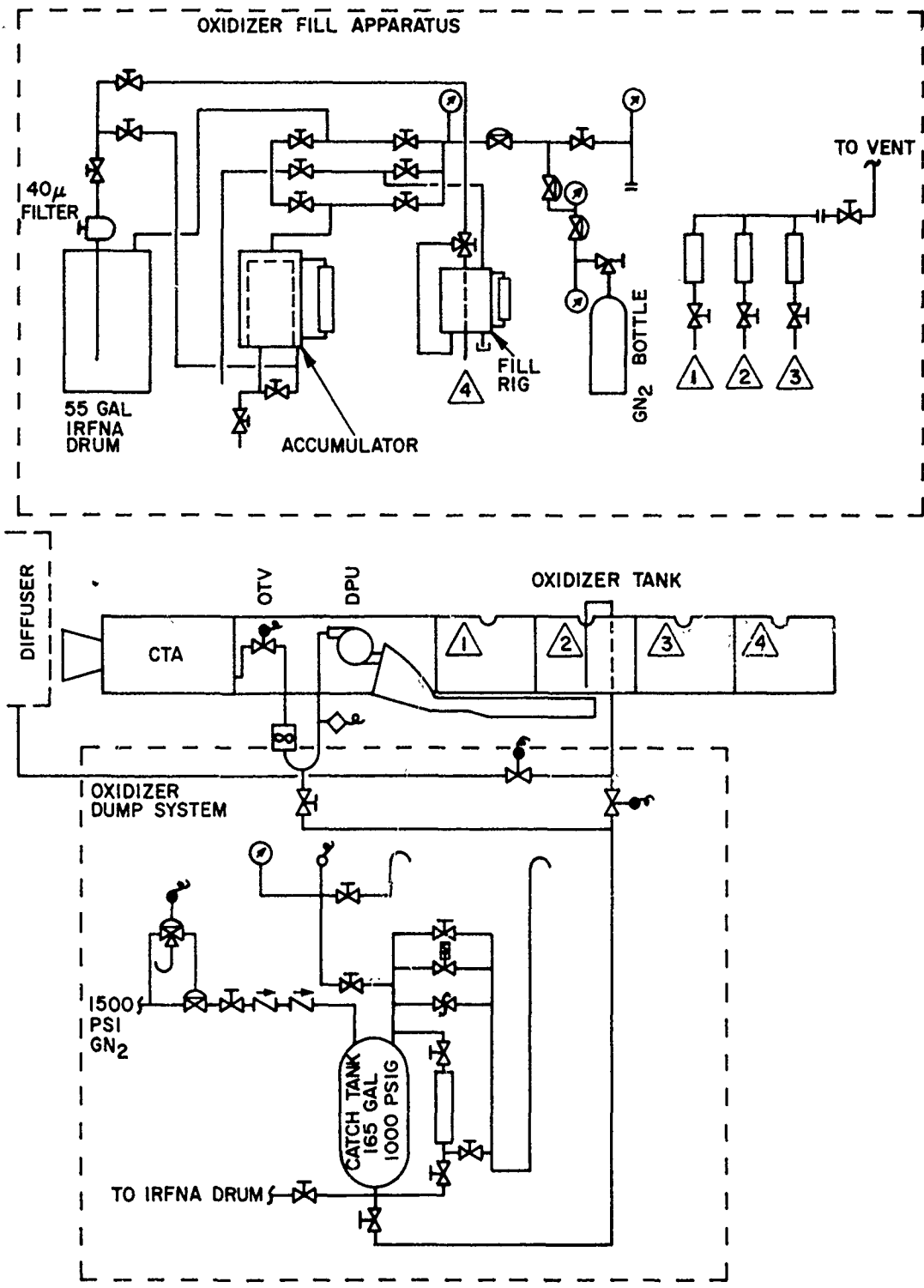


Figure 9. Schematic of Oxidizer Systems

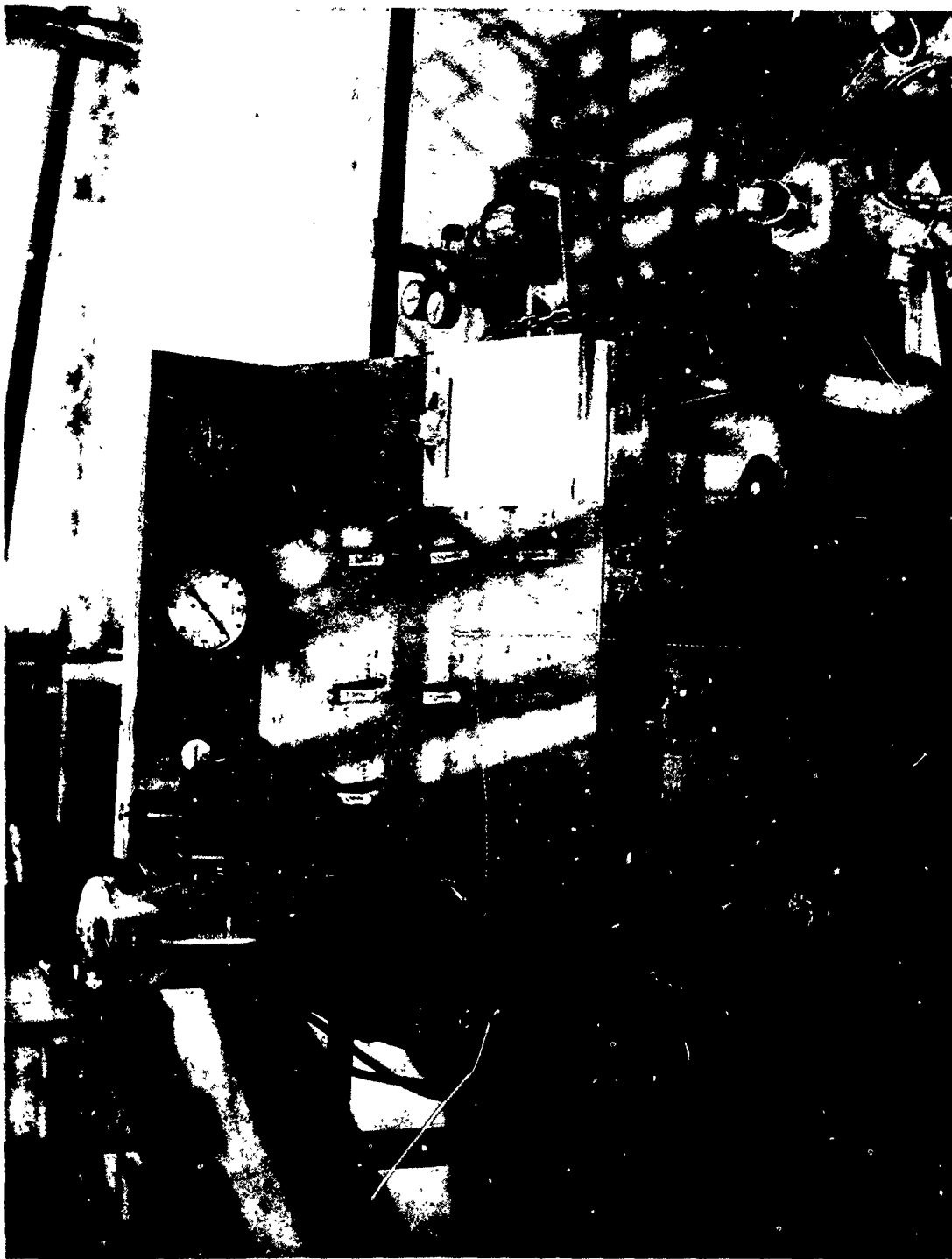


Figure 10. HAST Oxidizer Servicing Console

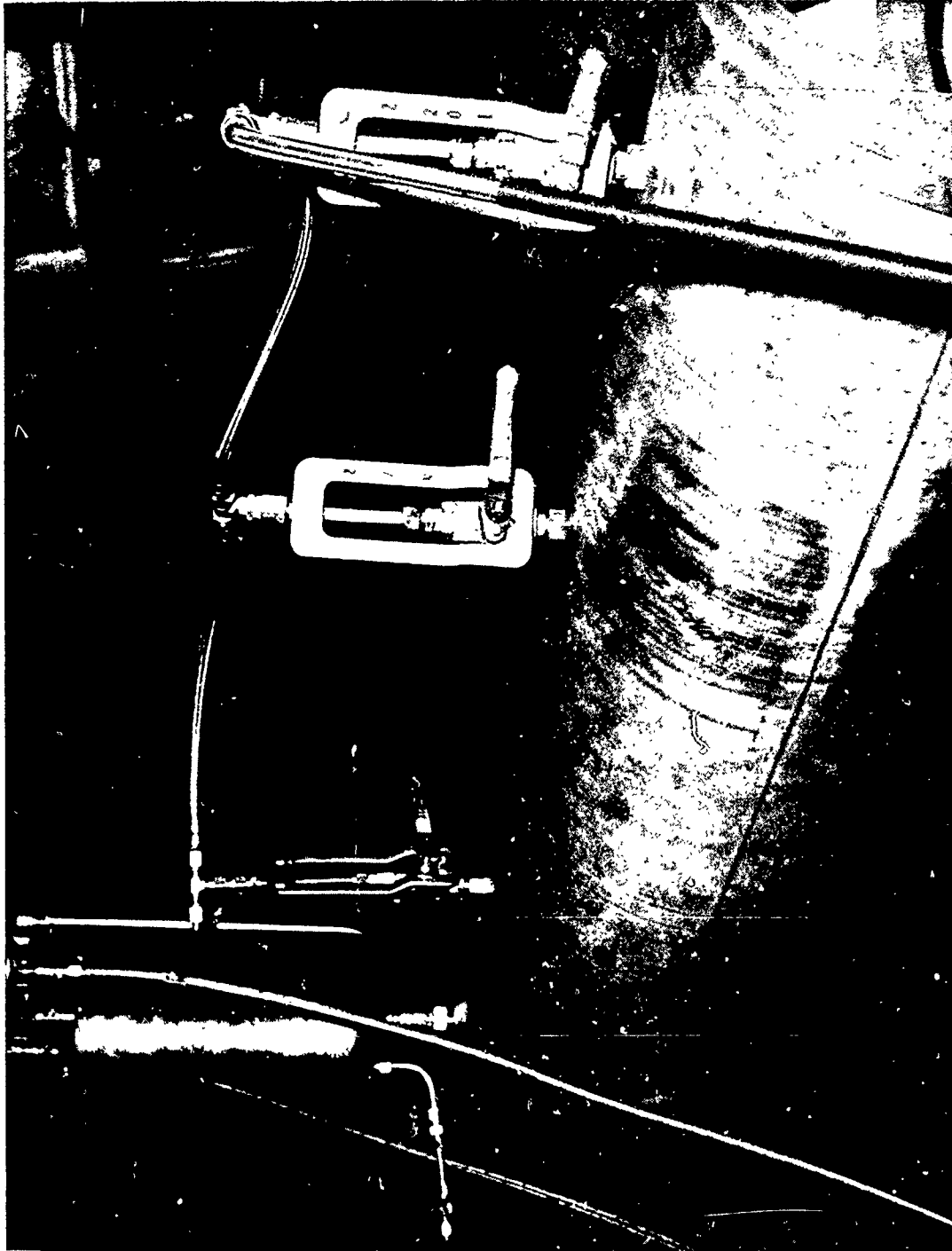


Figure 11. Fill and Vent Apparatus in Place on Oxidizer Tank

The emergency system provided for expelling the oxidizer from the HAST tank into a catch tank outside the test chamber. By opening appropriate remotely operated valves, nitrogen pressure in the HAST tank would expel the oxidizer through a dip tube in one of the compartments.

The catch tank was also used as the receiver during the OMA expulsion tests which were conducted prior to the PFRT tests. For these tests, the CTA was not installed. The oxidizer pump discharged to a facility throttle valve which simulated the OTV. This valve was a 3/4 in. Annin valve (Model Nr 1560, $C_v = 1.5$) with a Domotor controller. A square-edged orifice of 0.205 in. diameter was installed between the throttle valve and the catch tank to provide a back pressure equivalent to injector inlet pressure.

Nitrogen System

The facility gaseous nitrogen systems included means for driving the ram air turbine, filling the high pressure nitrogen storage tank, pressurizing the oxidizer tank, and purging the oxidizer tank and injector manifold after the test. These systems are shown schematically in Figure 12. Other than the turbine drive, these are conventional test facility systems and need no further discussion.

The turbine drive system was capable of providing a maximum gaseous nitrogen flowrate of 2 lb/sec and was designed so that the pressure in the DPU inlet duct could be controlled during a test. The system consisted of two independent branches, each containing a pressure regulator, an isolation valve, and a sonic orifice of 0.223 in. diameter. The two branches were made of 2 in. schedule 160 pipe, and fed into a common 4 in. schedule 10 pipe downstream of the regulators. A bellows was provided in this pipe just before it was attached to the thrust stand. A 6-in. diameter transition duct between this pipe and the DPU inlet contained

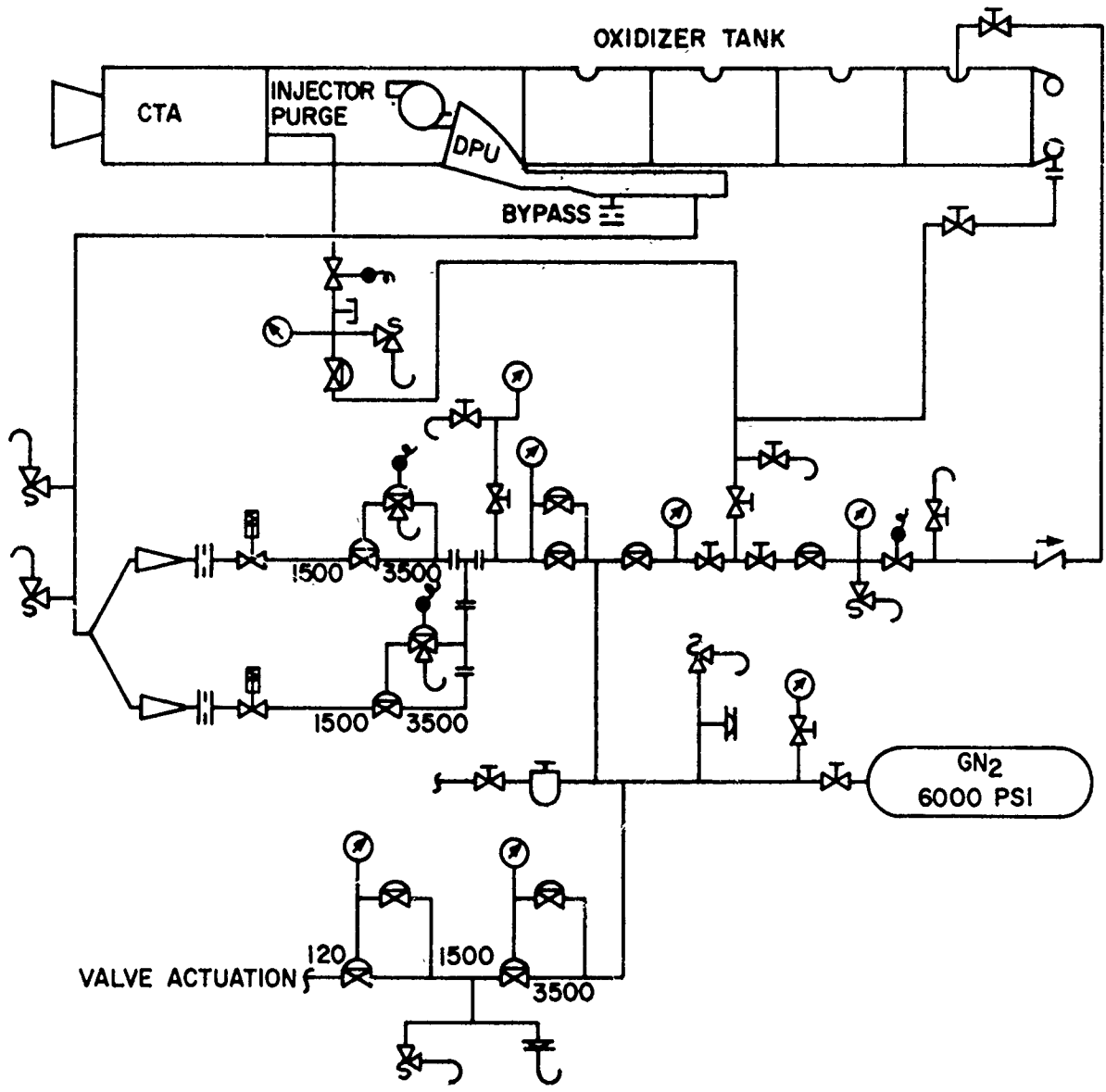


Figure 12. Schematic of Facility Nitrogen System

two by-pass orifices. The purpose of the by-pass was to reduce changes in duct pressure as the butterfly throttled the flow through the turbine. The orifices were 4 in. x 2-1/2 in. concentric reducers, and were placed on opposite sides of the duct so that there was no net thrust from this flow. The DPU inlet and by-pass orifices may be seen in Figure 3. The method of operating this drive system during a test is discussed in Section V.

Temperature Conditioning

Temperature conditioning of the HAST propulsion system was a requirement for two of the PFRT tests, one to be at -40°F and the other at $+125^{\circ}\text{F}$. The system was to be conditioned to these temperatures prior to the test but it was not required that the temperature be maintained up to the start of the test. Therefore, an environmental box was designed to completely enclose the propulsion system on the thrust stand. After conditioning, the box was removed for final test preparation such as installation of instrumentation transducers and the oxidizer flow loop. A portion of the box and its insulation may be seen in Figure 3.

The temperature conditioning system is shown schematically in Figure 13. For the cold conditioning, liquid nitrogen was flowed into copper coils in the top of the box, finally exiting as a gas at a temperature of -100°F . Temperature controllers monitored the temperature inside the box and the oxidizer temperature, operating an on-off valve in the nitrogen supply as required. For the hot conditioning, air inside the box was circulated through electric resistance heaters.

The liquid nitrogen system was satisfactory for the cold conditioning. However, the electric resistance heating was very slow, and the maximum temperature that could be obtained in the oxidizer when the hot test was first attempted was 120°F . After this test attempt was aborted by a thrust measurement problem, the propulsion system was heated for the second

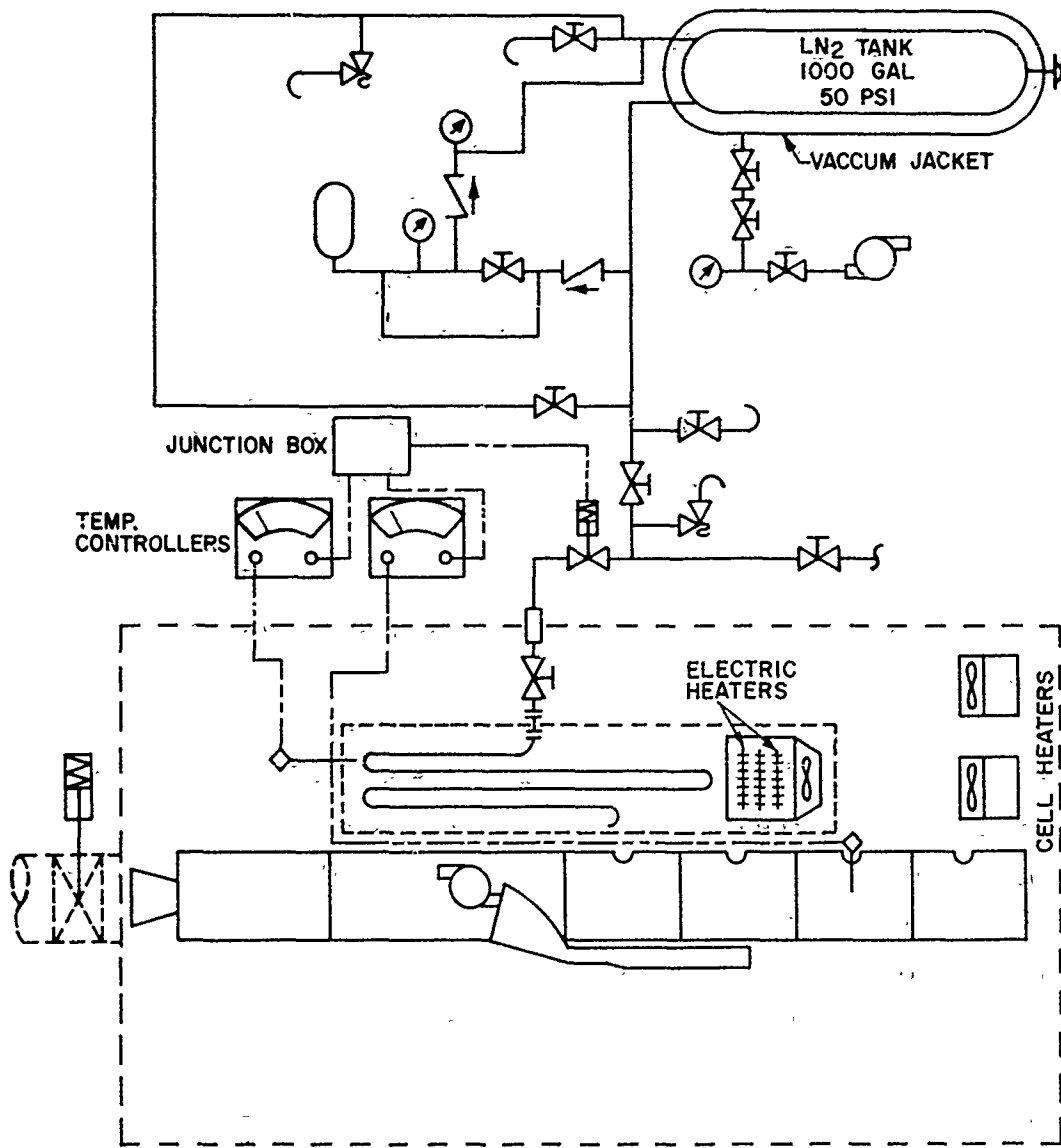


Figure 13. Schematic of Temperature Conditioning Systems

time by using the electric space heaters in the test chamber. This was more effective than using the environmental box and oxidizer temperatures up to 130°F were readily obtained.

Electrical

Functional control of the propulsion system for initiation and termination of a test was by means of the "launch box". This contained electrical switches that enabled a simulated flight start, including the automatic checkout of certain functions prior to permitting a simulated launch. The checkout was accomplished by the Digital Logic System (DLS), which also performed the sequencing of specific events to start the propulsion system. For these propulsion tests, the DLS checkout was limited to testing for 28 volt DC and 1500 Hz (30,000 rpm) output from the alternator.

To start a test, the "Select" switch was placed in the "On" position. This applied 28V DC from the facility power supply to the DLS. The facility isolation valves for the gaseous nitrogen turbine drive were opened but the butterfly valve remained closed until the "Launch Ready" switch was placed in the "On" position. This applied power to the butterfly actuator, which then moved the butterfly to the position required to maintain the nominal 32,000 rpm turbine speed. At this point the DLS checked for frequency and voltage from the alternator. If these were within specified limits, a "Ready" light was activated. If not, a "Fault" light was activated and a launch was prohibited. With a "Ready" light, depressing the launch switch activated the sequencing function in the DLS. Electrical signals then fired, in order, the nitrogen start squib, the oxidizer start squib, the thrust chamber igniter initiator, and then opened the OTV. An "OTV Shutdown" switch provided a 15V DC signal to close the OTV and terminate a test.

In the test facility installation, it was never possible to obtain a ready light when the DPU alternator output was inserted into the DLS. It was concluded that there must be an undefined incompatibility in the interface between the DPU, DLS, and the facility which was unique in this particular installation and not representative of a flight vehicle. Therefore, these ground tests were conducted by substituting 28V DC from a facility power supply, and 1500 Hz from an oscillator, into the DLS. With this substitution for the alternator output, a ready light was always obtained. Alternator output and turbine speed were verified by observation of strip chart recorders.

On the first PFRT test, the DLS sequencing circuitry malfunctioned and the OTV was opened early, at the same time that the oxidizer start valve was opened. Oxidizer was then in the thrust chamber when the ignitor was fired, resulting in a hard start with substantial overpressure but no damage. The malfunction was the result of corrosion after exposure to an IRFNA leak on the last OMA test. This DLS could not be repaired and another was not available, so it was functionally bypassed in the test installation. The sequencing function was accomplished by a facility electro-mechanical timer. The checkout functions were deleted.

The current output of the alternator was dumped through a resistive load bank. Initially, the turbine flowmeter used for oxidizer flow measurement was found to be susceptible to electromagnetic interference from the alternator. The interference was manifested as apparent flow indication when there was no flow, and an additive error to real flow measurement. The interference was greatly reduced by shielding the flowmeter and grounding to the vehicle frame, but it could not be completely eliminated. Since the primary function of the external electrical load was to provide a load for the ram air turbine so as to prevent over-speed before launch, there was no necessity to maintain this electrical power output once oxidizer was being pumped. The external load was manually switched off at three seconds after launch and the flowmeter interference was eliminated.

The electrical signals required to control the OTV were input from a facility control panel and power supply. A boost command of +10V DC was input prior to launch but the valve remained closed until the OTV ignition (start) command was input from the DLS or facility timer. The valve then opened with a 20-second ramp time as controlled by the valve internal electronics. As long as the boost command was present the valve remained full open. Removal of the boost command allowed the valve to be throttled by adjusting a potentiometer which controlled an analog input command within a range of -10 to +10V DC. This command voltage was pre-set to a value estimated to position the valve at the flowrate required for the initial sustain thrust, and upon removal of the boost command the valve rapidly moved to this position. The valve position was then adjusted as required to obtain the desired thrust at any instant, with the actual and desired thrust indicated on an X-Y plotter adjacent to the OTV operating panel. A position feedback voltage indicated actual pintle position but the control was an open loop system.

Instrumentation and Data Acquisition

Instrumentation transducer locations on the HAST propulsion system are shown in Figure 14. With the exception of the accelerometer, the output from all transducers was recorded on magnetic tape through a digital data acquisition system. This system sampled each data channel once every 10 milliseconds. The accelerometer output, as well as certain other pressures for which high response data was required, were recorded on magnetic tape by an FM system. Critical parameters required for the conduct of a test and for quick-look data were recorded on strip charts and an oscillograph.

In order to obtain a direct measurement of the oxidizer flowrate, a slight modification was made to the oxidizer system. A flowmeter is not a part of the flight system, and the line lengths were not sufficient to

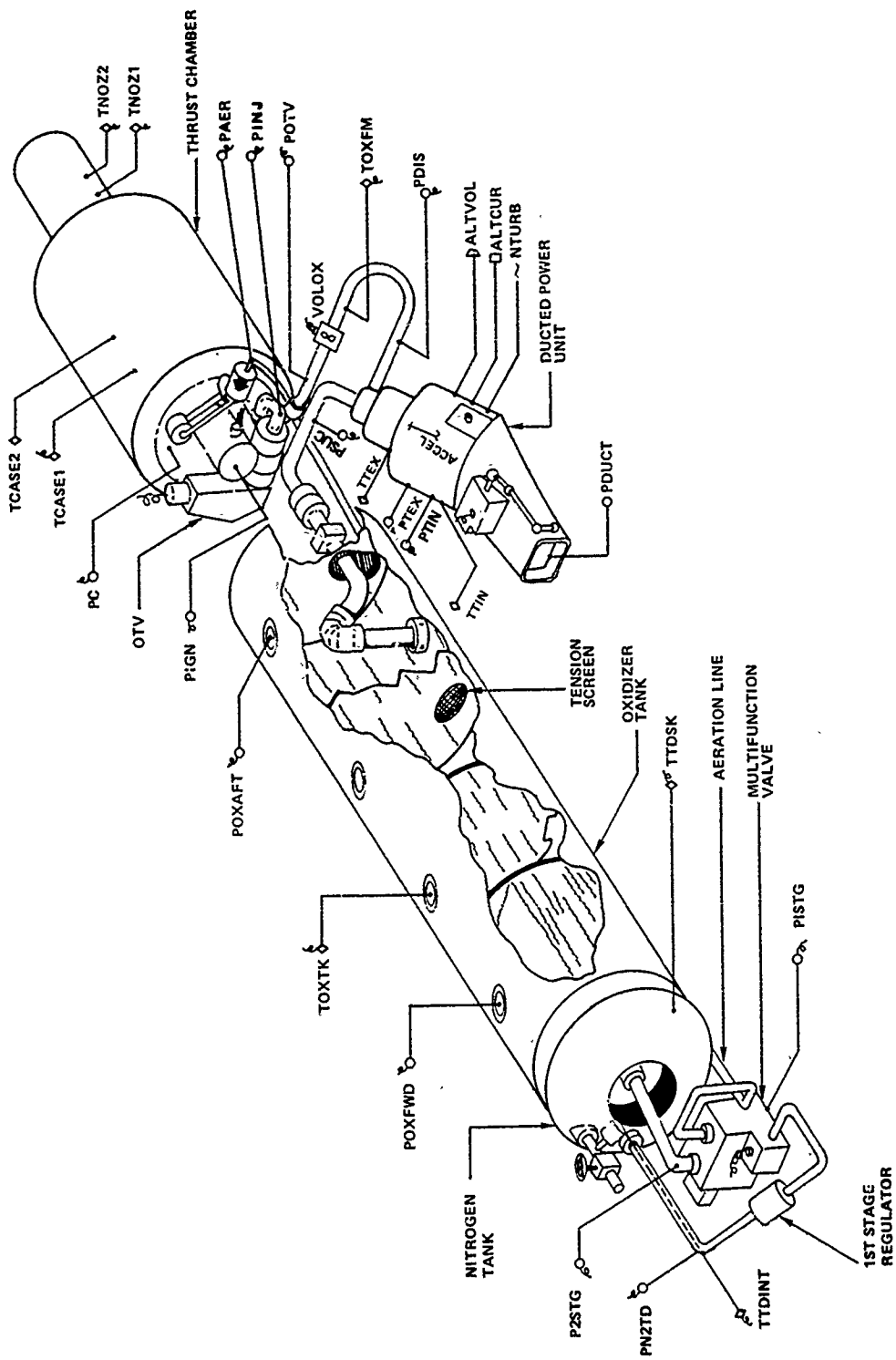


Figure 14a. Instrumentation Locations on HAST Propulsion System

<u>SYMBOL</u>	<u>LOCATION</u>
P1STG	FIRST STAGE REGULATOR OUTLET
P2STG	SECOND STAGE REGULATOR OUTLET
PN2TD	NITROGEN TORIOD
POXFW	OXIDIZER TANK FORWARD COMPARTMENT
POXAFT	OXIDIZER TANK AFT COMPARTMENT
PSUC	PUMP SUCTION
PDIS	PUMP DISCHARGE
POTV	OTV INLET
PINJ	INJECTOR MANIFOLD
PAER	AERATION MANIFOLD
PC	THRUST CHAMBER
PIGN	IGNITER
PDUCT	AIR SUPPLY DUCT (TOTAL)
PTIN	TURBINE INLET
PTEX	TURBINE EXHAUST

TEMPERATURES

TTDINT	NITROGEN TORIOD INTERNAL (GAS)
TTDSK	NITROGEN TORIOD SKIN
TOXTK	OXIDIZER TANK (LIQUID)
TOXFM	OXIDIZER AT FLOWMETER
TCASE1	THRUST CHAMBER CASE
TCASE2	THRUST CHAMBER CASE
TNOZ1	NOZZLE HOUSING
TTIN	TURBINE INLET AIR
TTEX	TURBINE EXHAUST AIR

FLOW

VOLOX	OXIDIZER FLOWRATE
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MISCELLANEOUS

<u>SYMBOL</u>	<u>LOCATION</u>
NTURB	TURBINE SPEED
ALTCUR	ALTERNATOR CURRENT
ALTVOL	ALTERNATOR VOLTAGE
ACCEL	DPU HOUSING ACCELEROMETER (3 AXES)

Figure 14b. Definition of Instrumentation Symbols

permit the installation of a flowmeter. A loop was added to the oxidizer line between the pump and the OTV, thus providing a length of straight line adequate for the installation of a turbine flowmeter. This flow loop, which may be seen in Figure 15, added approximately 20 psid to the pressure drop from the pump discharge to the OTV inlet.

All pressure transducers were of the strain gage type. Where available in the appropriate pressure ranges, absolute pressure transducers were used. These were principally in the lower ranges, up to 0-100 psia. When gage pressure transducers had to be used inside the altitude cell, it was necessary to determine if the reference side of the sensing diaphragm was sealed or vented to ambient pressure. A sealed transducer will continue to provide a gage pressure output referenced to atmospheric pressure even though it is in a vacuum environment, whereas the output of a vented transducer is always referenced to the local ambient pressure.

In most cases, neither the manufacturer's specifications nor inspection would indicate if the transducers were vented or sealed. A simple test was devised to answer this question. The transducer was connected to a small cylinder which was pressurized to approximately 50 psig. The electrical output, in digital counts, was observed for 15 minutes to insure that there were no leaks. The transducer and attached cylinder were then placed inside a bell jar which was evacuated to near the expected test cell pressure. The electrical output could be measured with the transducer in the bell jar, and again this was observed for 15 minutes. If the output did not change from the atmospheric reading, then it was known that the transducer reference cavity was sealed. If the output increased, this indicated that the reference was vented to the vacuum. The transducer and pressure cylinder were then returned to the atmosphere and the electrical output observed for 15 minutes. If the output did not return quickly to the original atmospheric reading, a leaking cavity or a partially plugged vent was suspected and the transducer was not used inside the altitude cell.

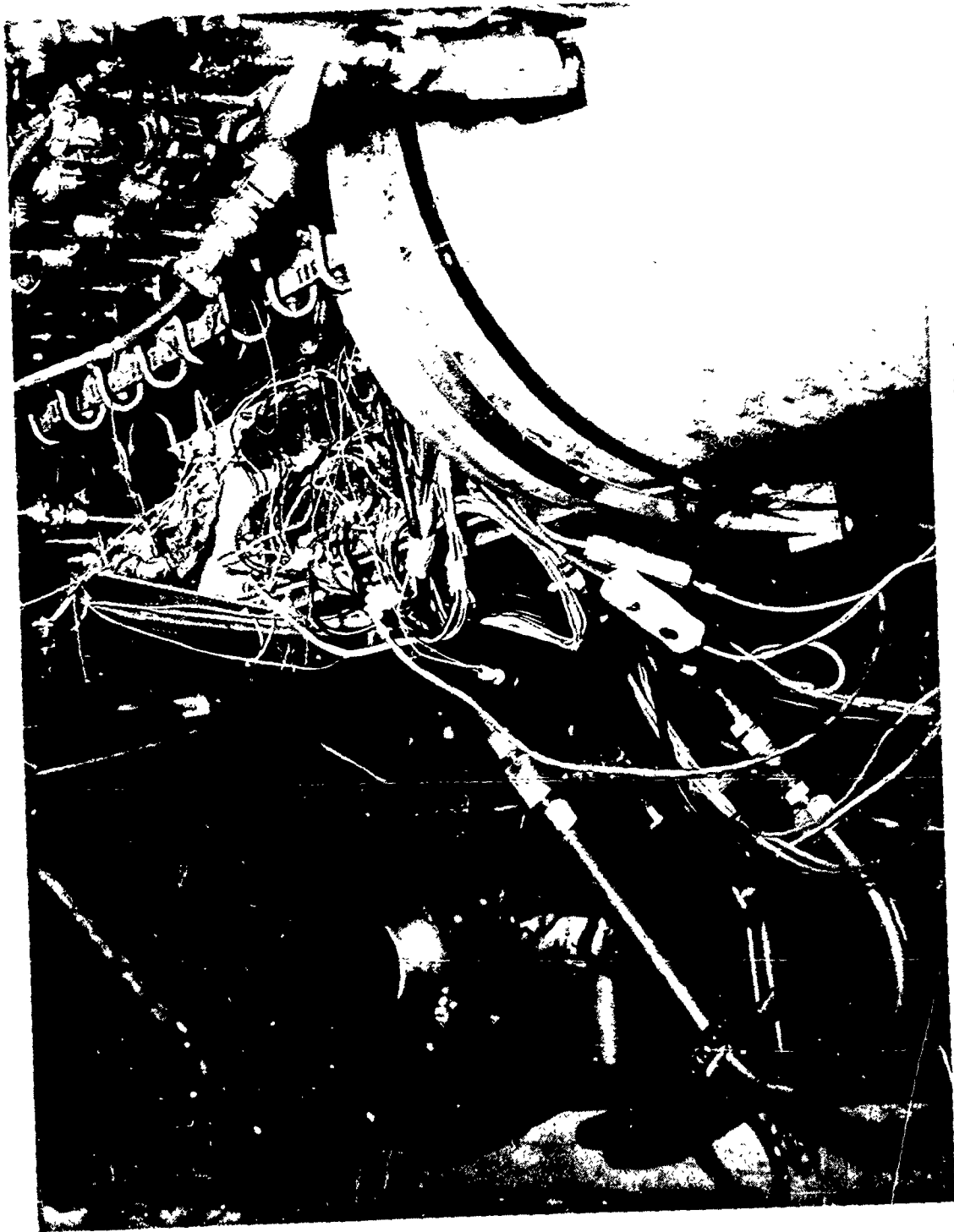


Figure 15. Oxidizer Flowmeter Installation

The only serious instrumentation problem was that of obtaining an accurate measurement of thrust. Errors were introduced by effects of the vacuum environment, and on some tests these were of such magnitude that the measured thrust could not be used for performance analysis. The existence of a problem was made evident by a large shift in the "zero" thrust reading, either when the cell was evacuated or a shift from pre-test to post-test at altitude. The shift continued to increase with time at altitude and thus could not be treated as a fixed tare force, with the data corrected accordingly. The load cell itself was pressure compensated so it should not have been affected by the local ambient pressure.

When the zero shift problem occurred on PFRT 1, the entire thrust measuring system was reviewed with the manufacturer. The review showed that the probable cause of the problem was excessively stiff flexures in the thrust stand. The movable member is a horizontal bed on which the test hardware is mounted. The bed is supported by vertical flat plate flexures extending from a thrust structure underneath, and of the same length as the bed. The thrust structure, in turn, is rigidly attached to the bottom of the test cell. The movement of the bed is limited, and measured by, a load cell which transmits the axial force into a thrust abutment. The horizontal bed is divided into three independent sections which can be joined to the required length to accommodate the test hardware. The HAST propulsion system required all three sections, whereas previously only a single section had been used.

The use of all three sections meant that a total of 22 flexures, each 7 in. wide, were between the movable bed and the thrust structure. It was suspected that the strain in the test cell wall when the cell was evacuated was transmitted through the flexures and caused a movement of the bed relative to the thrust abutment. This was reflected as apparent thrust in the output of the load cell. To correct this potential problem, the number of flexures was reduced to six, and these were only 2.5 in. wide.

Another possible cause of the problem was loads induced by the turbine drive supply. A 4 in. diameter pipe was inserted through the bottom of the cell, with a seal weld attaching it to the cell wall. The pipe was perpendicular to the movable thrust bed, and was rigidly attached through the simulated turbine inlet duct. A bellows provided flexibility in the vertical run of pipe. The nitrogen flowing through the pipe was chilled because of its high velocity, and it was possible that temperature changes in the pipe, plus pressure loads, imposed forces on the thrust stand that were not taken out by the bellows. The temperature changes would account for the time dependency of the zero shift. Additional transverse flexibility was provided in the vertical pipe by loosening the bolts in a flanged joint near the floor of the test cell. Since the internal pressure was only a few psia, a pressure seal was provided by taping the gap between the flange faces.

These changes were successful in eliminating the zero shift problem on PFRT 2. Prior to PFRT 3, calibration showed non-linearities in the thrust readout. It was found that there was a slight sag in the horizontal bed, allowing it to contact a mechanical stop. It was necessary to support the bed by two additional flexures, also of 2.5 in. width. There was then no problem with the thrust measurement on PFRT 3, and except for one human error, no further problems until PFRT 9. The error occurred prior to PFRT 4, when a retaining pin was incorrectly placed allowing a mechanical stop to be engaged. This introduced hysteresis when thrust was applied during the test.

The last problem occurred prior to PFRT 9, when a large zero shift was observed when the test cell was evacuated. It was found that a force was being applied by the hydraulic calibration ram. Evidently there was air trapped in the hydraulic line, and this created the differential pressure on the piston and the resultant force. There had been some indications of this problem before, so the calibration ram was removed from the thrust stand.

A slight discrepancy exists in all the thrust data because of the change in weight on the thrust stand. The test cell and the thrust stand had a downward slope of one-eighth inch per foot toward the exhaust duct. The configuration of the load cell and thrust abutment was such that a tensile force was imposed on the load cell by the weight of the propulsion system. This weight was reduced during the test because of the consumption of propellant, and since the load cell had been electrically zeroed with the loaded propulsion system in place, the effect was the same as an additional increment of thrust (compressive force) being applied to the load cell. The error at any instant is 1.04 percent of the cumulative weight change, for a maximum error of +6.67 lb at the end of the test. The data in this report have not been corrected to account for this error.

SECTION IV

TEST PROGRAM

Oxidizer Management Assembly Tests

Prior to initiating the PFRT tests of the complete HAST propulsion system, a series of oxidizer flow tests were conducted with the Oxidizer Management Assembly (OMA). The purpose of these tests was to verify the operation of this sub-assembly at simulated altitude prior to expending the CTA hardware. The tests also served to check out the test facility and instrumentation.

The OMA test configuration is shown schematically in Figure 16. The OMA itself was of flight configuration except for a manual isolation valve in the tank pressurization line, between the burst disc and the MFV. By closing this valve as soon as the altitude chamber was accessible after a test, the MFV could be isolated from residual IRFNA vapor in the oxidizer tank. This positive isolation provided protection for the MFV in addition to that afforded by the check valve at the tank pressurization outlet.

During these tests, oxidizer was pumped from the HAST oxidizer tank into a catch tank outside the altitude chamber. The catch tank was vented to the atmosphere. Flow control, which would be the function of the OTV in a complete flight configuration propulsion system, was accomplished by a facility throttle valve. The installation of this valve is shown in Figure 17. An orifice downstream of the throttle valve provided a back pressure equivalent to the CTA injector inlet pressure at full boost flow.

The throttle valve was operated in a manner that closely simulated the ramp of oxidizer flow after CTA ignition but did not simulate the transients of a flight propulsion system which occur at the time of opening the oxidizer start valve and the OTV. Specifically, with the DPU running at nominal speed, the DLS sequenced the nitrogen and oxidizer start

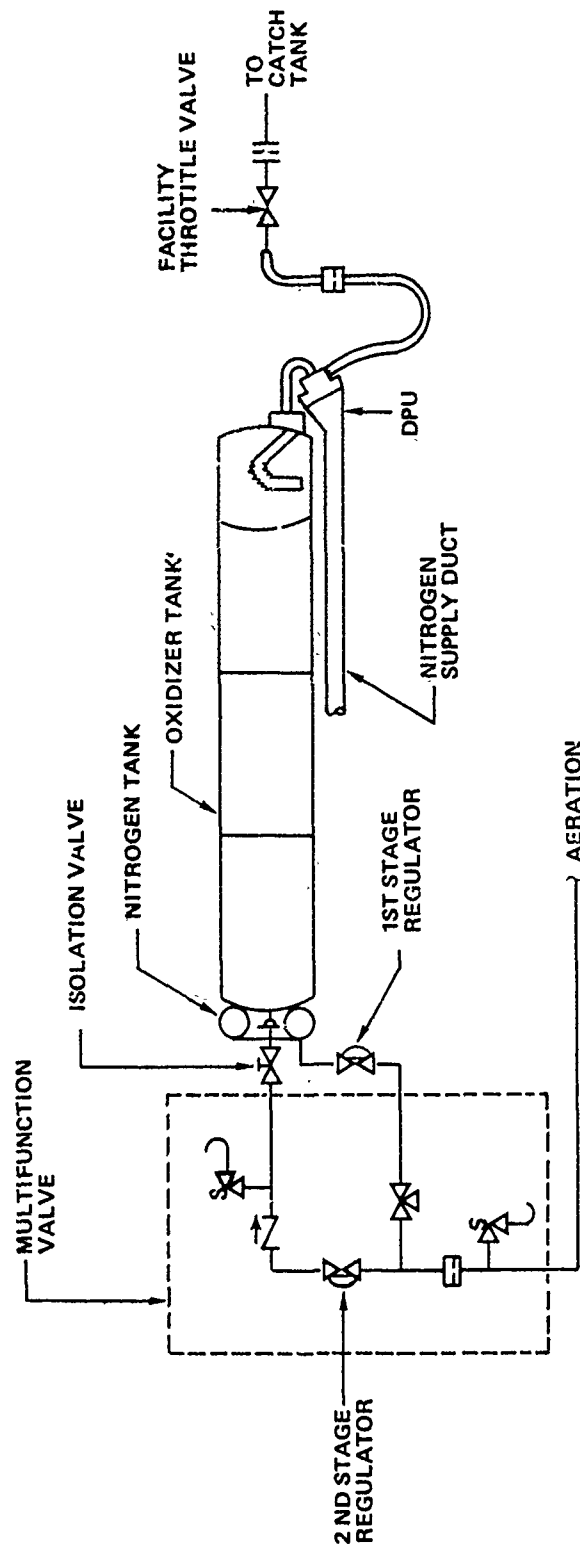


Figure 16. Schematic of OMA Expulsion Test Configuration

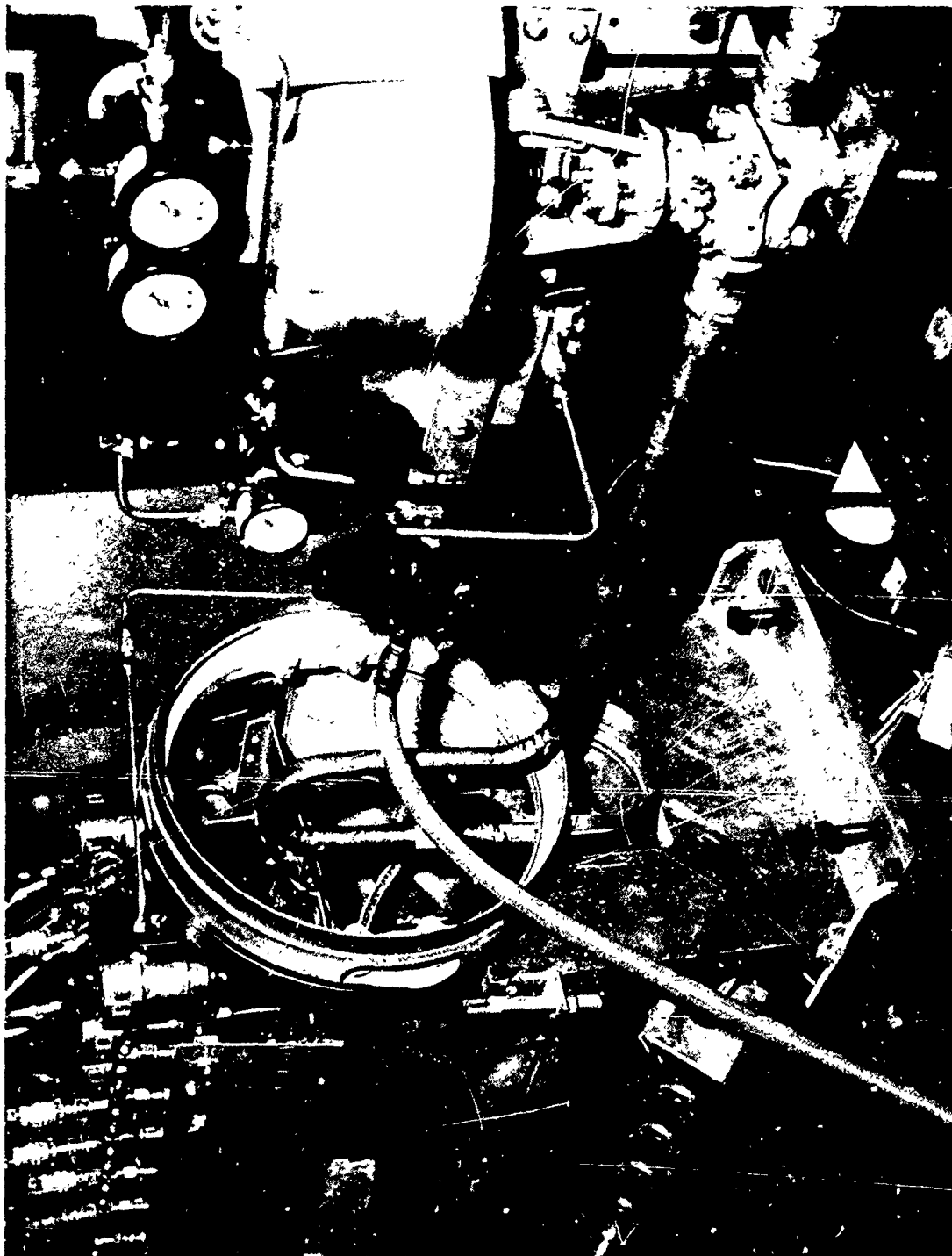


Figure 17. Throttle Valve for OMA Expulsion Tests

valves open at the times specified for the flight system, but the throttle valve was pre-positioned to allow a flow rate corresponding to the initial flow when the OTV has opened rapidly to its 50 percent open position in response to the OTV ignition command. The throttle valve was then opened to full boost flow at a rate corresponding to the 20-second opening ramp of the OTV. This rate was obtained by an operator manually following the desired flow versus time profile on an X-Y plotter. Simulated boost and sustain profiles of desired missions were obtained in the same manner.

At the time the OMA tests were being conducted, the lack of simulation of the initial start transient was not considered important. However, later experience during the PFRT tests and a special series of tests of the free siphon implied that a potential failure of the siphon may not have been observed during the OMA tests because of the starting technique. A failure of the siphon occurred on PFRT 2, and observations during the siphon tests showed that the siphon was subjected to violent oscillations when the start valve opened, allowing fluid to flow into an evacuated line, and somewhat less severe oscillations when the OTV opened. With the OMA test configuration, these water hammer effects would have been much less severe, or non-existent, when the start valve opened because the fluid discharged into a line which was open to the vented catch tank and was at near atmospheric pressure. The second set of pressure surges, corresponding to OTV opening, would not occur at all because the throttle valve was already open when the start valve opened.

Only two OMA tests were originally planned, one at ambient temperature and one at elevated temperature (+125°F). Because of several facility and test hardware problems, a total of five tests were required before the OMA operation was satisfactorily demonstrated. All these tests were at ambient temperature, and the elevated temperature test was deleted. Each of the tests is discussed in sequence below.

OMA 1 (Test RA 155)

The desired start sequence was obtained from the DLS, and with the throttle valve pre-positioned to the desired opening, an initial oxidizer flowrate of approximately 10 gpm was obtained. The throttle valve operator then controlled the valve to ramp the flow to the full boost condition. The resulting oxidizer flow profile is shown in Figure 18. At 29 seconds after launch, a flowrate of 15.8 gpm had been obtained, and then the flow began to decrease. At 67 seconds, there was an instantaneous drop to 4.2 gpm and then a further slight decay. The throttle valve was full open during this time. At 140 seconds, the valve was momentarily closed and then ramped open. It was then possible to obtain full boost flow until the oxidizer was depleted.

Post-test examination showed a tear in the Teflon sleeve of the free siphon and distortion of the wire helix. It was postulated that the siphon had been sucked down to the bottom of the tank just before full boost flow would have been obtained, and the flow was restricted. When the throttle valve was closed, the pressure forces holding the siphon down were removed, and the restriction was not re-established when the valve was again opened. At some time the siphon was torn and this additional flow path may have prevented the siphon being sucked down again when flow was reestablished.

Because of a tape drive malfunction, the digital data from this test could not be processed by the computer. The only data was that recorded on the strip charts and oscillograph. However, the pressure transducers at the pump suction and pump discharge were inadvertently isolated from the pressure source, and this critical data was not available in any form. This lack of data prevented a more thorough failure analysis for this test.

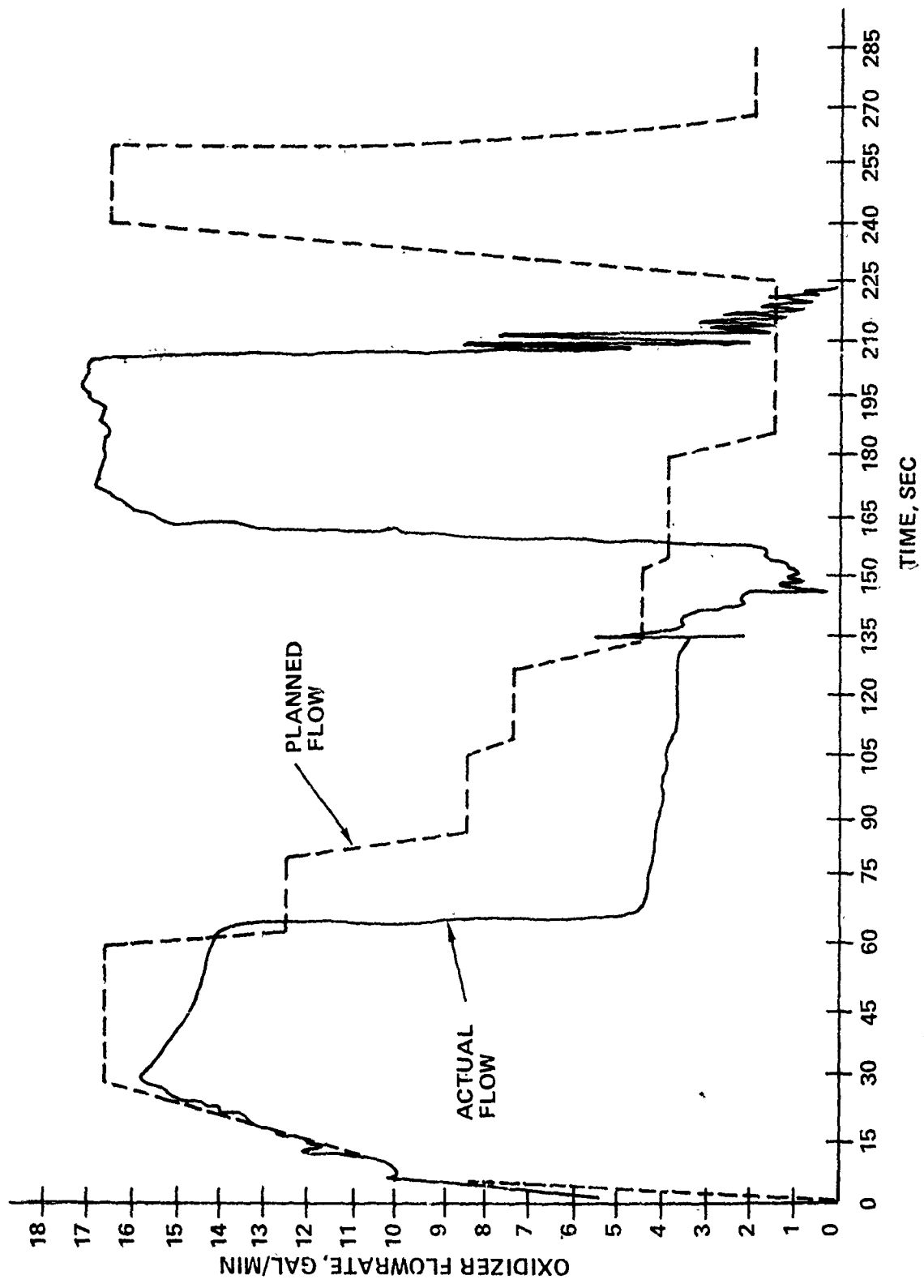


Figure 18. Planned and Actual Flow Profiles for OMA 1

The postulated failure mode is considered likely because this had previously been considered a potential problem with the initial siphon design and a number of siphons had been modified to insure adequate clearance. However, this particular siphon had not been modified. The siphons used for the rest of the OMA tests and the first two PFRT tests were of the modified configuration and clearance between the inlet and tank bottom was verified before each test. No further siphon problems occurred on the OMA tests.

OMA 2 (Test RA 156)

Other than the use of a modified siphon, no changes were made to the test configuration for OMA 2. The start was as planned, and the throttle valve was controlled to ramp the oxidizer flow from the starting value of 10 gpm toward full boost flow. However the maximum flow that could be obtained was 15.0 gpm, instead of the 16.8 gpm desired, and the pump pressure rise at this flowrate was only 375 psid instead of the 685 required. This pump cavitation was induced by low pump suction pressure. As indicated in Figure 19, the net positive suction pressure (NPSP) decayed to only 20.4 psia as flowrate increased, and significant cavitation had occurred when NPSP dropped below 21.4 psia. Pump testing by TMC had shown that a minimum NPSP of 25.0 psia was required at boost flow.

Again, a malfunction of the data acquisition system prevented the recording of data essential to a failure analysis. The data in Figure 19 were taken from strip chart records of critical parameters. The available data was not adequate to determine if the low pump suction pressure was due to a malfunction of the pressure regulator in the MFV or a flow restriction in the system.

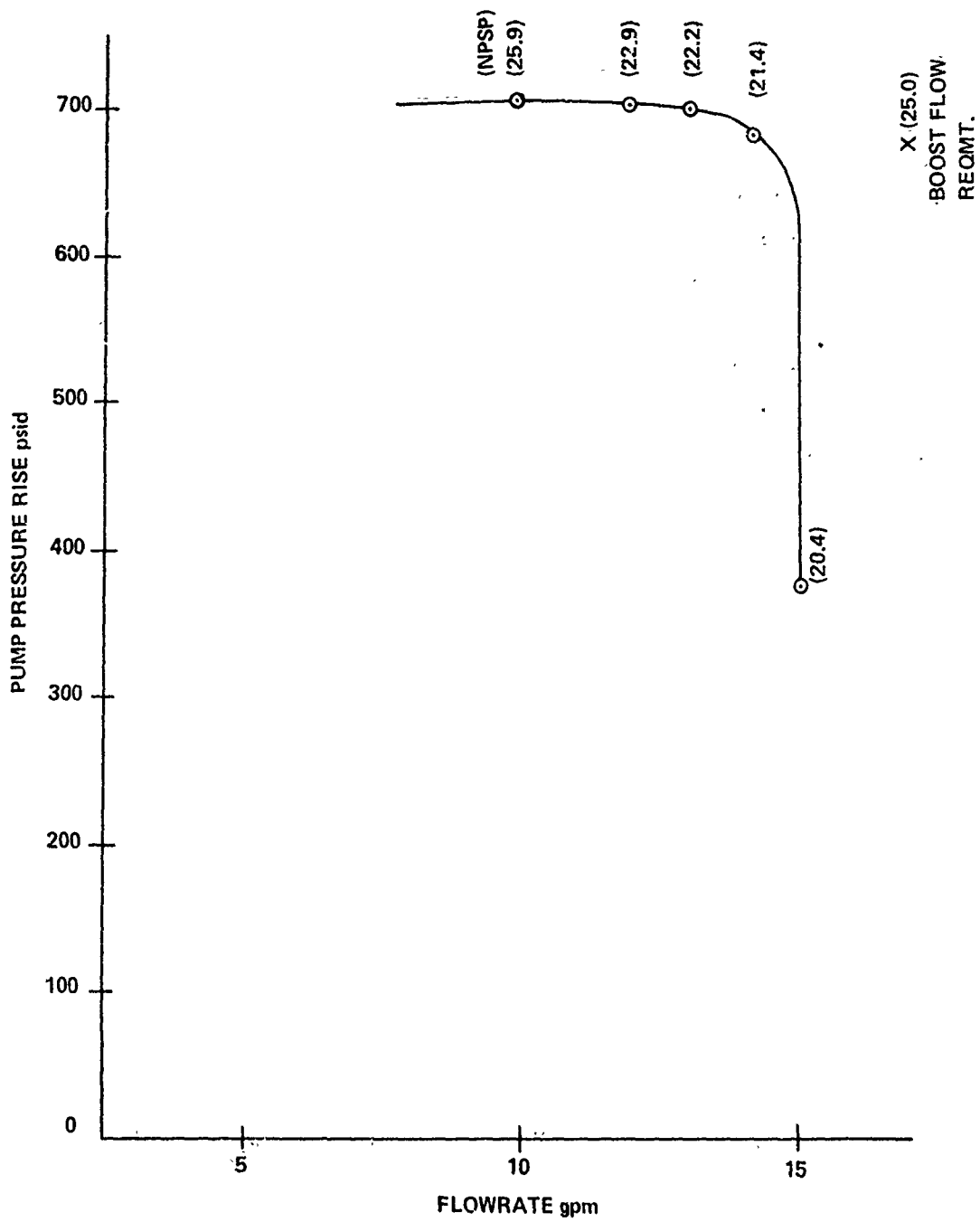


Figure 19. Pump Pressure Rise for OMA 2

OMA 3 (Test RA 157)

This test was a repeat of the previous test, with the objective of acquiring sufficient data to analyze the pump cavitation problem. The significant data from this test is shown in Figures 20 and 21. Cavitation occurred as before, with the pump suction pressure dropping to 20.0 psia at a flowrate of 14.7 gpm, and pump pressure rise decaying to 475 psid. The second stage regulator outlet pressure was 38.5 psia at the maximum oxidizer flowrate, but the aft compartment pressure was only 25.0 psia. The "Ox Tank Pressure Drop" parameter in Figure 21 is the difference between the regulator outlet pressure and the aft compartment pressure. In all the testing to date, the forward compartment had not been instrumented for pressure measurement so it could not be determined if the excessive tank pressure drop was occurring across the tension screen or between the MFV and the forward compartment.

The pressurization system components were bench-tested to determine the pressure drop occurring in this system. When the MFV was tested alone, an outlet pressure of 46.4 psig was measured at a nitrogen flow rate of 6.6 scfm. The isolation valve was then added and the pressure measured at its outlet. At the same gas flowrate, the pressure at the valve outlet was only 2.4 psig. This indicated that the isolation valve was severely restricting the flow of pressurization gas. The pressure drop was also measured through the burst disc that had been ruptured on the test, and a pressure drop of 6.0 psid was obtained at a gas flowrate of 8.0 scfm. This was somewhat high for the burst disc.

OMA 4 (Test RA 158)

For this test, the MFV isolation valve which had been used on the previous tests was replaced by a ball valve. A bench test of this valve showed that it had negligible pressure drop at the required flowrates. A pressure transducer was added in the oxidizer tank forward compartment to permit direct measurement of the pressure drop across the burst disc and tension screen.

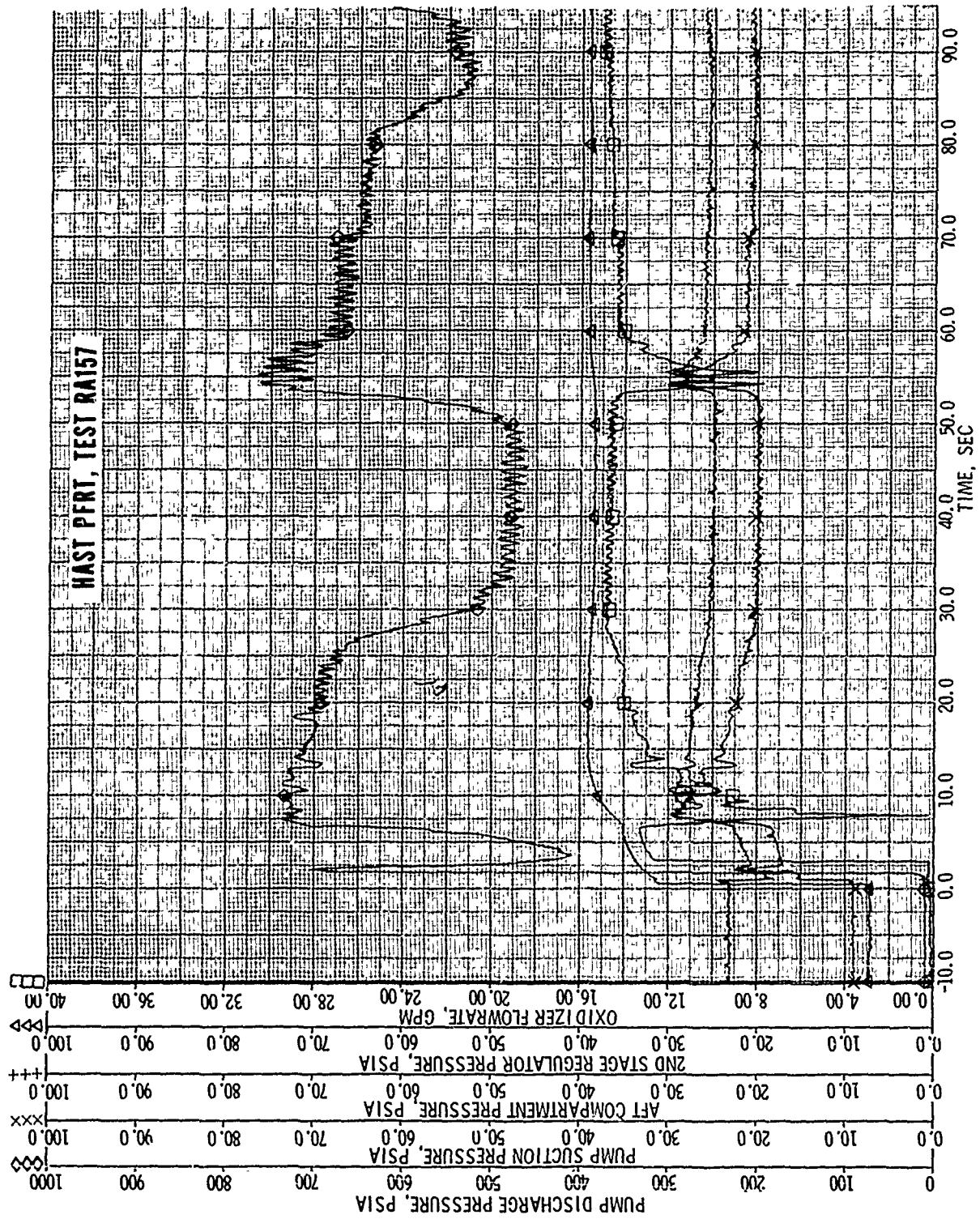


Figure 20. Pressure Parameters for OMA 3

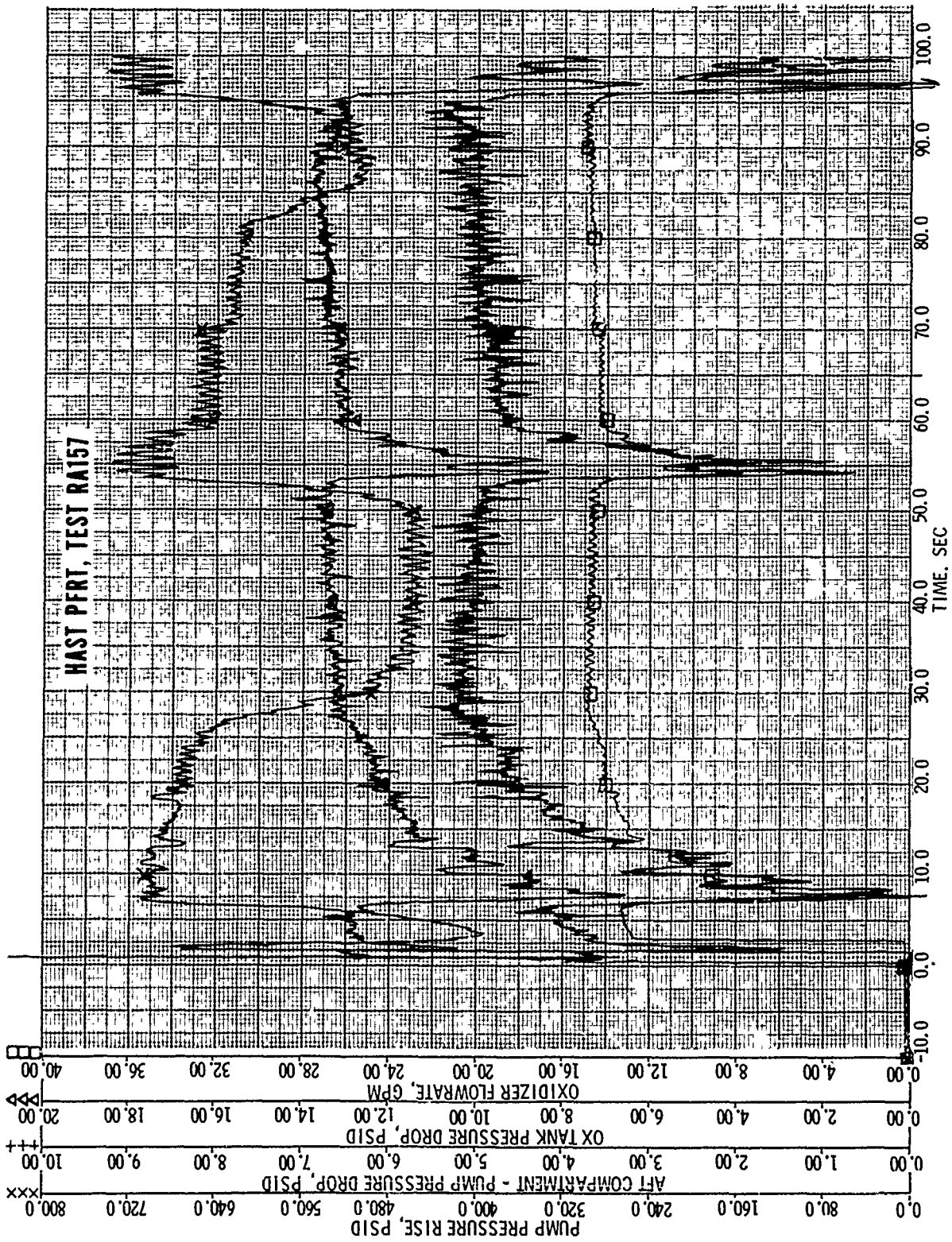


Figure 21. System Pressure Drops and Pump Performance for OMA 3

The pertinent data from this test is provided in Figures 22 and 23. The start appeared normal, and as shown in Figure 22, the oxidizer flowrate immediately came up to 8.5 gpm. However as the throttle valve was opened further, the flowrate did not increase, even when the valve was full open. Just after 17 seconds, the flowrate began to decay and finally reached a value of 4.2 gpm. Also, as shown in Figure 23, at 17 seconds the pump pressure rise dropped rapidly, indicating severe pump cavitation. The pump suction pressure was low from the beginning of the test and at this point dropped below 15 psia. The cause of the low suction pressure is evident from examination of the tension screen pressure drop in Figure 23. During the initial 20 seconds when the maximum flow was being obtained, this pressure drop had increased to 38 psid. Even with the much lower flows during the rest of the test, this pressure drop continued to increase and had reached nearly 50 psid at 100 seconds.

Since the tension screen pressure drop steadily increased during the test, it was evidently being plugged by particulate matter in the IRFNA. The IRFNA had been filtered during loading into the tank, so the particulates had to come from the tank itself. This tank had been used for the previous two tests, and it was suspected that corrosion products had accumulated in the tank and were being filtered out by the tension screen. The progressive increase of the pressure drop as opposed to a consistently high pressure drop argues against the tension screen itself having been subject to corrosion.

OMA 5 (Test RA 159)

This was the last test of the OMA prior to initiating the PFRT tests, and was the closest to a completely normal expulsion of any of the tests. A new oxidizer tank was installed for this test.

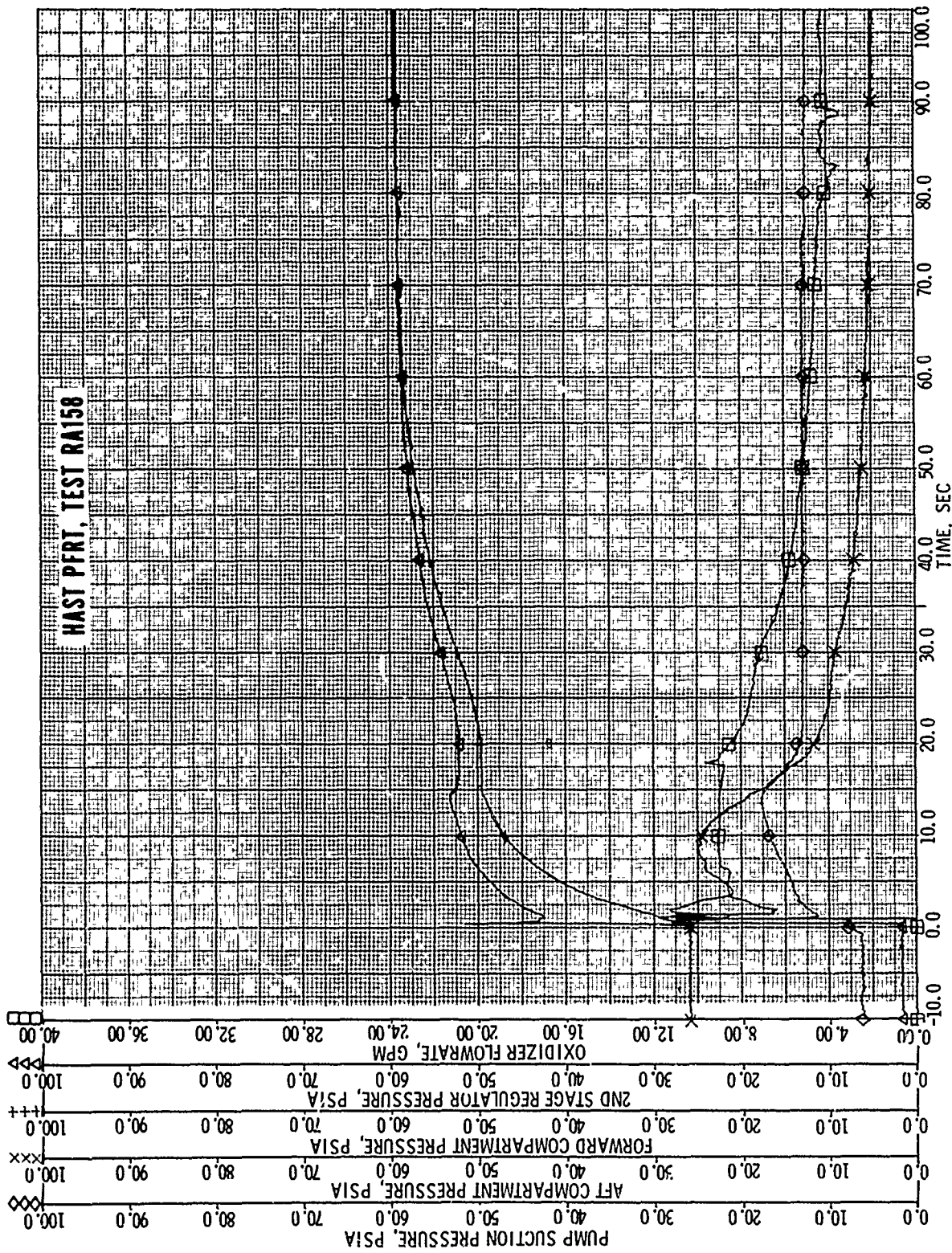


Figure 22. Pressure Parameters for OMA 4

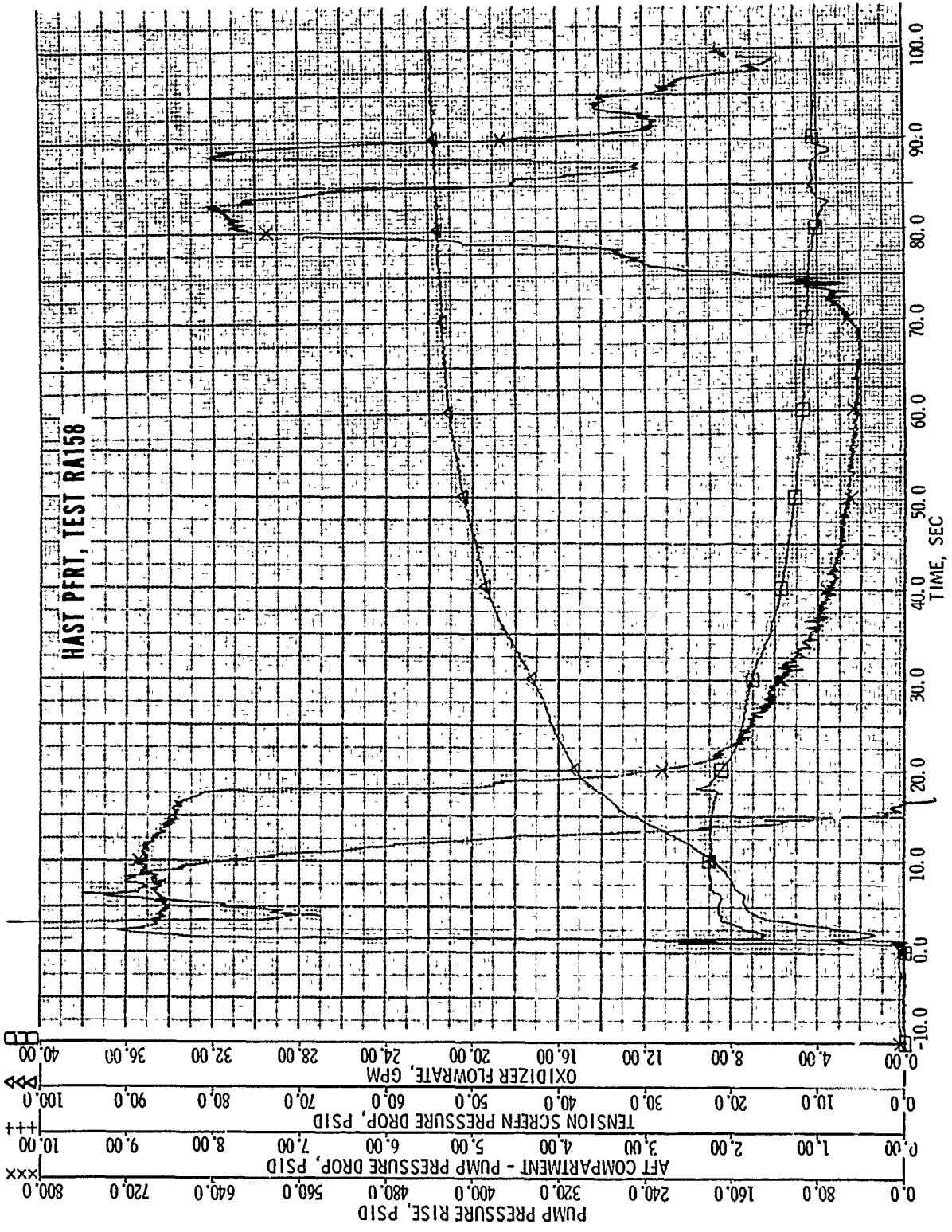


Figure 23. System Pressure Drops and Pump Performance for OMA 4

A review of all the previous OMA and flow bench test data led to the conclusion that changes in the pressurization system were necessary to insure that the minimum pump NPSP requirement was met. The set point of the second stage regulator in the MFV was increased by 10 psi, to a new value of 53 psig at 8.0 scfm. The burst disc holder was modified so that the leaves could more fully open, thus reducing the pressure drop after opening.

The OMA planned flowrate schedule is shown in Figure 24. As can be seen in the figure, the flowrate was to be increased in steps from the initial OTV open position to maximum rated flow, and then reduced in steps to a sustain thrust flowrate. This type of profile was to be repeated, but with a continuous ramp up and down rather than discrete steps.

The start sequence was normal, with the DLS correctly sequencing the MFV and oxidizer start valves. However, sometime during the first 10 seconds of the test, the flexible tube which connected the pump discharge pressure transducer to the IRFNA line broke at a brazed joint. This resulted in the discharge of a considerable quantity of IRFNA into the test cell for the entirety of the test. The data showed pressures throughout the oxidizer feed system to be within expected limits for the entire test. The significant system pressures and pressure drops are shown for the first 100 seconds of the test in Figures 25 and 26. It may be seen, in Figure 26, that the tension screen pressure drop is in the 11 psid range for the maximum flow rate recorded. However, it must be remembered that the flow meter is downstream of the broken flexible tube. Therefore the flowrate through the tension screen was greater than the data indicates, although the total magnitude is unknown. The pump suction pressure remained above 30 psia, well above the minimum allowable of 25 psia. It could be inferred from the plot of pump pressure rise with time that the flexible tube broke at about nine seconds, since the pressure begins to fall off steeply at about that point. However, IRFNA flowrate continues to rise, approximately as planned and commanded.

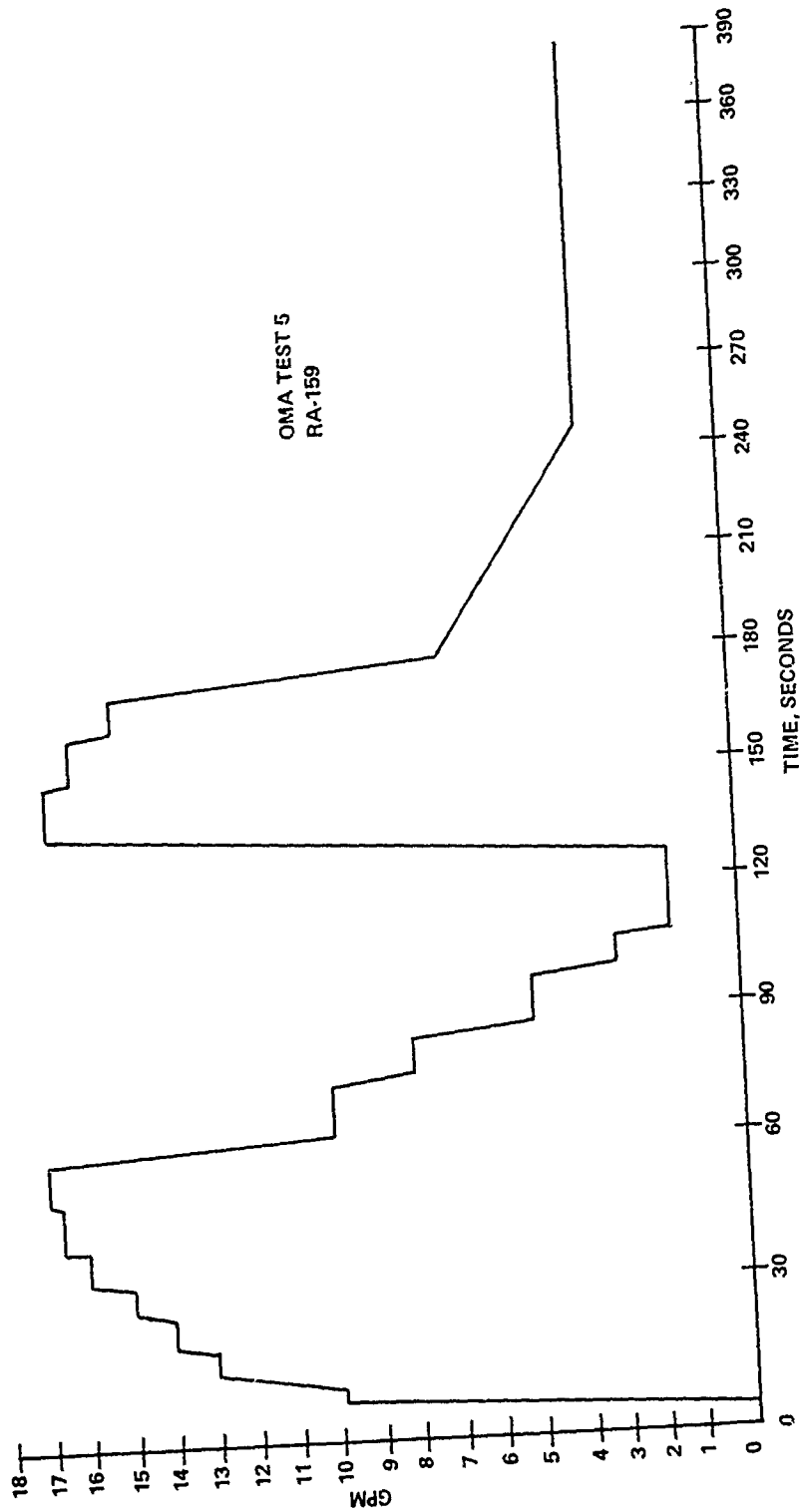


Figure 24. Planned Oxidizer Flow Profile for OMA 5

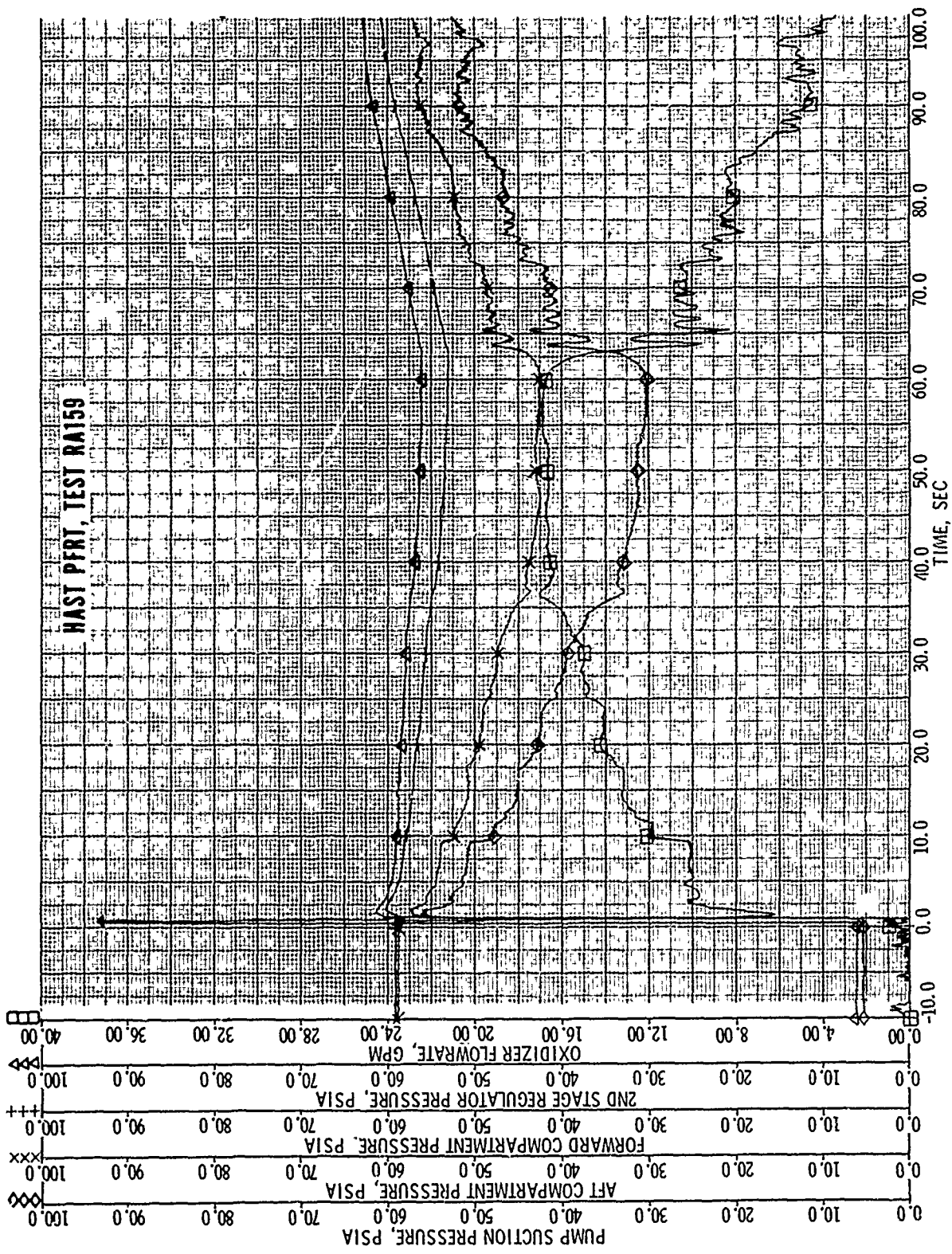


Figure 25. Pressure Parameters for OMA 5

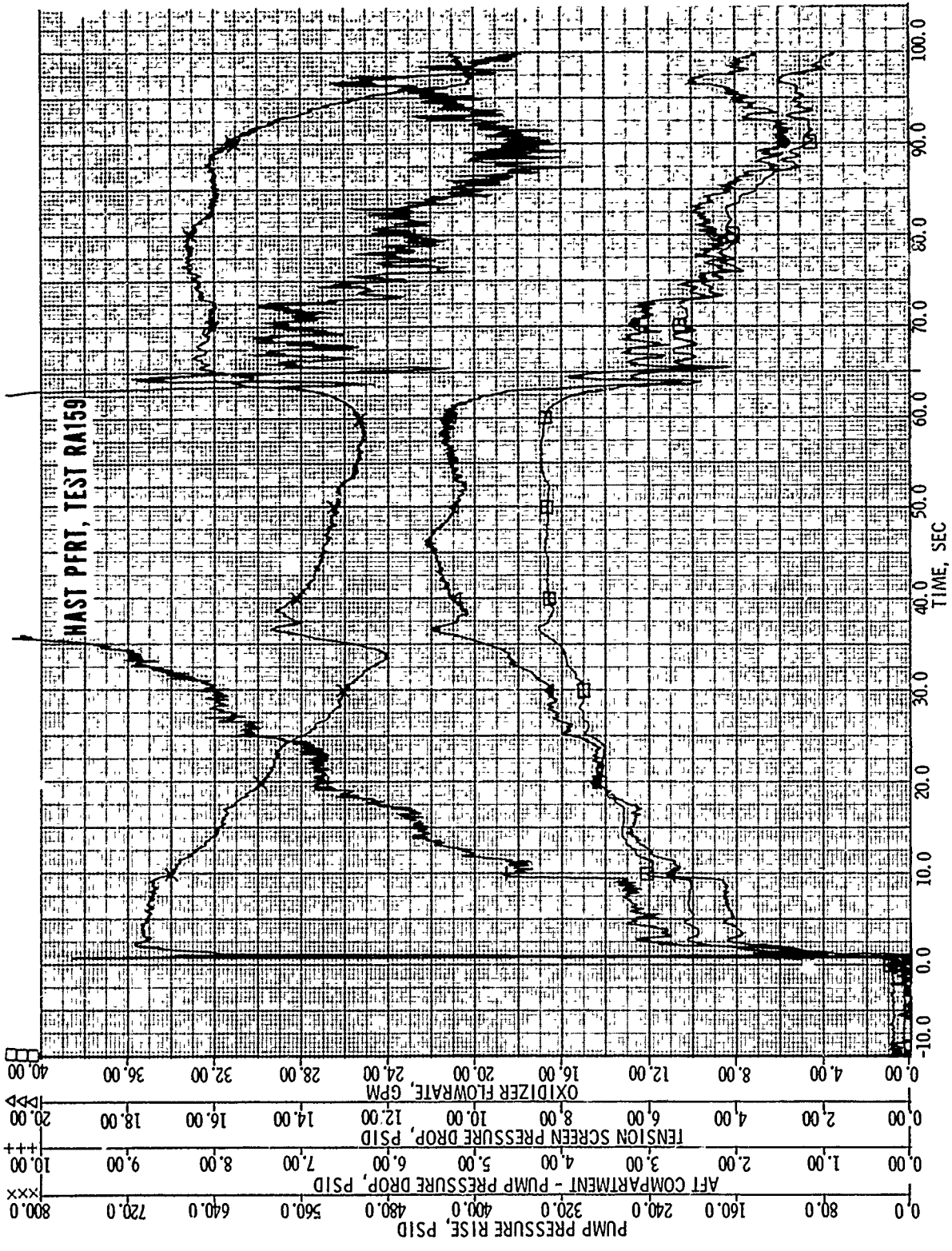


Figure 26. System Pressure Drops and Pump Performance for OMA 5

The pressure from the second stage regulator was initially 60 psia, dropping to a minimum regulated pressure of about 56 psia at about 60 seconds into the run. This characteristic is normal for the second stage regulator. The first stage regulator, not shown on the pressure plots, regulated low, ranging between 231 and 245 psig. The minimum specified regulation pressure is 275 psig and bench tests of the regulator consistently ran above 300 psig. Since the second stage pressure regulation was normal this low first stage pressure did not influence the test.

It was concluded that, despite the fact that oxidizer flowrate could not be absolutely determined, the test demonstrated satisfactory operation of the OMA. In particular, since the pump had not cavitated at higher than design boost flowrates, this problem had been solved.

Preliminary Flight Rating Tests

The completion of the OMA expulsion tests established confidence in the operation of this sub-assembly of the HAST propulsion system. The tests of the complete propulsion system were then initiated. These PFRT tests are described chronologically in this section in terms of the overall operation of the propulsion system. More specific details of the operation of particular components, and the resolution of problems that were encountered, may be found in Section V. System performance data and assessment thereof is provided in Section VI.

The significant data for each test are provided in the form of computer plots following the description of the particular test. In these plots, the time reference begins at the simulated launch. The thrust has been zeroed at launch by subtracting any tare force indicated on the load cell just prior to launch from all subsequent data. The thrust is that actually measured at the test cell pressure and has not been corrected to vacuum (zero ambient pressure) conditions. The cell was typically 0.12 to 0.27 psia, and the correction to vacuum would add 3.06 to 6.89 lb_f to the indicated thrust.

PFRT 1 (Test RA 160)

This test was a simulation of the first planned flight test, with cruise at Mach 2.0 at 50,000 ft after boost from launch at Mach 1.5 at 50,000 ft. Because at low thrust the hybrid motor operates at O/F ratios lower than the nominal design value, the long sustain time for this mission was expected to cause fuel depletion sooner than oxidizer depletion. This was considered undesirable because of potential overheating of the thrust chamber case. Consequently only 420 lbs of oxidizer was loaded into the OMA rather than the usual loading of 496 lb. The actual duration of boost thrust was 39 secs, and the propulsion system was manually throttled to match the required sustain thrust for 225 sec. The test was actually terminated by oxidizer rather than fuel depletion.

The significant data for this test are presented in Figures 27 through 32. Examination of the thrust curve in Figure 27 shows a positive zero shift of approximately 30 lb_f at the end of the test. Investigations of the problem immediately after this test, and after recurrences later in the test program, showed that the zero shift was present during the sustain portion of the simulated mission, introducing an error of as much as 10 percent of the apparent measured thrust. Since the engine was being throttled by matching the apparent thrust to a desired value, the throttling was erroneous. At any point in time, the actual thrust was lower than indicated, and thus the desired thrust profile was not accurately followed.

The error in controlled thrust was reflected in a lower oxidizer flowrate than would otherwise have been required. This in turn reduced the operating O/F ratio of the hybrid motor and reduced the specific impulse. The net result was that the measured total impulse and burn time for this simulated mission was not necessarily representative of an actual flight. The degree of error can be inferred when data analysis is completed by UTC and total impulse is calculated from measured chamber pressure.

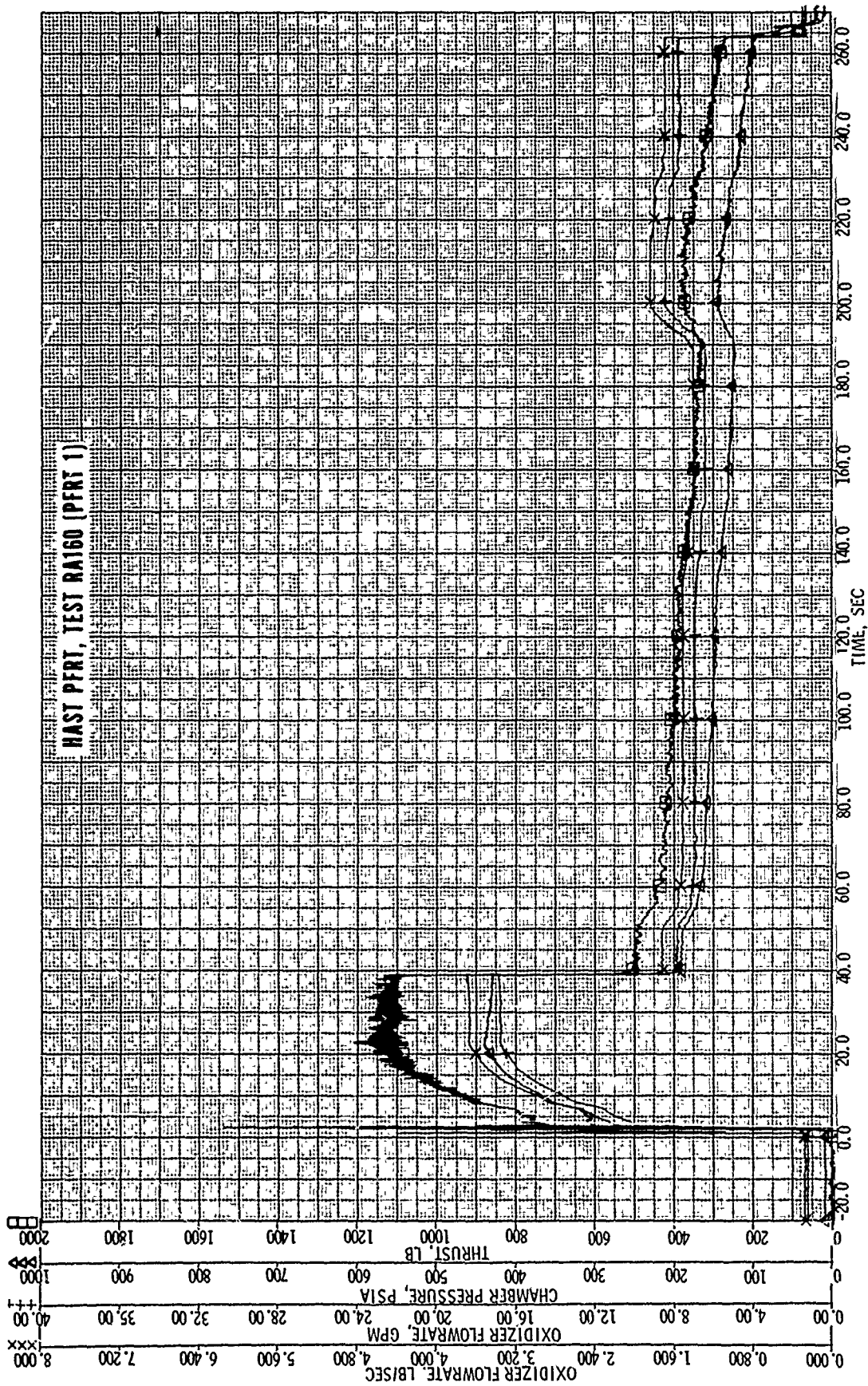


Figure 27. Thrust Chamber Parameters for PFRT 1

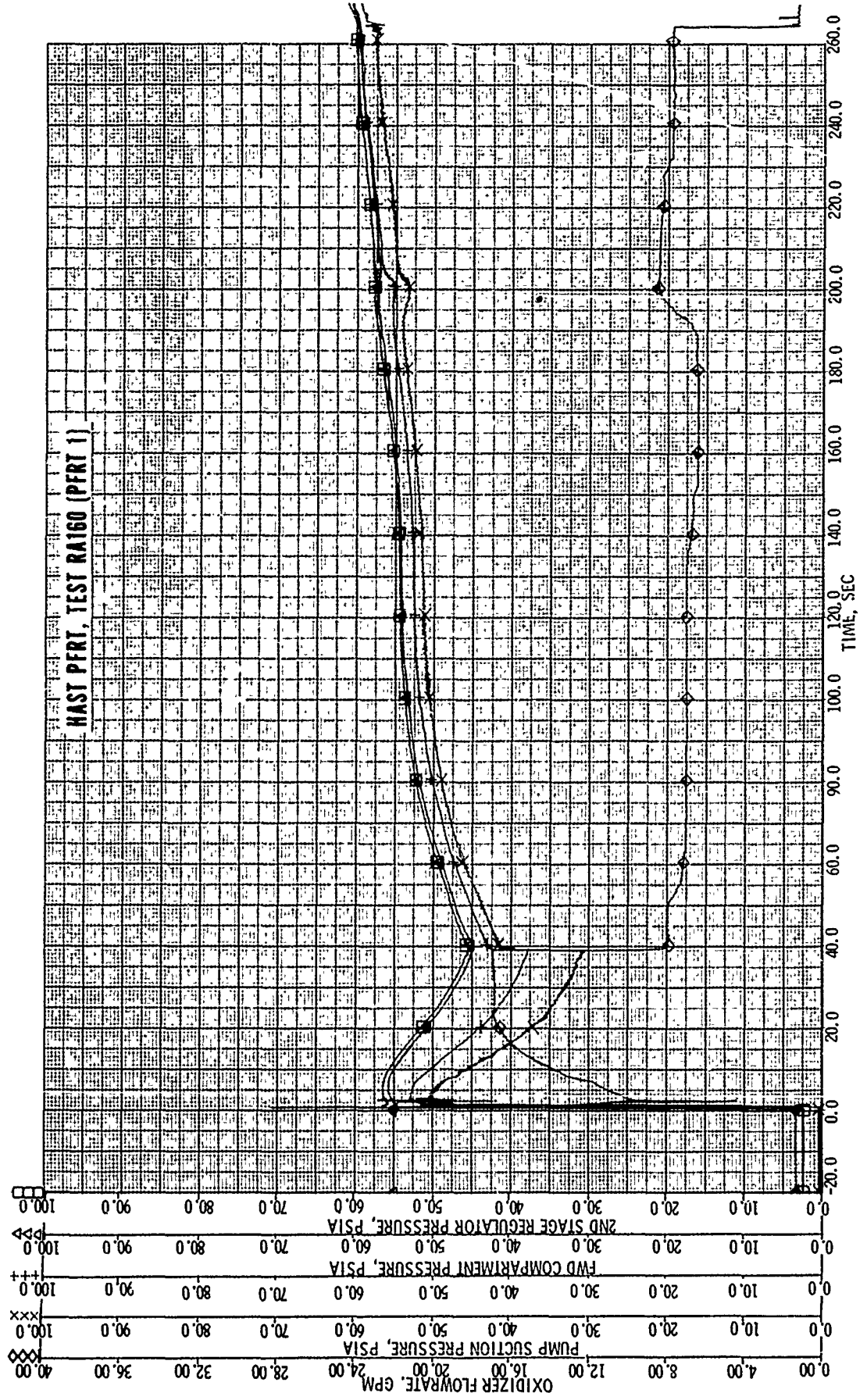


Figure 28. OMA Parameters for PFRT 1

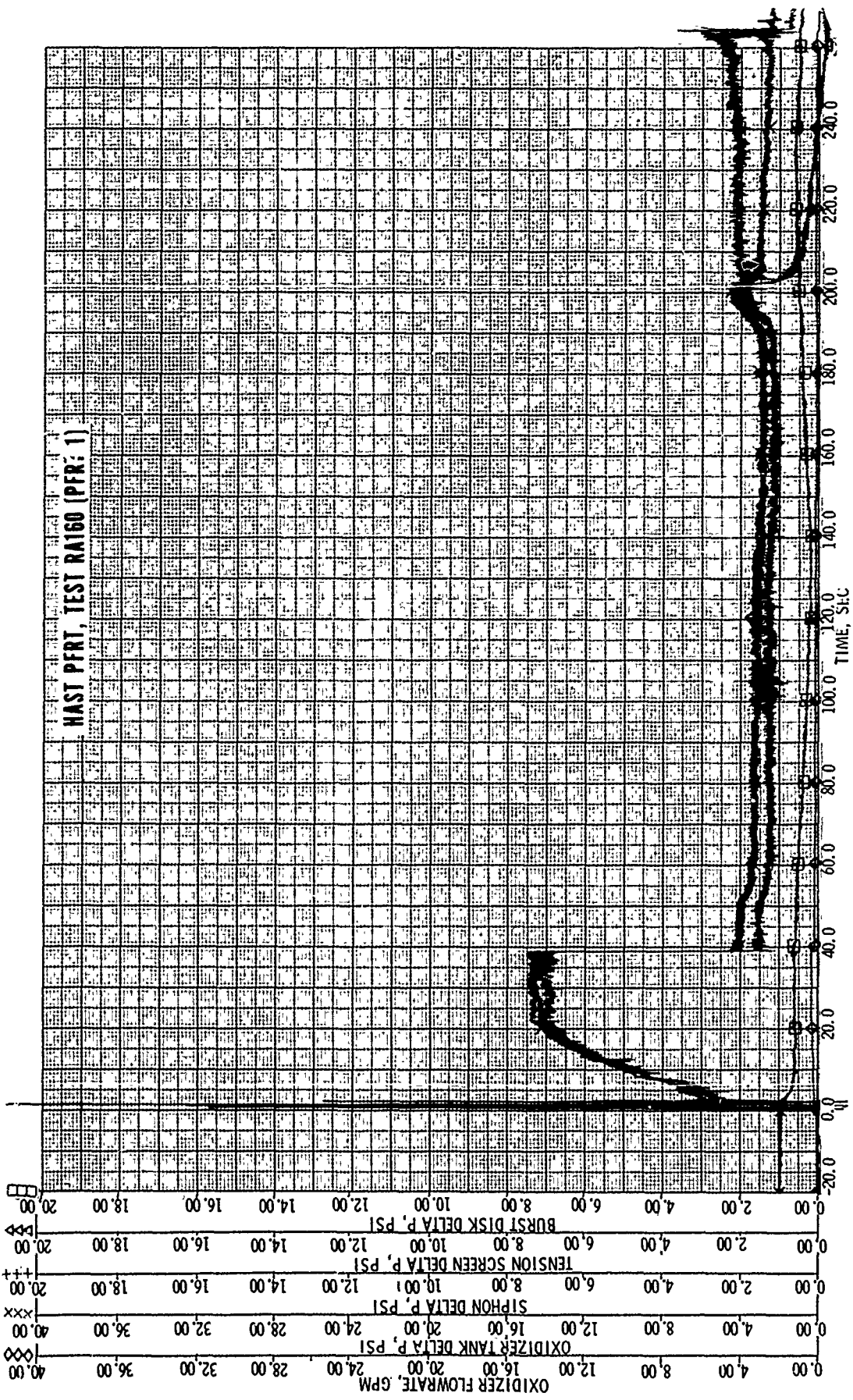


Figure 29. Pressure Drops in OMA for PFRT 1

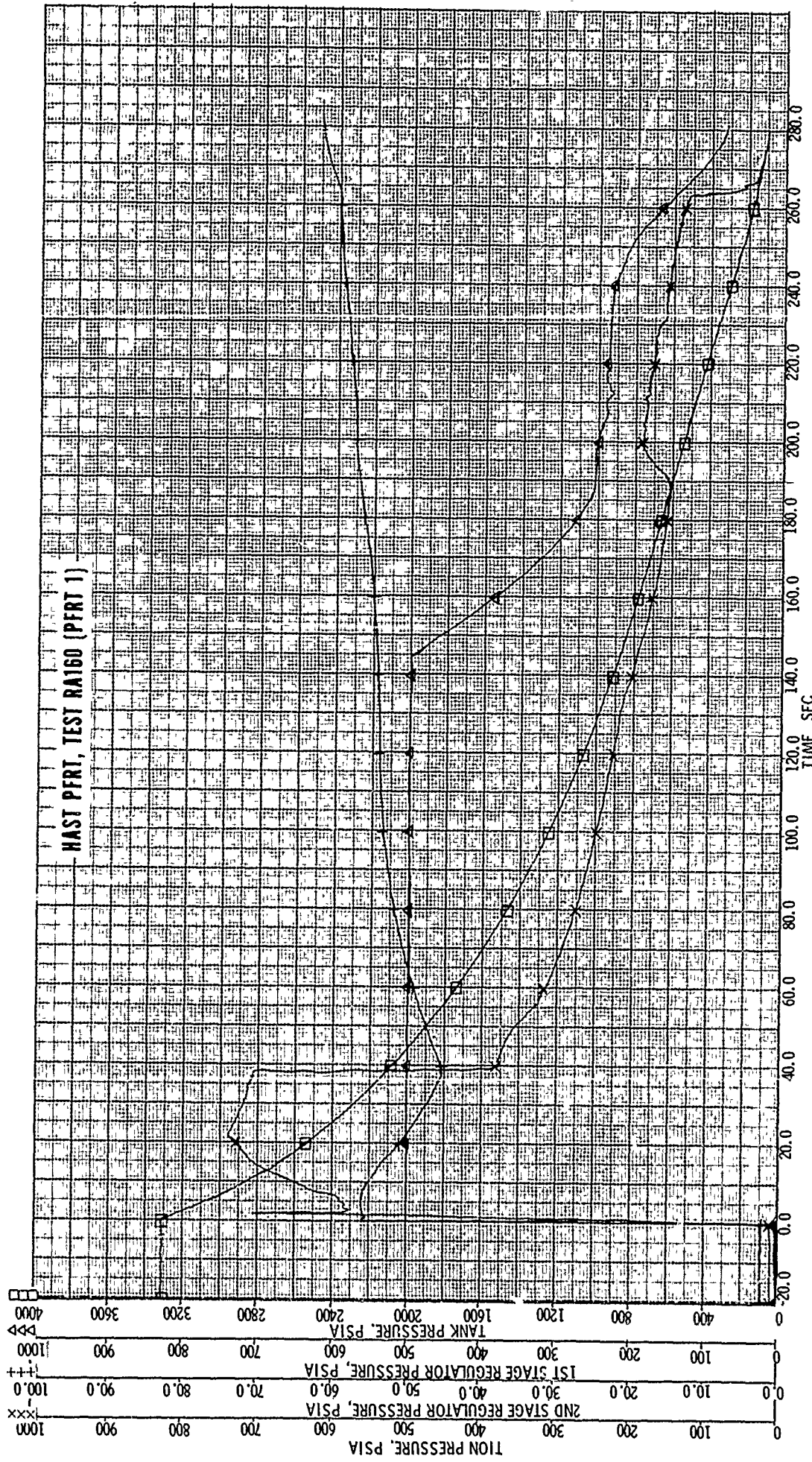


Figure 30. Pressurization Parameters for PRFT I

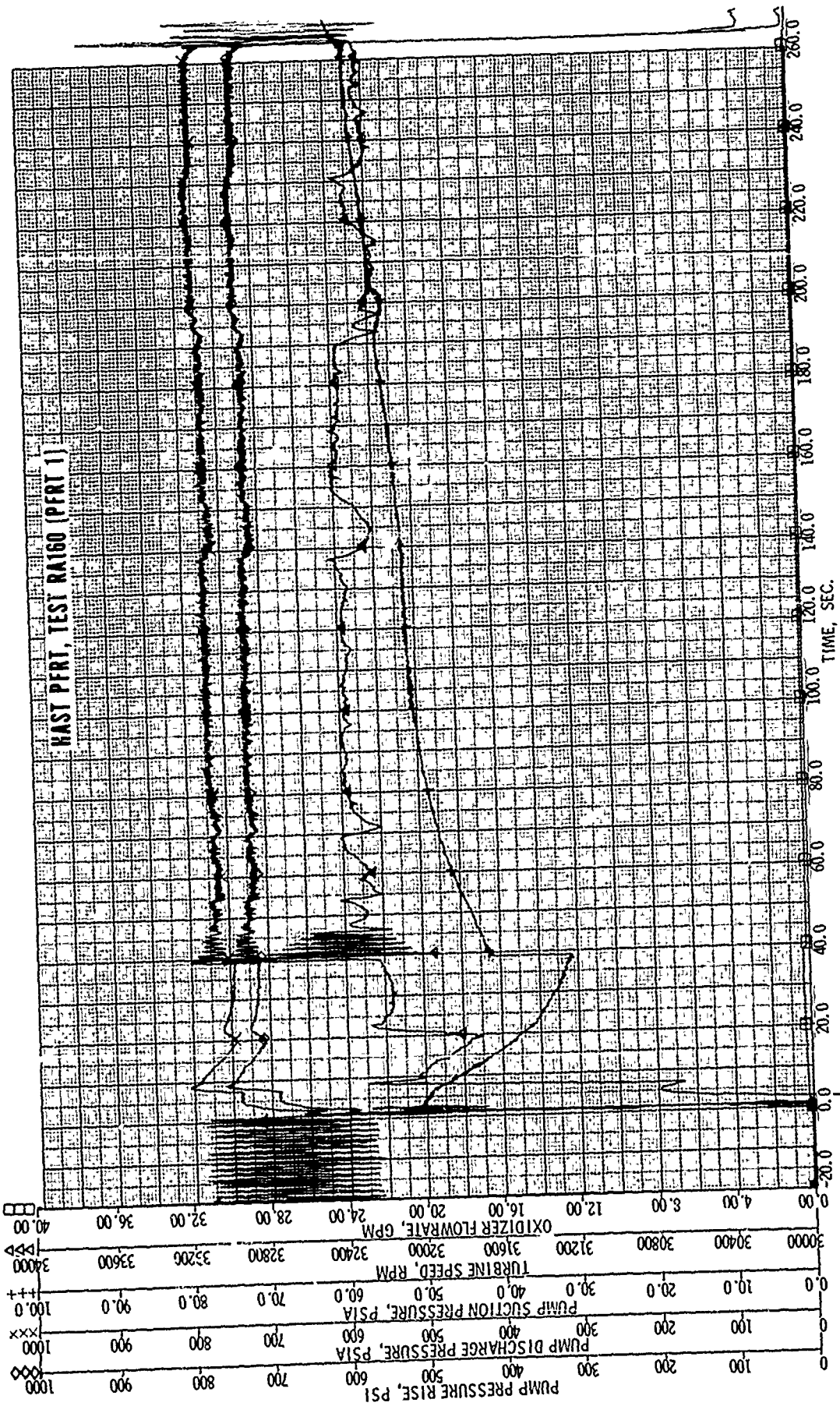


Figure 31. Pump Performance for PFRT 1

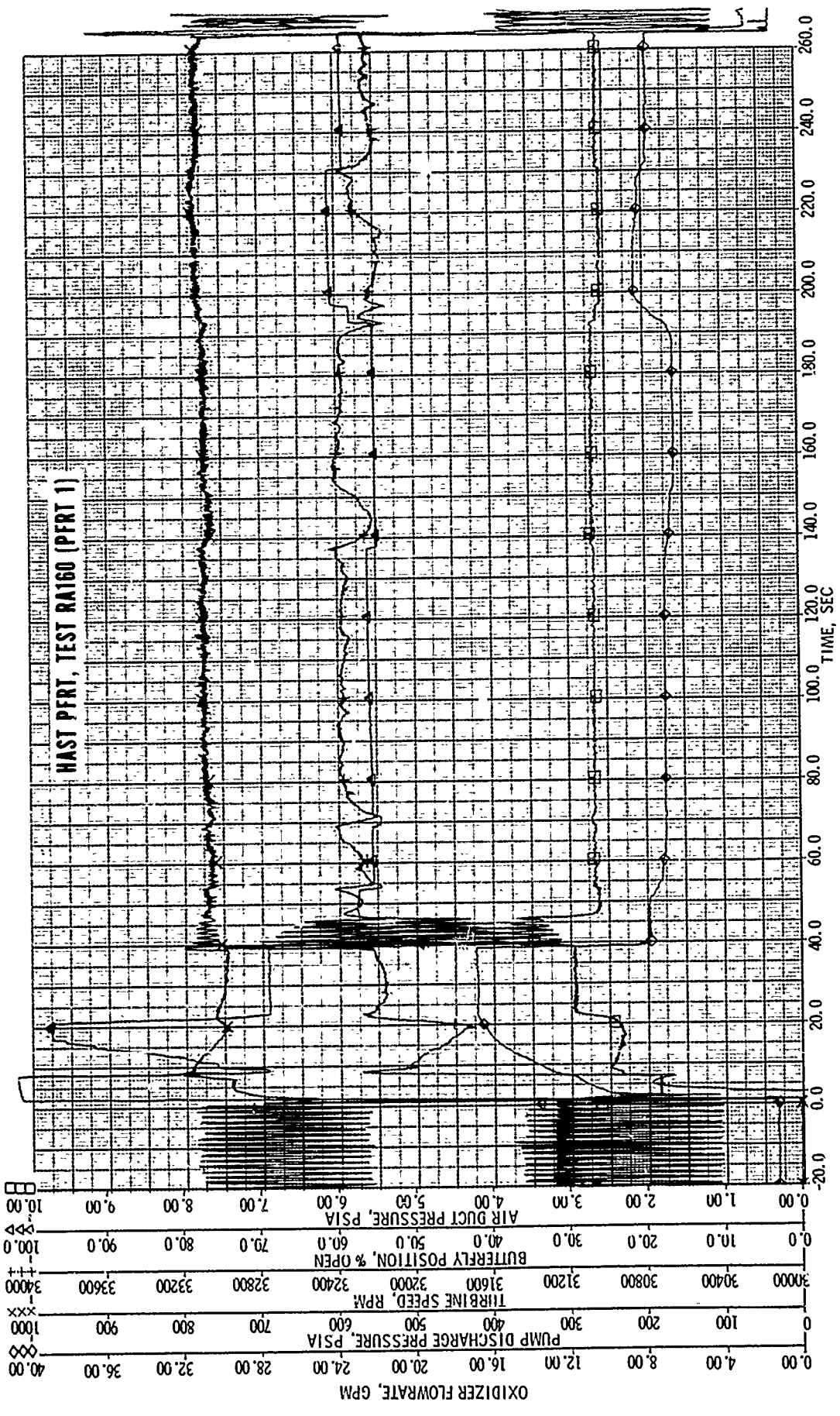


Figure 32. Ram Air Turbine Parameters for PFRT 1

The DLS did not properly sequence the propulsion system starting operations. In the normal sequence, the nitrogen start command occurs at +0.5 sec (time referenced to launch command at 0.0 sec), the oxidizer start command is at +0.9 sec, the igniter is fired at +1.7 sec, and the OTV is opened at +2.2 sec. On this test, the first three commands occurred at the correct time, but the OTV was opened at the same time as the oxidizer start valve. The presence of oxidizer in the thrust chamber when the igniter fired resulted in a hard start, with a spike in chamber pressure to over 700 psia. The start transient is shown in Figure 33. No damage to the thrust chamber resulted from this overpressure, and the rest of the test proceeded normally.

The malfunction of the DLS was the result of IRFNA corrosion. The circuitry and components had been saturated with IRFNA because of the leak on the last OMA test. Since another DLS was not immediately available, the start sequencing was accomplished by a facility timer on the remaining tests.

The IRFNA leak on the last OMA test was also the cause of another component failure. The first stage regulator was reused from the OMA test, and, as a result of the IRFNA exposure, failed in the open position on this PFRT test. The resulting regulator output pressures, aeration pressure, and nitrogen tank pressure are shown in Figure 30. The straight line in the plot of the first stage regulator pressure during the first half of the test indicates that this pressure exceeded the range of the transducer.

The regulator functioned only as an orifice to drop the pressure of the nitrogen before it reached the second stage regulator and aeration supply orifice. The high pressure overcame the check valve in the aeration manifold, and aeration gas flowed into the injectors during boost. During part of sustain there was also much higher than normal aeration flow. Then the excessive flow rapidly depleted the nitrogen tank, and at 199 seconds the inlet pressure to the aeration orifice dropped below the required

HAST PFRT, TEST RA160 (PFRT 1)

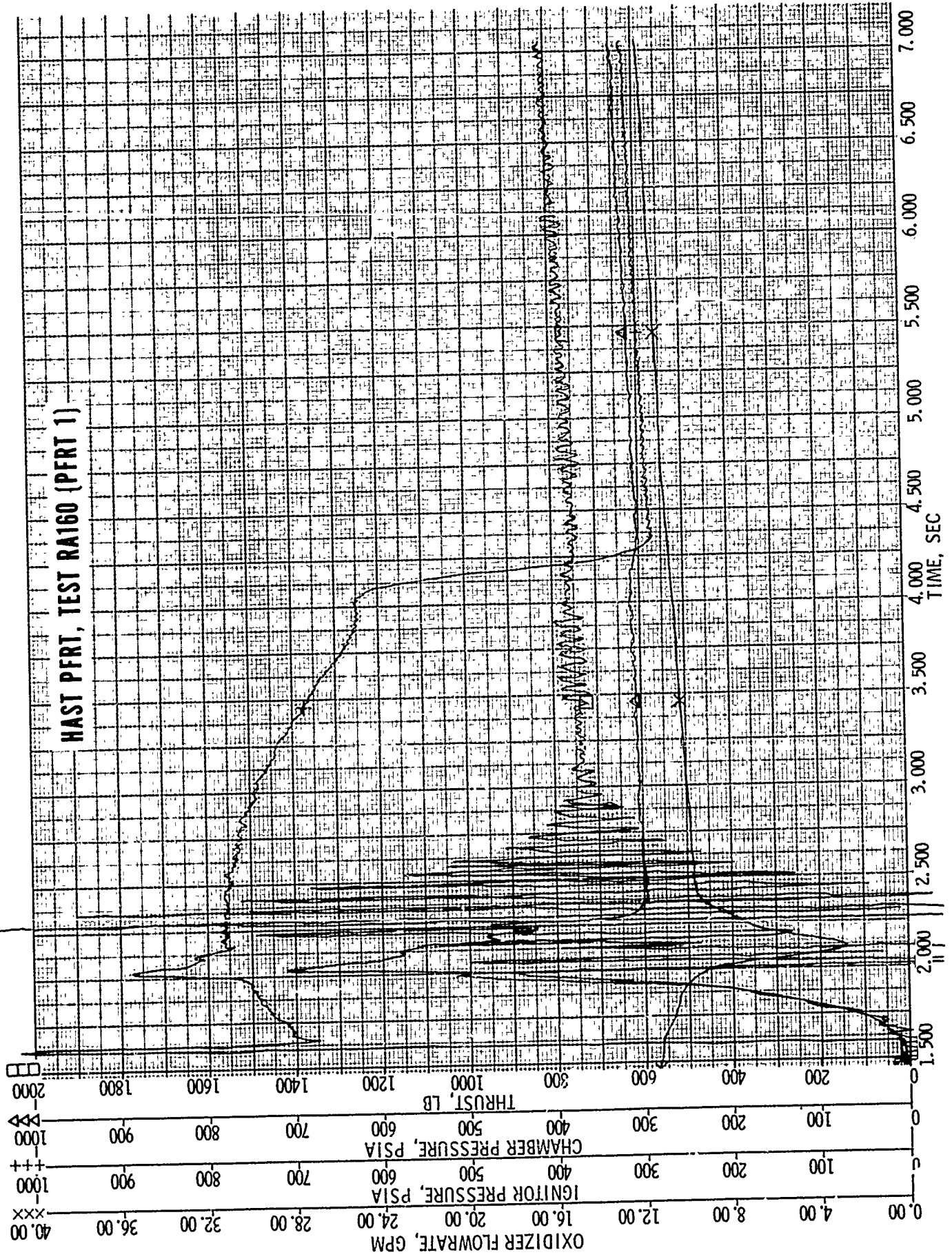


Figure 33. Ignition Transient for PFRT 1

minimum of 250 psia. The nitrogen tank was almost empty at the end of the test, with only 156 psia remaining when the oxidizer was depleted at 264 seconds. At this time the aeration orifice inlet pressure was only 146 psia.

Figure 30 also shows that the second stage regulator outlet pressure is lower than the set point of 53 to 68 psia. During boost, this pressure had dropped as low as 45 psia. This regulator had been bench-tested prior to installation on the test hardware and was within the set point range. The cause for the low output pressure was not determined.

A new DPU had been installed for this test. Immediately after the test, the turbine rotated smoothly and no problems were evident. However, after a few days had elapsed the shaft could not be rotated by hand. It was suspected that the seizure was due to an accumulation of salts in the viscoseal because the residual IRFNA could not be removed from that area.

PFRT 2 (Test RA 161)

This test was planned to be a simulation of the design baseline mission, with cruise at Mach 3.0 at 80,000 ft after boost from Mach 1.5 at 50,000 ft. The maximum amount of oxidizer, 496 lb., was loaded for this test.

Prior to this test, changes were made to the thrust stand to correct the zero shift problem. These changes are discussed in Section III. Because of the time required to make these corrections, the exposure time of the oxidizer tank to IRFNA vapor and liquid would have exceeded the time shown to have been acceptable in short term storage tests by BAC. Consequently a different oxidizer tank was installed for PFRT 2.

The O-ring seals in the MFV (second stage regulator) had been changed from Kel-F to Buna-N. The change was the result of low temperature qualification tests attempted by Futurecraft. At -40°F the Kel-F O-rings

had allowed nitrogen leakage into the reference cavity, thus increasing the reference pressure and raising the output pressure. The Buna-N O-rings had appeared to solve this problem and were used in the MFV on this and all subsequent PFRT tests. However, further qualification tests showed that the MFV still did not operate satisfactorily at the low temperature.

The plumbing from the MFV to the burst disc holder was changed to the actual flight vehicle plumbing. On the previous test, this connection had been made via a flexible stainless steel hose of nominal 0.375 in. diameter, which was a more easily made connection in the test cell. BAC had determined that there was a pressure drop of 2 to 3 psid through the 0.25 in. diameter lightweight tubing at maximum nitrogen flowrate. Since this is not a negligible pressure loss it was necessary to use the same plumbing on the PFRT tests to simulate the flight vehicle. The flight plumbing was used on this and all subsequent tests. This required deletion of the isolation valve between the MFV and burst disc which had been used on the OMA tests and PFRT 1.

In addition to being a test of the propulsion system at the design baseline mission, another objective of this test was to measure temperatures at various locations on the CTA during operation and during heat soak after shutdown. The missile boattail assembly was installed around the CTA nozzle, as shown in Figure 34. This assembly contains the aileron actuator motor and drive mechanism, the recovery system battery, and the destruct mechanism. An aluminum foil/asbestos insulation around the nozzle housing protects these components from thermal radiation. Temperatures were measured on the outside of this insulation to permit calculation of the radiation heating of adjacent components. Thermocouples were attached to the insulation by epoxy cements, at the locations shown in Figure 35. Temperature sensors, which indicated the maximum temperature by color change of temperature sensitive material, were placed on the components themselves.

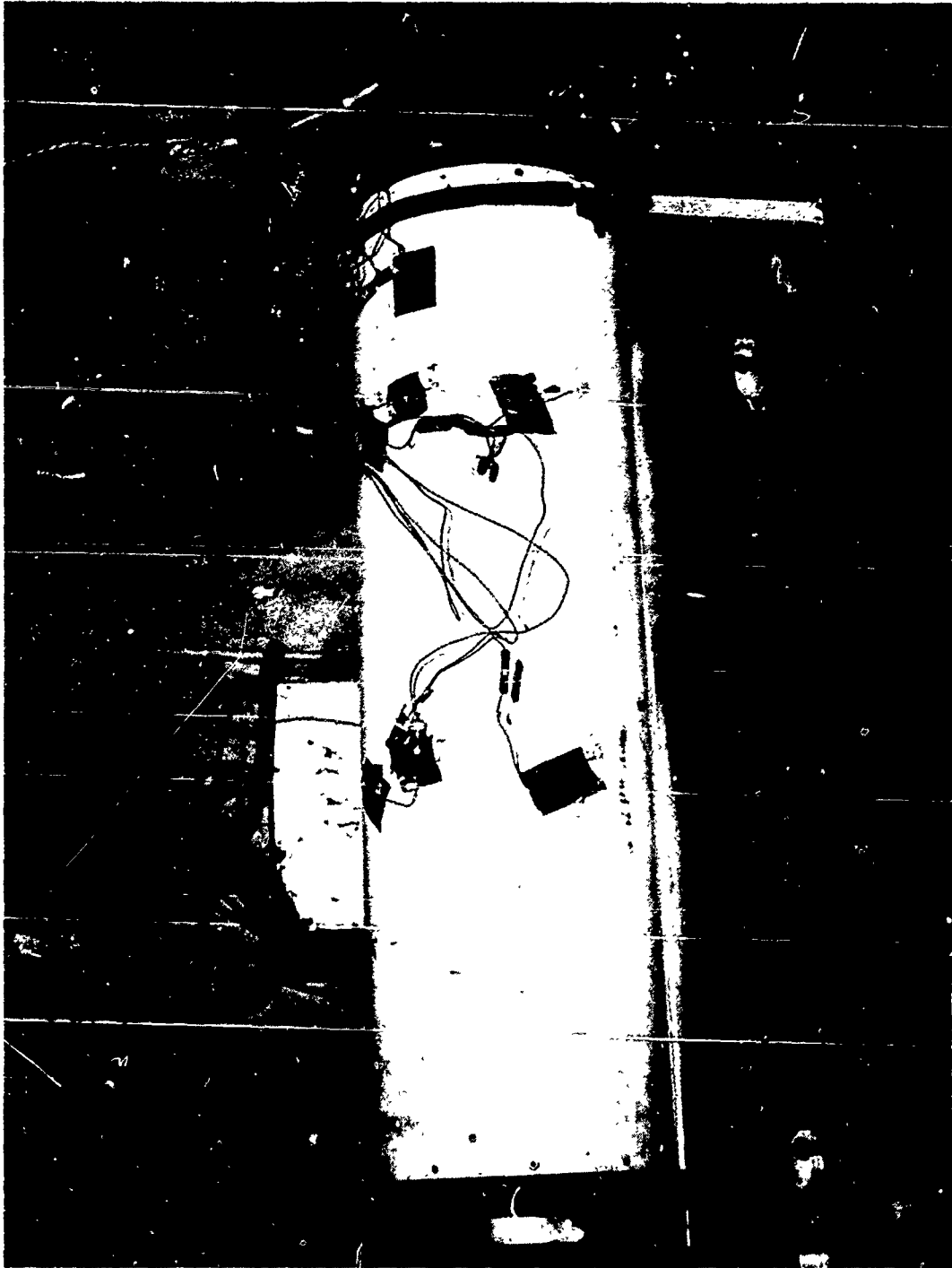


Figure 34. CTA with Boattail Assembly Installed

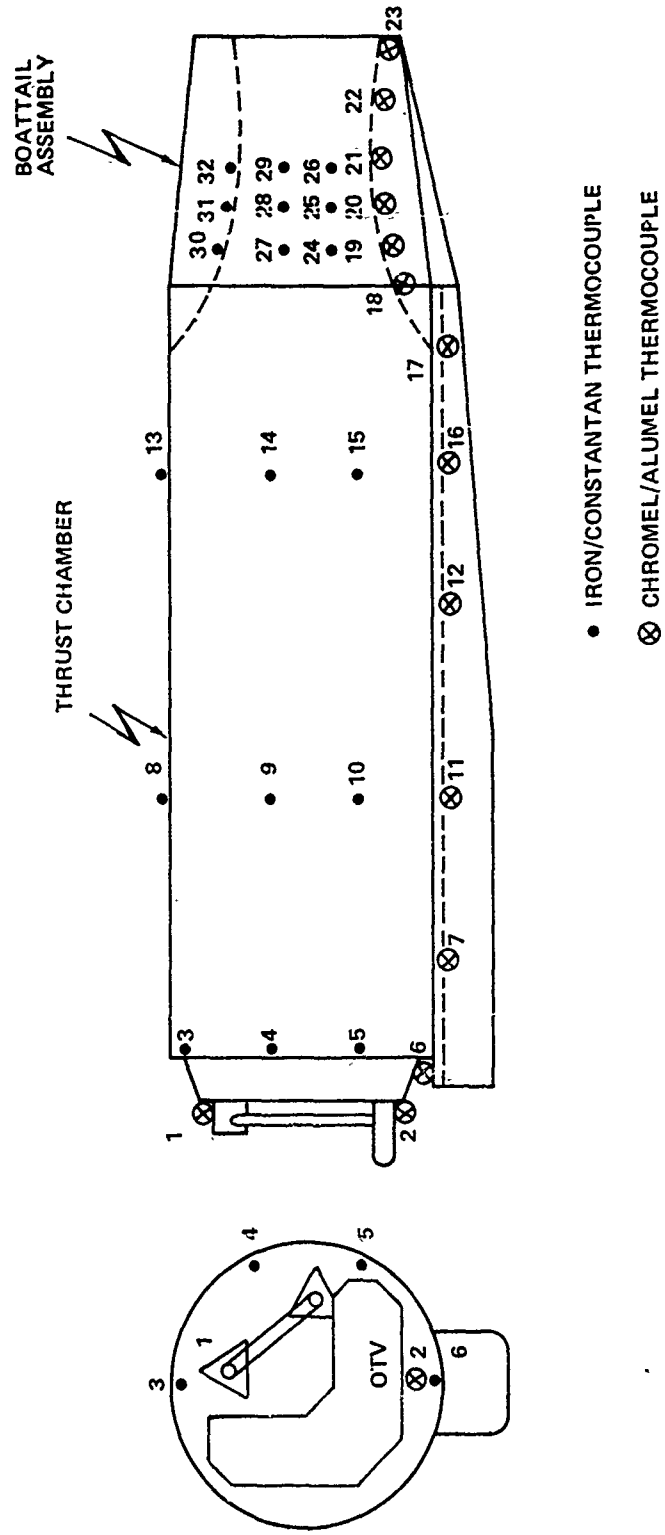


Figure 35. Thermocouple Locations on CTA for PFRT 2 and 3

As previously noted under the discussion of PFRT 1, the start sequencing was accomplished by a facility electro mechanical timer rather than the DLS.

The data for this test are shown in Figures 36 through 41. A normal start was obtained, and the OTV provided a normal ramp to its full-open position. However, at 19 seconds after launch, an instantaneous, almost complete shutoff of oxidizer flow occurred. As shown in Figure 37, the flow dropped from 16.0 gpm to 2.2 gpm. With the OTV remaining full open and pump speed at the nominal 32,000 rpm, the oxidizer flowrate continued at this low level until 217 seconds, at which time it increased to 6.6 gpm. The OTV operator then positioned the valve so as to match the desired sustain thrust until 291 seconds, and then opened the valve so as to acquire data at higher thrust. This flow was maintained until the oxidizer was depleted at 394 seconds.

Post-test examination of the free siphon, to the limited extent possible through the aft oxidizer fill port, showed a tear in the Teflon sleeve. It was postulated that the siphon had collapsed during the ramp to boost thrust, thereby severely restricting the oxidizer flow. The consequent high differential pressure eventually caused the Teflon sleeve to tear, creating a new flow path which bypassed the obstruction.

Before continuing with the PFRT tests, a series of flow tests were conducted with an oxidizer tank having a transparent window to study the response of the siphon during the start transient. These tests and their results, which led to a redesign of the siphon, are discussed at the end of Section IV.

A comparison of the pre-test and post-test thrust readings in Figure 36 shows that the zero-shift problem had been eliminated.

Although it was not noted until a problem of plugging of the tension screen was studied in depth after PFRT 4, the data indicate a slight increase of tension screen ΔP during this test. This is particularly evident in Figure 38, between 335 and 372 seconds, where the ΔP increases from 4.7 to 5.1 psid while the oxidizer flow is essentially constant at 9.3 gpm.

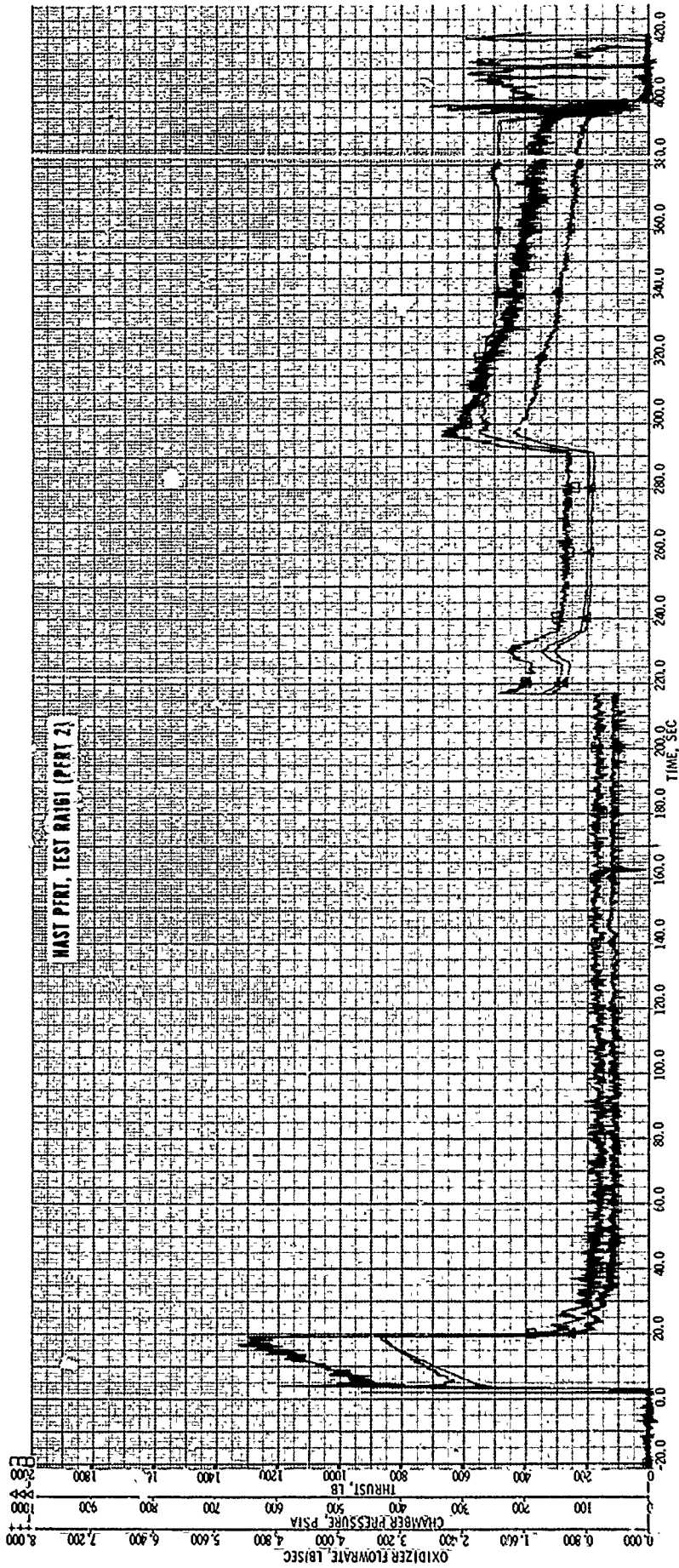


Figure 36. Thrust Chamber Parameters for PFRT 2

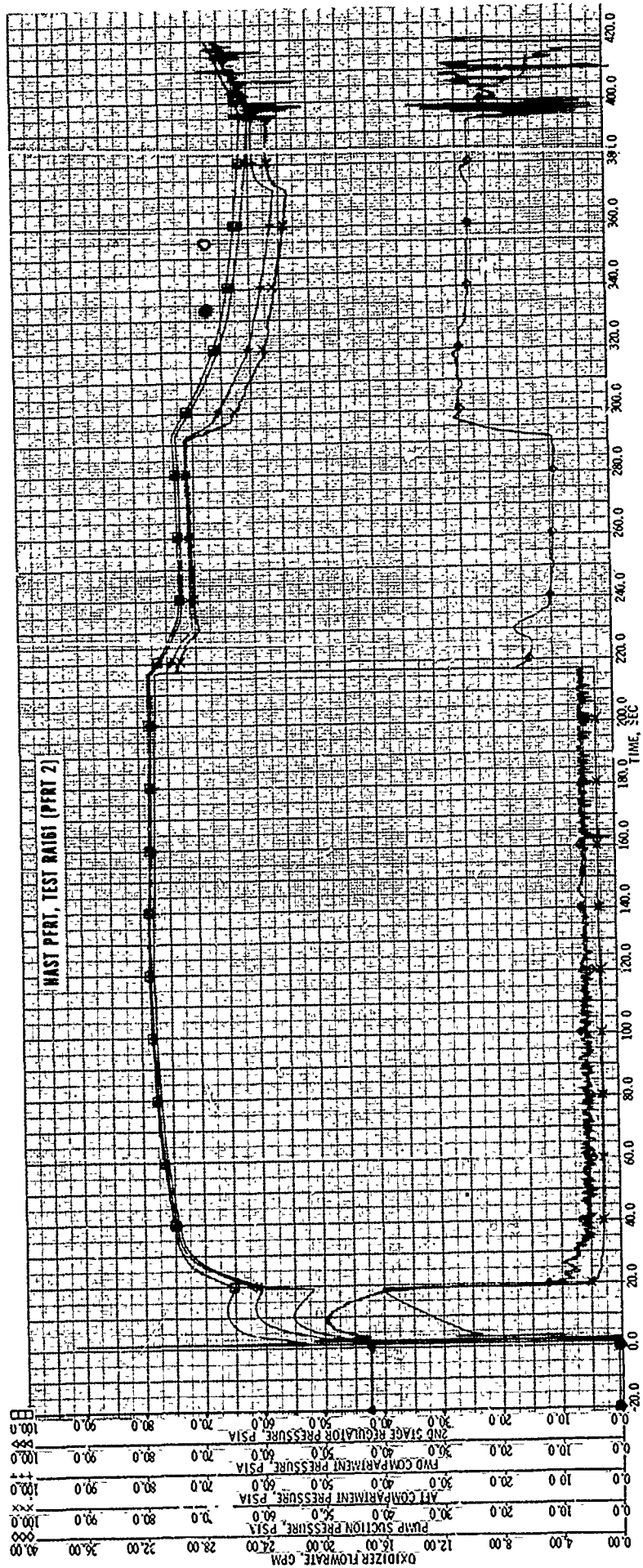


Figure 37. OMA Parameters for PFRT 2

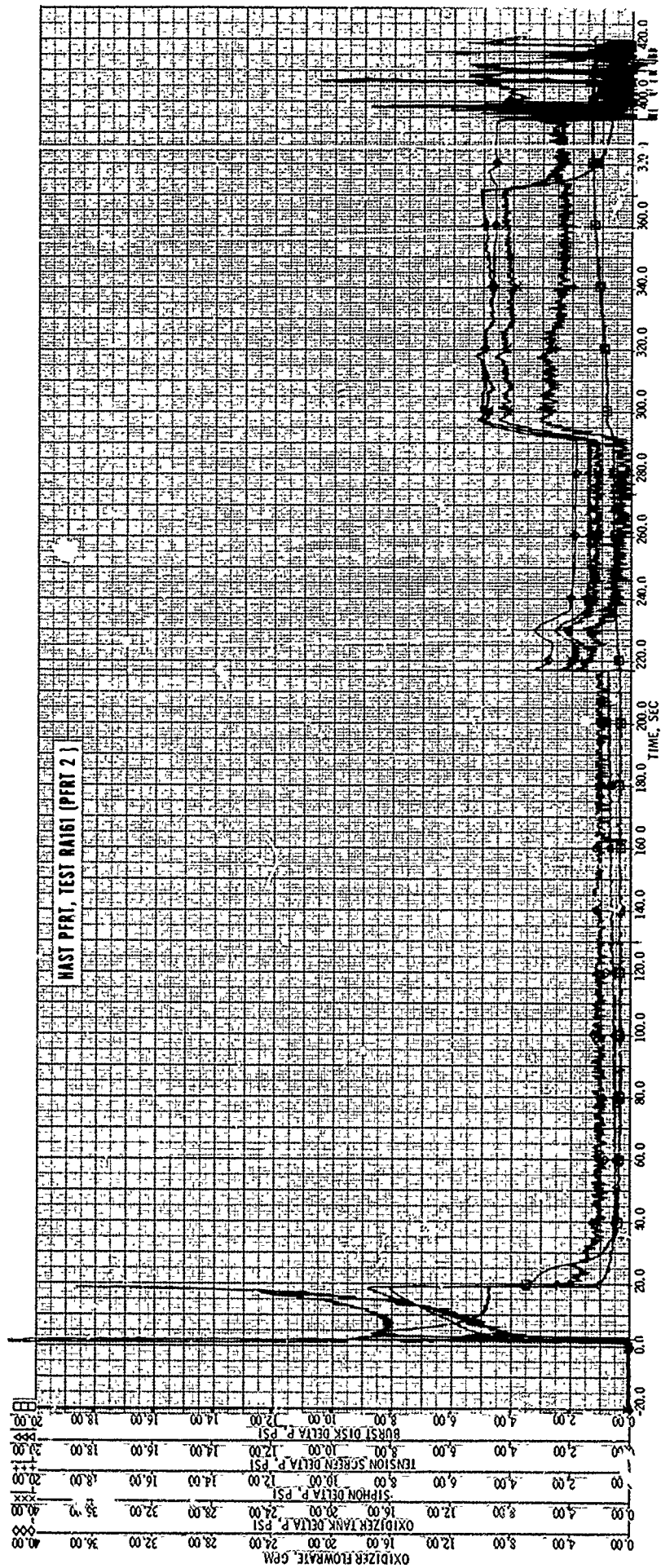


Figure 38. Pressure Drops on OMA for PFRT 2

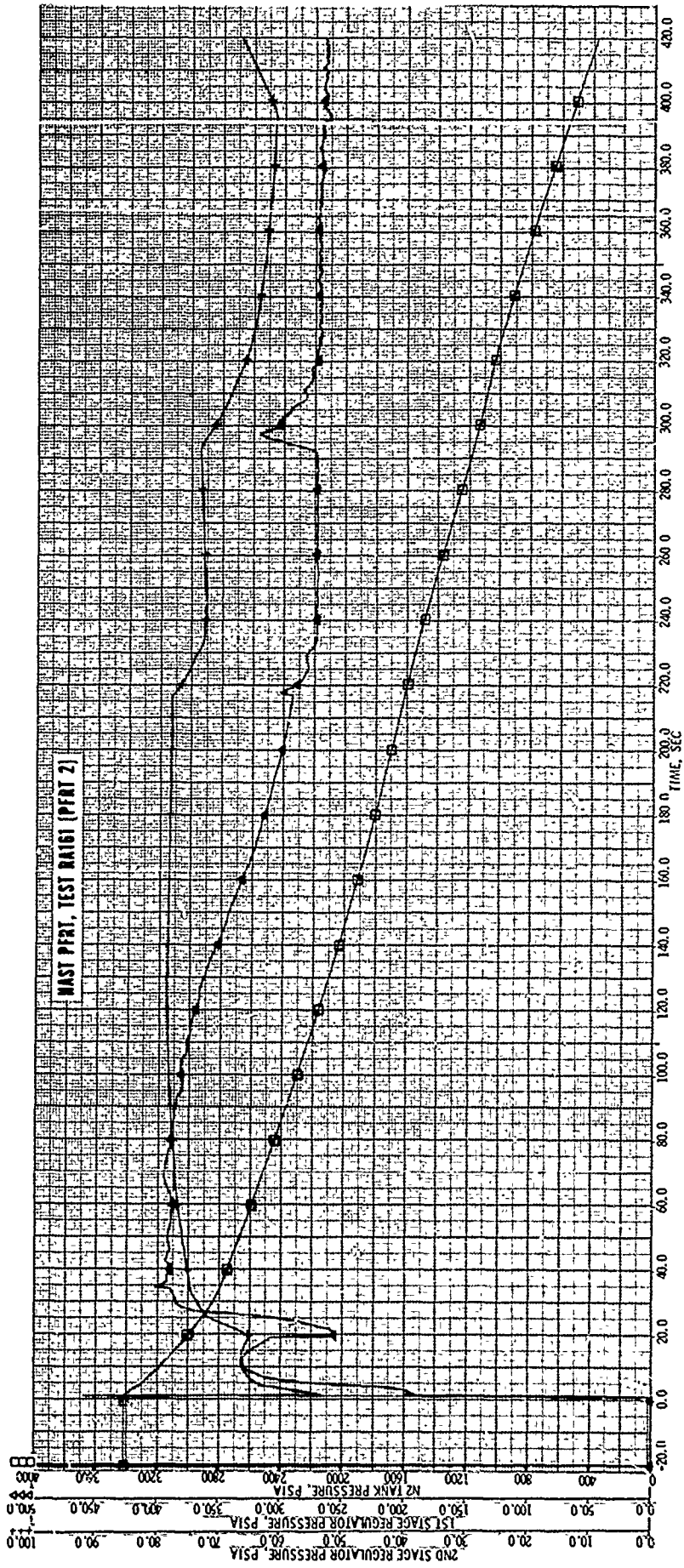


Figure 39. Pressurization Parameters for PFRT 2

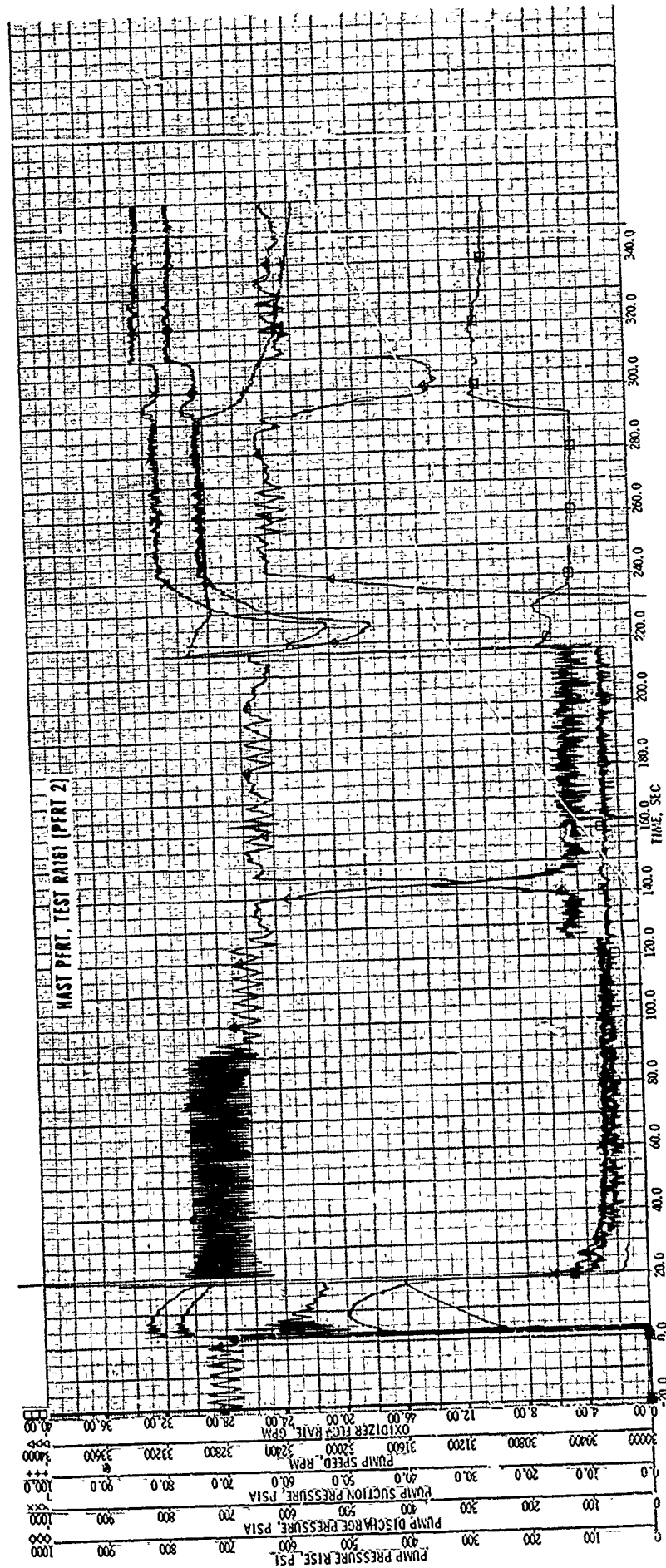


Figure 40. Pump Performance for PFRT 2

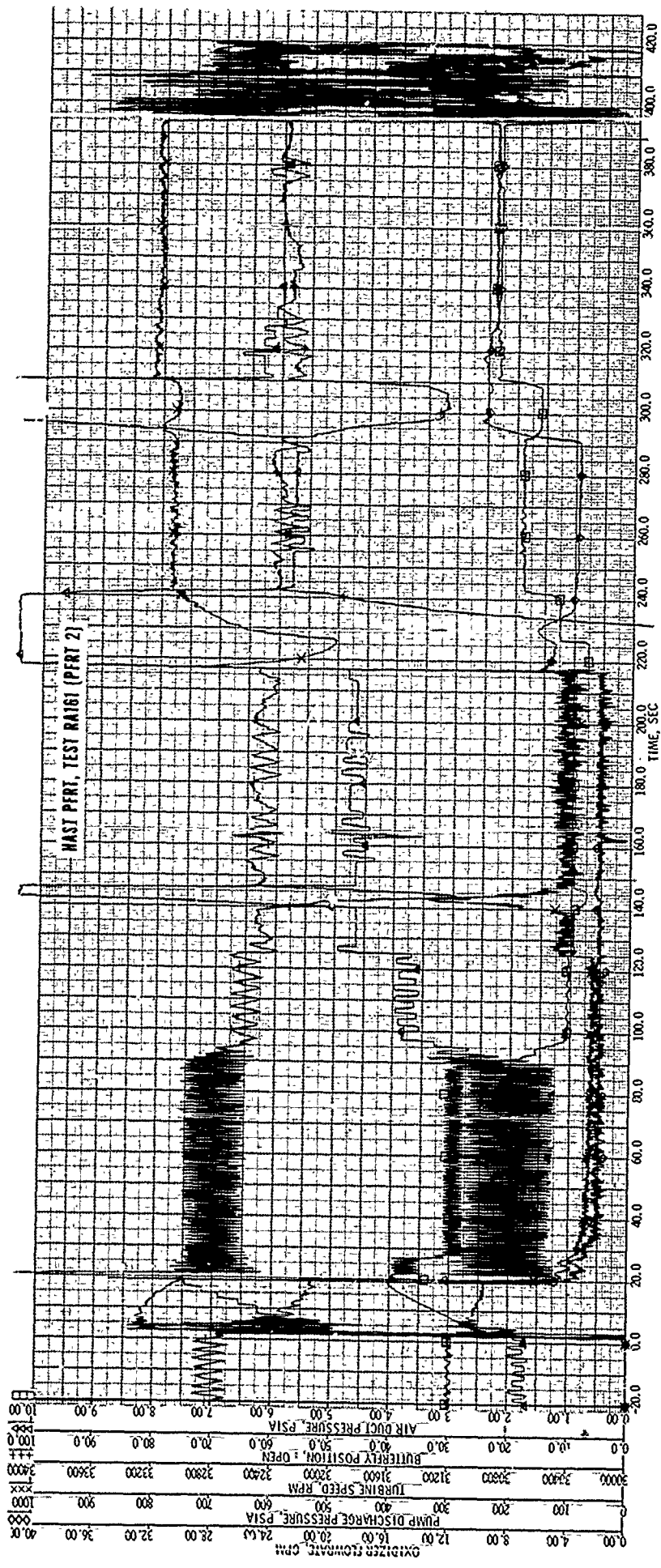


Figure 41. Ram Air Turbine Parameters for PFRT 2

PFRT 3 (Test RA 162)

The PFRT tests continued while the siphon redesign and qualification was underway. For the interim testing, the siphon was replaced by a rigid standpipe. The standpipe was installed in oxidizer tank S/N PT 4-1, used previously on PFRT 1. The tank was cleaned after this installation, using the production cleaning procedure. A new DPU was installed for this test. In the pre-test checkout, a faulty diode was found in the voltage regulator and the entire assembly was replaced with another DPU.

This test was a repeat of the Mach 3.0/80,000 ft mission planned for PFRT 2. The boost duration was 83 sec and the sustain duration was 196 sec. The computer plots of data for the complete test are shown in Figures 42 through 47. Because of a malfunction of the tape drive in the digital data acquisition system, no data was recorded for the time interval between 102 to 123 seconds. On the plots, a straight line is drawn between data points on either side of the missing data. The missing data was not significant to the overall analysis and interpretation of this test. Again, there were no problems with the thrust measurement. The "ringing" in the thrust trace was removed on subsequent tests by a 2 Hz filter in the input to the data acquisition system.

Data from the start transient are plotted in Figure 48, and are typical of the ambient temperature tests. The transient data were computed and plotted at a higher sample rate (100 samples/sec) than are the data for the complete test (10 samples/sec).

Since the CTA temperature measurements made during PFRT 2 were not representative of an actual mission, thermocouples and temperature indicators were installed in the same locations for this test, and the boattail assembly was installed. Maximum temperature on the CTA case was 1063°F, reached during the heat soak 120 secs after shutdown. The temperature indicators showed that the recovery battery had exceeded 200°F, and the aileron actuator had reached temperatures between 340°F and 390°F.

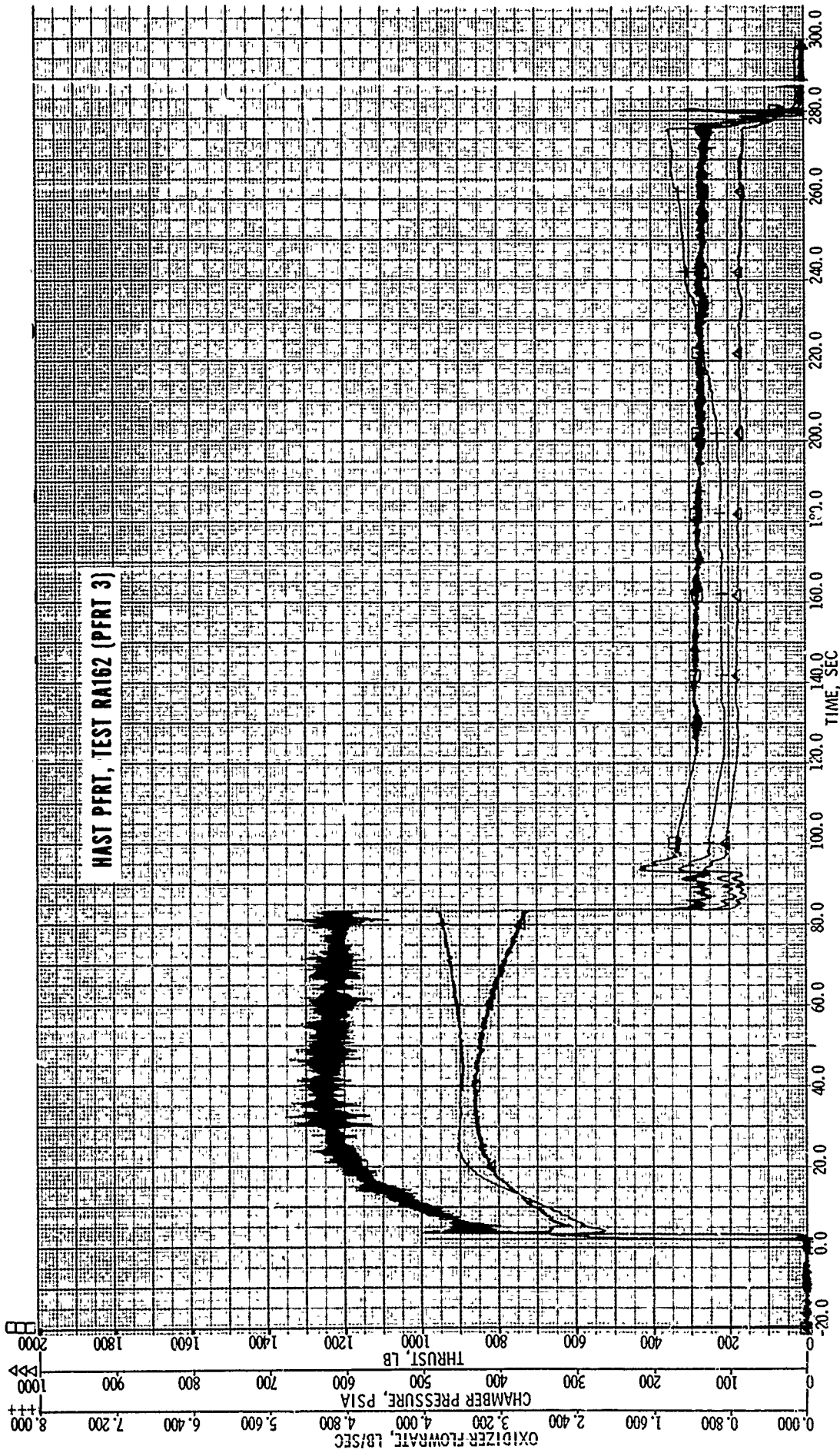


Figure 42. Thrust Chamber Parameters for PFRT 3

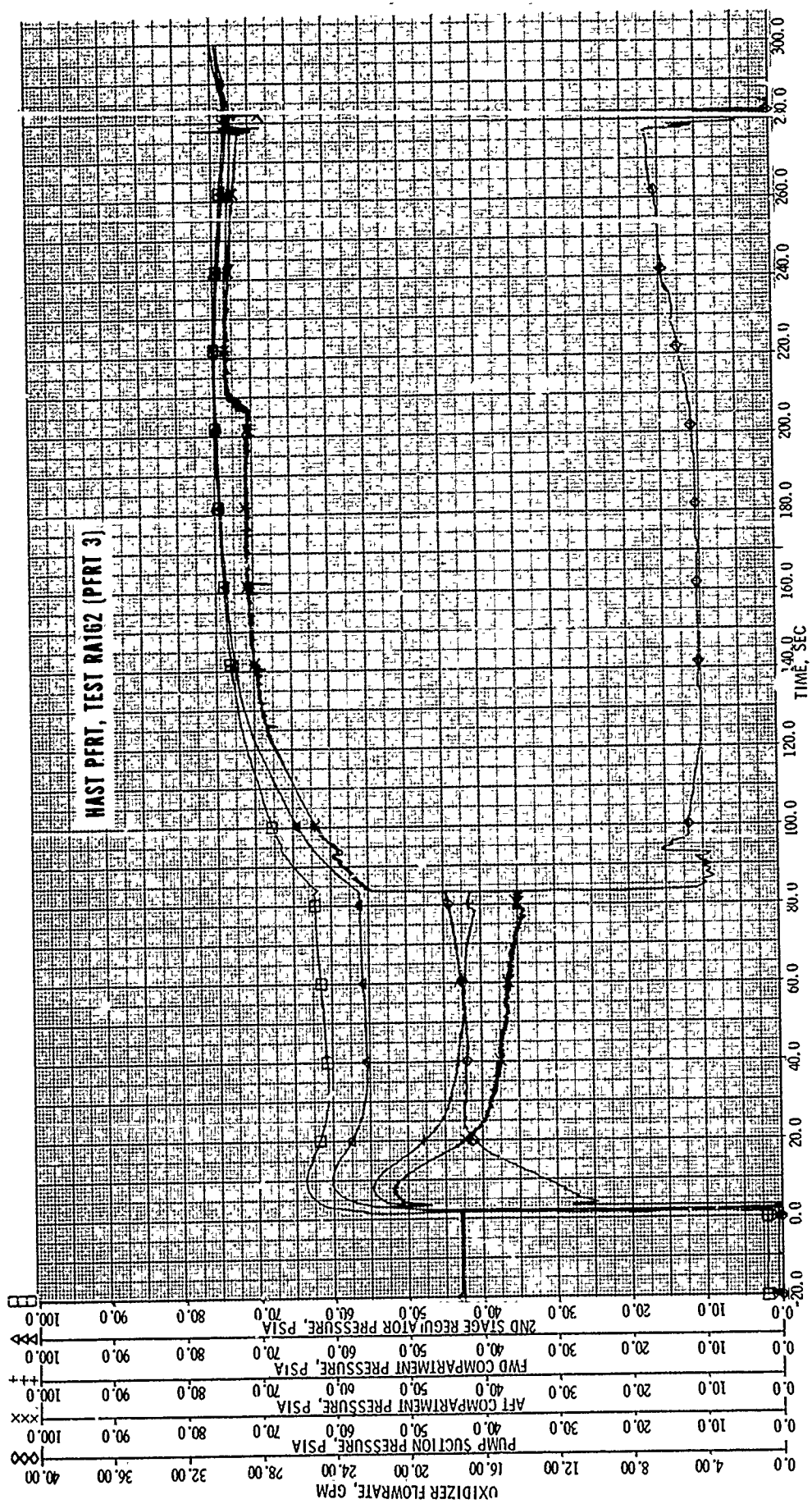


Figure 43. OMA Parameters for PFRT 3

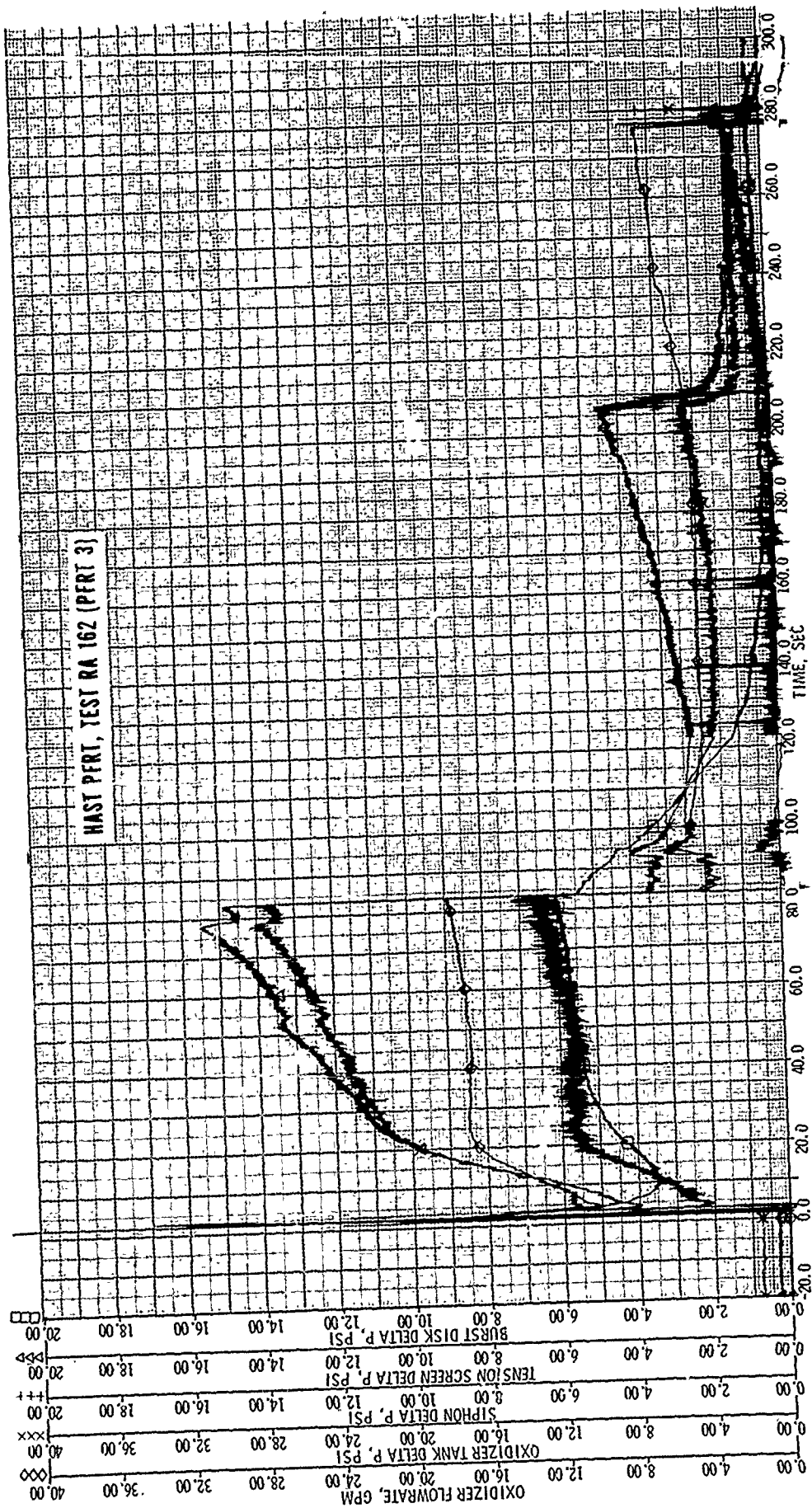


Figure 44. Pressure Drops in OMA for PFRT 3

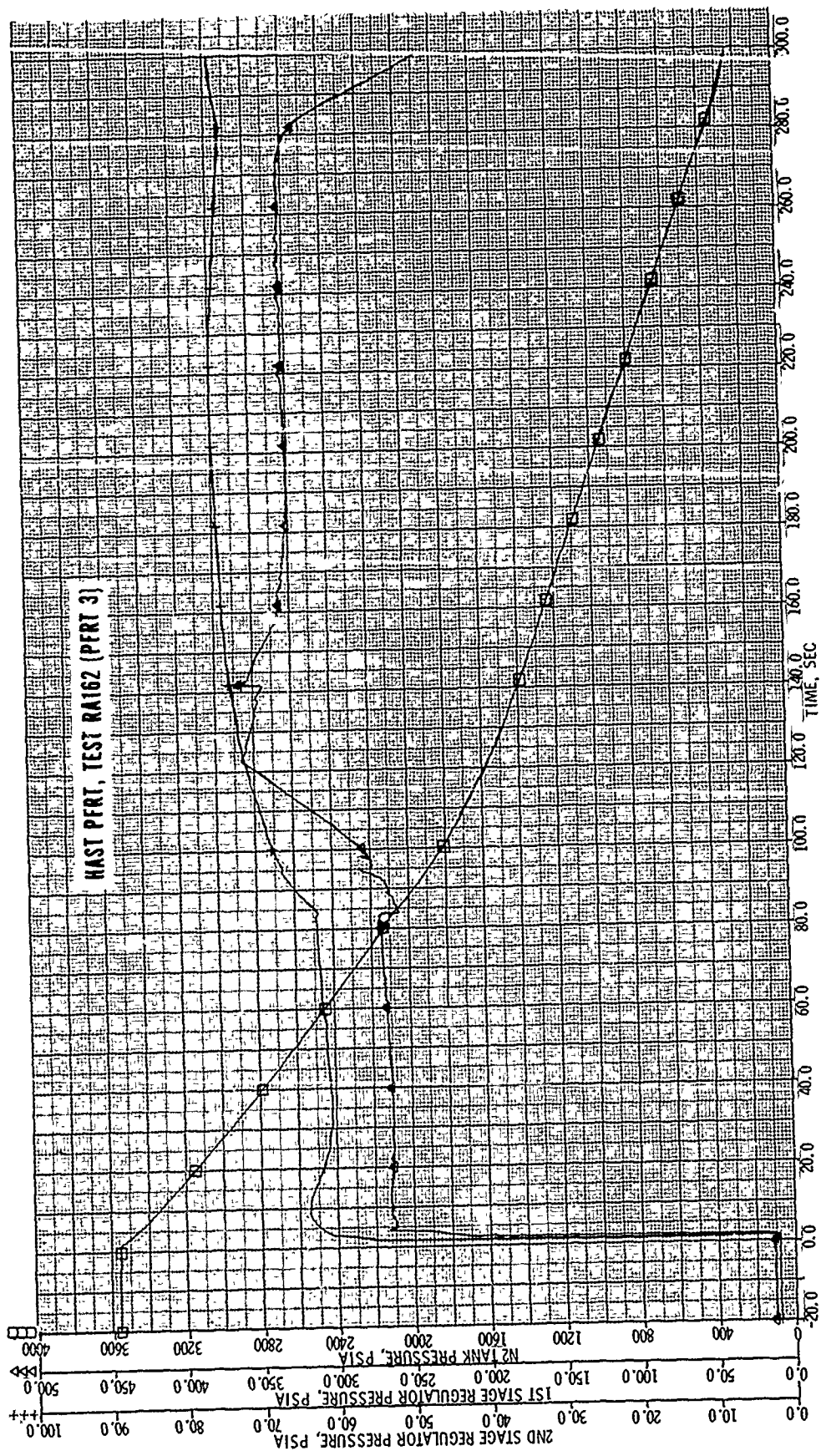


Figure 45. Pressurization Parameters for PFRT 3

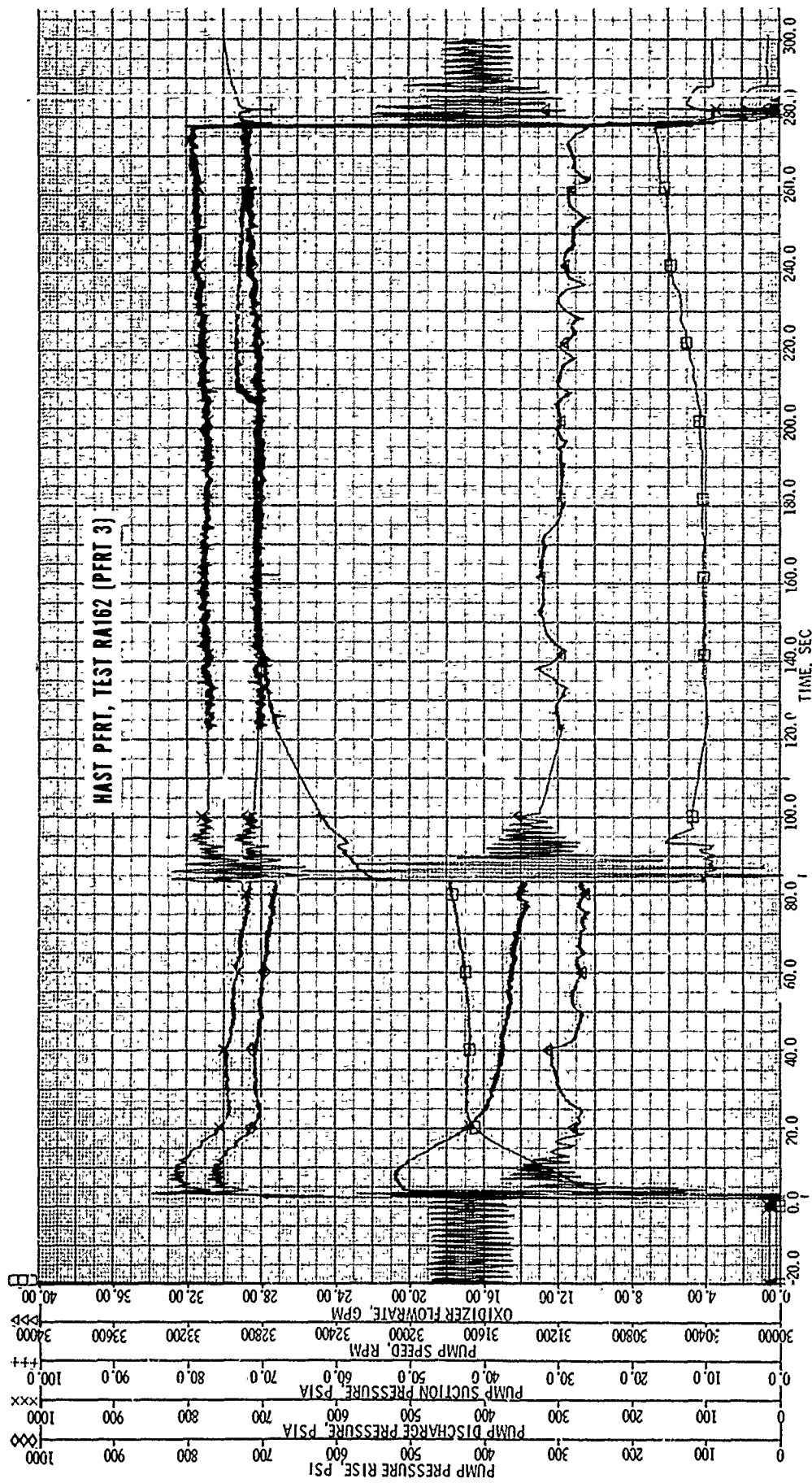


Figure 46. Pump Performance for PFRT 3

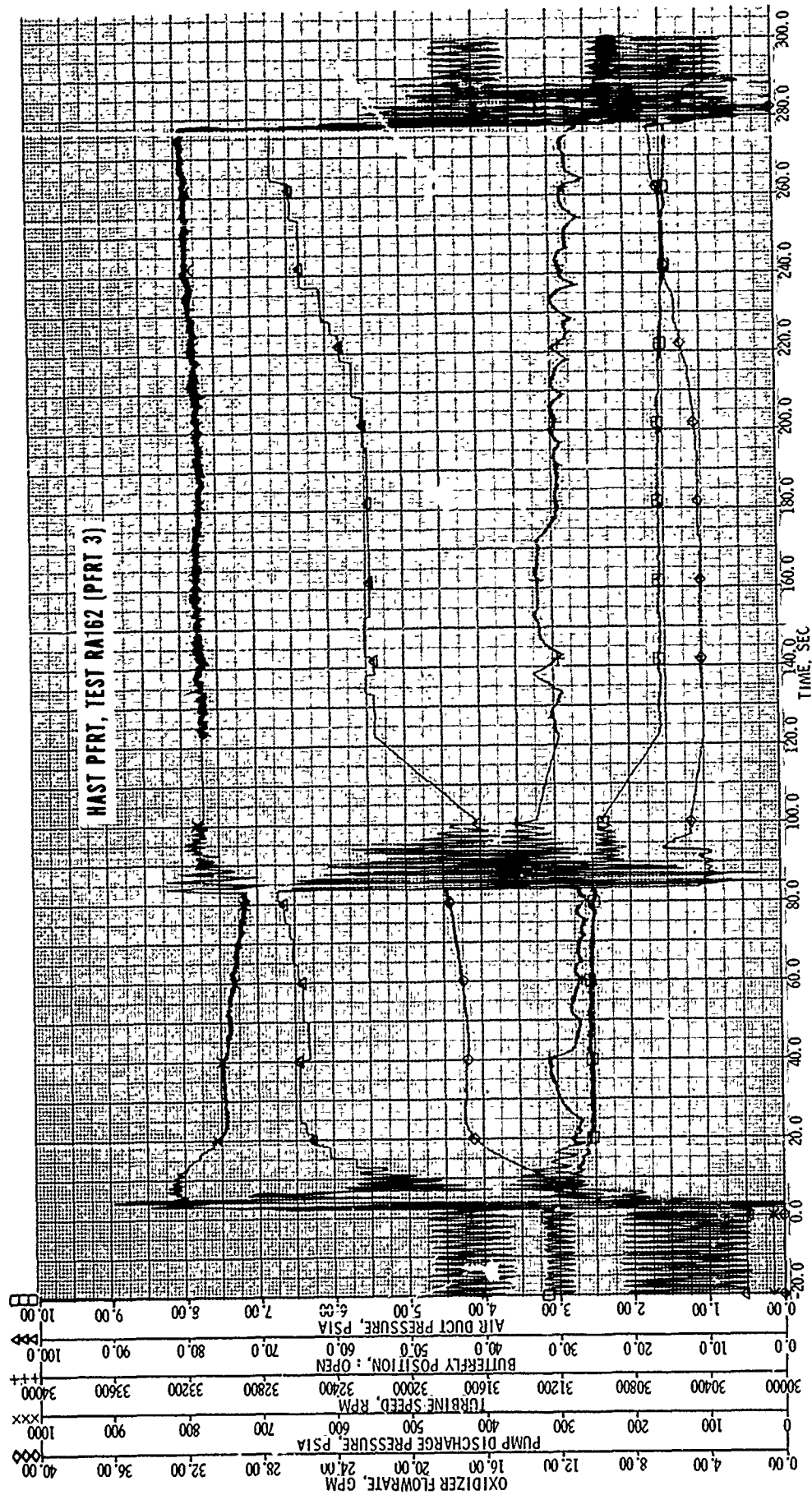


Figure 47. Ram Air Turbine Parameters for PFRT 3

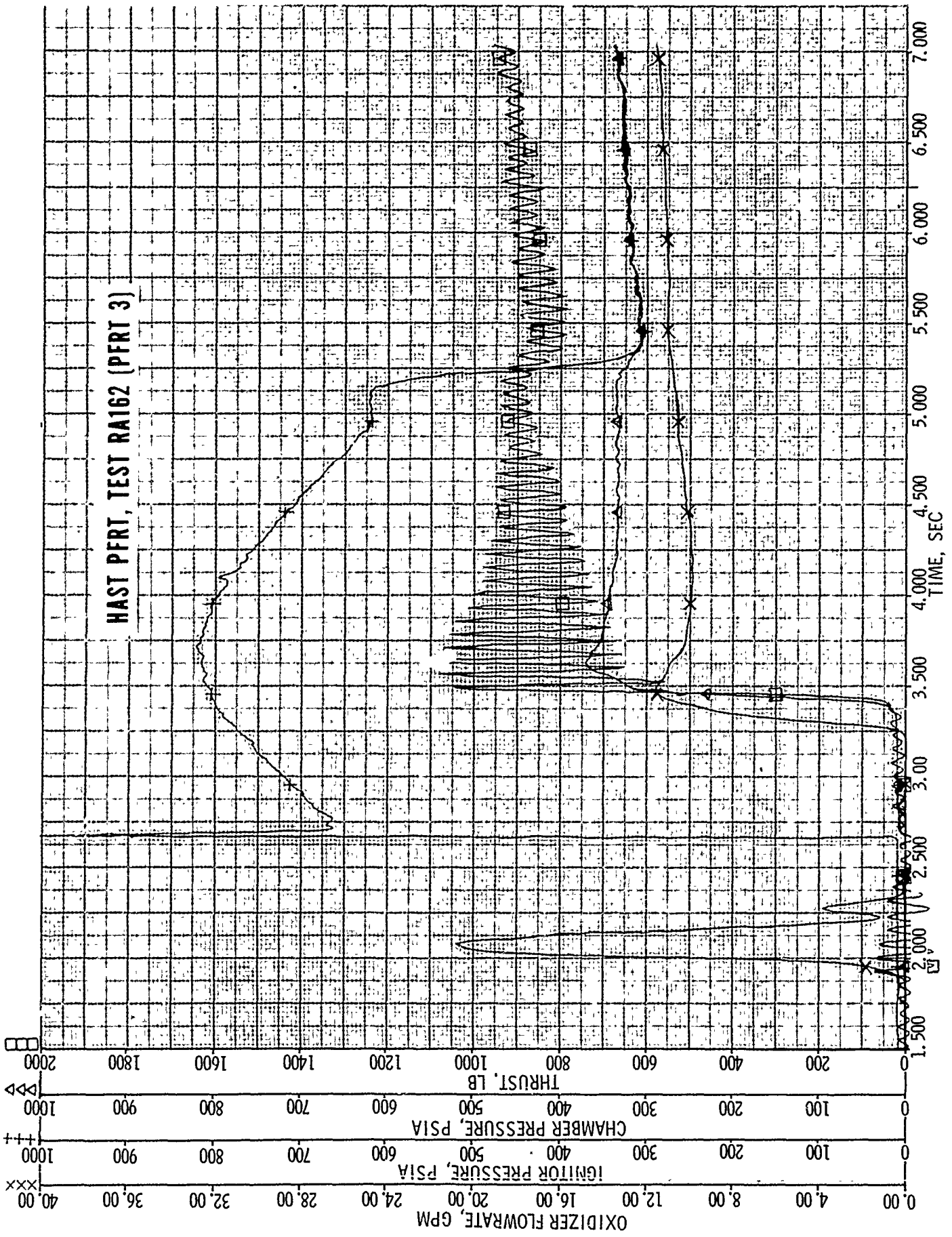


Figure 48. Ignition Transient for PFRT 3

As may be seen in Figure 44, there was a substantial increase in ΔP across the tension screen during this test. This is particularly evident during boost flow, when the ΔP increased from 10.8 to 15.5 psid with little change in oxidizer flowrate. It must be remembered that the parameter identified as "Tension Screen ΔP " is in reality the pressure differential from the forward compartment to the aft compartment, and thus includes not only the ΔP across the tension screen but also the ΔP through the transfer ports between compartments. The two slight decreases in ΔP , at 53 and 78 seconds, indicate that the forward and second tank compartment have emptied of liquid and the ΔP through the transfer port has been removed. The tension screen ΔP also continues to increase at constant flowrate during sustain. The large drop at 207 seconds indicates that the third tank compartment has emptied of liquid, and gas is now flowing through the tension screen. This oxidizer tank was not used for further testing.

In order to try to prevent the seizure of the visco-seal caused by post-test exposure to IRENA, it had been decided to remove the pump housing and flush the seal area with water. The back side of the impeller and the pump housing were found to be scored. Further disassembly and examination by The Marquardt Co. led to the conclusion that the scoring was not caused by the impeller rubbing the housing. Since grooves in the impeller did not match those of the housing, it was concluded that some hard particle had been caught in the small clearance (nominally 0.005 in.) between the impeller and housing. No such particles were evident in any of the oxidizer system, and the source of such particles could not be determined. No other pumps used in this test program showed any damage of this nature.

PFRT 4 (Test RA 163)

The duty cycle for this test simulated the Mach 2.5 at 60,000 ft flight test mission. The actual boost duration was 65 sec and the sustain duration was 209 sec. The data are presented in Figures 49 through 54.

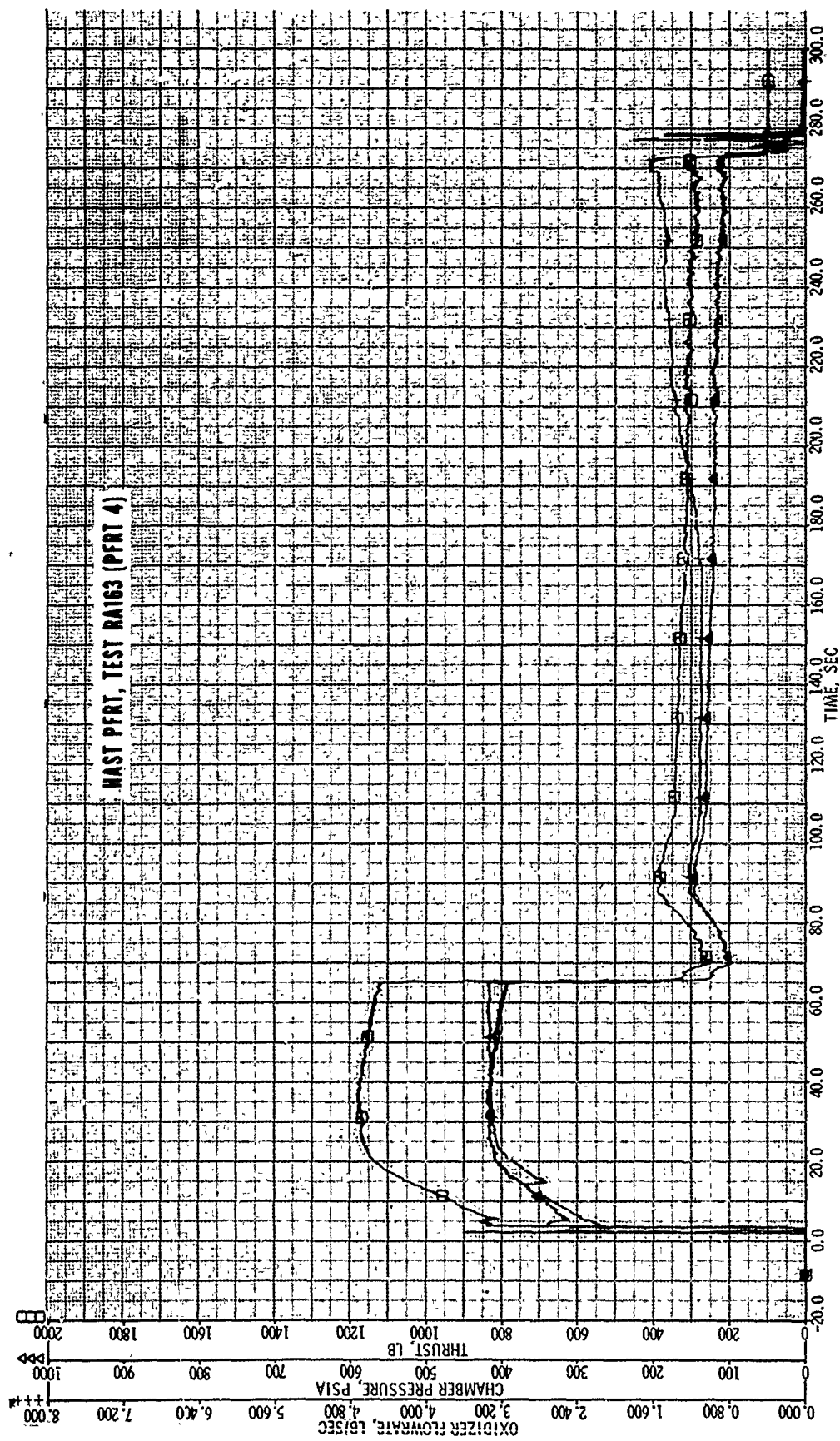


Figure 49. Thrust Chamber Parameters for PFRT 4

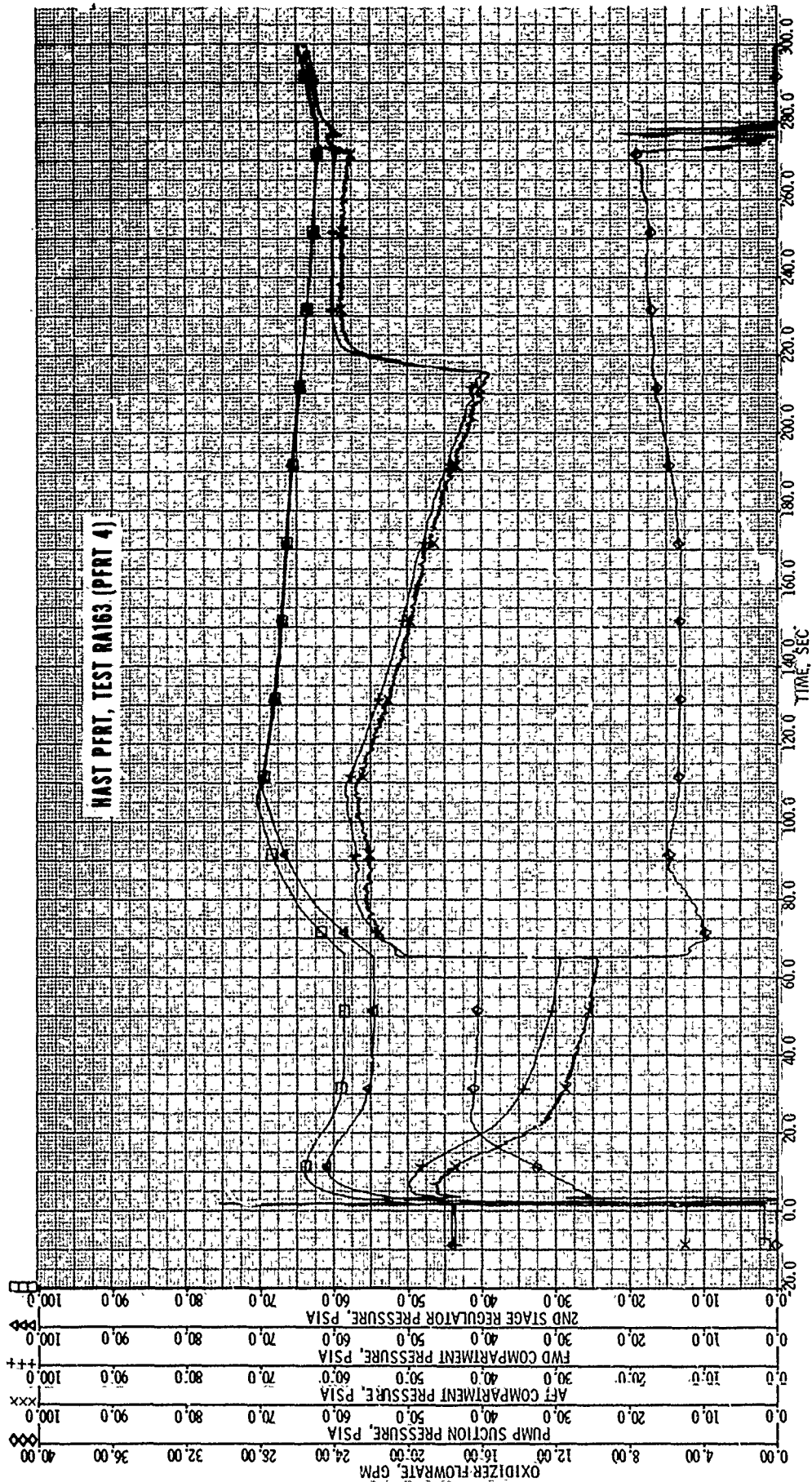


Figure 50: OMA Parameters for PFRT 4

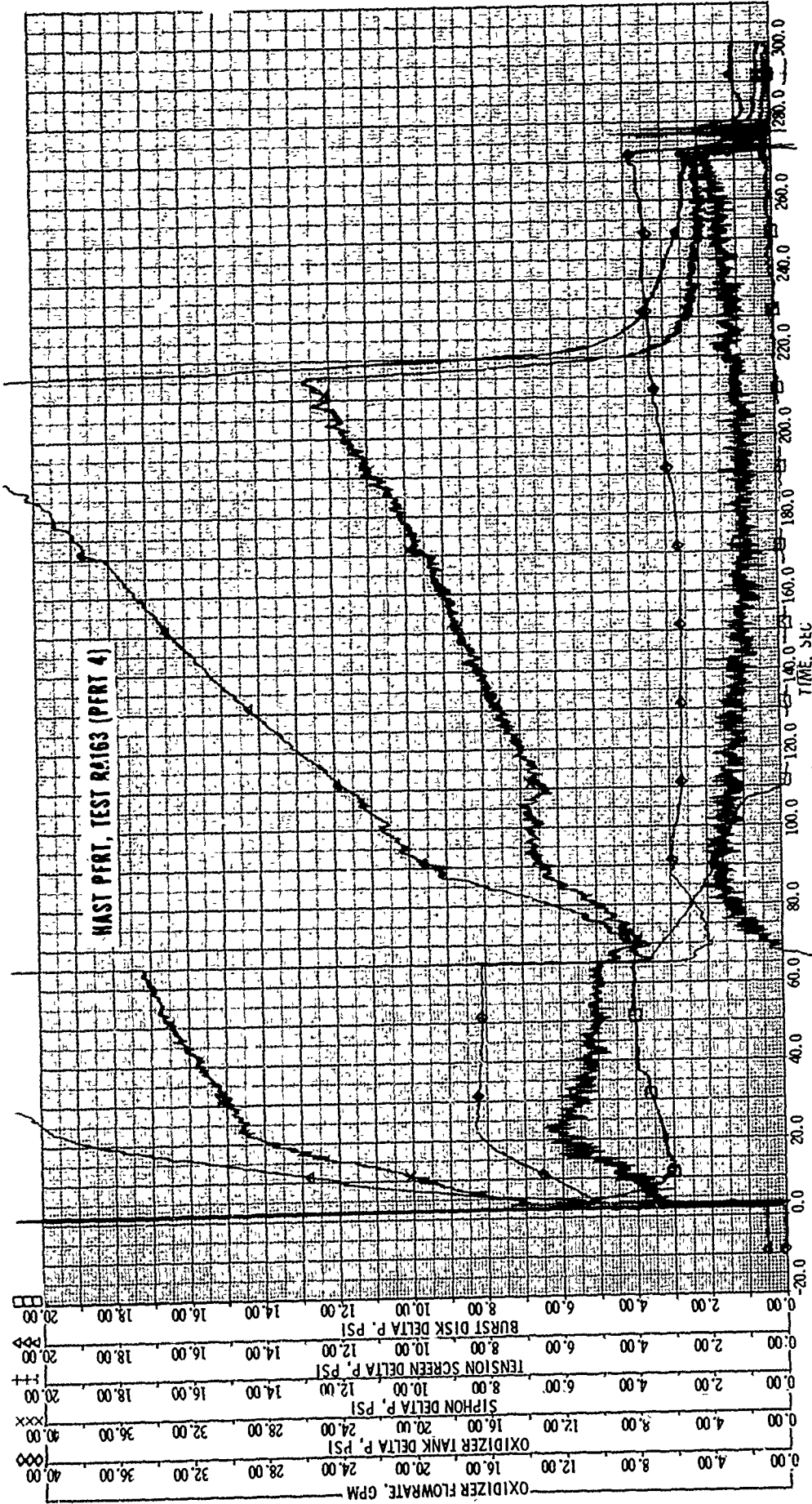


Figure 51. Pressure Drops in OMA for PFRT 4

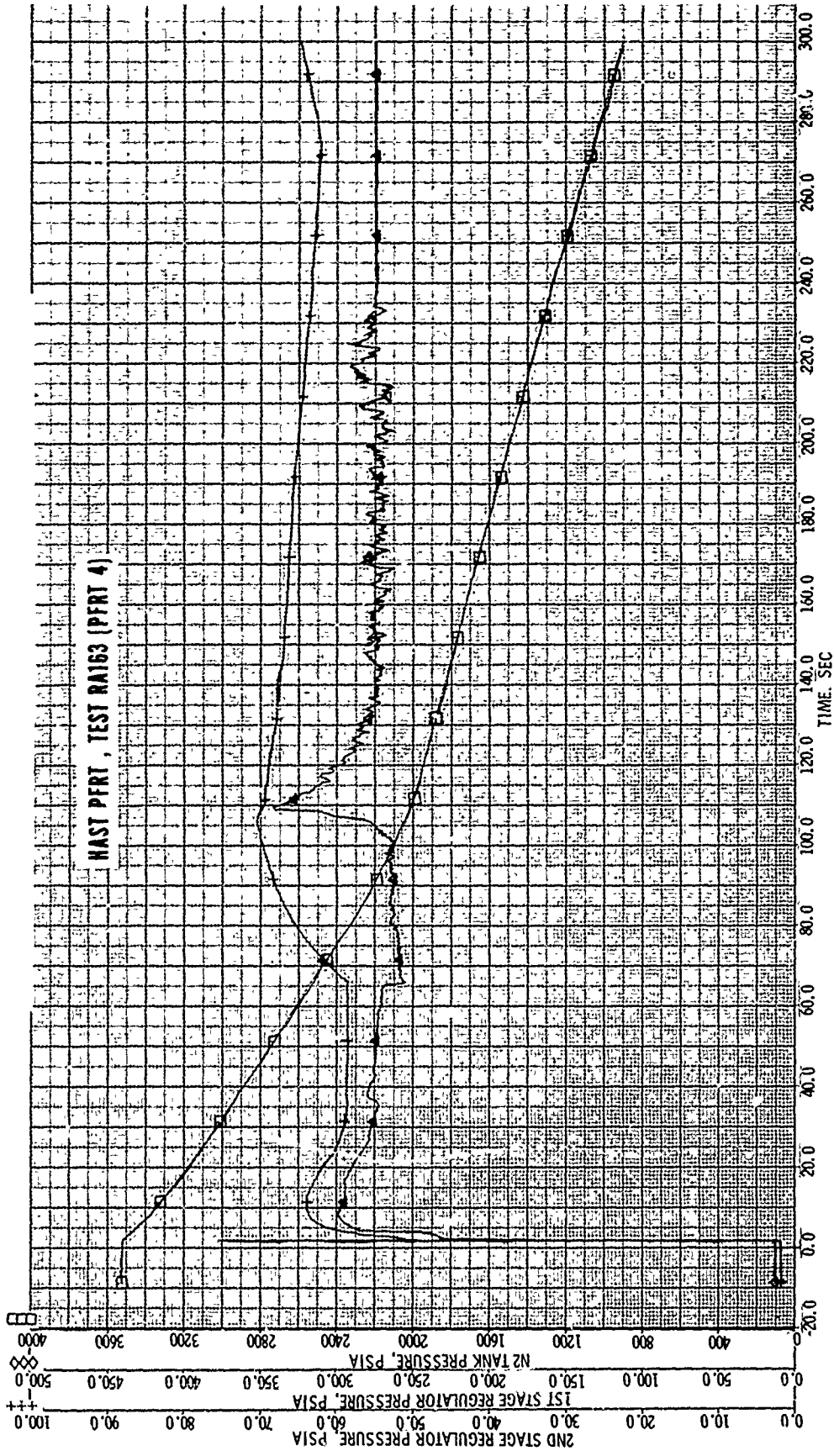


Figure 52. Pressurization Parameters for PFRT 4

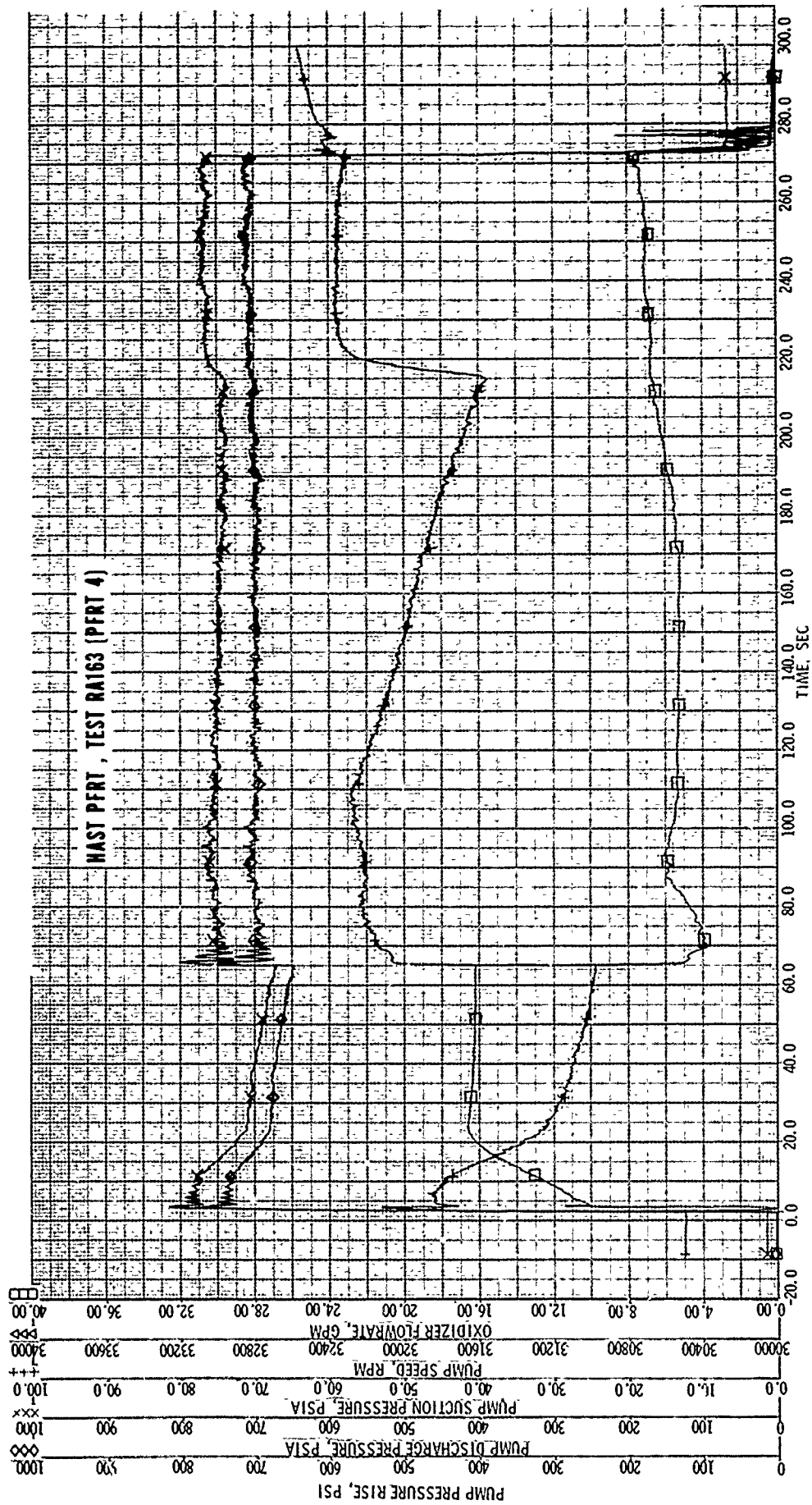


Figure 53. Pump Performance for PFRT 4

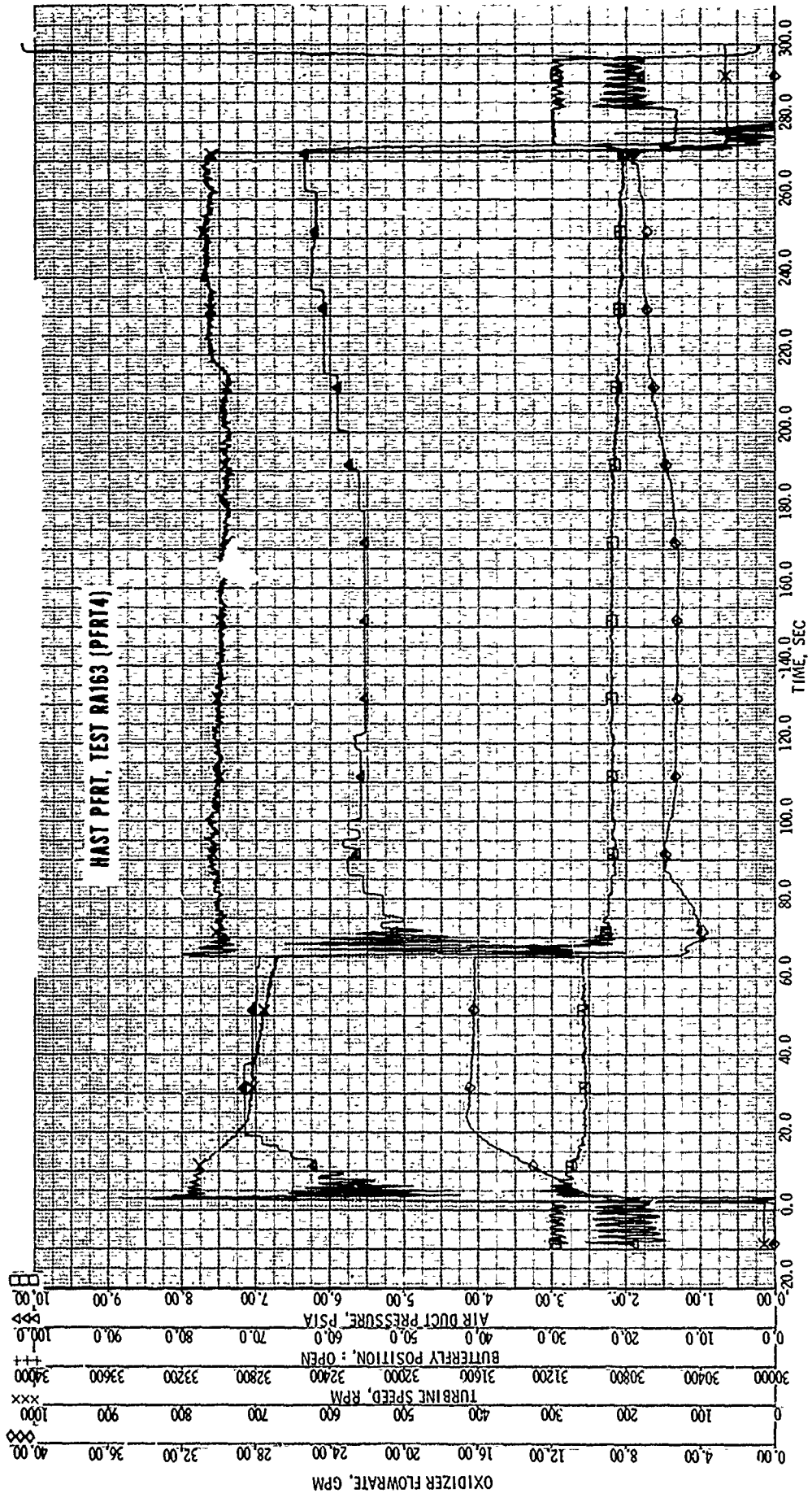


Figure 54. Ram Air Turbine Parameters for PFRT 4

A change was made in the method of venting overboard leakage from the DPU seal for this test. On previous tests, the overboard drain had discharged into the altitude cell exhaust duct. Because the engine exhaust pumped the test cell to a lower pressure than the steam ejectors alone could maintain, there was a backflow from the exhaust duct into the cell when the engine was shut down. This carried IRFNA vapors from the seal drain back into the cell, and was possibly the source of IRFNA which entered the alternator housing. This was possible because there was not a positive seal on the turbine end of the alternator assembly. The only seal was a labyrinth seal on the turbine periphery used to control air leakage around the blades. In order to completely remove the IRFNA leakage from the cell, the drain was brought through the cell wall and discharged into an open container.

A motion picture was made of the seal drain during the test. During boost, there was no flow from the drain, indicating no seal leakage. Immediately upon transition to sustain operation, a substantial leakage flow was evident. Approximately nine pounds of IRFNA was collected in the open container. The seal leakage occurs during sustain because of higher pump suction pressure, which is the result of higher output pressure from the second stage regulator at the reduced gas demand, and also the reduction of pressure drops in the oxidizer system, particularly across the tension screen. The measured leakage cannot be considered representative of the seal leakage which would occur in flight. The back pressure on the seal in this case was approximately 13.4 psia, whereas in flight the back pressure would be much lower, and the leakage probably higher. It would not have been possible, other than by relatively complex means, to collect the seal leakage when the drain discharged inside the cell because the liquid immediately vaporized. Consequently there is no measurement of seal leakage under actual operating conditions.

Immediately after the test, IRFNA was seen to be dripping from the alternator housing. Subsequent examination at The Marquardt Co. showed local erosion of the J-seal and distortion of the secondary seal on the pump-end bearing. This was apparently the result of the higher than normal pressure in the seal cavity because of the atmospheric vent, and consequent high ΔP across the J-seal and bearing. Because of failure of these seals, IRFNA had entered the bearings.

This test was also used to verify the operation of a switch, actuated by chamber pressure, which is part of the missile recovery sequencing. One of the criteria that must be met to initiate operation of the recovery system is that chamber pressure has been present and has now decayed. A flight pressure switch was installed and the operation of its contacts recorded. The pressure switch was actuated during the start transient when chamber pressure reached 24 psia, and again actuated at the end of the run when chamber pressure decayed to 14 psia.

The thrust measurement for this test is not valid because of a substantial zero shift in the load cell. A comparison of the pre-test and post-test thrust zero in Figure 49 shows a positive shift of 98 lb. The shift was due to an improperly placed mechanical stop in the thrust stand. This introduced hysteresis such that the thrust stand did not completely return to its original position when the thrust was removed.

As shown in Figure 51, the screen ΔP at the end of the ramp to boost flow was very high, at almost 20 psid, and then increased with time to over 25 psid at the end of boost. This ΔP was so high that slight cavitation is evident in the pump, as shown in Figure 53. The pump pressure rise decayed from 680 psid to 650 psid as pump suction pressure decayed to 24.5 psia, with no change in oxidizer flowrate. The progressive screen plugging continued during sustain, and even with the lower sustain flowrate the ΔP was 24.4 psid just before gas started to flow through the screen.

PFRT 5 (Test RA 164)

The thrust profile for this test was that required for the Mach 4.0 at 90,000 ft mission. The boost duration of 125 sec was the longest of the PFRT tests and was the most severe test from the standpoint of nozzle erosion. The sustain duration was 43 seconds.

The computer plots of data from this test are shown in Figures 55 through 60. The apparent anomalies in the first 20 seconds of data are the result of overheating of the data acquisition system. The principal effect was random errors in the internal time reference, which causes an otherwise valid data point to be misplaced in time on these plots. A review of the data confirmed that it was valid except for these random errors in the first 20 seconds, and these had no overall impact. The computer integration of thrust and oxidizer flow was corrected by deleting the data points which had an erroneous time reference. The errors were obvious because the point-to-point time progression was interrupted.

Prior to this test, the oxidizer tank cleaning procedure was changed to eliminate a final nitric acid pickling. It had been postulated that the pickling attacked the grain boundaries and increased the effective surface area for corrosion. The tank used for this test had been previously used for proof tests at UTC and then cleaned by BAC with the new procedure, after installing a rigid standpipe in place of the free siphon. As may be seen in Figure 57, the initial tension screen ΔP was only 5 psid during boost. This was somewhat lower than the nominal ΔP of 7 to 9 psid. This ΔP remained constant as long as the oxidizer flowrate remained constant, and only increased when the flowrate increased because of nozzle erosion.

A new DPU was installed for this test. In the pre-test checkout, the alternator failed to produce the required 28V DC. The problem was traced to a faulty voltage regulator, and the regulator was changed. The required output was then obtained.

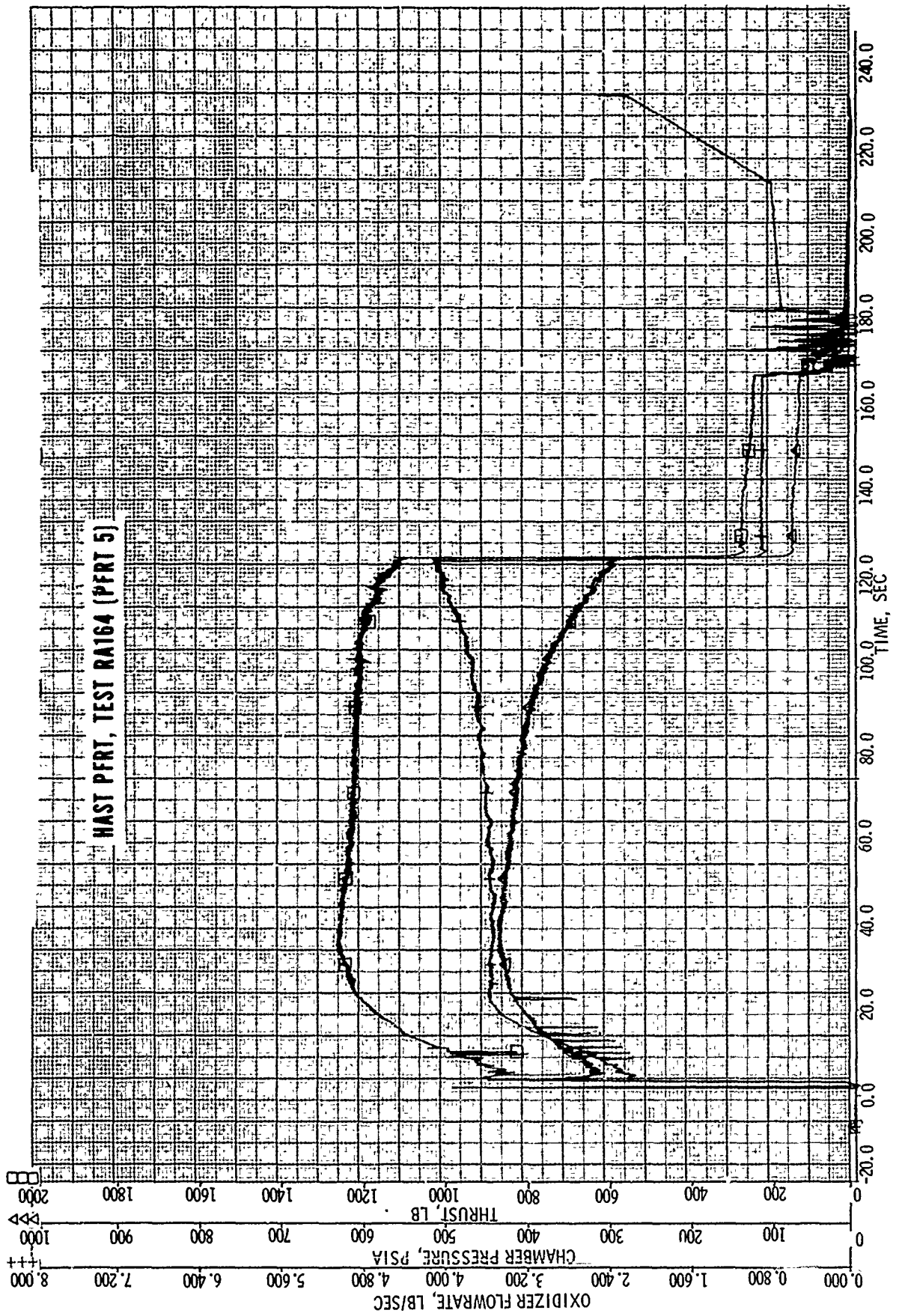


Figure 55. Thrust Chamber Parameters for PFRT 5

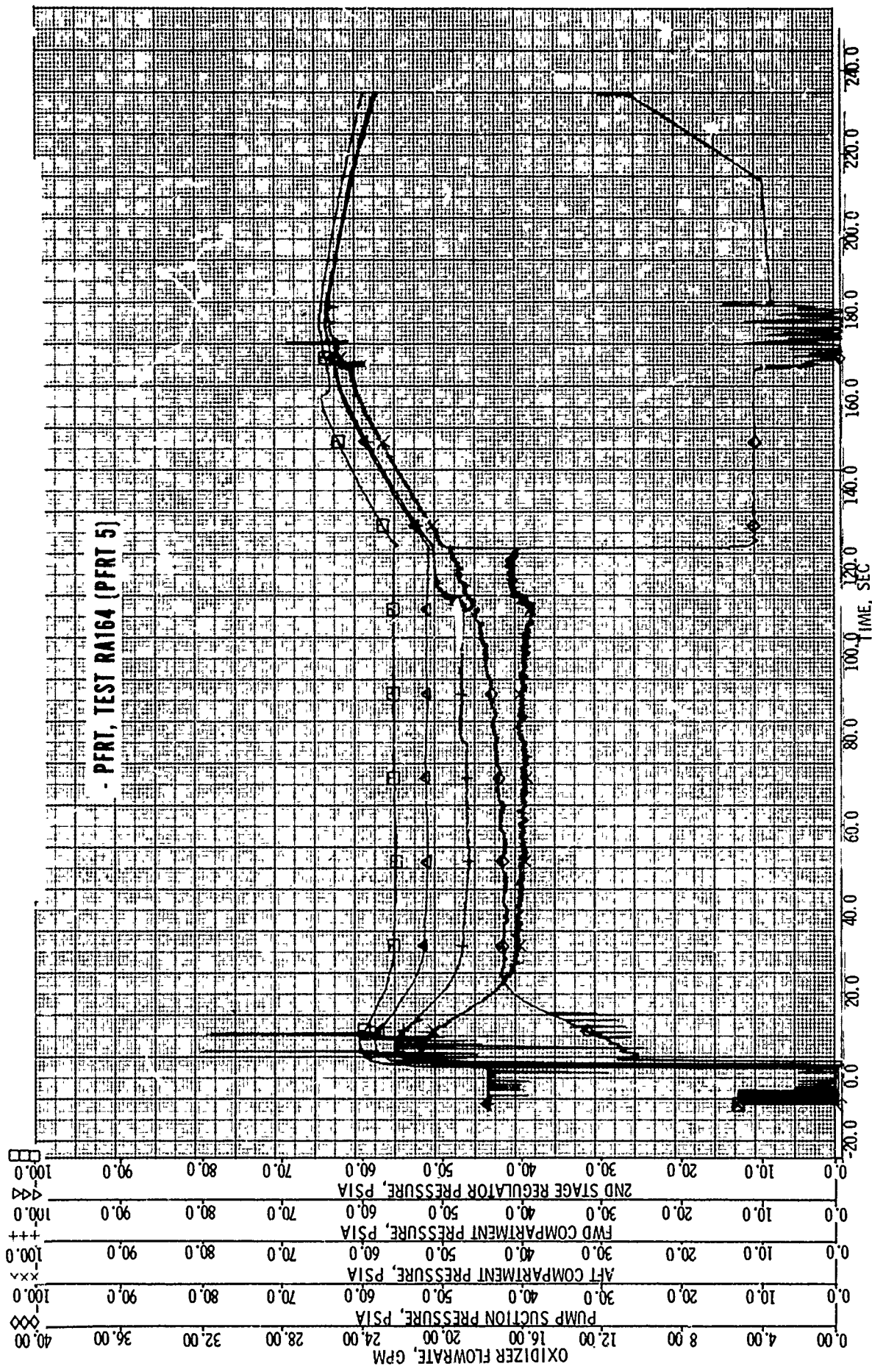


Figure 56. OMA Parameters for PFRT 5

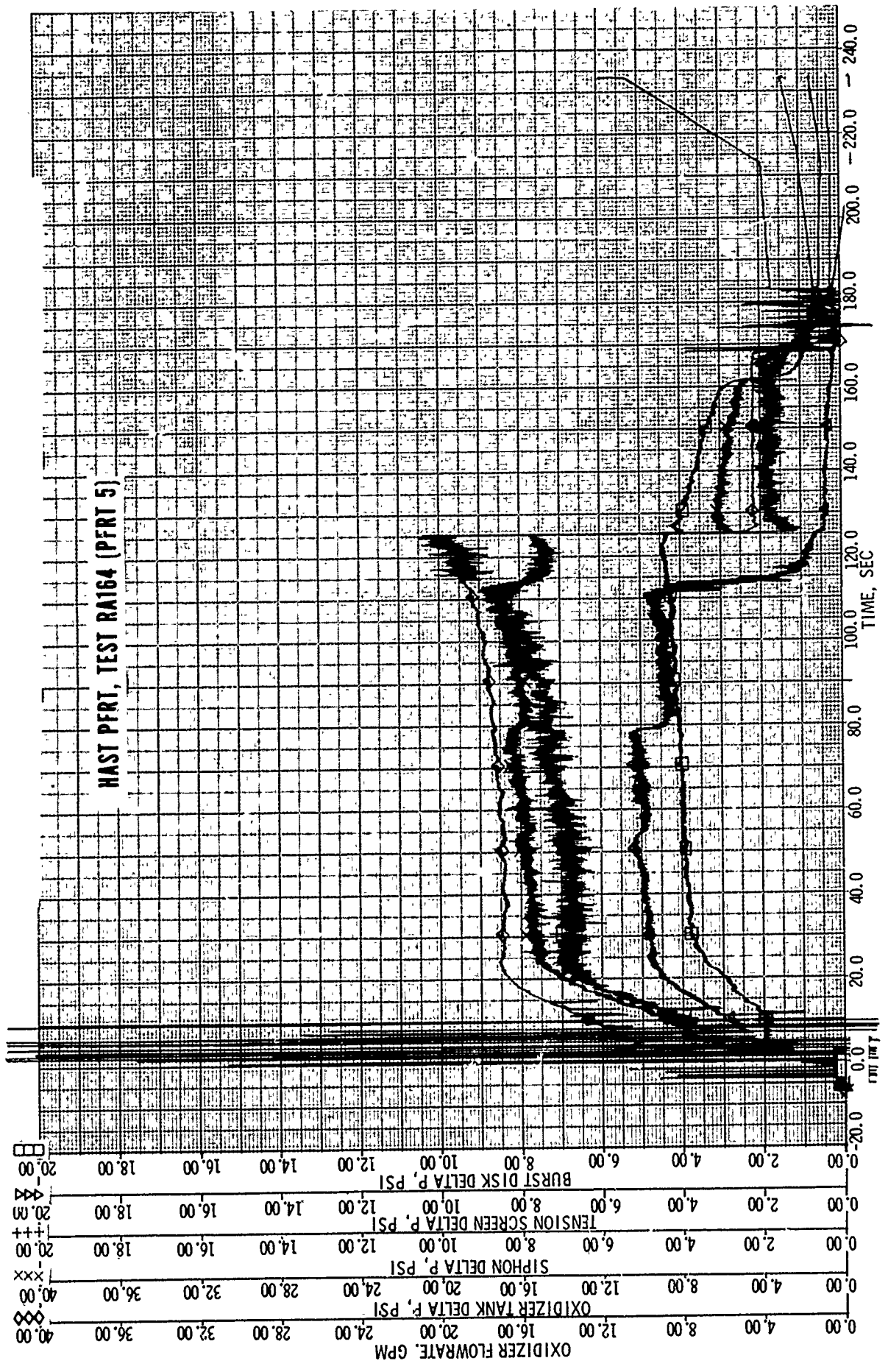


Figure 57. Pressure Drops in OMA for PFRT 5

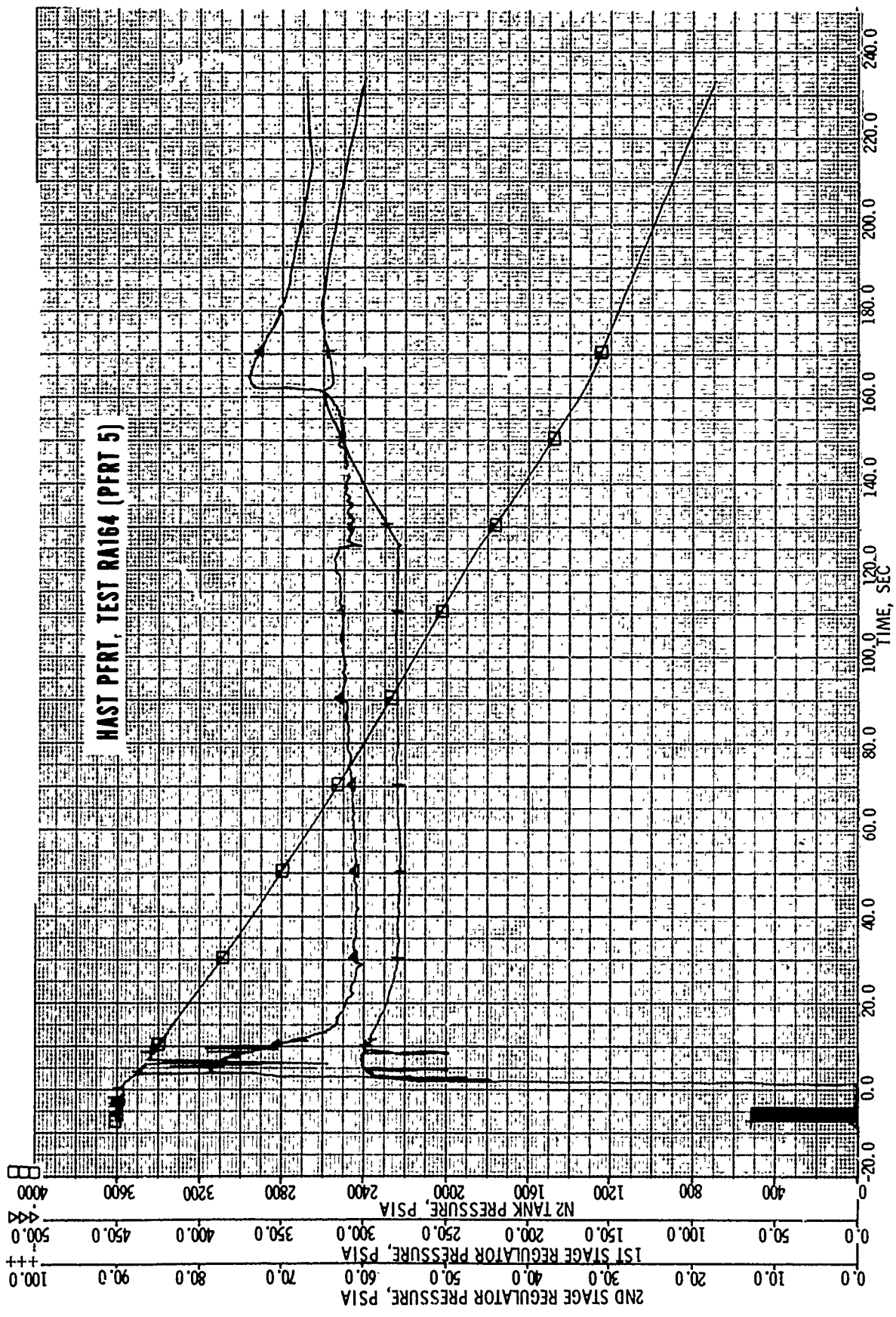


Figure 58. Pressurization Parameters for PFRT 5

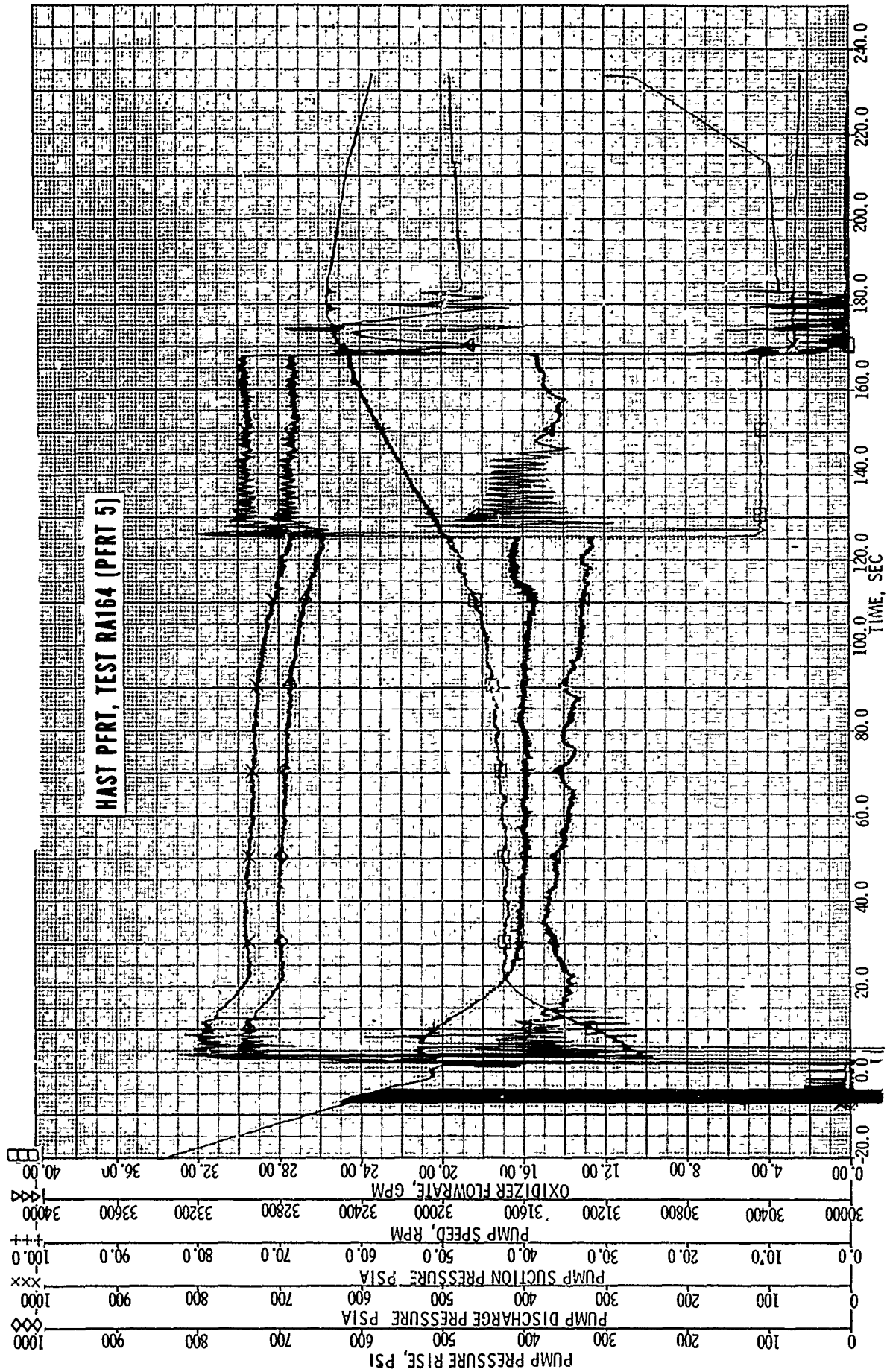


Figure 59. Pump Performance for PFRT 5

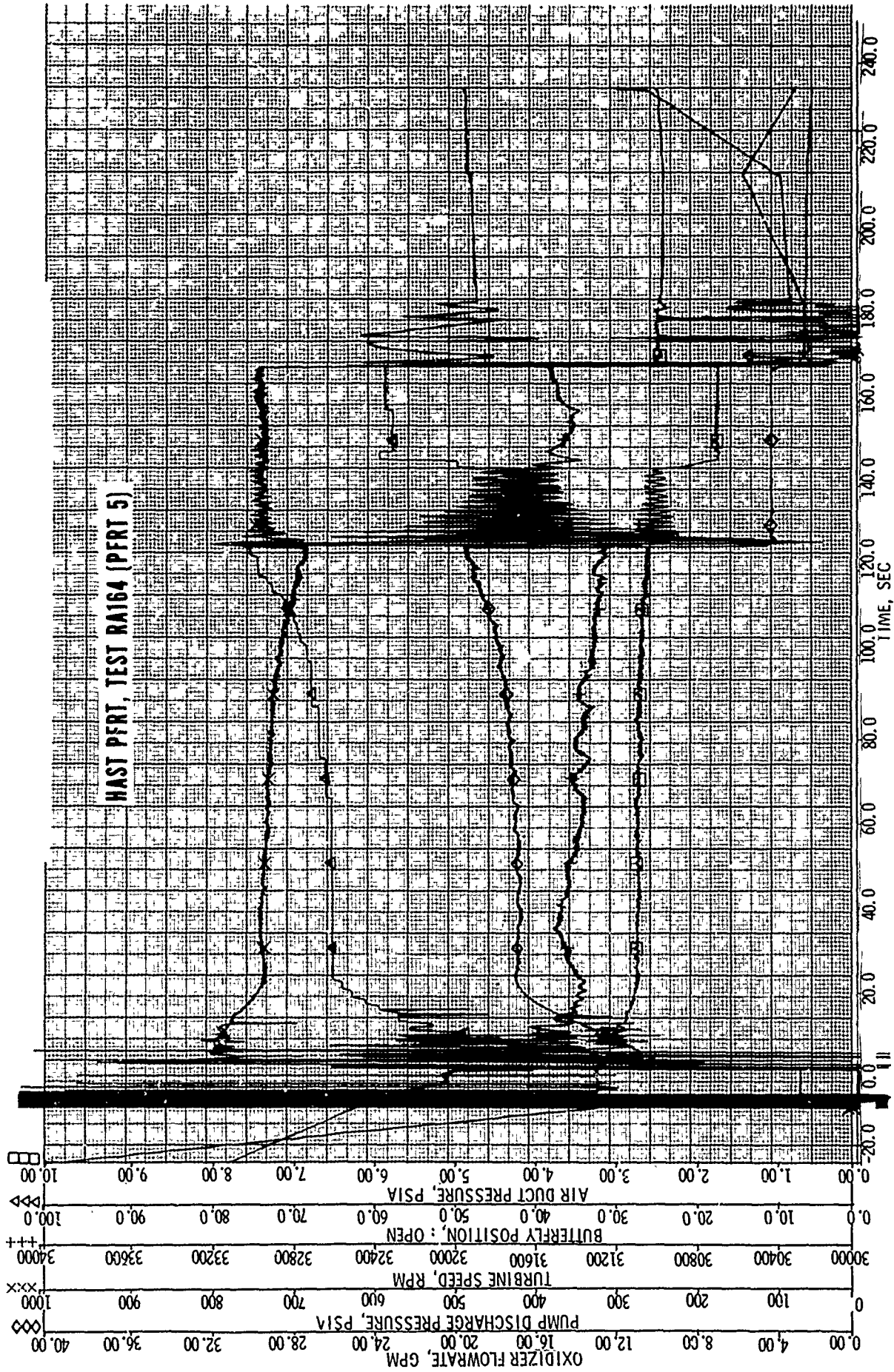


Figure 60. Ram Air Turbine Parameters for PFRT 5

The visco-seal drain was again vented into the test cell exhaust duct. The engine shutdown procedure was changed so as to leave the OTV open until the test cell was at atmospheric pressure. Previously, the OTV had been closed as soon as the oxidizer was depleted, which allowed residual pressure in the oxidizer tank to act against the pump seal. With the OTV open, the residual pressure was vented through the thrust chamber. However, after the pressure was vented, gases resulting from decomposition of residual hot fuel in the thrust chamber were able to flow back through the oxidizer lines to the pump. A brown, gummy residue was found in the oxidizer lines and in the pump housing. Removal of the pump impeller and housing showed that this residue was present in the visco-seal, and traces were evident on the slinger. This residue may be seen in Figure 61.

Since the deposits were fuel decomposition products, they were potentially reactive with IRFNA if allowed to remain in the pump for subsequent tests. Complete cleaning was not possible without disassembly of the balanced rotating assembly. Therefore this DPU was removed and returned to The Marquardt Co. for inspection and overhaul.

The boattail assembly was again installed for this test. Thermocouples were attached by epoxy cement to the recovery battery, aileron actuator motor and linkage, and the destruct squib. However, the overheating of the data acquisition system required that it be shut down 565 secs after the firing was terminated, and maximum soakback temperatures were not recorded. The maximum temperatures recorded were 210°F on the battery, and 221°F on the actuator. The thermocouple on the squib malfunctioned and valid data was not obtained.

The plumbing for the chamber pressure switch was installed into the thrust chamber forward closure in a flight configuration although the switch itself was not installed. Thermocouples were epoxied onto the tubing so as to measure the driving temperature for heating of the switch. The maximum temperature reached was 172°F at the end of the test.

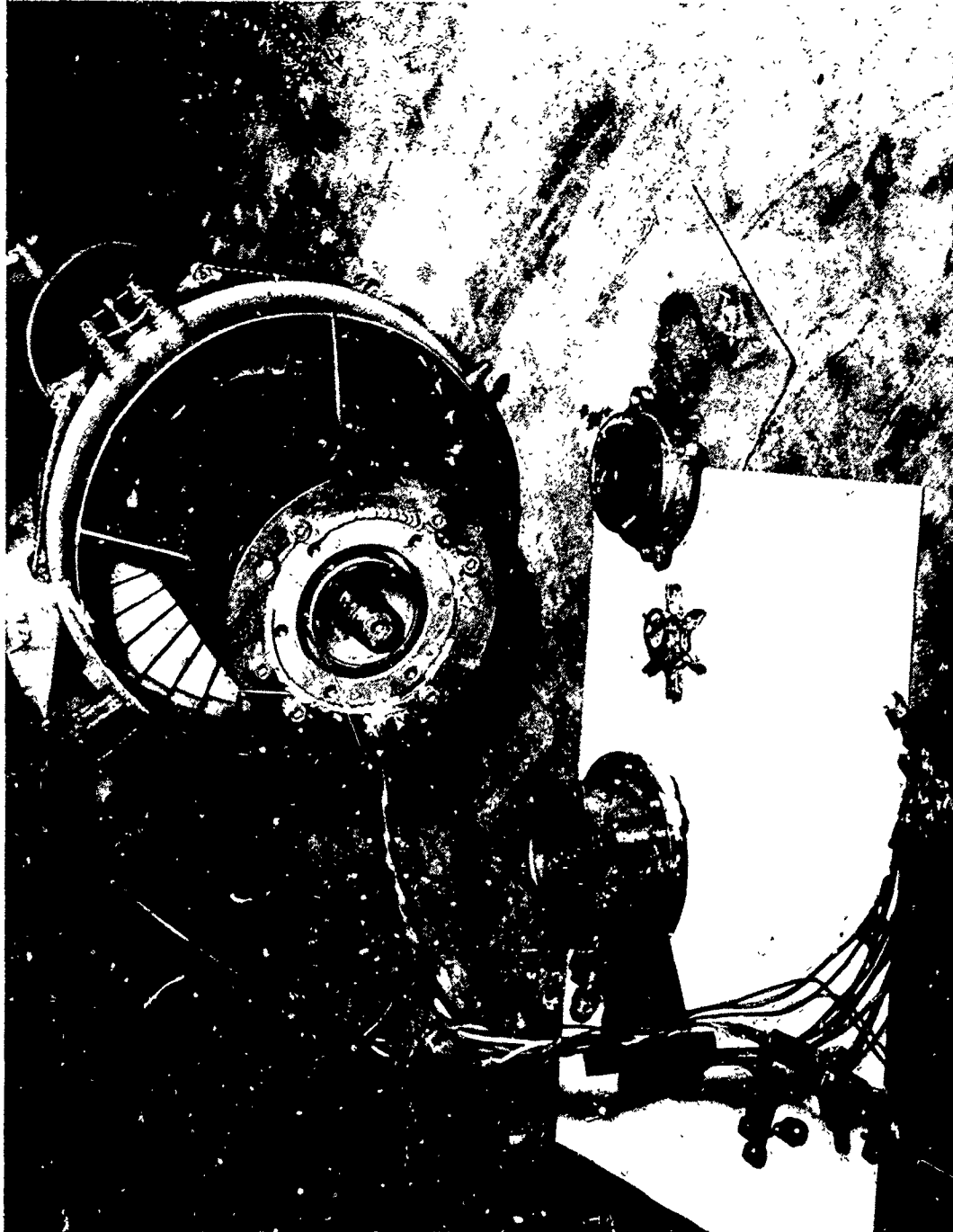


Figure 61. Fuel Decomposition Residue in DPU after PFRT 5

PFRT 6 (Test RA 165)

This test was the demonstration of the throttling capability of the HAST propulsion system. The mission consisted of boost to Mach 2.5 at 60,000 ft, with a 180° turn at the cruise condition. This required throttling back up to almost full boost thrust after the transition from boost to sustain thrust. The boost duration was 63 seconds, and the sustain duration, including the simulated turn, was 203 seconds. The data are shown in Figures 62 through 67. The throttling is illustrated in Figure 62. This throttling was accomplished smoothly, and the system was responsive to OTV command inputs. The irregularities in the thrust profile are the result of the OTV operator being unable to continually match the desired thrust curve on the compressed time scale of the X-Y plotter.

The oxidizer tank from PFRT 5 was reused for this test. The tank had been loaded with 496 lb. of IRFNA within four hours after the completion of PFRT 5 and had been stored in this condition for five days until PFRT 6. The tension screen ΔP , shown in Figure 64, was initially 4.0 psid at boost flow and increased slightly with time, to 4.5 psid at 63 seconds.

Another DPU had been installed for this test. The shutdown procedure remained the same as for PFRT 5, except that a nitrogen purge was introduced into the oxidizer injector manifold while the oxidizer tank was being vented at altitude. This was expected to prevent flow of the fuel decomposition gases into the oxidizer system. However this had no effect, and the appearance of the pump and oxidizer lines was essentially the same as after PFRT 5. The DPU was removed and returned to The Marquardt Co.

PFRT 7 (Test RA 166)

The mission selected for this test was one for which it was predicted that the fuel would be depleted prior to the oxidizer. The objective was to

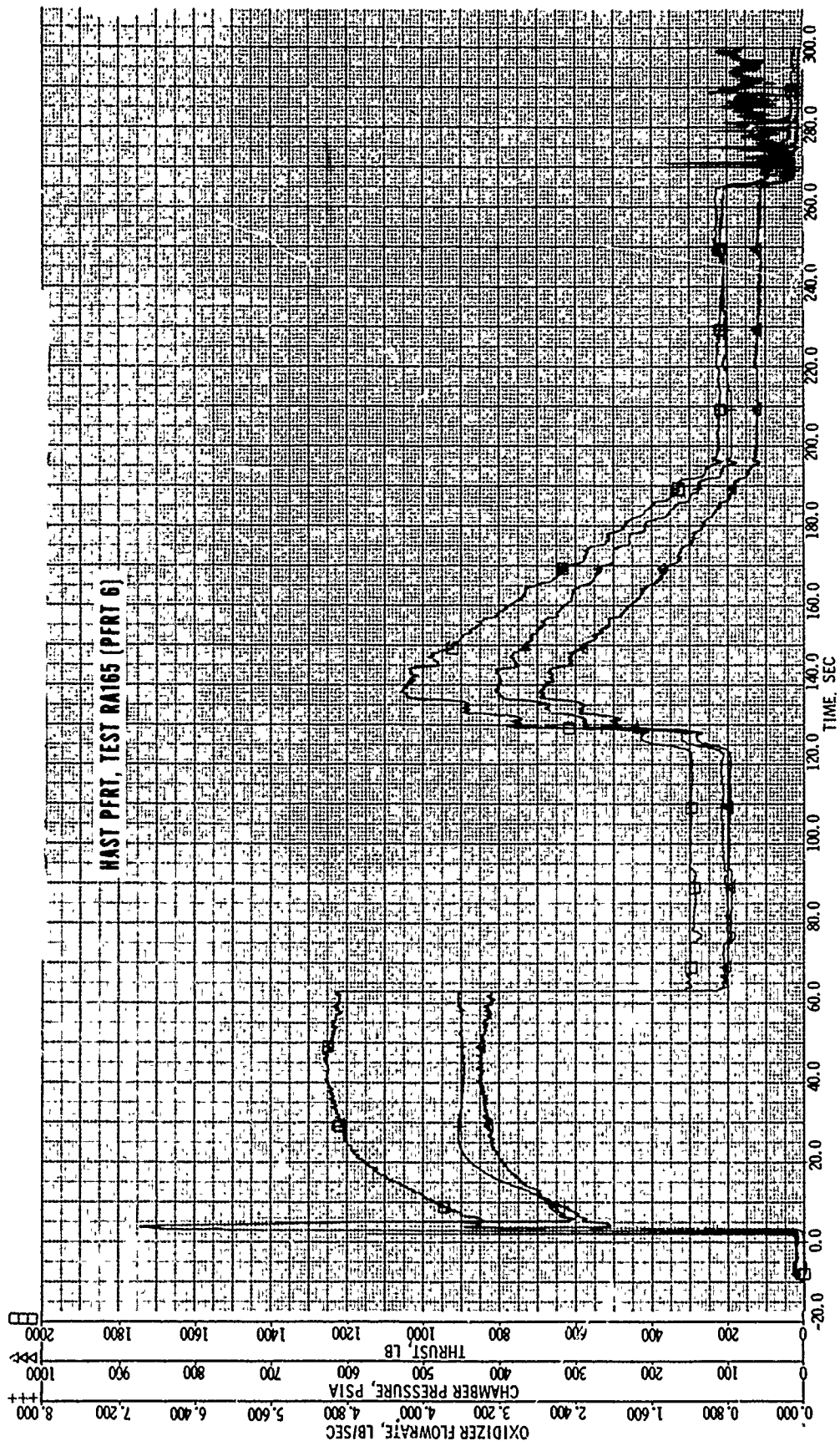


Figure 62. Thrust Chamber Parameters for PFRT 6

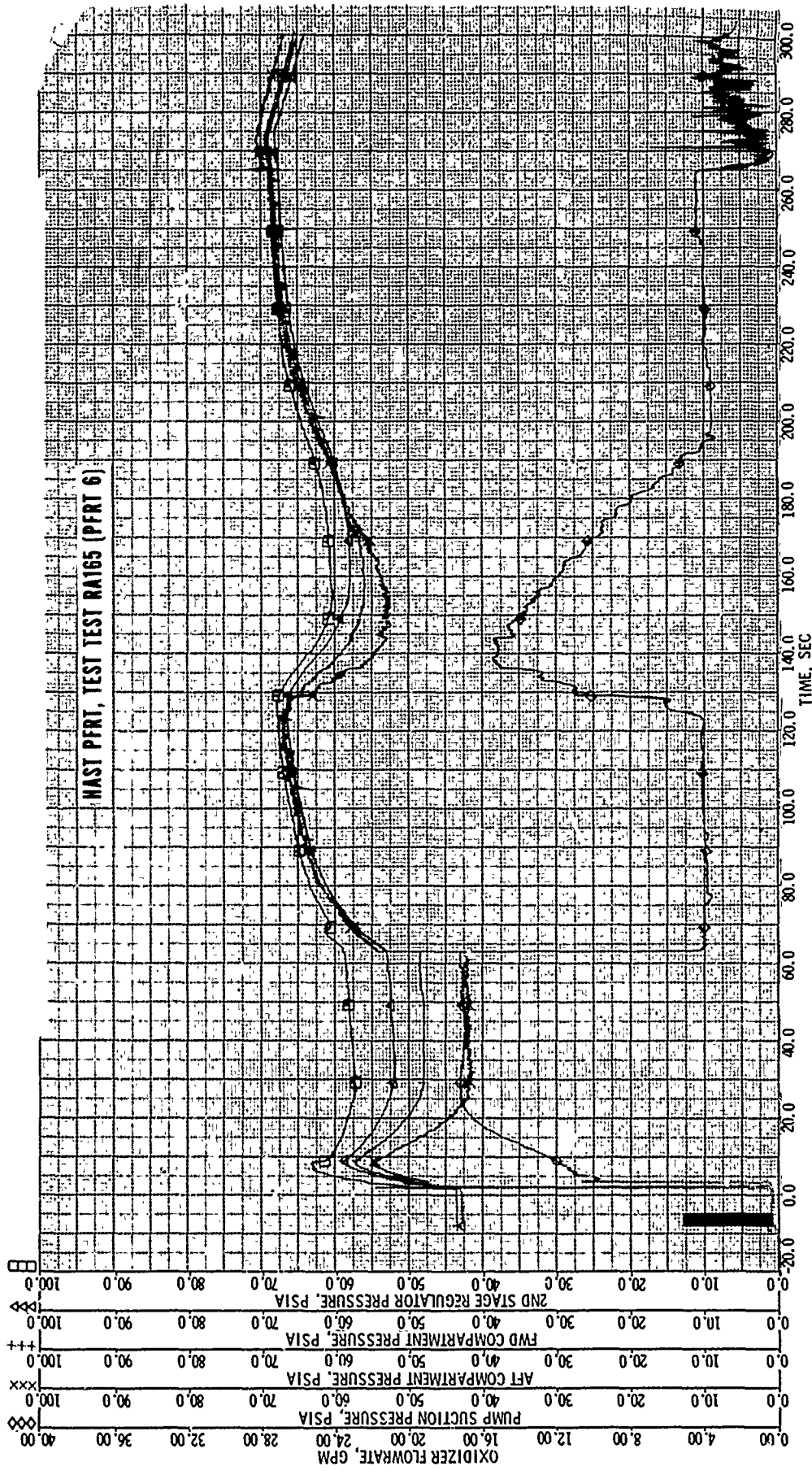


Figure 63. OMA Parameters for PFRT 6

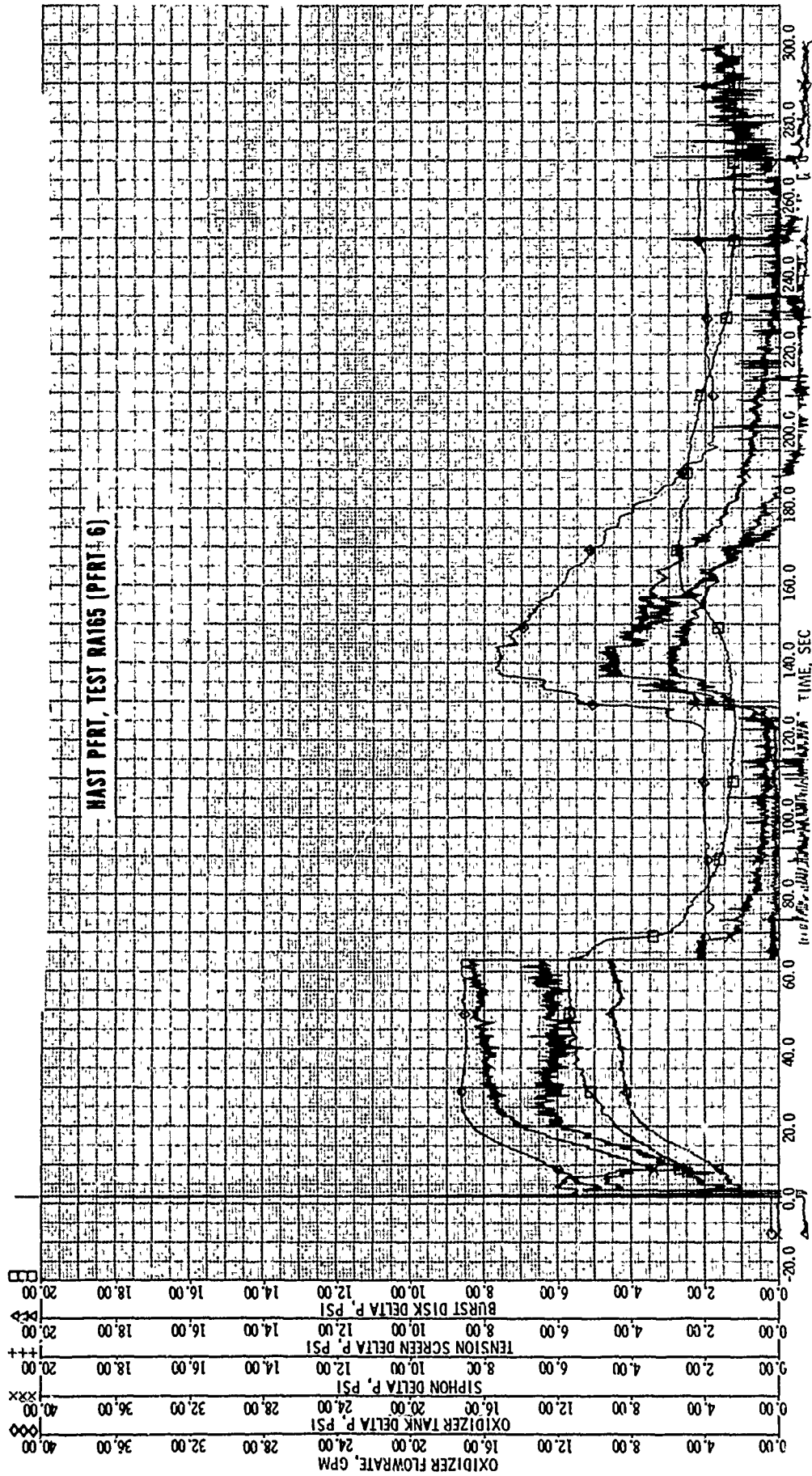


Figure 64. Pressure Drops in OMA for PFRT

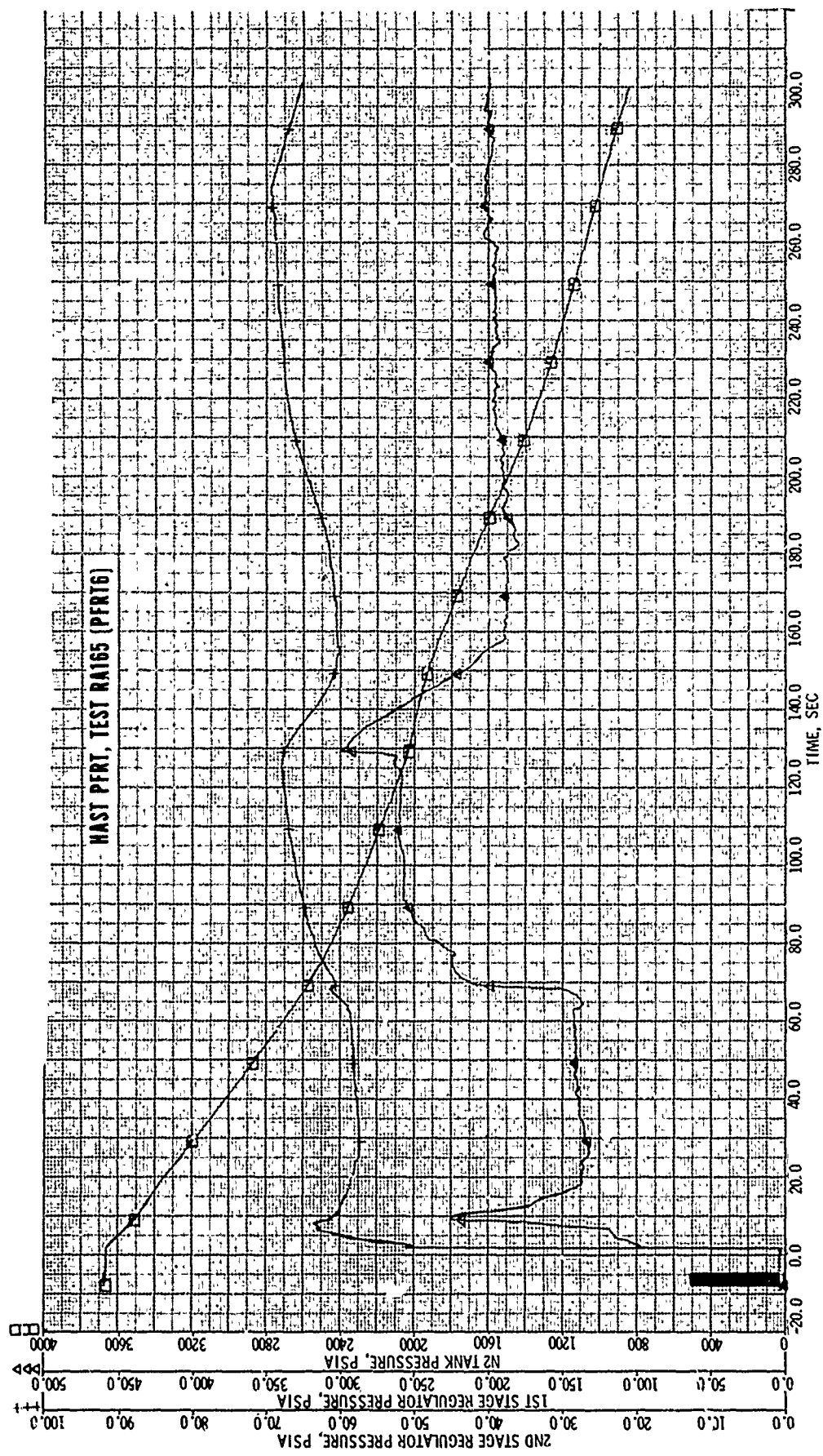


Figure 65. Pressurization Parameters for PFR16

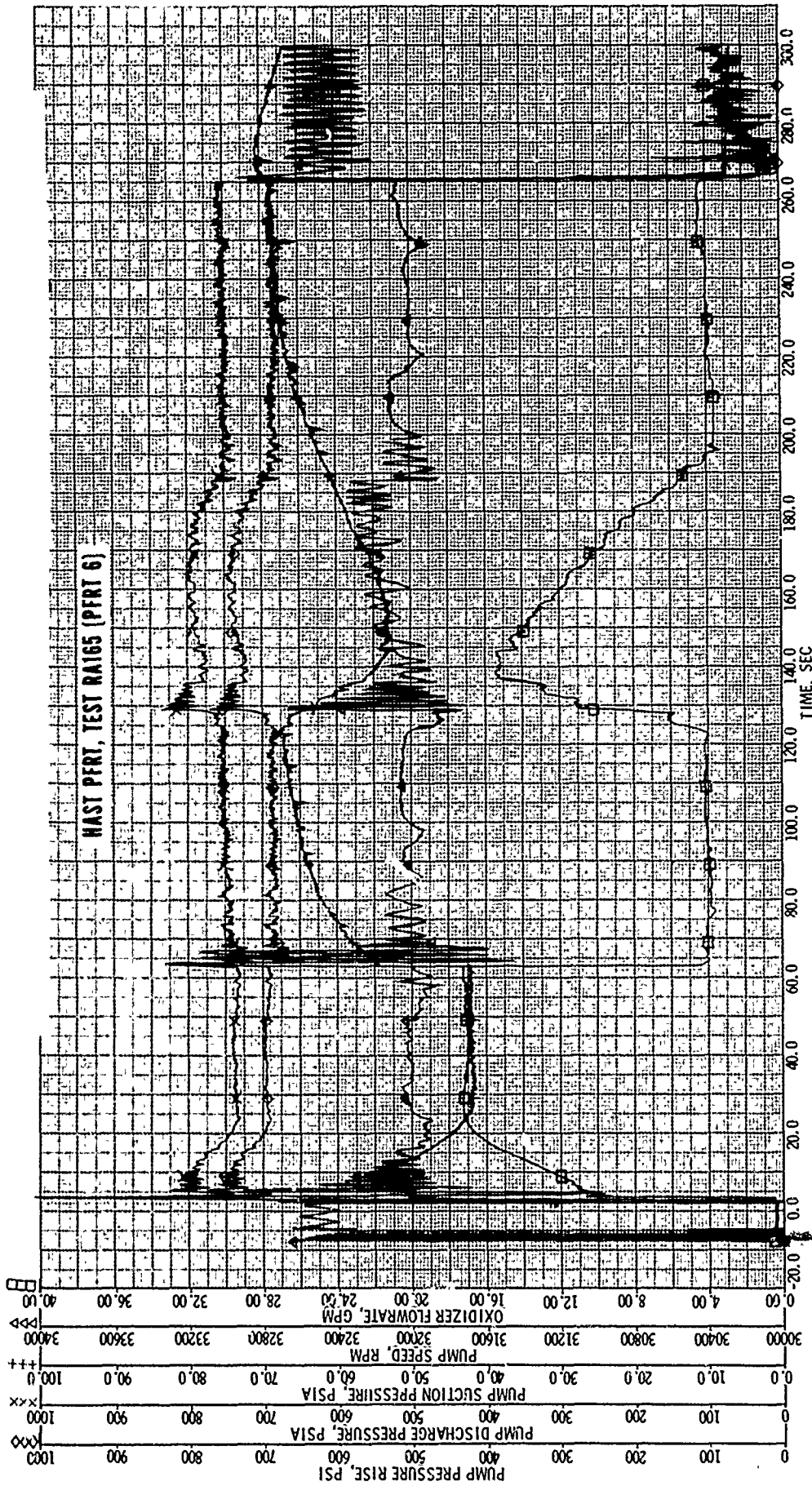


Figure 66. Pump Performance for PFRT 6

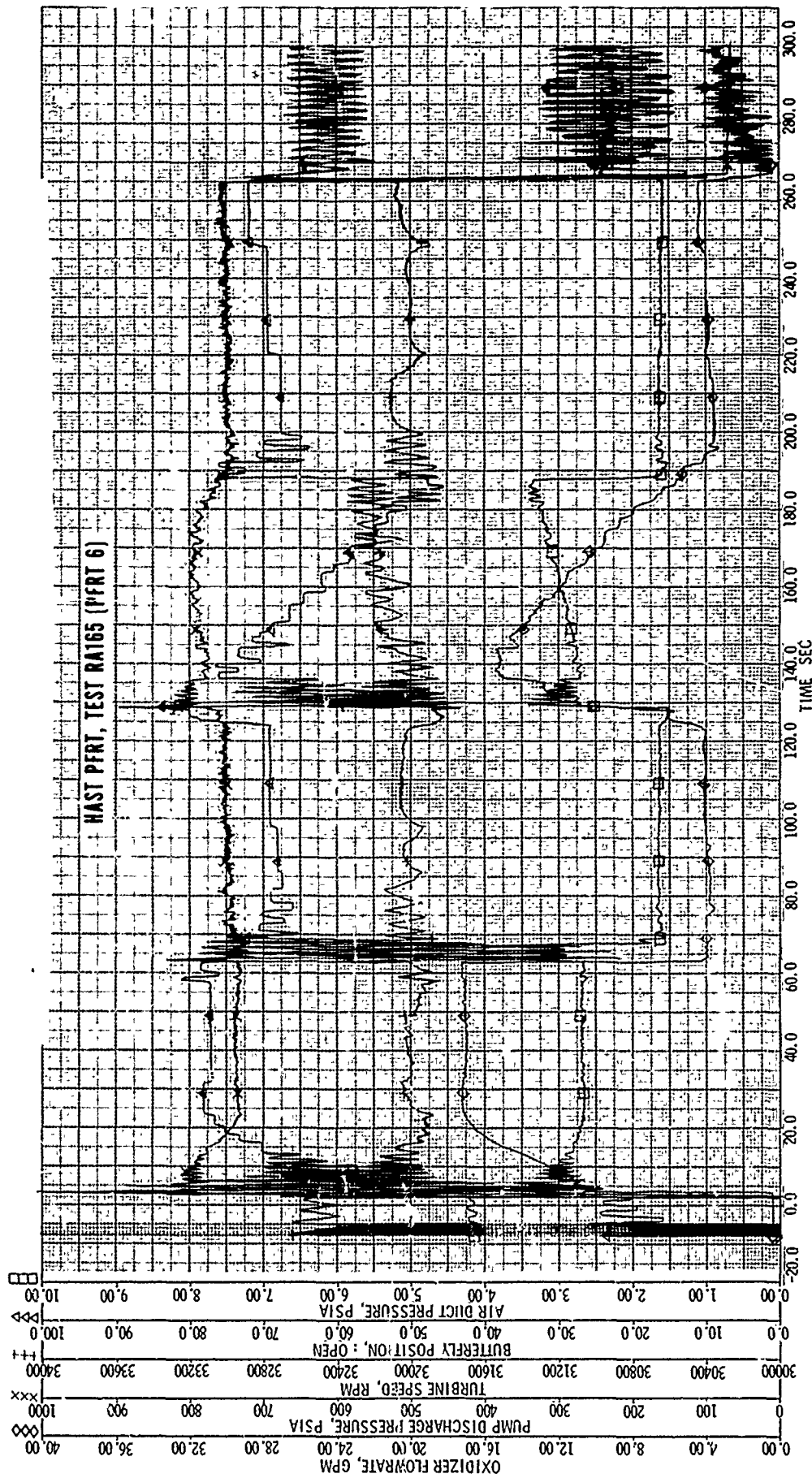


Figure 67. Ram Air Turbine Parameters for PFRT 6

evaluate any detrimental effects on the TCA case of having oxidizer contact the exposed hot steel case wall in areas where the insulation had been removed. The specific mission was Mach 2.0 at 80,000 ft, which is a corner of the HAST operating envelope in which the dynamic pressure is too low to drive the turbine at rated speed during the entire boost phase. The boost duration was 87 seconds and the sustain duration was 187 seconds. The data are presented in Figures 68 through 73.

The turbine power-limited condition was simulated by programming boost cut-off at the time at which the missile was predicted to reach an altitude where the ram air pressure was inadequate to drive the turbine at rated speed. The OTV was then controlled to follow a thrust profile which decreased according to the predicted effect of the turbine power limitation. At the time where boost cut-off was predicted for an actual flight, the OTV was rapidly commanded to a more nearly closed position, simulating the transition to sustain thrust. The resulting thrust profile is shown in Figure 68.

Figure 68 also shows that the fuel was not depleted before the oxidizer as there is no change in thrust until the flowmeter indicates oxidizer depletion. Thus the unique objective of this test was not achieved.

The instrumented boattail assembly was again installed for this test, with thermocouples in the same locations as on PFRT 5. Heat soakback data were recorded for 35 minutes after shutdown. Maximum temperatures reached were 391°F on the aileron actuator, 218°F on the battery, and 368°F on the destruct squib.

The oxidizer tank was the same as used for the previous two tests. After PFRT 6 it had been filled with IRFNA and was stored in this condition for nine days until this test, making a total of 16 days exposure to liquid IRFNA. The tension screen ΔP , shown in Figure 70, was initially 4.9 psid at boost flow, and again there was only a 0.5 psid increase during boost. Thus it appeared that the revised cleaning procedure had solved the tank corrosion problem.

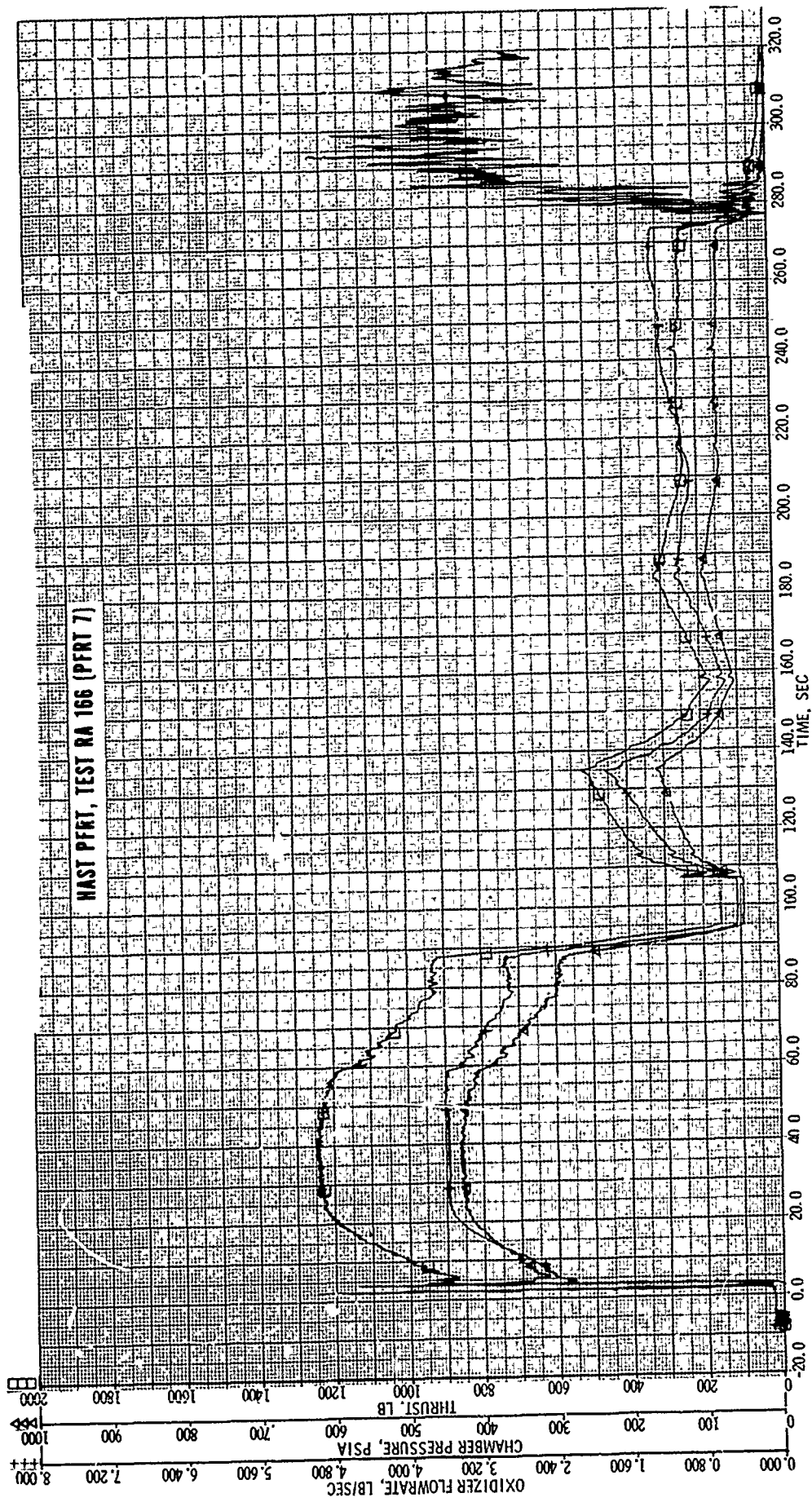


Figure 68. Thrust Chamber Parameters for PFRT 7

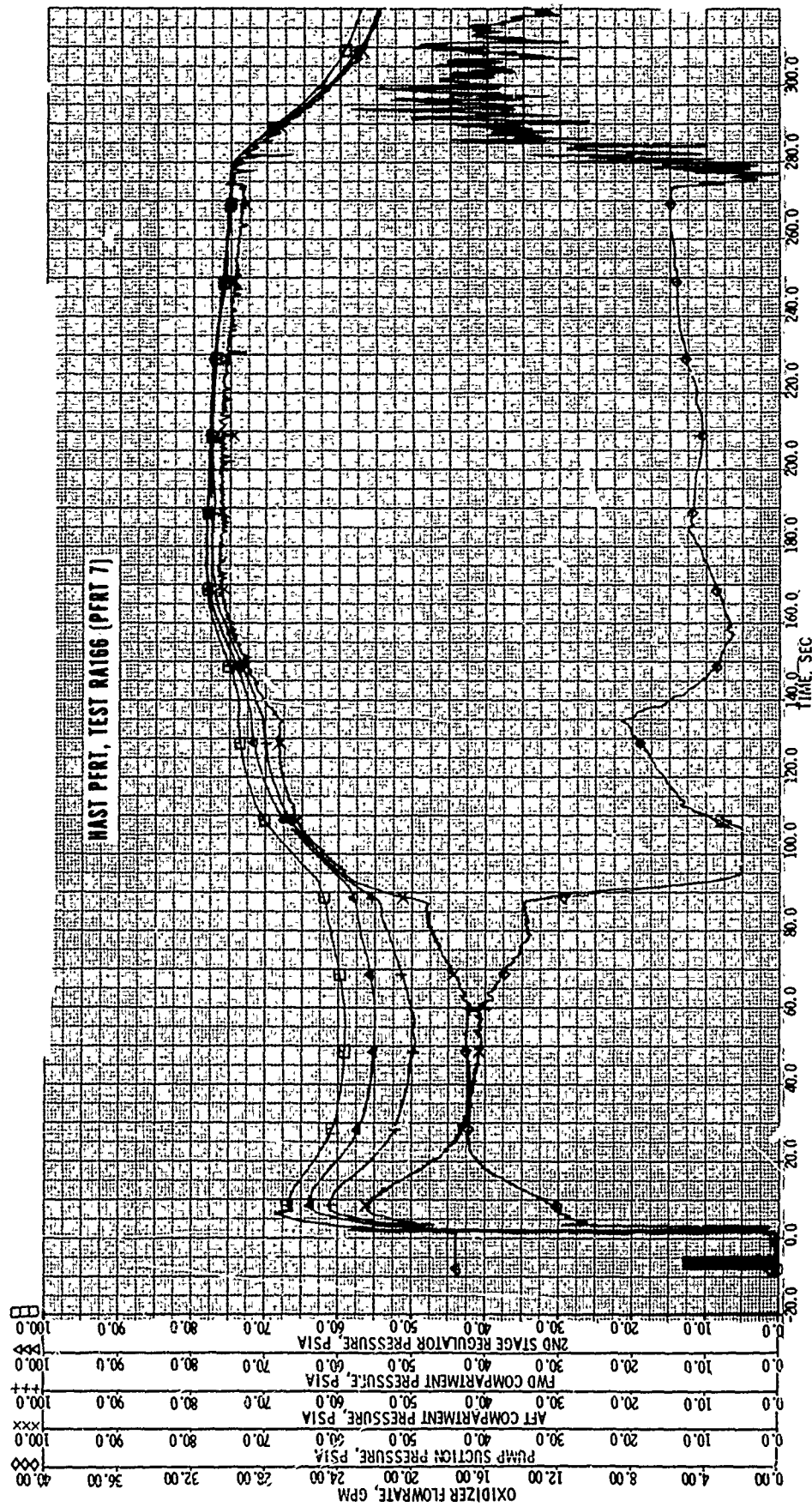


Figure 69. OMA Parameters for PFRT 7

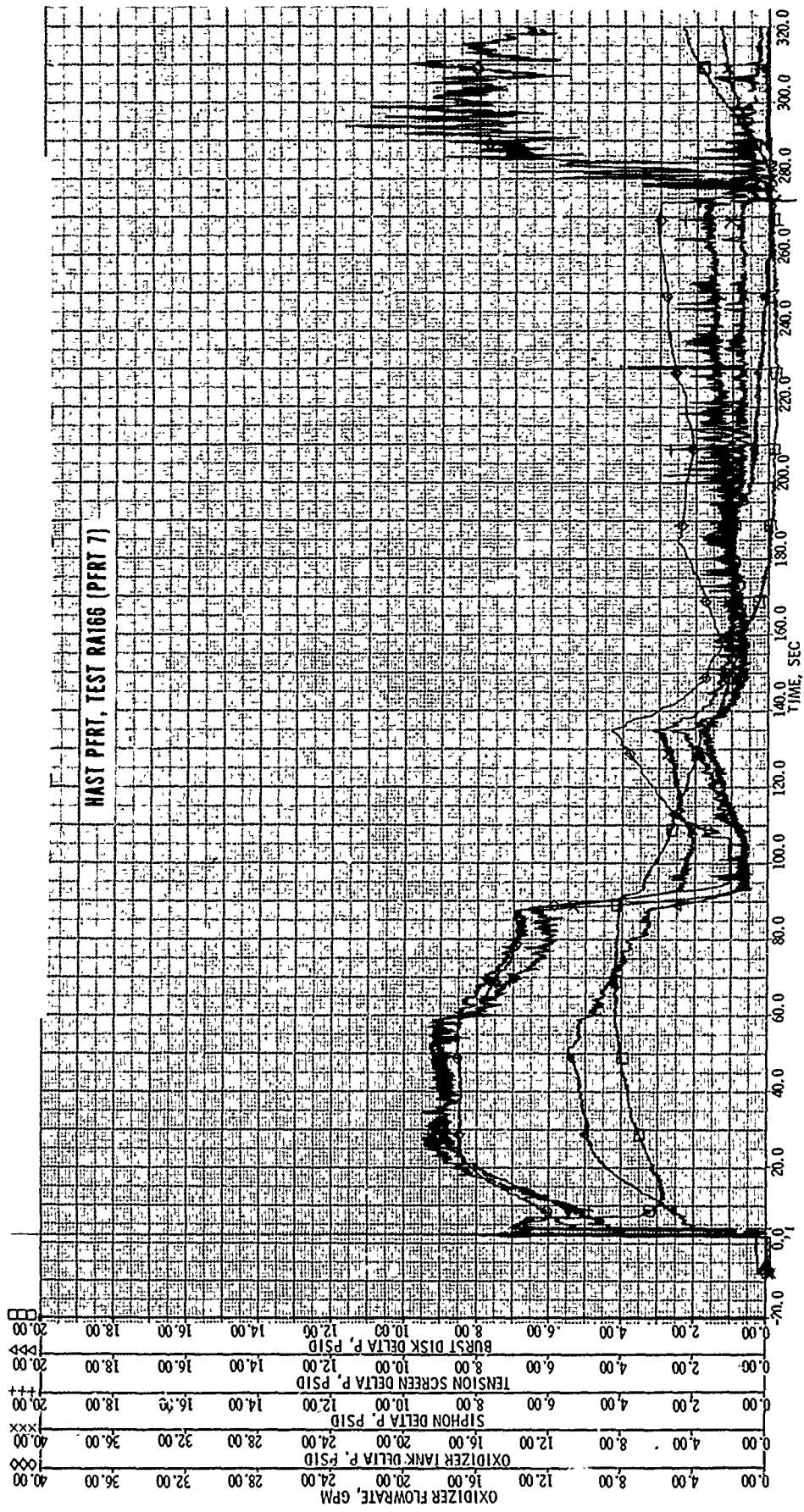


Figure 70. Pressure Drops in OMA for PFRT 7

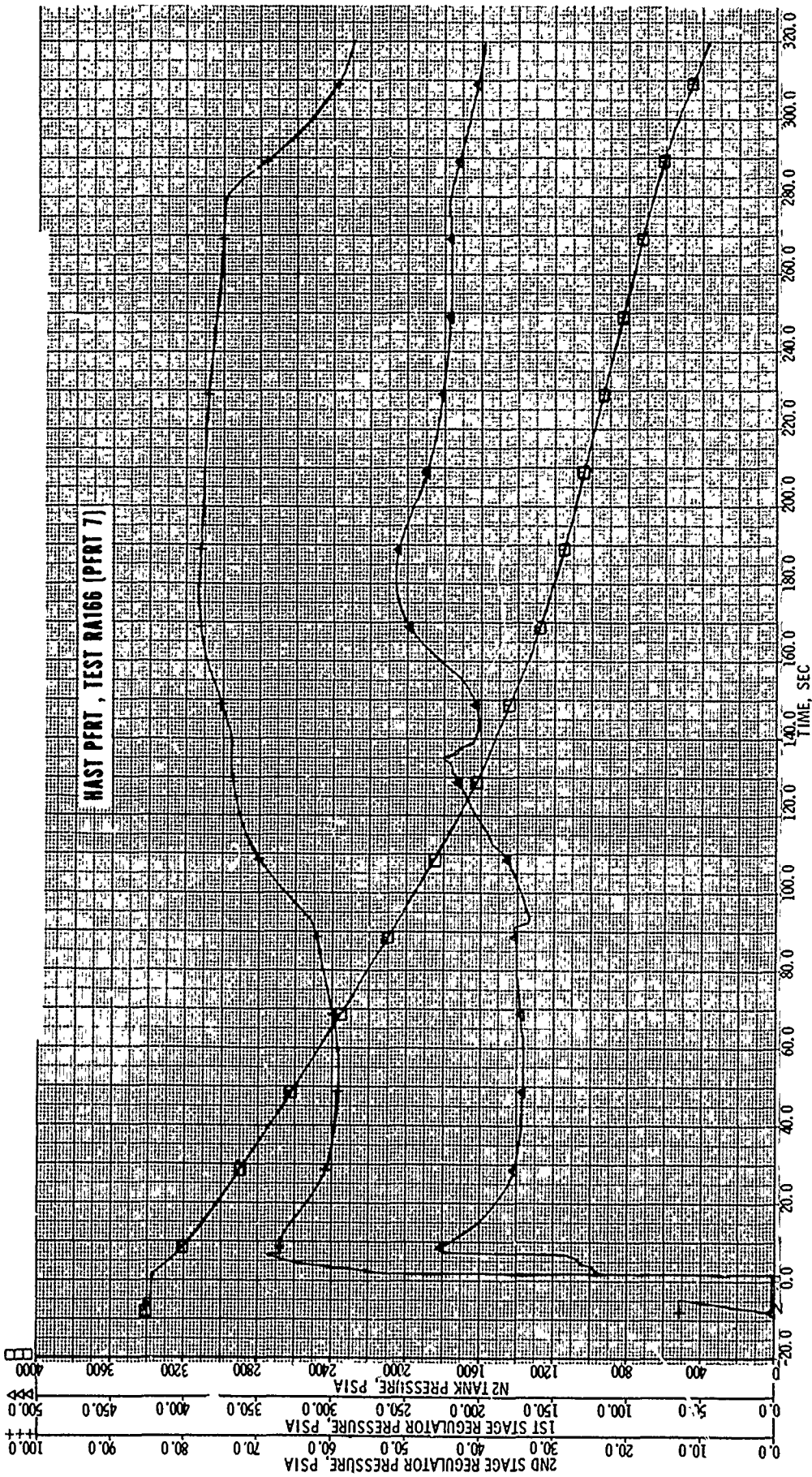


Figure 71. Pressurization Parameters for PFRT 7

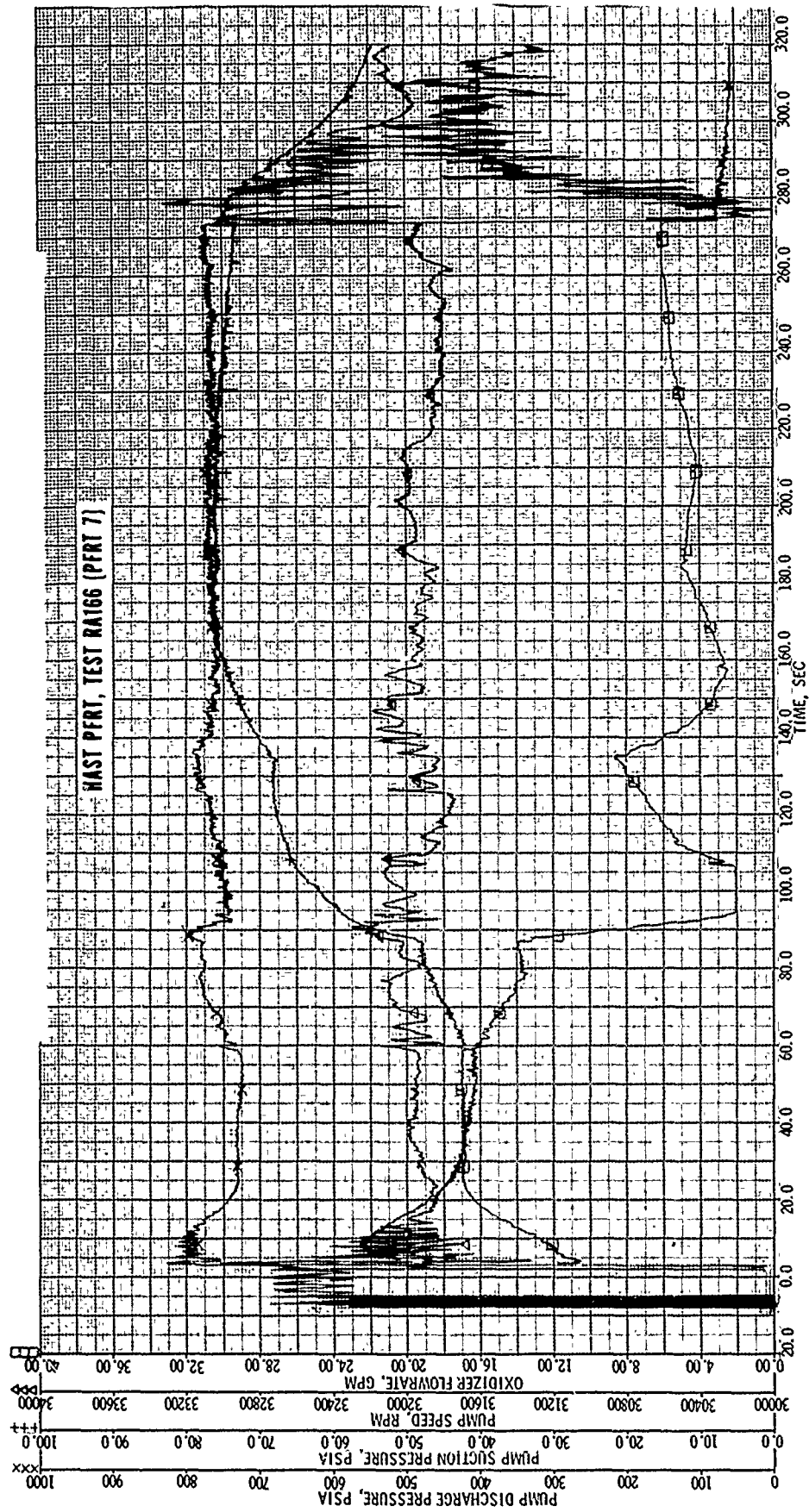


Figure 72. Pump Performance for PFRT 7

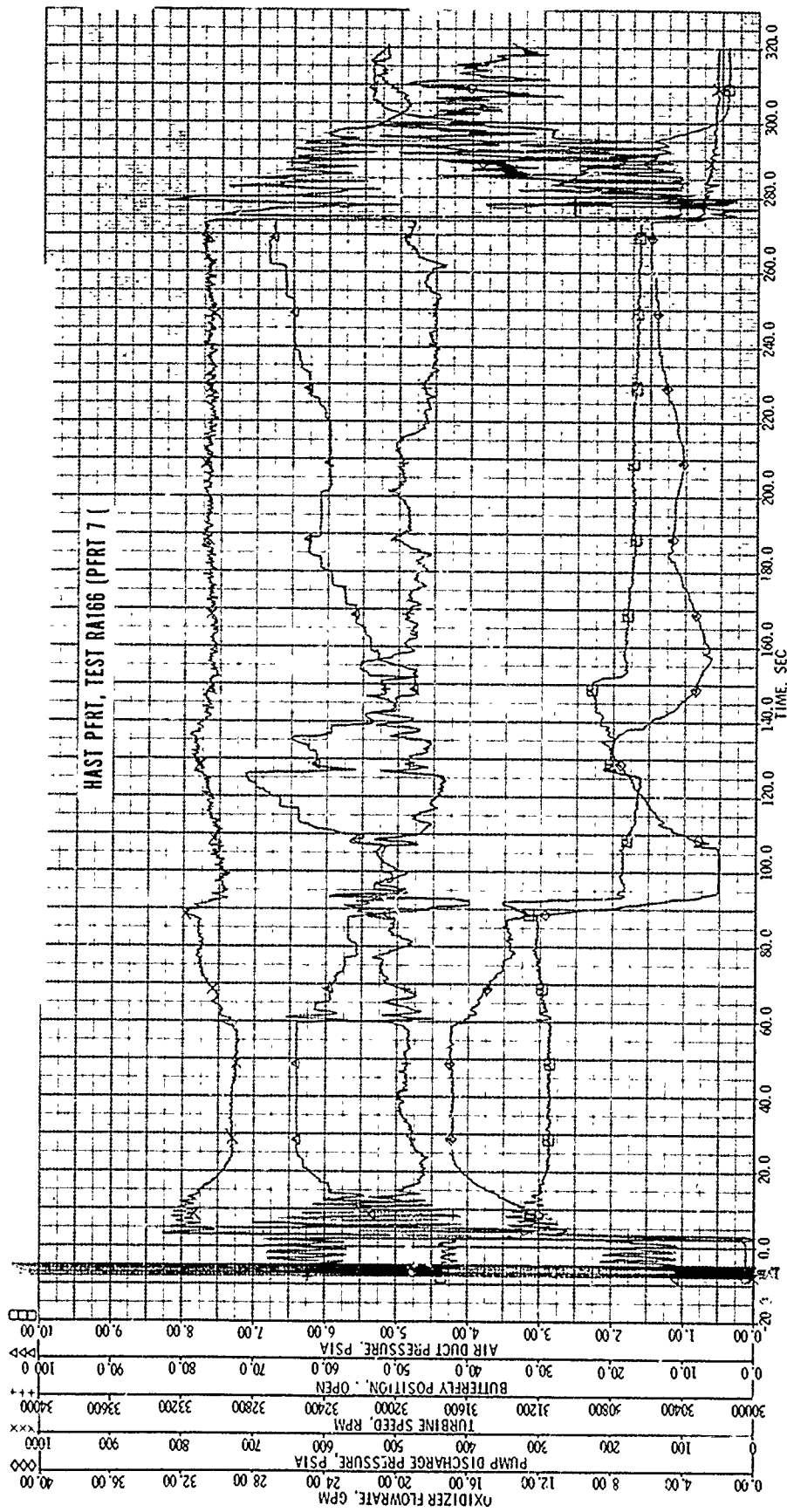


Figure 73. Ram Air Turbine Parameters for PFRT 7

A new DPU had been installed for this test. The shutdown procedure was revised so that the OTV was closed after all pressure in the oxidizer tank had been vented. The test cell was then brought back to atmospheric pressure with the OTV closed and the DPU rotating as long as possible. This procedure was successful in preventing both IRFNA entering the bearings and residual fuel gases from entering the oxidizer lines and pump seal. The same DPU was reused for the next two tests, with the same shutdown procedure.

PFRT 8 (Test RA 167)

This test demonstrated operation of the propulsion system after having been temperature conditioned to -40°F . The duty cycle was the design baseline mission, Mach 3.0 at 80,000 ft. At the time this test was to be conducted, problems were being encountered with qualification testing of the MFV and first stage regulator at -40°F . Rather than delay the PFRT testing until these problems were resolved, the regulators were omitted from the temperature conditioning prior to this test.

A modified DPU speed controller was used for the first time in the PFRT test series. The gain of the feedback circuit had been reduced so as to improve the stability of the butterfly position at the expense of speed control accuracy. Turbine speed was now allowed to vary ± 2000 rpm about the nominal set point of 32,000 rpm, whereas the previous design requirement had been ± 200 rpm.

A modified free siphon was also introduced into the test series. The modification, consisting of an increased diameter and reduced spacing between coils of the helix, was intended to provide resistance to the collapse which had occurred on PFRT 2.

The propulsion system, loaded with oxidizer and with the CTA igniter and all squibs installed, but without the MFV and first stage pressure regulator, was temperature conditioned to -40°F and maintained

at that temperature for eight hours. Although the regulators were not installed, the toroidal nitrogen tank was filled with gaseous nitrogen to 3500 psig prior to starting the temperature conditioning. After the conditioning box was removed, the MFV, first stage regulator, flow loop, and the pressure transducers were installed. After this and other pre-test procedures were accomplished, approximately two hours had elapsed, and the oxidizer had warmed to -5°F at the start of the test.

The data for the complete test are shown in Figures 74 through 79. The start transients for this test are shown in Figure 80, and may be compared to the start transients for an ambient temperature test in Figure 48. The only significant difference that can be noted is that the ignitor peak pressure is somewhat less for the cold test than at ambient temperature. Also, the igniter pressure history is substantially different on the cold test. This had no effect on ignition in the thrust chamber, and in fact the chamber pressure transient is smoother, with less overshoot, than on the ambient temperature test. One ignitor of this design had been successfully tested at -65°F , so there is no obvious explanation for the anomalous behavior on this test.

The operation of the new free siphon was satisfactory. There was no evidence of a failure mode such as had been seen on PFRT 2.

The DPU butterfly position was completely stable. Figure 79 shows that there are no oscillations in butterfly position or turbine speed during the pre-launch operation with only the alternator load on the turbine. More significantly, the butterfly position remains stable when the pump load changes drastically at the transition from boost to sustain oxidizer flowrates.

Although the butterfly is stable, there are wide variations of turbine speed as the load changes. This demonstrates the larger dead band resulting from the reduced circuit gains. Although the turbine speed was within the allowable error of $\pm 2,000$ rpm after the transition to sustain,

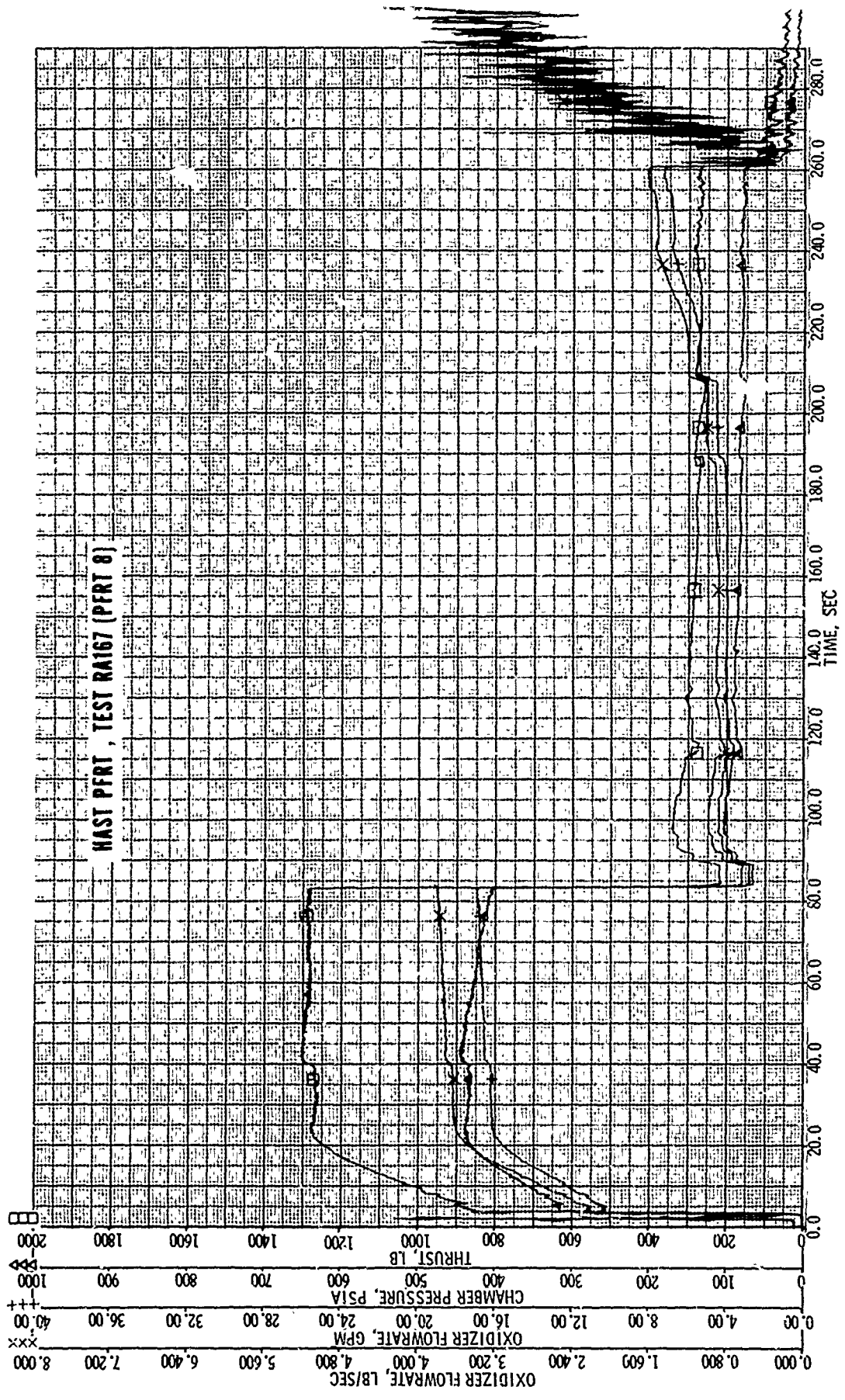


Figure 74. Thrust Chamber Parameters for PFRT 8

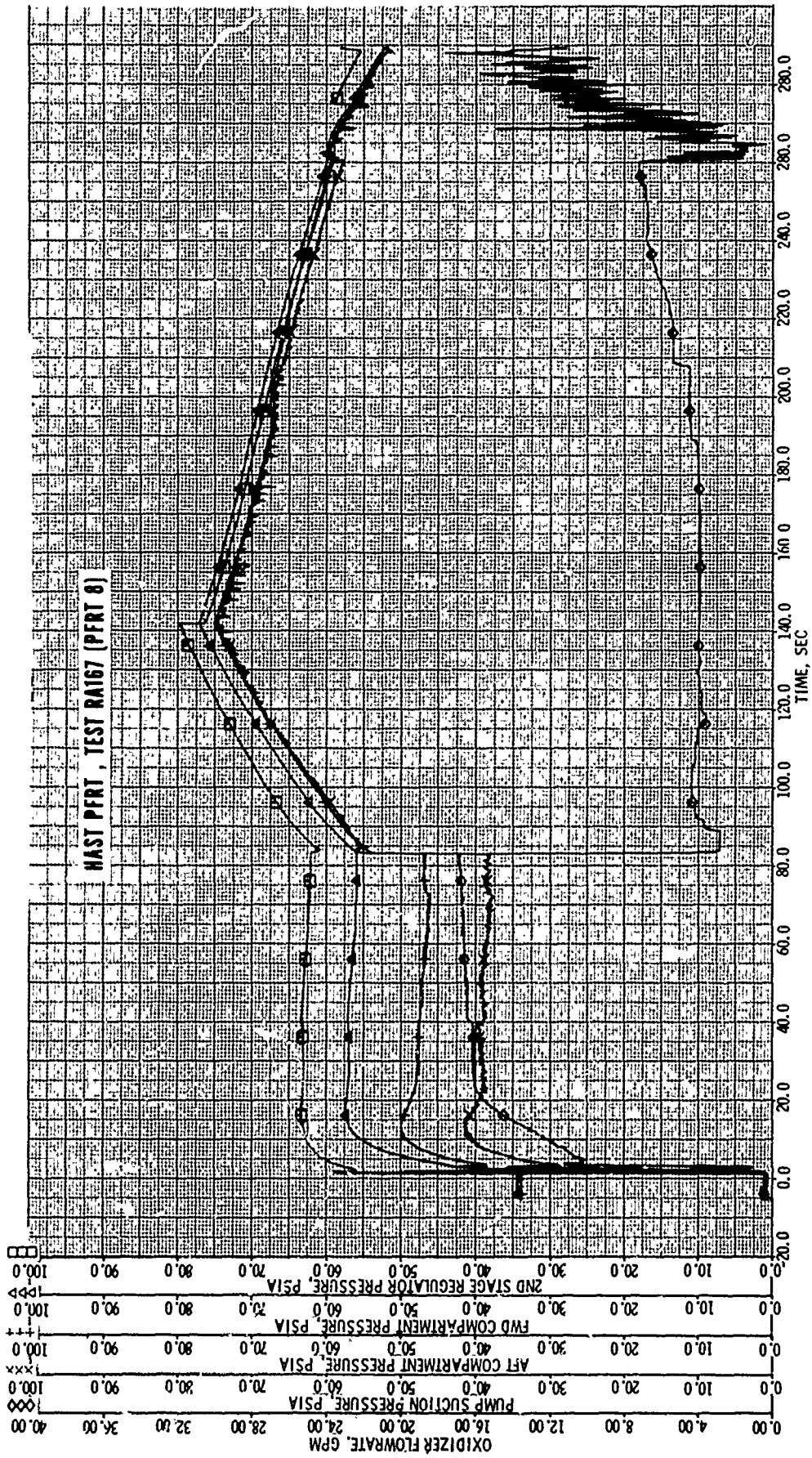


Figure 75. OMA Parameters for PFRT 8

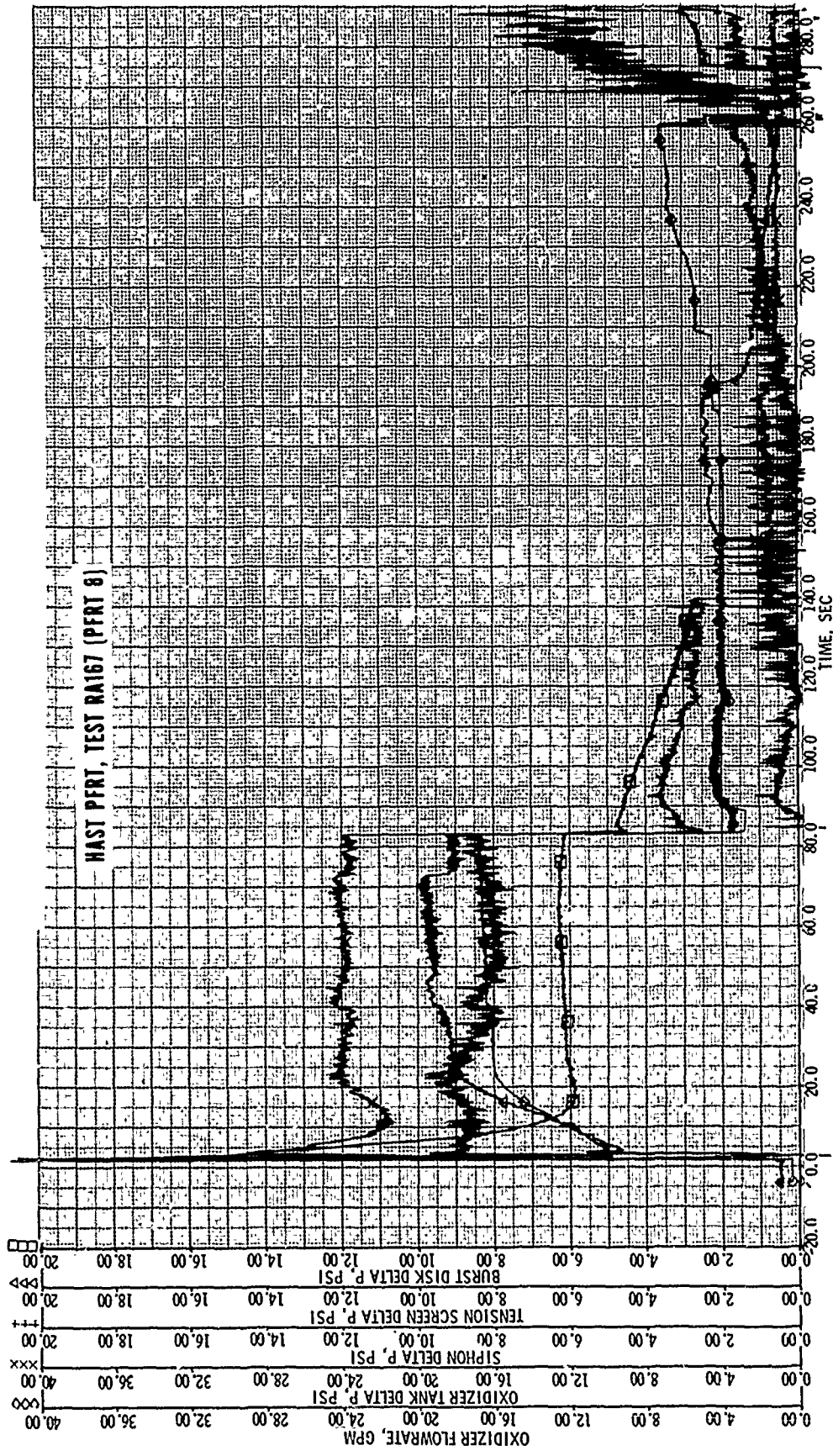


Figure 76. Pressure Drops in OMA for PFRT 8

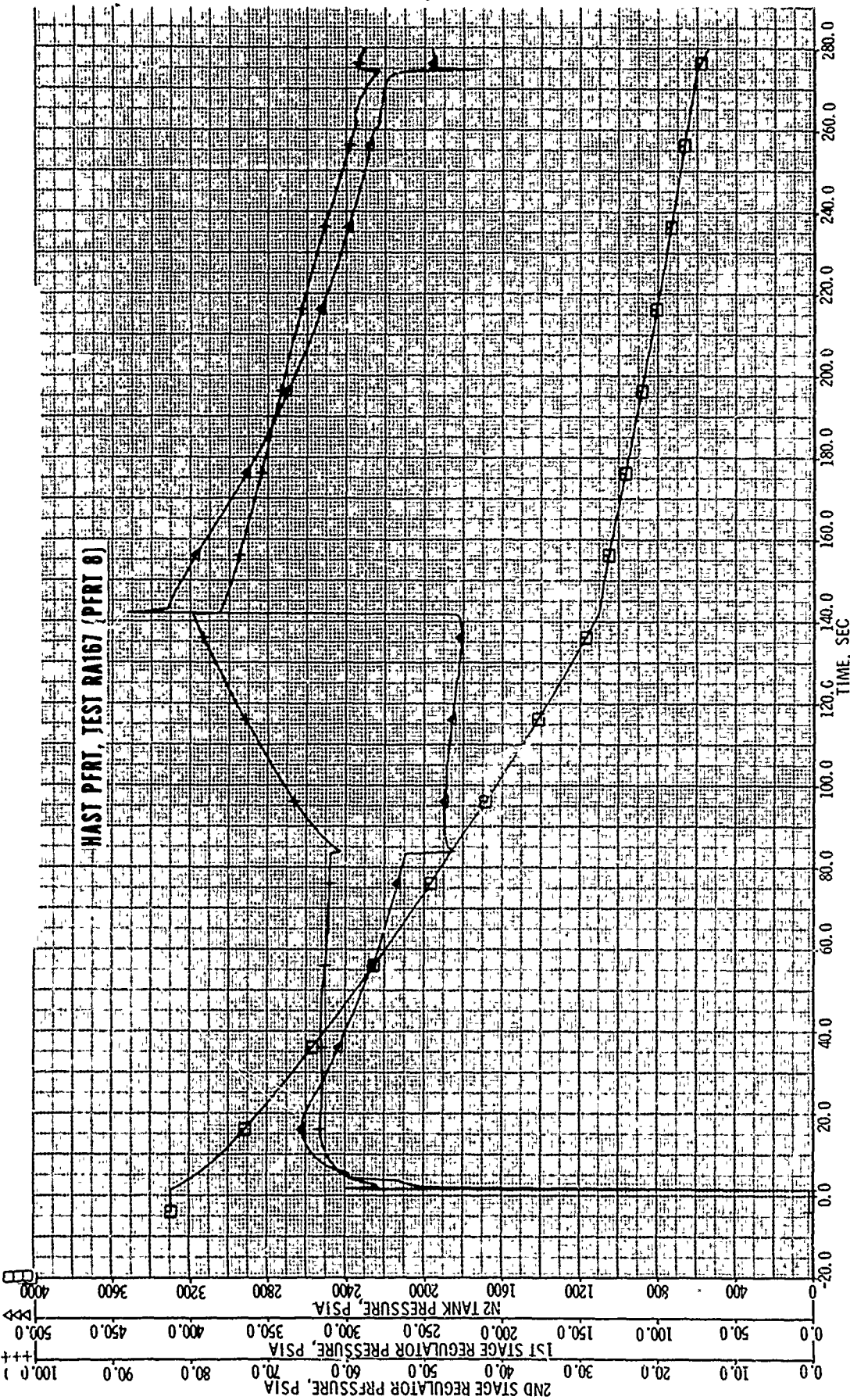


Figure 77. Pressurization Parameters for PFRT 8

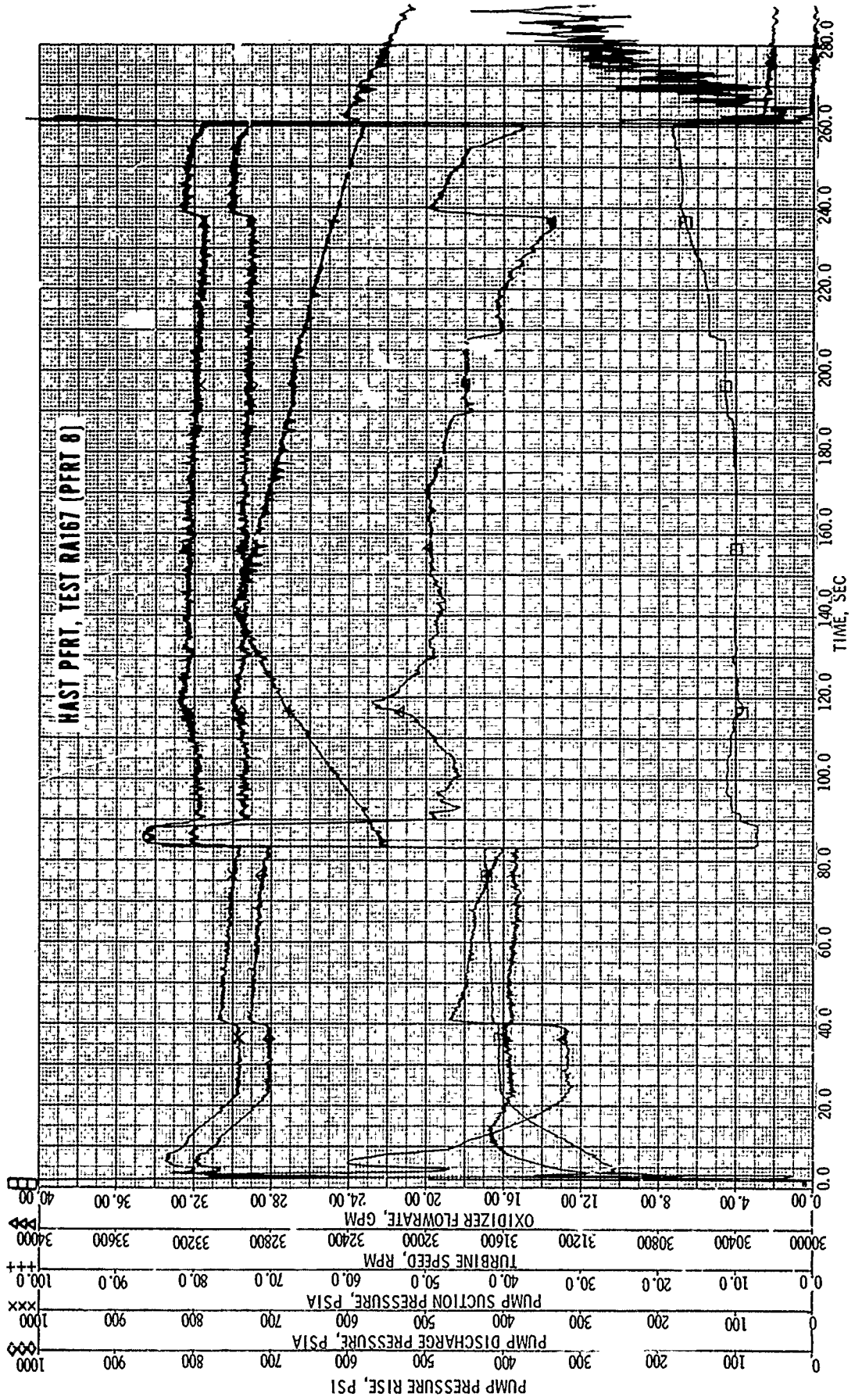


Figure 78. Pump Performance for PFRT 8

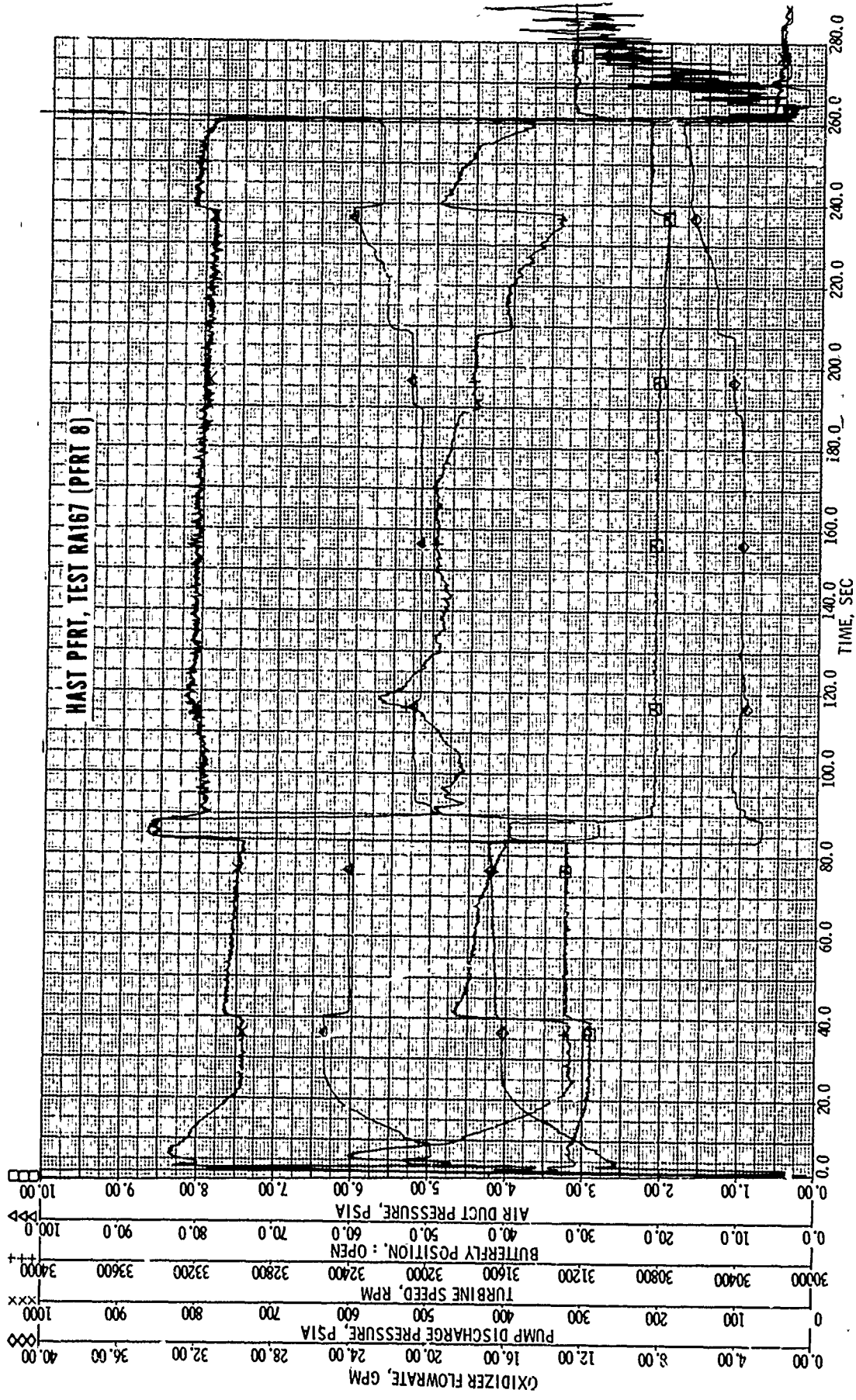


Figure 79. Ram Air Turbine Parameters for PFRT 8

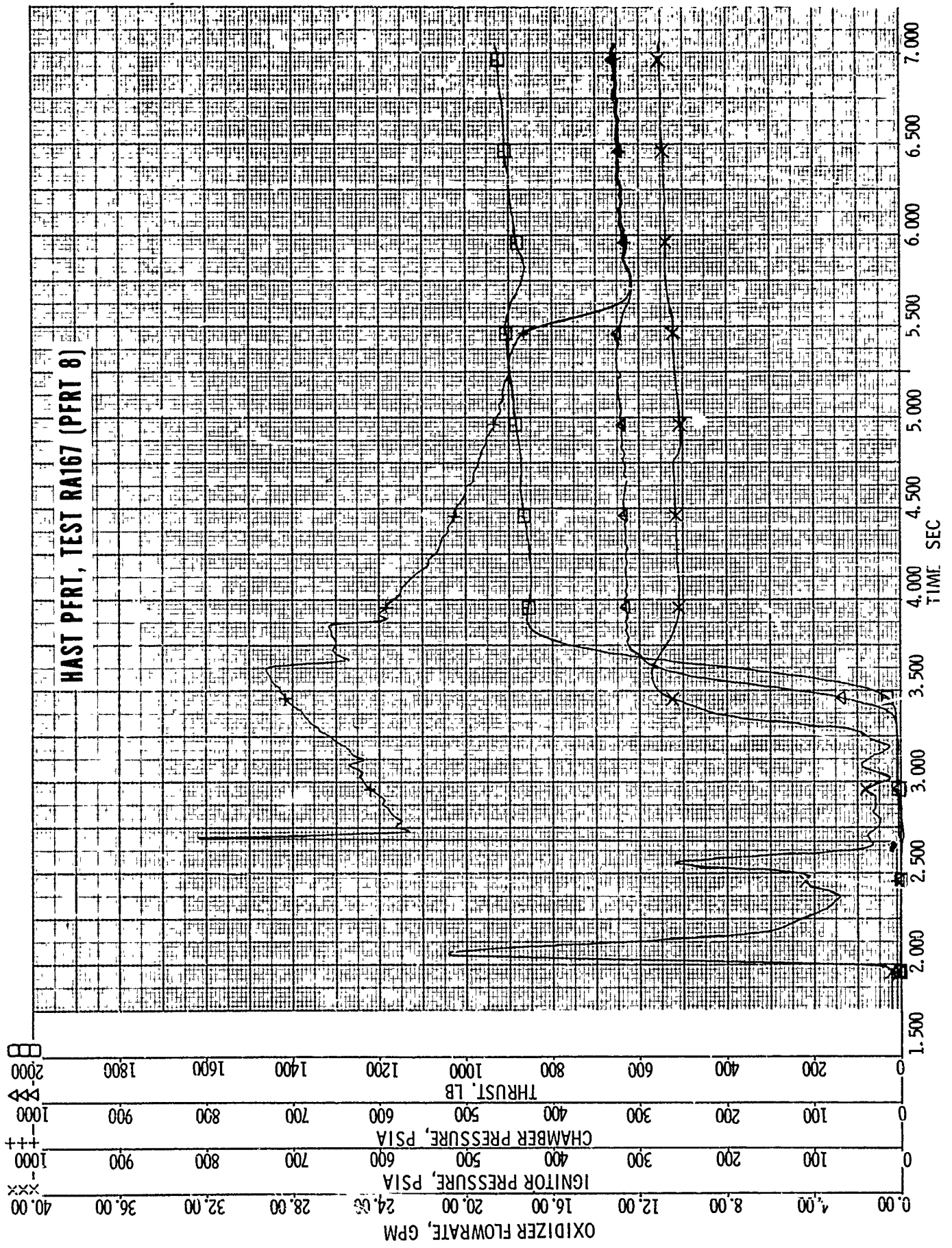


Figure 80. Start Transient for PFRT 8

the pressure in the supply duct was reduced to bring the speed nearer the nominal 32,000 rpm. Likewise, the pressure was increased at one point during boost to raise the turbine speed to the nominal value. The resultant increase in oxidizer flow caused the step increase in thrust which is seen 40 seconds after launch.

The second stage regulator in the MFV failed closed during the sustain portion of the test, at 142 seconds after launch. The effect on tank and pump suction pressures is shown in Figure 75. The apparent decrease of second stage regulator output pressure to a level slightly below the forward compartment pressure is due to instrumentation error and does not indicate backflow out of the tank. The failure occurred 60 seconds after the transition to sustain, and the tank pressure had increased from the 56 psia maintained during boost to 77 psia. This increase in regulator output pressure at low pressurization gas flowrates is characteristic of this regulator. Since at the time of the failure there was a large ullage volume at high pressure, the tank blowdown rate was slow enough that the pump suction pressure was always well above the required minimum. Thus the failure had no effect on the test.

The thrust measurement on this test is subject to an error due to zero shift in the load cell. The load cell was electrically zeroed with the test cell at atmospheric pressure, and when the cell was evacuated the load cell output shifted to -17 lb. At the end of the test, with all apparent loads removed and the cell still evacuated, the load cell output stabilized at +13 lb., for a total positive shift during the test of 30 lb. Seven pounds of this can be accounted for by the change in weight on the thrust stand (see thrust measurement discussion in Section III), leaving 23 lbs for possible thrust measurement error. Since it is not possible to determine at what point during the test this shift occurs, or at what rate, the thrust measurement cannot be corrected for this zero shift. Since the thrust during sustain is on the order of 300 lbs, the zero shift is a significant error in the thrust being measured.

PFRT 9 (Test RA 168)

This test demonstrated operation of the propulsion system at the design baseline mission after having been temperature conditioned to +125°F. Since the pressure regulators had satisfactorily passed the hot qualification tests, both the first stage regulator and the MFV were in place during the conditioning cycle. Otherwise the conditioning was accomplished as for the last test.

The propulsion system was heated to +125°F and held at that temperature for eight hours. After completing the pre-test preparations, the test cell was evacuated. A zero shift of +60 lb. was noted on the load cell output after the cell pressure had stabilized. Since there was no assurance that this tare would remain constant during the test, and in fact past experience suggested that it would not, the test was cancelled and the propulsion system allowed to return to ambient temperature.

The tare was found to be caused by loads being applied by a hydraulic ram used for calibration of the thrust stand. The configuration of the hydraulic system was such that it was very difficult to bleed all the air from the lines. When the cell was evacuated, residual air in the hydraulic lines caused a positive pressure on the ram piston and a net force on the load cell. The ram was removed from the thrust stand prior to attempting this test again.

A checkout of the thrust measuring system was made at simulated altitude before again temperature conditioning the propulsion system. The test consisted of observing the load cell output as the cell was evacuated and while the cell was maintained at a constant pressure for several minutes. The load cell showed a negligible zero shift when the test cell was evacuated, and the shift increased with time at a rate of 5 lb/min. This was acceptable and the propulsion system was again heated to +125°F (oxidizer temperature).

The system was held at 125-130°F for eight hours and then the conditioning box was removed. Fiberglass insulation was placed over the oxidizer tank to reduce the heat loss during the pre-test operations. The oxidizer temperature at the start of the test was 128°F and dropped to 117°F at the end. The data are plotted in Figures 81 through 86, and the ignition transient is shown in Figure 87.

There were no problems with the thrust measurement. The change in thrust tare from the beginning to the end of the test was +15 lbs., of which 7 lbs., is due to the change in weight on the thrust stand. The remaining 9 lbs. is generally consistent with the drift rate of 2 lb/min seen on the altitude checkout.

As can be seen in Figure 81, the boost thrust was approximately 50 lb. lower than expected. The boost thrust would be lower than nominal because of the reduced mass flowrate with the lower density hot oxidizer. The effect of temperature on mass flowrate had apparently not been taken into account in the predicted thrust.

The increase in thrust during sustain, at 162 seconds after launch, is the result of a malfunction in the X-Y recorder which was used for thrust control. An apparent shift in gain caused a thrust readout lower than the real value, and seeing this drop, the operator increased the oxidizer flow to raise the apparent thrust to the desired level. In reality, the thrust was now higher than desired. The plotter malfunction did not affect the recording of thrust data on the digital system, and thus the data plot of Figure 81 shows only an increase in thrust and chamber pressure.

Since the thrust (and oxidizer flowrate) was higher than required for sustain at this simulated flight condition, the duration is slightly reduced from that which would have been obtained at the correct thrust. It was estimated that, at the correct thrust, the duration would have been six seconds longer. The actual sustain duration was 178 seconds, after a boost duration of 83 seconds.

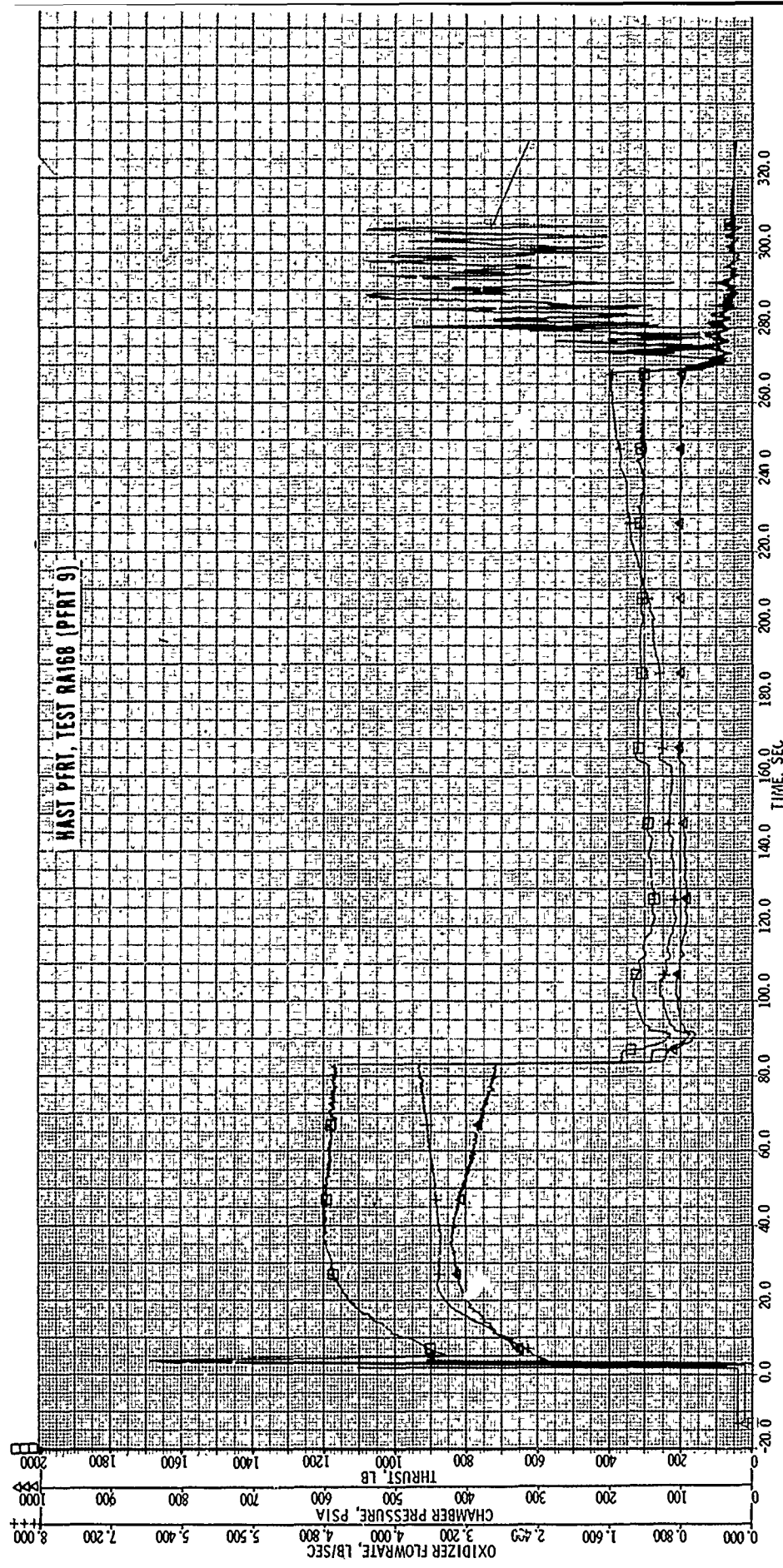


Figure 81. Thrust Chamber Parameters for PFRT 9

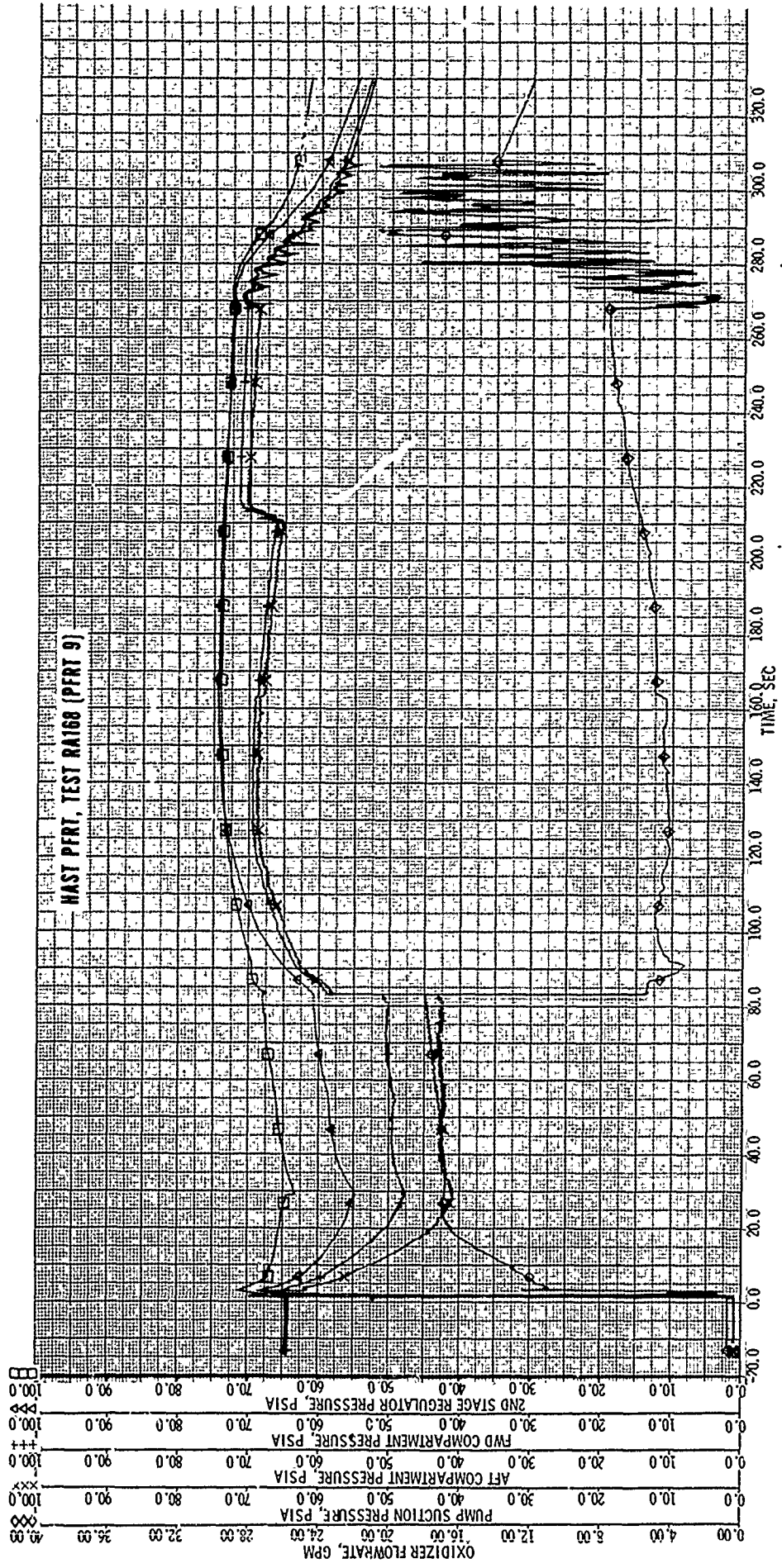


Figure 82. OMA Parameters for PFRT 9

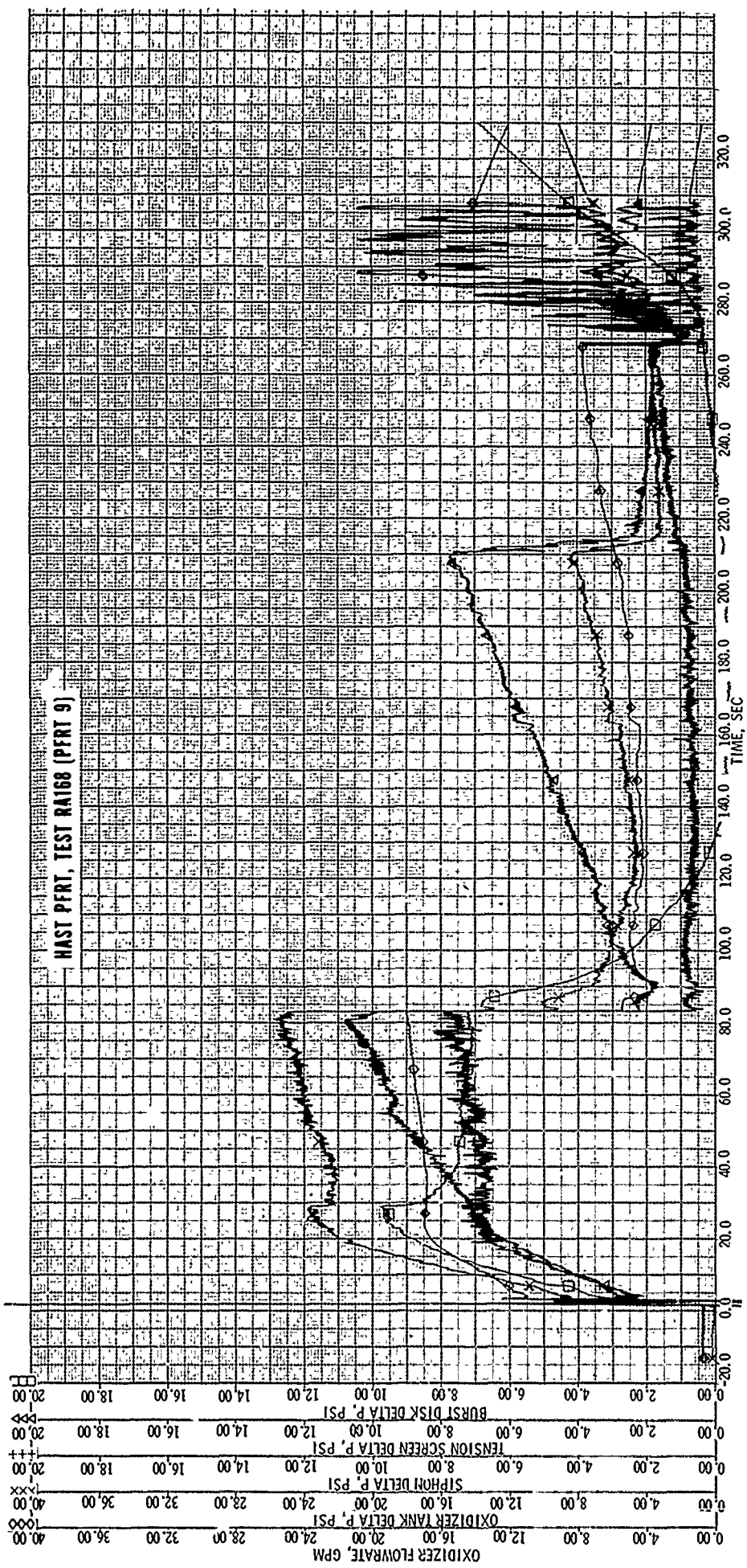


Figure 83. Pressure Drops in OMA for PFRT 9

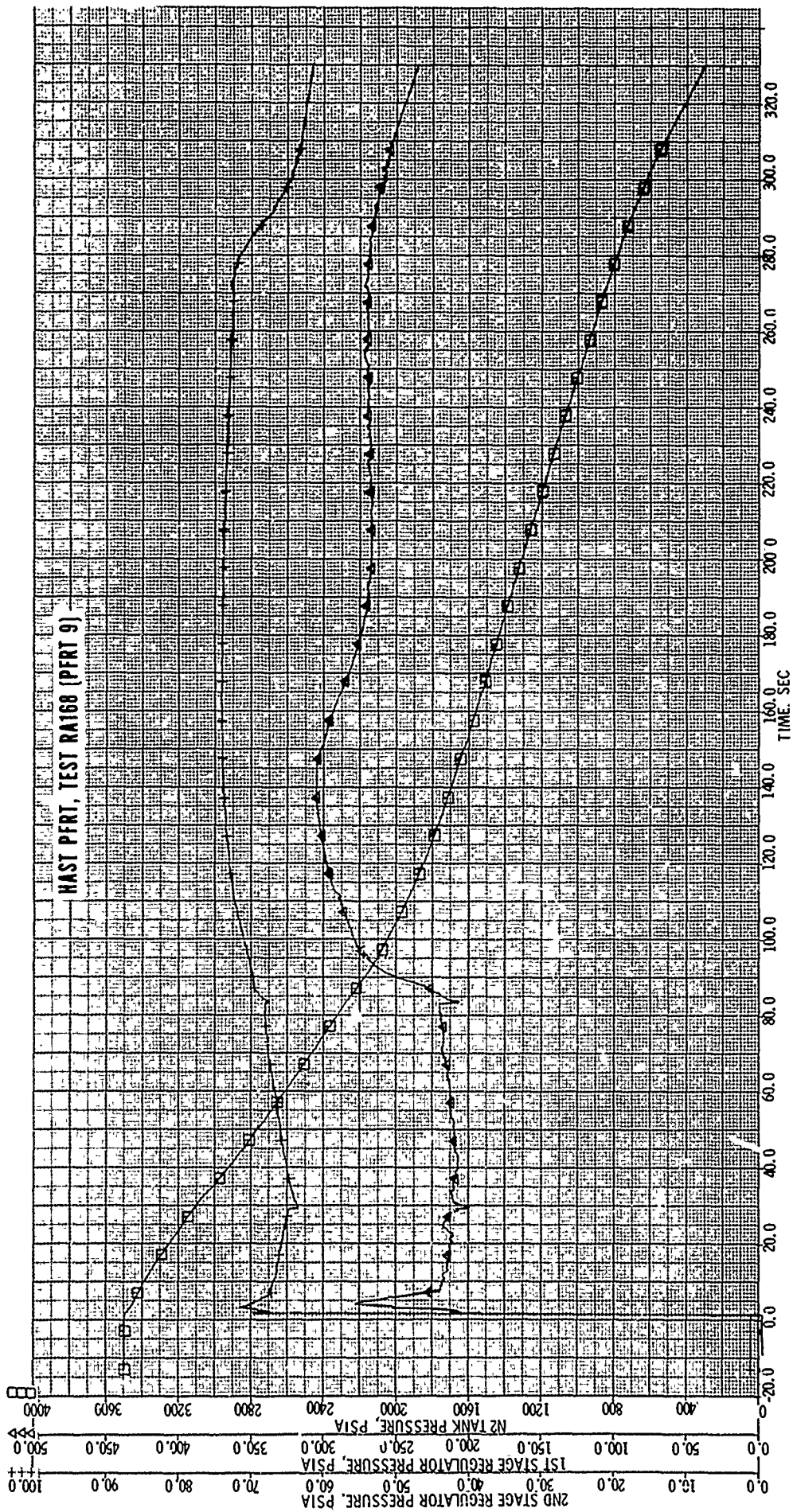


Figure 84. Pressurization Parameters for PFRT 9

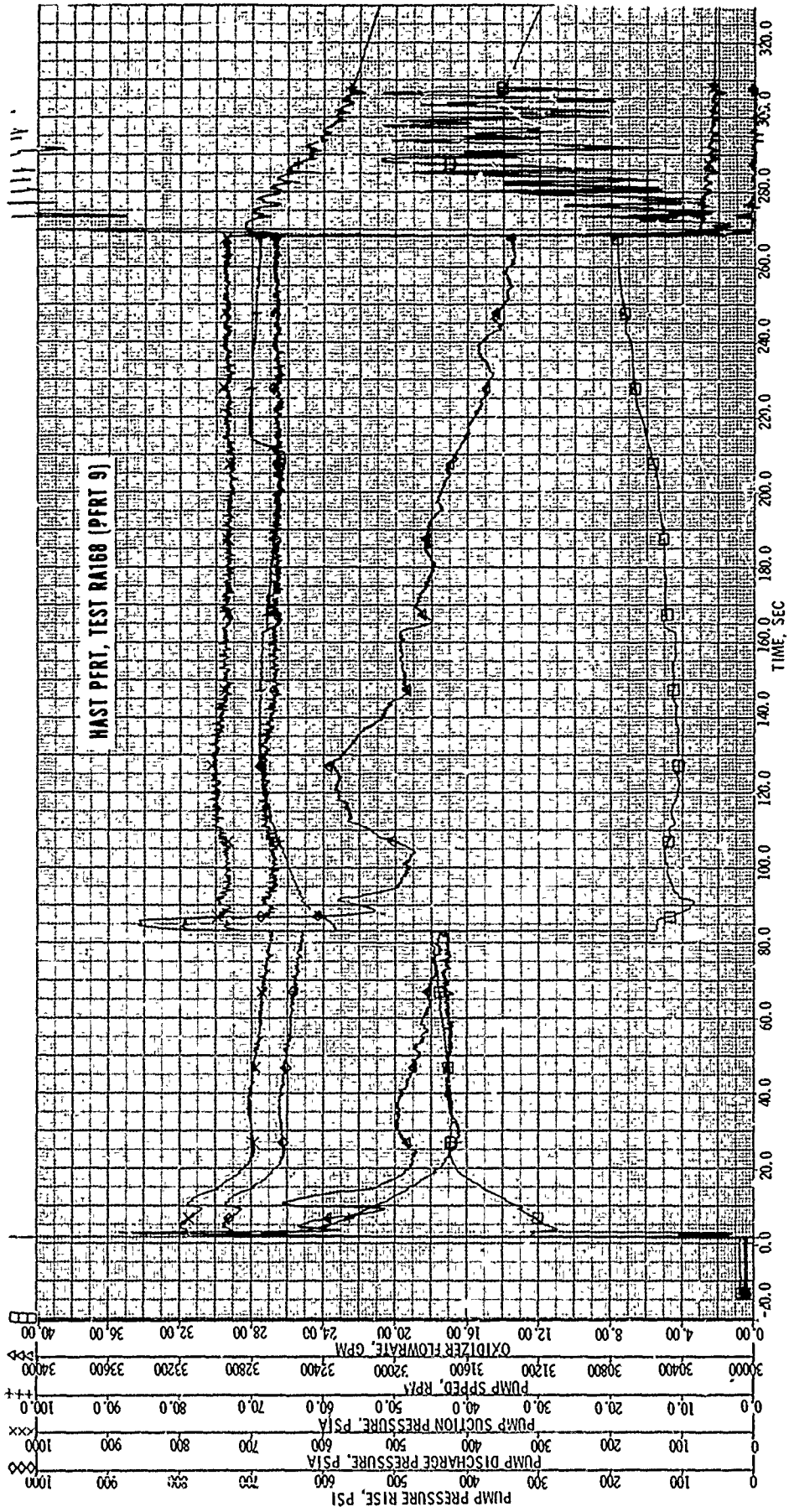


Figure 85. Pump Performance for PFR 9

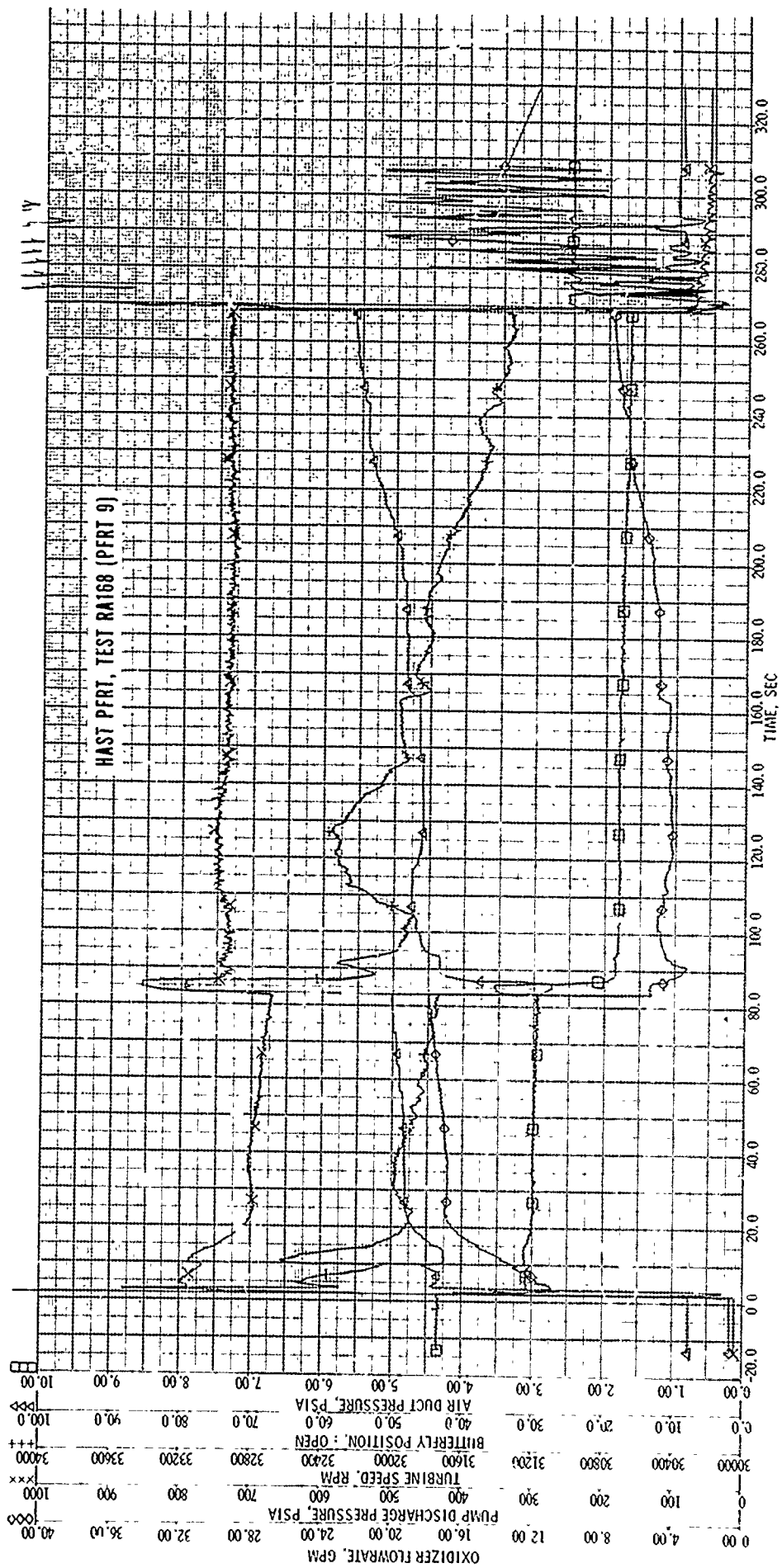


Figure 86. Ram Air Turbine Parameters for PFRT 9

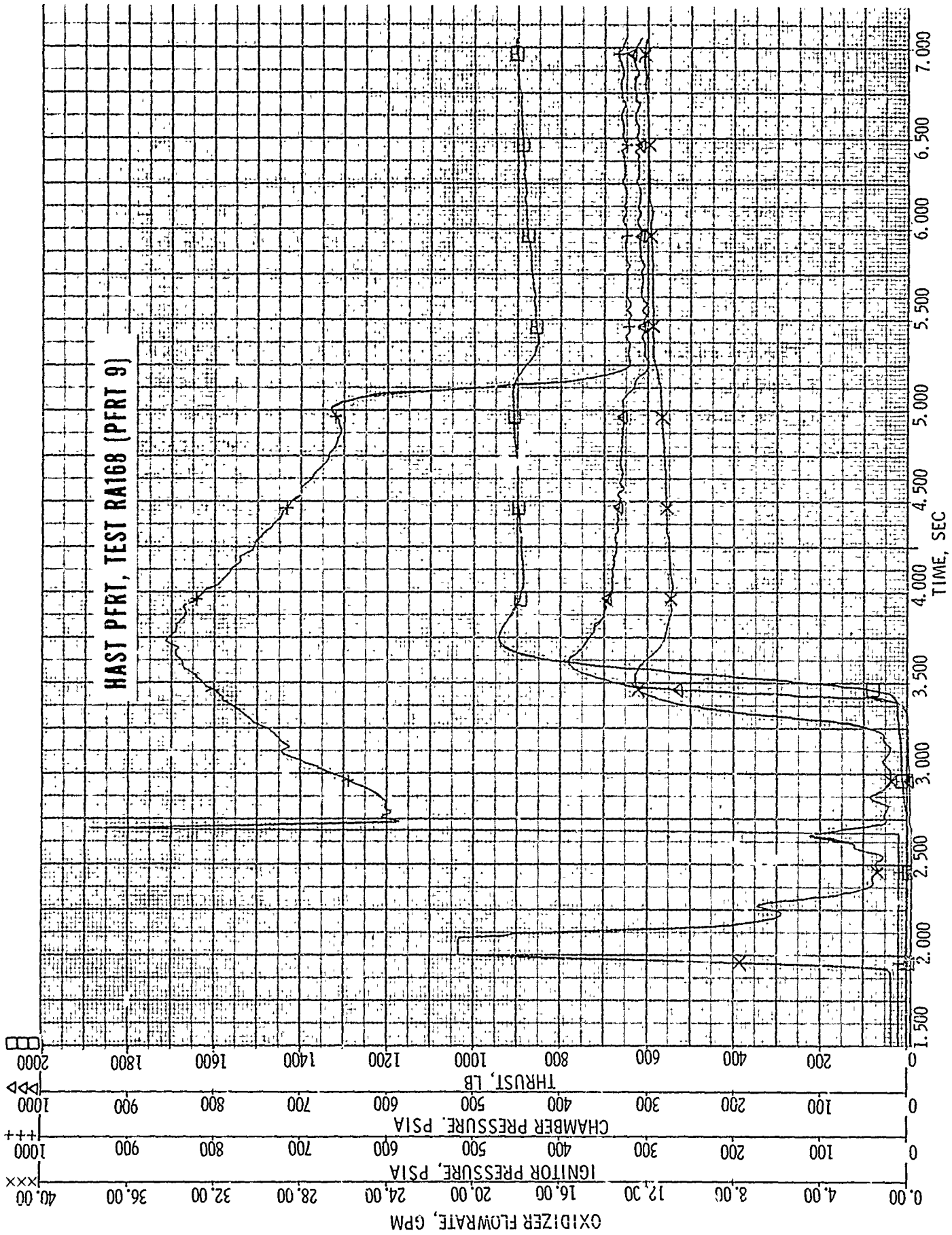


Figure 87. Ignition Transient for PFRT 9

This test used the same oxidizer tank, with the free siphon, as the previous test. Again the operation of the siphon was satisfactory, with no evidence of a potential failure mode. The limited post-test examination of the siphon (through the aft compartment fill port) did not show any damage to the siphon. This examination also showed negligible residual oxidizer in the tank.

The pressure drop measured across the oxidizer tension screen indicated that the screen was being progressively plugged during the test. As shown in Figure 83, the restriction was evident during both boost and sustain, with the pressure drop increasing almost linearly with time while there was little change in oxidizer flowrate. The rapid decrease in pressure drop at 211 seconds indicates that the liquid level in the forward compartments has dropped below the top of the screen, providing a path for gas flow into the aft compartment.

The DPU shutdown procedure was the same as used on PFRT 8. There was no evidence of oxidizer in the pump seal.

Free Siphon Tests

After the failure of the siphon of PFRT 2, a special series of tests was instituted to determine the cause of the failure. The tests were planned to provide visual observation of the siphon during the flow start transient and steady outflow from the tank. The test apparatus and starting procedures were designed to duplicate the operating conditions of the PFRT tests.

An oxidizer tank was modified by Beech with the installation of plexiglass windows on both sides of the aft compartment. The test installation is shown in Figure 88 and the siphon may be seen in Figure 89. The welded siphon mounting plate interface at the tank outlet was modified to a flanged installation so that the siphon could be easily replaced.



Figure 88. Free Siphon Test Installation

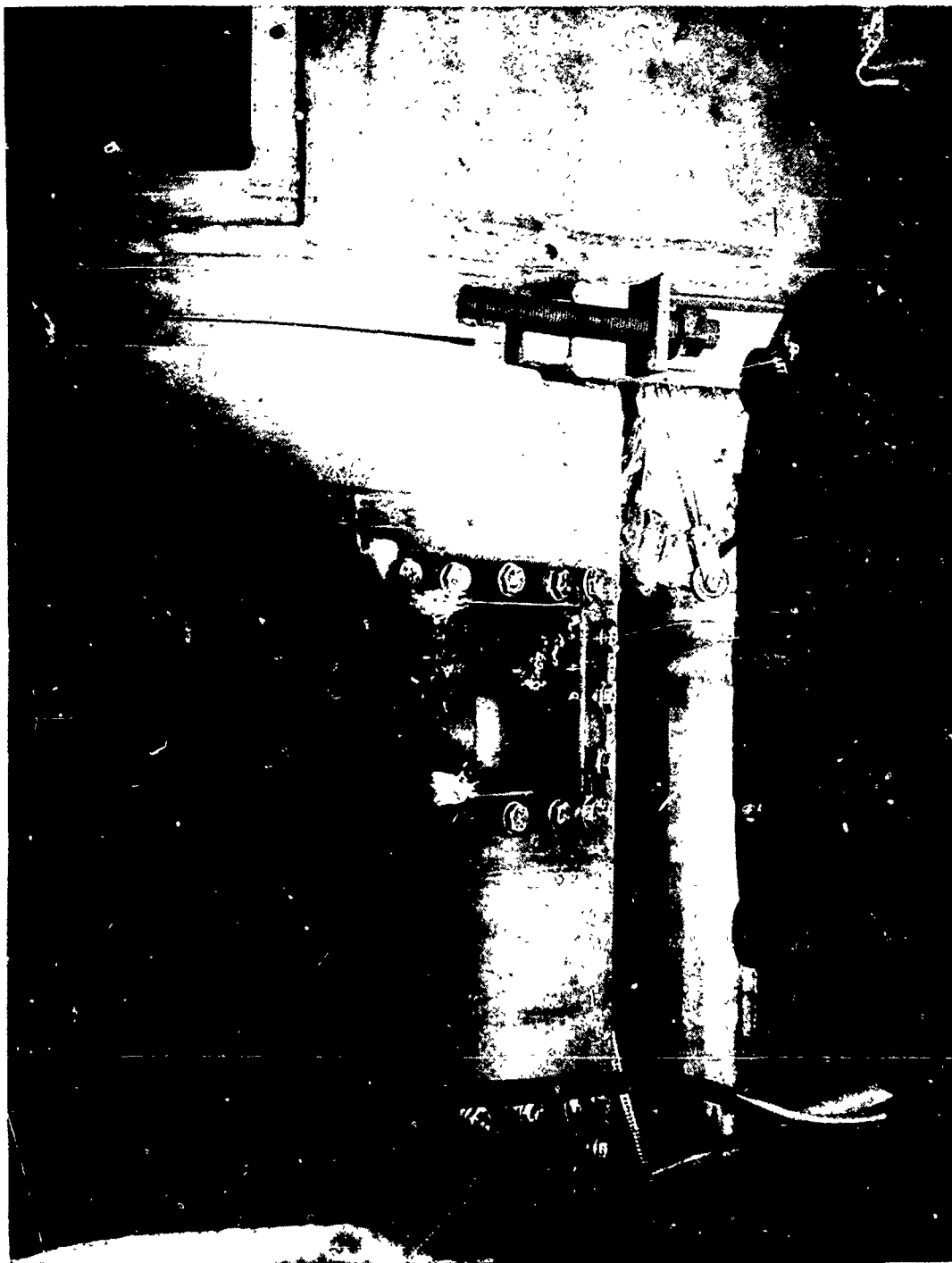


Figure 89. Windowed Tank with Free Siphon Installed

The first stage regulator and MFV were used to pressurize the tank. A solenoid valve was installed upstream of the MFV, providing the same function as the internal shear cap for starting the gas flow. This valve eliminated the requirement for replacing the shear cap at the MFV inlet after each test, and also added the capability for terminating the gas flow short of depletion of the nitrogen toroid. This valve was opened by the same electrical signal that normally fired the pressure cartridge to open the shear cap. The same regulators were used for all the siphon tests.

The burst disc at the tank pressurization inlet was not replaced after the first test. Thus, during the remaining tests there would be a very slight difference in the initial tank pressurization transient. Normally, when the MFV shear cap opens, a pressure spike is seen at the outlet of the second stage regulator. This lasts only a few milliseconds, until the burst disc ruptures and allows the gas to flow into the tank. This difference in pressurization transient was not considered significant to the purposes of this test, so for convenience the disc ruptured on the first test was left in place.

A prototype OTV was used in place of the flight OTV. Functionally, the prototype was identical, and the mechanical interfaces were the same as the flight unit. The OTV discharged into a flight injector manifold, with the injectors in place. The OTV and the injectors were bolted to a back pressure fixture in a manner identical to their attachment on the thrust chamber forward closure. This fixture may be seen in Figure 90. Flow passages carried the discharge from the four injectors into a central plenum. An orifice at the exit of the plenum provided a back pressure to the injectors identical to chamber pressure at boost thrust.

The test fluid was water. The volumetric flow rate was adjusted to 21 gpm so as to have the same mass flowrate as the IRFNA at the 16.8 gpm boost flowrate. Facility water was used, and after the first test there

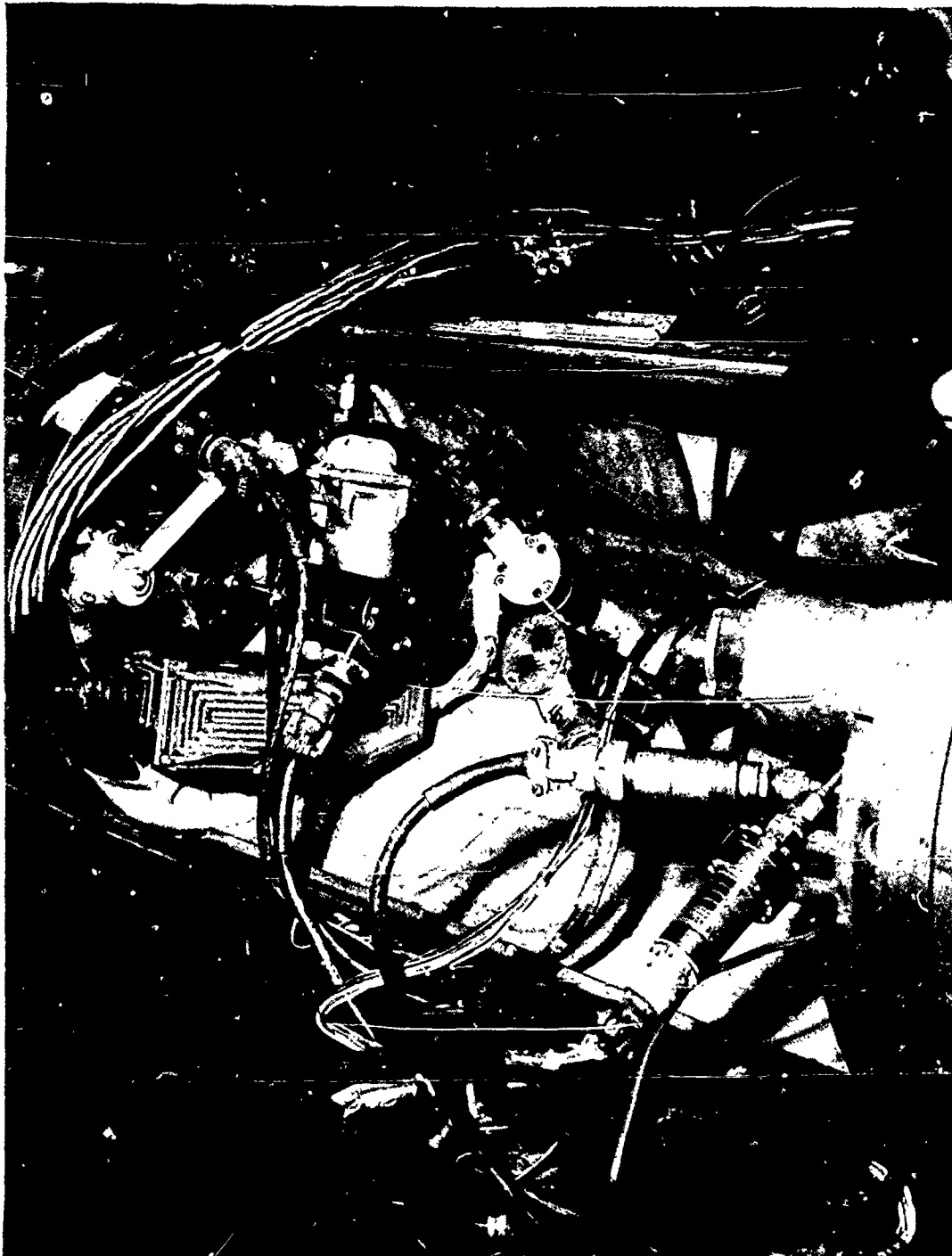


Figure 90. Prototype OTV and Flow Fixture

was evidence of accumulation of particulates in the tank. To avoid potential plugging, the tension screen was removed. Although this resulted in a higher pressure in the aft compartment, it was not considered of significance in the test results.

A total of six tests were made, using two siphons. Both siphons were of the standard configuration and had been fabricated by Beech using the same techniques as used for the siphons in the PFRT tests, and had been subjected to the same acceptance tests. Thus, as far as could be determined, both siphons were identical and were also identical to the siphon which failed on PFRT 2.

All tests were conducted at simulated altitudes of approximately 90,000 ft. The starting procedure and event sequencing for a test were the same as for an actual test firing. Motion picture and television recordings were made of the siphon during the test. Real time observations were also made by means of the television.

The first three tests used one of the siphons. The first two of these tests were needed to adjust the size of the back pressure orifice to obtain the desired water flowrate. The flowrate of 21 gpm was obtained on the third test.

The siphon was seen to experience violent oscillations at the time the start valve opened, and similar, but less severe, movements at the time the OTV started to open. There were no evident differences in the magnitude of the movements among these three tests. Post-test examination did not reveal any deformation or other damage to the siphon.

The other siphon was then installed for similar tests. On the first test (Run Nr 4), this siphon exhibited essentially the same response as the previous siphon. Again, there was no evident deformation after the test.

On the next test (Run Nr 5), at the time the start valve opened the siphon partially collapsed against the lip of the outlet tube. It remained in this position as flow increased during the OTV opening ramp and as

long as boost flow was maintained. However, there was no flow restriction, and at the transition to sustain flow, the siphon resumed its normal position.

Post-test examination of the siphon showed that the wire helix had shifted within the Teflon sleeve near the attachment to the outlet tube. The result was a lateral shift of part of the helix relative to the centerline. However, there was no evidence of damage to the Teflon and no apparent flow obstruction. Since there is no bond between the wire and the Teflon, very little force is required to shift the wire helix.

The test was repeated with the first siphon. The usual reaction to the valve opening was seen but there was no deformation of the siphon.

Although only one of these six tests resulted in an actual collapse of the siphon, such a collapse appeared imminent on the other tests. Also, it was quite apparent that the type of collapse which was observed could potentially obstruct the flow. This obstruction could easily happen if there were a greater degree of distortion or a somewhat different position when collapsed. Thus it was concluded that the failure mode of PFRT 2 had been identified even though the failure was not strictly duplicated.

Under a separate project authorization, a short-term program was conducted by the AFRPL to evaluate an alternate siphon configuration (Reference). The alternate consisted of an off-the-shelf welded metal bellows of approximately the same dimensions as the original Teflon siphon. The metal bellows was evaluated in start transient and expulsion tests with a transparent tank having geometry similar to the aft compartment of the HAST oxidizer tank. The start transients of the flight configuration propulsion system were simulated by pressure blow-down into an initially evacuated discharge line. There was no evidence of impending failure during the start transient, and expulsion characteristics were similar to those of the Teflon siphon. It was concluded that the metal bellows could be considered as an inexpensive alternate approach if additional problems occur with the Teflon siphon, either in immediate static and flight tests or during long-term storage.

SECTION V
COMPONENT RESULTS

In this section, significant results of the test program are discussed as they relate to specific components. The details of component problems and their solution are provided.

Pressure Regulators

The pressure in the oxidizer tank is controlled by two stages of regulation. The first stage regulator, supplied directly from the nitrogen toroid, has a specified outlet pressure of 340 to 280 psig over a gas flow range of 1 to 10 scfm. The second stage regulator, contained within the MFV, now has a specified outlet pressure of 68 to 53 psig over a flow range of 1 to 8 scfm.

At the start of the OMA expulsion tests, the second stage regulator set point was 43 psig at 8 scfm. During these tests, it was found that the pump inlet pressure was not being maintained at a level high enough to suppress cavitation, and this was partially due to the low set point of the regulator. The problem had not occurred previously during sea level testing of the propulsion system because the regulator is a gage pressure device and its output pressure is referenced to ambient pressure. Thus at sea level the absolute pressure output was approximately 13 psi higher than in the altitude cell, and the pump inlet pressure was high enough to suppress cavitation. Along with other changes to reduce system pressure losses, the regulator set point was increased by 10 psig, to the present specification of 53 psig at 8 scfm. As long as pressure losses in the rest of the system remained at near nominal values, this regulator setting provided adequate pump suction pressure and no further changes were made.

During the PFRT tests, the second stage regulator output generally fell within the specification limits. Where there were deviations, the pressure was higher than the limits. This is, of course, a safe deviation from the standpoint of continued propulsion system operation but it does have the adverse effect of increasing pump seal leakage.

The only significant problem with the second stage regulator during the PFRT series occurred on PFRT 8. The regulator failed in closed position at 142 seconds after launch. Since this was during the main portion of the mission, and there was a large ullage volume at relatively high pressure in the oxidizer tank, the tank pressure remained at a level high enough to provide adequate pump suction pressure for the rest of the mission. Thus the failure had no effect on this test. However, a similar failure during boost, when the tank pressure and ullage volume would have been much lower, would likely result in pump cavitation and failure of the propulsion system to meet mission performance requirements.

The MFV was completely disassembled and examined immediately after the test. There was no evidence of any abnormality which could explain the failure. This was the only regulator failure of this nature to occur during the PFRT test series or during regulator qualification testing. The problems during qualification had all resulted in high output pressures. The difference between this and other tests is that the MFV was colder. Although the MFV was not included in the pre-test temperature conditioning, the nitrogen pressurization gas was chilled during the conditioning, and was further chilled during blowdown of the nitrogen tank. A thermocouple bonded by epoxy cement to the exterior of the MFV body indicated a temperature of -23°F at the time the regulator failed. The nitrogen gas temperature within the toroidal tank was indicated to be -18°F at the same time. This apparent discrepancy could not be resolved. The only ambient temperature test on which the MFV temperature was measured was PFRT 4. Although not the same duty cycle, the measured temperatures are indicative of operating temperatures of the MFV on the ambient temperature PFRT tests. At 142 seconds, the MFV temperature was $+33^{\circ}\text{F}$,

and at the end of the test (273 seconds) the temperature was +17°F. The thermocouple which measures the gas temperature failed on PFRT 4. However a comparison may be made with gas temperatures on PFRT 3, which used the same design baseline duty cycle as PFRT 8. At 142 seconds, the gas temperature was +40°F, having started at +91°F at launch. The gas temperature on PFRT 8 was +51°F at launch.

The first stage regulator experienced a failure in the open position on PFRT 1. Post-test examination showed that the O-ring seals had been attacked by IRFNA. The O-rings were made of Buna-N, which is not compatible with IRFNA but normally will not be exposed. For this test, the regulator was reused from the previous OMA test and had been externally exposed to IRFNA because of a leak at the pump discharge pressure fitting. This failure was thus due to unique circumstances, and problems of this magnitude did not again occur with the first stage regulator.

The only other problem with the first stage regulator were instances of low output pressure and erratic operation. These occurred on PFRTs 6, 7, and 8. In some cases, the pressure dropped as low as 175 psia. The outlet pressure was always high enough to allow the second stage regulator to function normally, and the only impact on the overall system was reduced aeration gas flow. This possibly reduced thrust chamber performance but the effect cannot be quantitatively evaluated. The cause for the erratic regulator operation was not determined.

Burst Disc

The nitrogen pressurization system is isolated from the oxidizer tank by means of a burst disc located in the tank forward dome. The disc ruptures at a differential pressure of 20 ±5 psid in the flow direction, and can withstand a differential pressure of 150 psid in the reverse direction. The disc is made of aluminum, and breaks into two semi-circular leaves along stamped grooves. The two leaves are retained by a tab at their outer edge.

During the OMA expulsion tests prior to the PFRT tests, it was observed that there was a substantial flow restriction across the opened burst disc. The pressure drop of two of the burst discs was measured in a flow bench apparatus using a rotameter. The measurement was made with the discs still in their holder. The disc from OMA 3 had a pressure drop of 6.0 psid at a nitrogen flow rate of 8.0 scfm, while the disc from OMA 4 had a pressure drop of 9.0 psid at the same flowrate. The pressure schedule had allocated 4.0 psid for the pressure drop across the burst disc, and this higher pressure drop was adding to the problem of low pump suction pressure which was primarily caused by the low output pressure from the regulator.

It was evident from examination of the ruptured burst disc that the leaves were not fully opening, thus restricting the flow passage. The configuration of the adapter was such that there was a reduced internal diameter just downstream of the disc, and the leaves were being restrained by the wall of this section. This problem had not occurred during previous development or proof tests because the higher output pressure of the regulators had produced a greater force on the burst disc at opening and the leaves were deformed against the restraining wall.

Prior to OMA 5, the adapter was modified by Beech so that a large part of the restraint at opening was removed. The pressure drop across the burst disc during boost flow on OMA 5 was then 3 psid. During the PFRT tests, pressure drops were typically 4 to 6 psid. This was acceptable since the regulator output pressure had also been increased.

The configuration of the burst disc adapter also posed problems with the installation of the burst disc and its susceptibility to leakage. The disc was sandwiched between two mating flat surfaces which were held together by an external nut. In tightening the nut, it was possible to apply torque to the burst disc and distort it. Extreme care was required to install the disc and have a leak-tight assembly. The standard procedure was to leak check the assembly with nitrogen in the reverse flow direction before installing it in the oxidizer tank.

Even with the leak check, there were two instances of leakage after loading of oxidizer into the tank. The first of these occurred prior to PFRT 2. Disassembly of the adapter showed that one corner of the disc had been crimped during assembly. The other incident of leakage occurred prior to PFRT 5. The cause for this leakage was not evident from examination of the burst disc, and in fact a leak check after removal of the adapter from the tank and before disassembly did not reveal a leak.

The standard procedure was to install the pressure regulators just before the test. In both instances of oxidizer leaks, the leaks were discovered when a cap on the adapter was removed to allow connection of the pressurization line from the MFV. This procedure prevented damage to the regulators, which contain seals not compatible with IRFNA.

Tank and Tension Screen

The function of the tension screen is to retain propellant in the aft tank compartment during vehicle maneuvers. The screen material is 304 stainless steel. The nominal pressure differential for liquid flow through the screen is 7 psid at the boost flowrate of 16.8 gpm.

The tension screen became one of the more serious problems of both the OMA and PFRT test series, and was the cause of failure of one of the OMA tests. However, it is important to make the distinction that the problems were not caused by the tension screen per se, but were due to IRFNA corrosion of the 17-7 PH tank wall. The corrosion products then plugged the fine pore screen.

The first instance of plugging occurred on OMA 4, and was so severe that the pump cavitated and the flowrate decayed to 4.2 gpm. It was concluded that the screen was plugged by corrosion products created during previous exposure of the tank to IRFNA. This same tank had been used for the previous two OMA tests, and thus had a total exposure time of 35 days. For most of this time the tank had contained only IRFNA vapors and a small amount of liquid which was residual after the expulsion tests. Since

the IRFNA vapors are more corrosive than the liquid, these likely created the problem. The tank was inadvertently flushed with water before a detailed internal examination could be made, so there is no direct evidence confirming the nature of the corrosion products.

As a corrective measure for this problem, the IRFNA exposure time for the tank was limited to 30 days. This time limit was based on short term tests by Beech which had shown no increase in tension screen ΔP after liquid storage up to 30 days. If a tank was to be reused, it was refilled with IRFNA as soon as possible after a test. This limited the vapor exposure, and was usually accomplished within four hours after a test.

Evidence of tension screen plugging appeared on PFRT 3 and 4. In these cases, there was an increase in ΔP with time at constant flowrate but the ΔP was within acceptable limits of the overall pressure schedule. Therefore, these incidents had no direct impact on the success of these tests. However, it was obvious that this problem could have serious consequences.

Examination of the tank used for PFRT 4 showed several lumps of a greenish-brown gelatinous material adhering to the interior walls. Chemical analysis showed this material to be nitrates of iron, nickel, and chromium. These are the expected products of corrosion of the 17-7 PH tank material by IRFNA.

The two tanks used for these tests had both been cleaned by Beech shortly before the tests. They had been filled with IRFNA only one to two days prior to the tests. It was evident that extremely rapid corrosion was taking place in the tanks. Since the tanks had been reused from previous tests, it was suspected that the prior history had an effect on the accelerated corrosion rate. There was some substantiation of this theory by the observation that a slight increase in screen ΔP was seen on PFRT 2, and a much greater increase was seen when this same tank was reused for PFRT 4.

Both tanks had been used a number of times previously, and had been cleaned after use. S/N PT 4-1 had been used for DPU tests at The Marquardt Co. (using water and freon), OMA tests 1 and 5, and PFRT 1. Prior to its use on PFRT 3, it had been cleaned four times. S/N PT 1-1 had been used for temperature cycling and storage tests at Beech/Boulder and for PFRT 2. Prior to its use on PFRT 4, it had thus been cleaned six times. After reviewing this history, the cleaning process was suspected to be causing increased corrosion rates.

The cleaning procedure used each time was the normal Beech production cleaning process for tanks of the same material. The process included pickling in a mixture of nitric acid (20-40 wt. percent) and hydrofluoric acid (1.7-5.0 wt. percent), with the balance being water. Because of the high HF content, this solution can etch the surface of the material, and expose grain boundaries for corrosion. After repeated cleaning, the effective surface area can have significantly increased, thus accelerating the corrosion rate.

For tanks to be used in the remainder of the test program, the pickling operation was omitted except for the initial cleaning after manufacture. A laboratory-scale test program was initiated by Beech to measure the corrosion rate after repeated cleaning cycles which included the pickling operation. Results of these tests will be published by Beech.

One tank cleaned by this procedure was used for PFRTs 5, 6, and 7. There were no cleaning operations between these tests, and the total time of exposure to IRFNA was 15 days. For all three of these tests, the initial tension screen ΔP at boost flow was approximately the same, and there was a small increase in ΔP with time. Specifically, on PFRT 5 the ΔP increased from 4.0 to 4.5 psid in 25 seconds, and on PFRT 7 the ΔP increased from 4.7 to 5.3 psid in 24 seconds. These data were taken at the times of constant flowrate of 16.8 gpm and do not include the time when flowrates increased because of nozzle erosion.

Another tank cleaned by the revised procedure was utilized for the last two tests, PFRTs 8 and 9. On PFRT 8, which was the cold test, screen ΔP was higher than with the previous tank, starting at 9.0 psid and increasing to 9.5 psid in the next 15 seconds of constant flowrate. The rate of increase did not change substantially during the rest of the test.

PFRT 9 was the hot test and was conducted after two temperature conditioning cycles of the loaded tank. The maximum temperature of the oxidizer on each of these cycles was 125°F, and it was maintained at that temperature for eight hours on each cycle. Four days had elapsed between the start of the first hot conditioning cycle and the actual test, and a total of 21 days had elapsed from the time the tank was filled prior to the cold test until the hot test.

As may be seen in Figure 85, there was a substantial increase in screen ΔP with time on this test. Although the initial ΔP at boost flow was lower than on the previous test, at 6.8 psid, it increased to 8.0 psid during the next 15 seconds of constant flow. The ΔP increased to 10.8 psid just before boost cutoff. A linear increase of ΔP with time was also evident during sustain, with the ΔP increasing from 2.8 psid to 7.7 psid in 110 secs. Note that the ΔP with sustain flowrate of only 6.8 gpm is as high as the ΔP during part of the boost phase. Although increasing rather rapidly, the screen ΔP remained within acceptable limits and had no impact on the success of this test. However, this behavior is a cause for concern and raises doubts about storability of a loaded propulsion system.

Free Siphon

The free siphon provides the capability of acquiring the liquid oxidizer in the aft tank wherever it may be located in response to the local acceleration vector. This prevents unporting the tank outlet during vehicle maneuvers that would tend to drive the propellant away from the outlet. In essence, the free siphon is a flexible hose constructed by heat shrinking a seamless Teflon sleeve over a stainless steel wire helix. The helix is restrained longitudinally by a support chain. There was one failure of the

siphon during the OMA expulsion tests and one failure during the PFRT tests.

The first failure, on OMA 1, is illustrated by the oxidizer flow profile in Figure 18. The oxidizer flowrate had almost reached the full boost condition when it began to decay. After closing the throttle valve and then ramping it open, full boost flow was obtained.

It was postulated that the failure was the result of the siphon being sucked down to the bottom of the tank when the flow was being accelerated. This had previously been identified as a potential failure mode of the initial siphon design, and most of the siphons already built had been modified to assure that adequate clearance was maintained between the inlet and the tank bottom. The modification consisted of shortening the support chain and strengthening the attachment bail. However, this particular siphon had not been modified. All the remaining siphons had the modified chain and attachment configuration and the required clearance between the inlet and tank bottom was verified after assembly. No further problems with the siphon occurred on the remaining four OMA tests or the first PFRT test.

The second failure, on PFRT 2, occurred at 19 seconds after launch, roughly the same time as on OMA 1. However this failure differed from the earlier one in that there was an instantaneous, almost complete shutoff of oxidizer flow with no prior indication of a restriction. Since the pump suction pressure had started to decline at 10 seconds, it was postulated that the siphon had partially collapsed during the start transient and caused an increase in ΔP through the siphon. As the flowrate increased, pump suction pressure continued to decrease until finally the pump cavitated. The postulated failure mode of OMA 1 was not definitely confirmed, and a comparison with the failure on PFRT 2 leads to implications that these may indeed be the same type of failure.

A series of water flow tests of the free siphon were conducted to determine if there were susceptible failure modes which would account for the behavior seen on PFRT 2. The test apparatus duplicated the flight propulsion configuration, with a transparent windowed tank which allowed visual observation of the siphon during water expulsion. These tests showed that the flow transients during the initial opening of the oxidizer start valve and the OTV created conditions which were likely to cause collapse of the siphon. In one instance a partial collapse of the siphon was seen in a mode which could explain the failure on PFRT 2.

Other start transient tests were also conducted by Beech in a simpler apparatus which used direct pressurization for expulsion from the tank. Similar observations were made of the behavior of the siphon during the initial valve opening transients.

The siphon was redesigned by Beech with the intent of eliminating the observed failure mode. The basic fabrication approach and materials were not changed. The spacing between coils of the wire helix was reduced, and the diameter of the helix was increased from 1.5 to 3.0 inches. The orientation of the standpipe was also changed so that the flexible portion of the siphon was only required to bend through an angle of 90° as compared to the 135° angle of the previous configuration. The dimensional changes provided greater stability and resistance to the loads imposed during the start transients. The improvement was verified in the Beech flow apparatus prior to testing the new siphon on the PFRT tests.

While awaiting verification of the new design, the PFRT tests proceeded without a siphon. The existing outlet standpipe was rotated 180° about the discharge port so that most of the oxidizer in the aft compartment would be expelled. The amount of oxidizer unavailable was calculated to be 8 lb., the same as with the siphon. PFRTs 3 through 7 were conducted in this manner.

The new siphon was used on the last two tests, PFRT 8 and 9. These were the cold and hot tests, respectively. The operation of the siphon was satisfactory, with no evidence of a potential failure such as had occurred on PFRT 2 or OMA 1. There were no apparent effects of either the hot or cold temperatures on operation of the free siphon.

Ducted Power Unit

The function of the Ducted Power Unit (DPU) is to pump the oxidizer from tank pressure to the required OTV inlet pressure, and to provide electrical power for the vehicle. Power is provided by a ram air turbine, driven by air admitted through a normal shock inlet. The turbine, alternator, and pump are mounted on a single shaft. An electronic circuit maintains a constant shaft speed of 32,000 rpm by positioning a butterfly throttle valve in the air inlet duct.

In the altitude test cell, the turbine was driven by gaseous nitrogen in a connected-pipe configuration. This drive system was designed only to provide the power required by the DPU and no attempt was made to simulate the inlet pressure that would be encountered at altitudes and speeds required of the mission duty cycles being tested. The pressures and mass flowrates in the nitrogen supply could be regulated during a test.

During checkouts of the DPU drive system prior to initiating the OMA expulsion tests, it was found that the butterfly position would not remain stable when the pressure in the inlet duct, upstream of the butterfly valve, was greater than 5 psia. This pressure required the butterfly to be less than 50 percent open to control the turbine speed with electrical load only. Position oscillations of as much as 30 percent of the available travel were seen. Since the inlet pressures would be higher than 5 psia over much of the planned HAST flight envelope, a possible butterfly instability in flight was indicated. Analysis of the instability and investigations of possible correction were undertaken by both Beech and AFRPL. Rather than awaiting the results of these efforts, the OMA and PFRT tests continued by setting duct pressure low enough that the butterfly had to be more than 50 percent open.

Typically, a total nitrogen flowrate of 1.0 lb/sec was desired during the boost portion of the PFRT tests. This includes the bypass flow. This total flow was obtained by setting one branch of the supply system for a flow of 0.6 lb/sec and the other for 0.4 lb/sec. The test was started with only the high flow branch open. With only electrical load on the turbine prior to launch, butterfly oscillations were observed. As soon as the pump load was added with the start of oxidizer flow, the oscillations ceased. During the boost ramp, the additional pump power requirement caused the butterfly to approach the full open position, and the low flow leg of the nitrogen supply was opened. At boost cut-off, the drastically reduced pump power requirement usually caused the butterfly to go so far closed that it was unstable. If this occurred, the low flow leg was closed and the reduced duct pressure resulted in a stable position. The duct pressures were also adjusted as needed to keep the butterfly between 50 percent and 75 percent open as power requirements changed. Figure 91 shows the butterfly position and duct pressure of a typical test (PFRT 3).

A modified speed controller became available for the last two PFRT tests. The gain of the feedback circuit had been reduced to improve the stability of the position control. However with the stability improvement, the accuracy of the speed control suffered. Whereas the original controller had maintained the turbine speed at the nominal 32,000 rpm \pm 200 rpm, the modifications resulted in an error of \pm 2,000 rpm. This is an acceptable error because the effect on oxidizer flow of such changes in pump speed will be compensated by the vehicle flight controls.

An altitude checkout of the modified speed controller was conducted prior to its use on PFRT 8. With and without electrical load, the inlet duct pressure was varied so as to drive the butterfly from nearly closed to full open. No oscillations were observed over the complete range of positions. Turbine speed varied within the error expected. The speed tended to increase as the butterfly went further closed with increasing duct pressure.

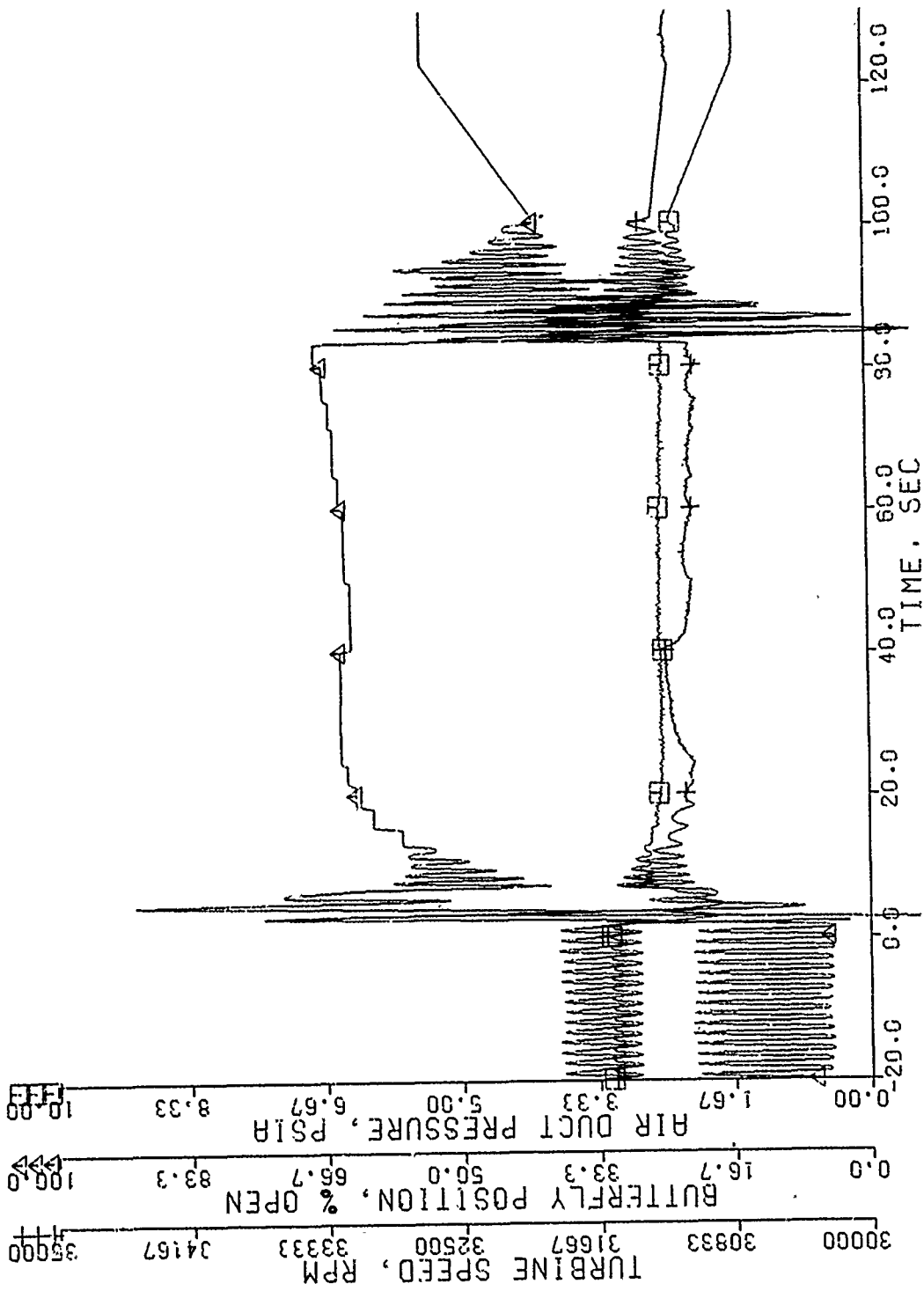


Figure 91. DPU Speed Control with Original Controller

The operation of the modified speed controller on PFRT 8 is illustrated in Figure 92. With the modified controller, the butterfly position is always stable, with none of the oscillations seen previously prior to launch and at the transition from boost to sustain. It may be noted that turbine speed varies more widely than on the earlier test. This same speed controller was used on PFRT 9 with similar results.

Although the HAST propulsion system was designed to be reused, reuse of the DPU was not possible during much of the PFRT test program. The problem was susceptibility of the turbine shaft bearings and the alternator windings to IRFNA corrosion, and the lack of positive static seals to prevent residual IRFNA from entering these critical areas after shutdown of the propulsion system.

There were two instances of alternator damage from IRFNA which was suspected of having entered through the turbine end of the housing. The only seal at this end was a labyrinth seal intended to limit air leakage past the tip of the turbine wheel. On OMA 1, there was an IRFNA leak from the flow loop plumbing. The IRFNA was washed from the test cell with water, and in so doing, some IRFNA was carried into the alternator housing. The other instance occurred on OMA 5, when there was a leak from a broken pressure sensing line at the pump discharge. The area of the DPU was enveloped in IRFNA vapor, making it highly probable that IRFNA would enter the alternator. During this test the butterfly actuator motor also failed because of corrosion by IRFNA. It should be noted that these two instances of alternator damage are peculiar to ground test operations and are not necessarily representative of the flight test environment.

The other observed aspect of the IRFNA corrosion problem is representative of problems that could occur in flight tests. There were several instances of leakage of residual IRFNA into the alternator after the test was completed, with no evidence of external leaks from the IRFNA feed system. This leakage occurs through the seals on the pump end of the shaft, where there is no positive static seal.

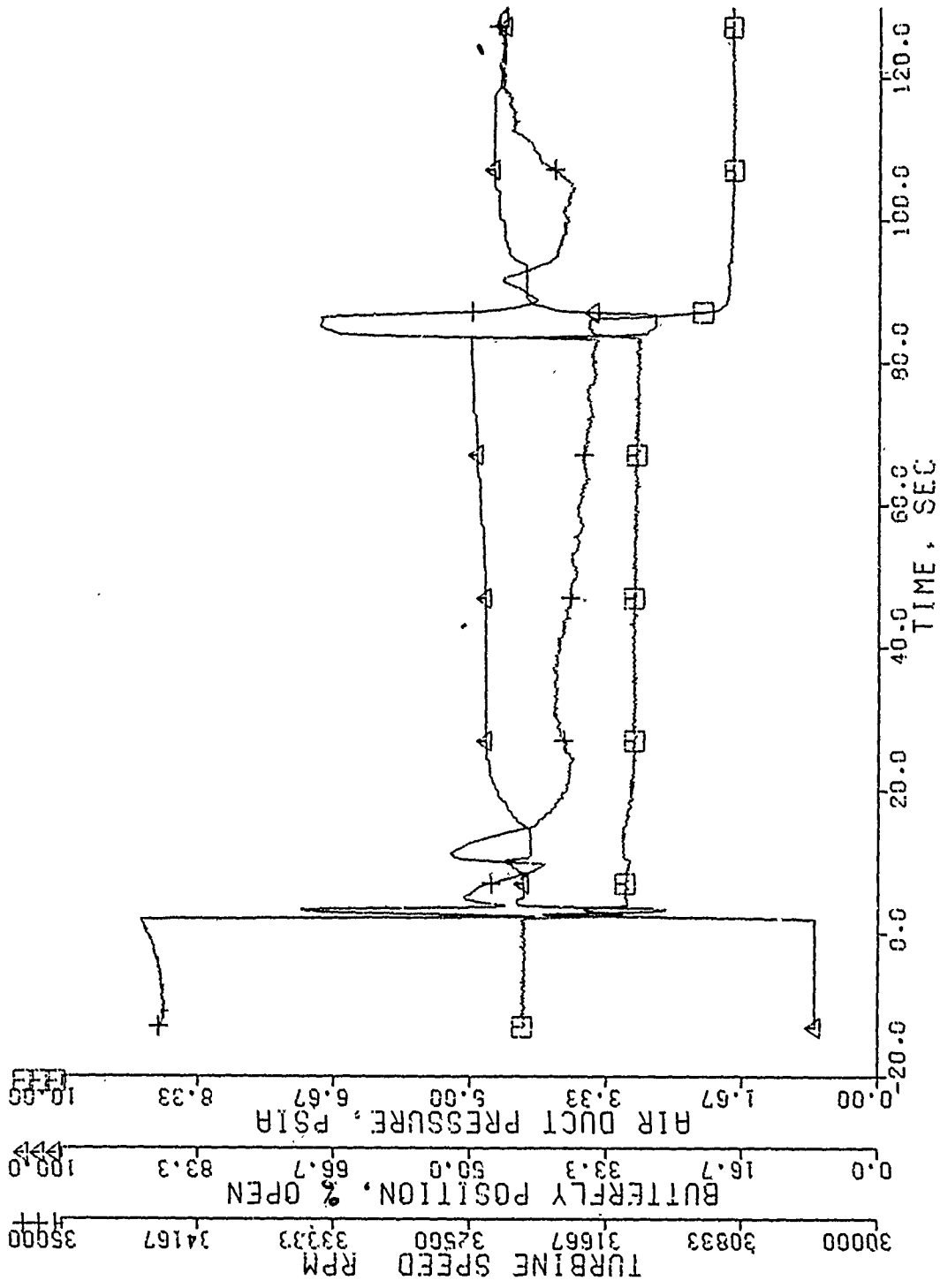


Figure 92. DPU Speed Control with Reduced Gain Controlled

Dynamic sealing between the pump and alternator is accomplished by a visco-seal which is largely effective only so long as the shaft is rotating at or near the design speed. Static sealing prior to start is accomplished by a Teflon J-seal which is initially in contact with the shaft. During rotation of the shaft, frictional heating causes the Teflon to expand away from the shaft and a running clearance is established.

Since the J-seal must cool before it will again contact the shaft, there is no seal until sometime after the shaft stops. Also, the speed dependency of the visco-seal means there is a less effective dynamic seal as the shaft speed decays. The result is a probability that, with residual pressure in the oxidizer tank after a test, oxidizer will leak past the seals during and/or shortly after shutdown of the DPU.

Oxidizer leakage through the seals did occur on the first three PFRT tests. The DPUs from these tests could not be reused without refurbishment by TMC. However, at the time it was not specifically determined that the leakage was through the pump seals, and it was suspected that the problems were again due to IRFNA vapors which entered the alternator housing through the turbine seal. Even without any leaks from the oxidizer feed system, there was a possible source of vapor from the pump seal cavity drain. This drain discharged into the test cell exhaust duct, and during engine operation the leakage was expelled with the engine exhaust gases. However, this exhaust flow attached to the diffuser and pumped the test cell to a lower pressure than could be maintained by the steam ejectors. Consequently, when the engine was shut down, there was back flow from the exhaust duct into the test cell, and oxidizer from the seal drain could be carried into the cell by this backflow.

An attempt was made to eliminate the seal drain as a potential source of oxidizer inside the cell on PFRT 4. Instead of discharging into the exhaust duct, the drain was brought through the cell wall and discharged into an open container at atmospheric pressure. However, this created additional problems of greater magnitude than when the drain was vented into the exhaust duct. The near-atmospheric pressure on the J-seal caused

failure of this seal and allowed a large quantity of IRFNA to enter the bearings and alternator housing.

For PFRT 5 and 6, the seal cavity was again vented into the exhaust duct. After the test was completed, the OTV was left open until the test cell was at ambient pressure. This provided a vent path for residual pressure in the oxidizer tank and nitrogen pressurization system and reduced the pressure tending to force oxidizer past the pump seals after shaft rotation had stopped. Even though the nitrogen drive gas for the DPU was still flowing when the cell was being brought back to ambient pressure, the back pressure on the ram air turbine soon became too high to permit rotation of the turbine.

With the OTV open and all pressure in the oxidizer tank vented, gases produced by thermal decomposition of residual fuel in the thrust chamber flowed back through the oxidizer system and condensed as a brown, gummy residue in the visco-seal, and on the slinger. A nitrogen purge was introduced into the oxidizer injector manifold after PFRT 6 but the same residue was present in the pump.

For PFRT 7, the seal drain was vented into the exhaust duct as on the previous two tests. However the shutdown procedure was changed. All residual pressure in the oxidizer and nitrogen tanks was vented through the OTV while the test cell was still evacuated. The OTV was then closed before starting to return the cell to atmospheric pressure, and the turbine continued to rotate until the back-pressure became too high. This procedure was successful in preventing the IRFNA from entering the alternator and bearings, and in preventing the backflow of fuel decomposition products. The same DPU was reused for PFRTs 8 and 9 with no refurbishment.

This successful shutdown procedure may, or may not, be representative of an inflight shutdown, depending on the cruise altitude. In flight, OTV closure is a part of the recovery sequence and occurs when the vehicle descends below 50,000 ft. For a high altitude mission, enough time may elapse between propellant depletion and descent below 50,000 ft to allow

venting of the oxidizer tank and pressurant system. However, for a mission with cruise near 50,000 ft, a relatively short time will elapse between propellant depletion and closing of the OTV, and the residual pressure will likely not be vented. In this case there can be residual oxidizer leakage through the pump seals and damage to the DPU as was seen on the early PFRT tests. Thus there are serious questions as to the reusability of the DPU in this present configuration. Extensive overhaul may be required after some flights.

Controlled Thrust Assembly

The Controlled Thrust Assembly (CTA) consists of the thrust chamber assembly (which includes the case, solid fuel grain, closures, injectors, igniter, and the nozzle) and the oxidizer throttle valve (OTV). No problems were observed with any of these components during the test program. The only anomaly was a peculiar igniter pressure history on PFRT 8, which was the cold test. The igniter pressure for this test is shown in Figure 80 and may be compared to a typical pressure trace in Figure 48. There was no obvious explanation for this behavior.

In several instances, the fuel grain was completely consumed except for a few slivers. In these cases, the insulation was adequate to protect the case wall after the fuel had been consumed in a particular area. In no instance were hot spots visible during a test, and significant heating of the case, as indicated by paint discoloration, did not occur until after shutdown. A typical temperature history of the case is shown in Figure 93.

The nozzle throat erosion measured for each test is shown in Table I. These are based on pre-test throat diameter measurements, with the assumption that all erosion occurs during boost. The 20-second initial starting ramp is not included as part of the boost time. The throat erosion is generally on the order of 0.001 in/sec.

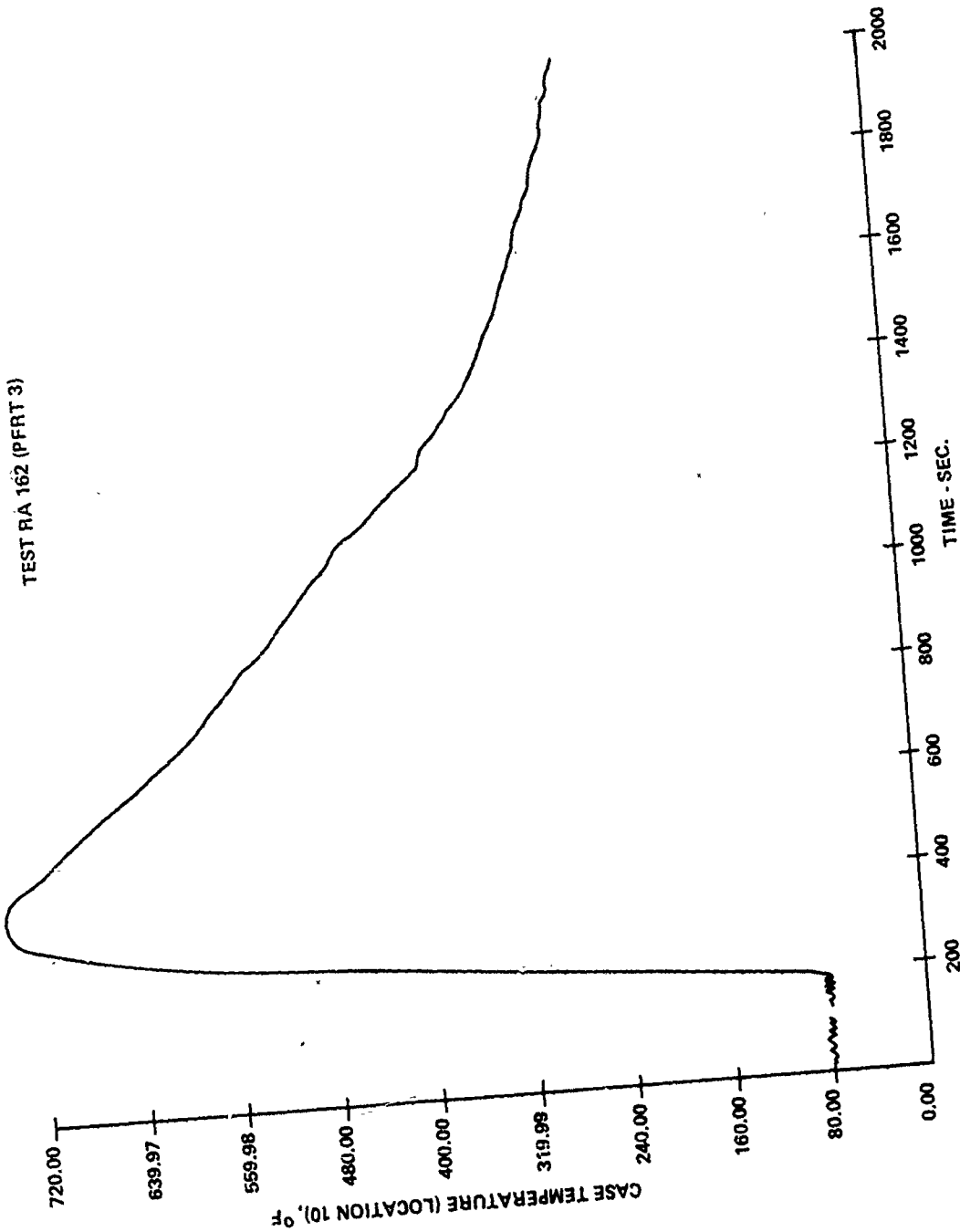


Figure 93. Typical CTA Case Temperature History

TABLE I
CTA NOZZLE THROAT EROSION

PFRT Nr	Duration (Sec) Boost/Sustain	Throat Diameter (Inch) Initial/Final	*Throat Erosion Rate (In. x 10 ⁻³ /Sec)
1	39/225	1.472/1.497	0.66
2	-	-	-
3	83/196	1.468/1.570	0.81
4	65/209	1.470/1.491	0.23
5	125/43	1.472/1.730	1.26
6	63/203	1.471/1.671	**2.57
7	87/187	1.472/1.656	1.44
8	83/178	1.471/1.615	1.20
9	83/186	1.470/1.623	1.27

*All erosion is assumed to occur during boost

**May not be real rate because possible erosion during throttling not considered

The effect of throat erosion on chamber pressure, oxidizer flowrate, and thrust is illustrated in Figures 94 and 95. It may be noted that little erosion, as indicated by a loss in chamber pressure and increase in oxidizer flowrate, occurs until approximately 50 seconds. These effects of erosion are more pronounced toward the end of the long boost mission.

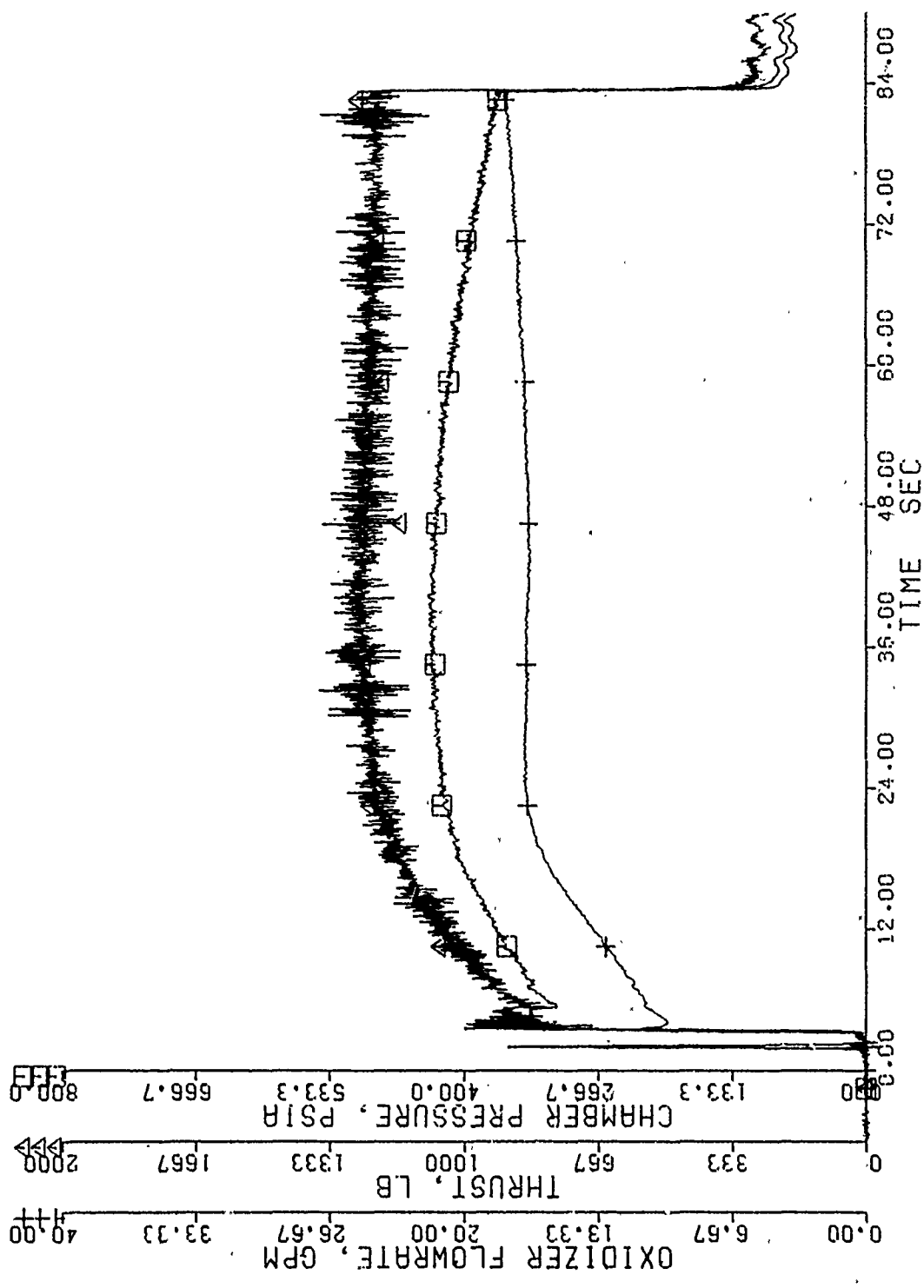


Figure 94. Effect of Nozzle Throat Erosion During Boost

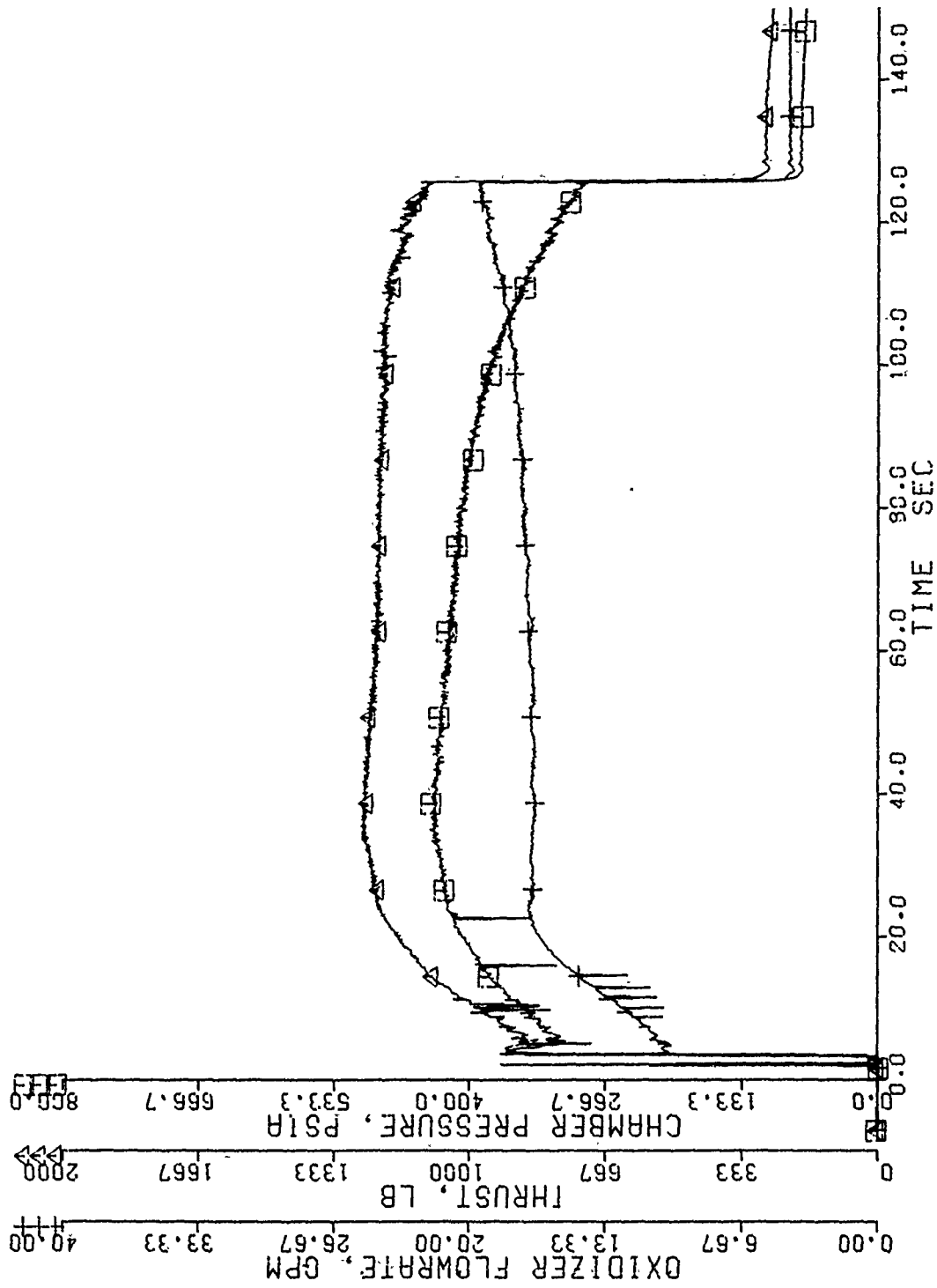


Figure 95. Effect of Nozzle Throat Erosion During Extended Boost

SECTION VI

PROPULSION SYSTEM PERFORMANCE

The total impulse measured for the PFRT tests is shown in Table II. The data shown are based on measured thrust which has been corrected to vacuum (zero nozzle back pressure) and then integrated over the time period of the test, from launch to propellant depletion. Since the thrust did not terminate cleanly, propellant depletion was taken at the time chamber pressure decayed below 50 psia. At this time it was assumed the propulsion system would no longer be producing useful thrust.

It may be noted that the system typically delivered total impulses near 150,000 lbf-sec. The highest total impulse was delivered on PFRT 5, which had the longest boost and shortest sustain of any test. Typically, a longer sustain time would degrade the total impulse because the hybrid system tends to operate at a more fuel-rich oxidizer-to-fuel ratio as the propellant flowrates are reduced, and this results in lower specific impulse. This accounts for the lower performance on PFRT 1, which had the longest sustain time of any test. No other trends were noted, and the temperature conditioning was not seen to have any significant effect on system performance.

Propellant utilization, both fuel and oxidizer, is shown in Table III. Fuel utilization was generally quite good, as may be seen by comparing the fuel actually consumed on each test to the nominal loaded weight of 153 lb_m. On all tests, the oxidizer was depleted before the fuel. On PFRT 1, only 420 lb_m of oxidizer was loaded because it had been predicted that the lower O/F ratio during the long sustain time would have resulted in fuel depletion substantially before oxidizer depletion if the full amount of oxidizer was loaded. This prediction was not valid, as illustrated by the fact that only 135.8 lb_m of fuel had been consumed when oxidizer was depleted. The erroneous thrust readout on PFRT 1 may have contributed to the occurrence.

TABLE II

HAST PROPULSION SYSTEM PERFORMANCE

PERT Nr	Mission Cruise Mach Nr. @ Altitude	Duration, (Sec)		Impulse, (lbf-sec)		Sustain Thrust, (lbf)		Sustain Chamber Pressure, (psia) Start/End	Remarks
		Total	Boost/ Sustain	Total	Boost/ Sustain	Start/End	Start/End		
1	M2/50K	264	39/225	-	-	-	-	190/96	Thrust not valid
2	M3/80K	-	-	-	-	-	-	-	Siphon Failed
3	M3/80K	279	83/196	150,934	95,676/ 55,258	300/260		90/80	-
4	M2/65K	274	65/209	-	-	-	-	145/115	Thrust not valid
5	M4/90K	168	125/43	159,352	147,412/ 11,940	285/251		76/68	-
6	M2.5/60K 180° Turn	266	63/203	152,419	69,614/ 82,805	NA/210		NA/68	Throttled during Sustain
7	M2/80K	274	87/187	148,351	94,062/ 54,289	-/240		-/68	Boost Includes simulated turbine power limited condition
8	M3/80K (-400F)	261	83/178	149,869	98,772/ 51,097	325/270		98/80	-
9	M3/80K (+1250F)	269	83/186	149,048	91,876/ 57,172			85/-	-

TABLE III
PROPELLANT UTILIZATION

PFR Nr	Duration (Sec)		Total Fuel Consumed (lbm)		Total Oxidizer Consumed (lbm)		Oxidizer Consumed (lbm)	Remarks
	Boost/Sustain		Consumed (lbm)	Percent of Loaded	Consumed (lbm)	Percent of Loaded		
1	39/225		135.8/88.8		407.4/97		114.8/296.6	420 lb _m Oxidizer Loaded
2	-		145.0/94.8		-		-	
3	83/196		149.1/97.5		475.8/95.9		279.6/196.2	
4	65/209		145.9/95.4		450.7/90.9		195.1/255.6	
5	125/43		142.4/93.1		478.6/96.5		438.6/40.0	
6	63/203		147.3/96.3		467.6/94.3		202.0/265.6	
7	87/187		147.3/96.3		470.3/94.8		275.8/194.5	
8	83/178		150.5/98.4		469.0/94.6		282.0/187	
9	83/186		153.0/100.0		484.4/97.7		276.5/207.9	

Except for PFRT 1, the oxidizer loaded weight was 496 lb_m. Approximately 8 lb_m is unavailable to the siphon, so the usable loading is 488 lb_m. The actual oxidizer consumed was obtained by integrating the instantaneous flowrate, as determined from the flowmeter, over the duration of the test. The difference between this quantity and the total usable weight is due to pump seal leakage, plus inaccuracies in the initial loading and flowmeter errors.

The hybrid ballistics analysis is being accomplished by UTC. Their results will include instantaneous I_{sp} and O/F ratios, and total impulse calculated from measured chamber pressure. This analysis will be reported by UTC.

SECTION VII
CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The overall conclusion that can be drawn from the PFRT test program is that operation of the total propulsion system was generally quite satisfactory. Problems which had significant impact on the overall system were identified during the OMA tests and were corrected. Although there were several further component problems during the PFRT tests, these were generally of a less catastrophic nature. The one exception is the siphon failure on PFRT 2, which was the only component failure to result in complete failure of a PFRT test. These problems, and other deficiencies identified during the test program, have either been corrected or are acceptable for flight tests. The latter category refers to deficiencies which may result in mission performance degradation or increased refurbishment costs but are not likely to result in a flight failure. The tests demonstrated that ignition and operating characteristics were safe for flight. Therefore, it was concluded that the HAST propulsion system is ready for flight tests.

Free Siphon

The modified free siphon was shown to be capable of satisfactory oxidizer expulsion in a static condition. No problems can be anticipated for those flight tests which are essentially non-maneuvering, involving no more than climb to a specified altitude. The effectiveness of the siphon in acquiring propellant under maneuvering conditions can conclusively be evaluated only on actual flight tests. In the event the siphon is not capable of acquiring propellant, the result would be a premature termination of the flight.

DPU Speed Control

The modified DPU speed controller was demonstrated to be stable under the test facility operating conditions. Again, this component cannot be completely demonstrated except in the real flight environment, where it must control turbine speed over varying duct pressures in a real inlet system. However, a specific problem cannot be anticipated based on the results of the PFRT tests.

Surface Tension Screen

The tension screen was always satisfactory for the first use in a new tank, or one just cleaned by the revised process, when the tank had been loaded with IRFNA for only a few days. Since this will normally be the case for the flight test vehicles, there should be no problem with excessive tension screen pressure drop.

DPU Oxidizer Seals

The inadequacy of static seals for the DPU bearings and alternator will not jeopardize the success of a flight test mission. However, there is no assurance that residual oxidizer and nitrogen pressure will be vented before the DPU dynamic seal becomes ineffective at reduced shaft speed. In this event, there is a strong possibility of post-shutdown damage to the bearings and alternator. This will add to the cost of refurbishing the flight test vehicles.

Pressure Regulators

The pressure regulators are the components most likely to have an adverse impact on the flight tests. Their operation during the PFRT tests can be termed acceptable, in that the tank pressure was always well above the minimum required to prevent pump cavitation, but there were several instances of erratic operation. The most prevalent was low output pressure from the first stage regulator, which results in low aeration pressure

and possible degradation of thrust chamber combustion efficiency. Although there is not enough data to quantify this effect, such an occurrence in flight could reduce the cruise range, and in an extreme case, result in burnout short of the recovery envelope and loss of the vehicle. The second stage regulator was, in general, more predictable but had a tendency to regulate on the high side of the allowable output pressure. The consequent higher pump suction pressure increases seal leakage and will, in flight, also reduce the cruise range. The one definite failure of the second stage regulator seems to be a unique event, having never occurred again in the PFRT or in a large amount of regulator development and qualification testing. Therefore, the probability of a similar failure on the flight tests would seem to be extremely low.

The regulators can also potentially be damaged by exposure to IRFNA after shutdown. Although there is a check valve at the outlet of the MFV, its opening pressure is so low that there is not enough seating force to completely prevent backflow of vapor from the tank. This potential corrosion of the regulators can also add to refurbishment costs.

Recommendations

As a result of the PFRT program, several recommendations can be made for improvements in the HAST propulsion system before it is put into production. These encompass improvements in performance, reliability, and storability.

Pressure Regulators and Burst Disc

The pressure regulators should be improved, both to be more reliable and to reduce the variation of regulated pressure with changes in gas flow requirements. The present regulator has an outlet pressure characteristic which significantly increases the regulated pressure as gas flow demand decreases during sustain thrust operation. This, when combined with the reduced oxidizer system pressure drop at low flow rates, results in a

much higher pump inlet pressure and increased seal leakage. The improved regulators should be packaged in one assembly, and this should provide for positive isolation from the oxidizer tank after shutdown. This could be accomplished by a normally open squib-activated valve at the regulator outlet. This isolation valve would not only protect the regulators from IRFNA corrosion but, by shutting off the pressurization supply, allow residual pressure in the oxidizer tank to be more rapidly vented and remove the pressure against the pump dynamic seal.

The burst disc at the oxidizer tank pressurization inlet should be eliminated in favor of a normally closed squib-actuated start valve. This would virtually eliminate the potential for liquid leakage in the stored condition and would also remove the flow restriction imposed by the present burst disc after opening. This start valve could be incorporated in the same package as the isolation valve and regulators.

A different approach to the pressure regulation is recommended to accomplish all the above improvements in one system. The recommended approach is a pulse modulated, or "bang-bang," system. The continuous acting pressure regulators would be replaced by an on-off solenoid valve which is actuated through a pressure switch sensing either tank pressure or pump inlet pressure. With the valve closed, pressure in the tank would blow down to a pre-set level which would cause the pressure switch contacts to close. The solenoid valve would then be opened and pressurization gas would flow into the tank until the pressure increased to a pre-set level which causes the pressure switch contacts to open. The valve then closes and remains closed until the pressure again drops to the lower level. This cycle continues, with pressure being controlled within a band about some nominal value. The tank pressure could be easily controlled to a desired value within a band width of 2 to 4 psia over the entire range of gas flow rates.

In addition to greatly improved accuracy in regulated pressure, this system would be virtually insensitive to temperature. This would eliminate the low temperature problem now plaguing the current regulator. The solenoid valve of the bang-bang system could also accomplish the function of tank isolation at shutdown for which a squib valve has been suggested. It might be possible for this solenoid to also provide isolation for the tank when it is to be stored filled with oxidizer, thus also accomplishing the function of the suggested start valve.

With the bang-bang system, a pressure regulator would still be needed to provide a continuous supply of aeration gas at the specified minimum pressure. This would be similar to the first stage regulator in the current system, and, like this regulator, it would also provide lower inlet pressure to the bang-bang valve. The nominal regulated pressure band of the current first stage regulator would make it acceptable for this application, but the erratic behavior observed during the PFRT test make this particular regulator questionable for production application. Either this regulator must be made more repeatable or a better regulator obtained.

If system dynamics permit, the sensing pressure switch should be located at the pump inlet. Thus pump inlet pressure would be controlled directly rather than being influenced by pressure losses downstream of a controlled tank pressure. This would avoid the increased seal leakage which now occurs because of the higher pump suction pressures at sustain flowrates. This increased pressure is partially due to the regulator characteristic but is also due to reduced pressure drop across the burst disc, tension screen, and siphon, and will thus occur even if the tank pressure is held constant. Controlling the pump suction pressure would also allow the system to compensate for increases in tension screen pressure drop because of clogging from corrosion products.

DPU Oxidizer Seals

An improved seal is needed in the DPU between the pump and alternator. Although the dynamic seal (visco-seal) functioned as designed, a seal which could maintain essentially zero leakage with the suction pressure typical of sustain operation would increase the missile cruise duration (time-on-station). The improved dynamic seal would be needed only if the recommended pulse modulated pressurization system, with pressure controlled at the pump inlet, is not employed. In either event, a positive static seal is a necessity to prevent alternator and bearing corrosion after shutdown.

New Oxidizer Shutoff Valve

A shutoff valve should be added between the oxidizer tank and the DPU. This would isolate the tank after shutdown and further reduce the possibility of damage to the DPU from residual oxidizer.

Alternate to Surface Tension Screen

It is not likely that the tension screen propellant retention device can meet the long term storage requirements (up to five years). Although corrosion of the screen itself may degrade its effectiveness, the more likely problem is clogging by corrosion products produced upstream of the screen. The experience of the PFRT program indicates that corrosion products of sufficient quantity to affect the pressure drop across the screen are produced after storage of a few days or weeks. Corrosion products may continue to be produced during storage, particularly if the passivation layer is broken off the tank wall by handling. It is highly likely that sufficient corrosion products will be produced to restrict flow through the screen.

The tension screen should be replaced by a propellant retention device that is not susceptible to plugging or corrosion. The simplest device would be a standpipe from the bottom of the aft compartment bulkhead, expelling

into the aft compartment near the top. A conceptual sketch of such a device is shown in Figure 96. The standpipe would permit liquid and/or gas flow into the aft compartment as dictated by the volume of liquid remaining in the tank and the vehicle attitude. It would then prevent backflow of liquid from the aft compartment under any conceivable vehicle attitude and acceleration.

Long Term Oxidizer Storage

Long term storage tests should be conducted to demonstrate that the OMA can meet the five-year storage requirement. The testing should include functional evaluation of the siphon to show there are no adverse effects on the Teflon sleeve, such as might be induced by cold flow. These tests should also demonstrate acceptable storage characteristics over the currently required -65 to $+165^{\circ}\text{F}$ temperature range.

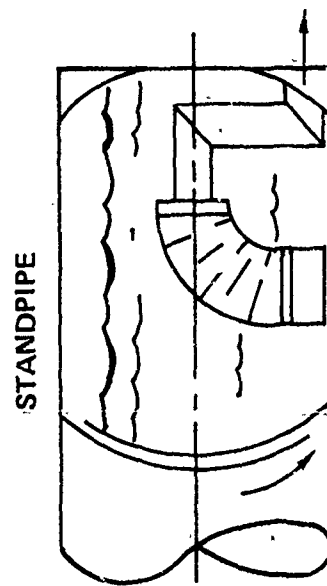
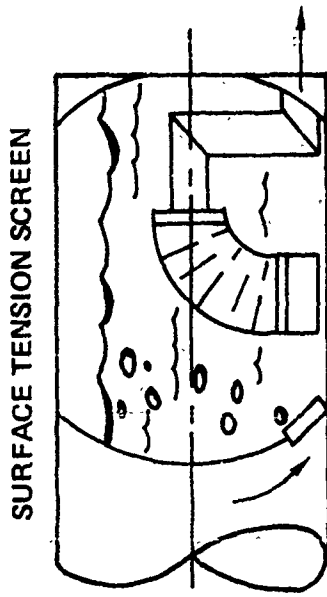


Figure 96. Suggested Alternate Propellant Retention Device for Tank Aft Compartment

REFERENCE

Miller, K.C., Capt, USAF, "Free Siphon Replacement," AFRPL-TR-73-106 (Dec 73).

APPENDIX A

LOG OF TEST COMPONENTS BY SERIAL NUMBER

<u>Test Nr</u>	<u>Test Date</u>	<u>1st Stage Regulator</u>	<u>MFV</u>	<u>Oxidizer Tank</u>	<u>DPU</u>	<u>CTA</u>
RA 152	3 Nov 72	NR	NR	PT4-1	0012	NA
RA 153	27 Nov 72	NA	NA	PT4-1	0012	NA
RA 154	28 Nov 72	NA	NA	PT4-1	0012	NA
RA 155 (OMA 1)	1 Nov 72	NR	115	PT4-1	0012	NA
RA 156 (OMA 2)	8 Dec 72	NR	115	PT4-3	0005	NA
RA 157 (OMA 3)	18 Dec 72	NR	116	PT4-3	0005	NA
RA 158 (OMA 4)	9 Jan 73	NR	115	PT4-3	0005	NA
RA 159 (OMA 5)	7 Feb 73	NR	112	PT4-1	0006	NA
RA 160 (PFRT 1)	10 Feb 73	NR	112	PT4-1	0010	0007
RA 161 (PFRT 2)	10 Mar 73	NR	107	PT1-1	0002	0011
WET 1-4 (SIPHON)	6-10 Apr 73	NR	114	PT5-1	0002	NA

APPENDIX A (Continued)

<u>Test Nr</u>	<u>Test Date</u>	<u>1st Stage Regulator</u>	<u>MFV</u>	<u>Oxidizer Tank</u>	<u>DPU</u>	<u>CTA</u>
RA 162 (PFRT 3)	3 May 73	115	107	PT4-1	0013	0015
RA 163 (PFRT 4)	24 May 73	111	111	PT1-1	0012	0014
RA 164 (PFRT 5)	28 Jun 73	113	116	PT4-2	0005	0017
RA 165 (PFRT 6)	3 Jul 73	106	102	PT4-2	0006	0018
RA 166 (PFRT 7)	12 Jul 73	NR	114	PT4-2	0010	0020
DPU Speed Control Checkout	21 Aug 73	NA	NA	PT4-5	0010	NA
RA 167 (PFRT 8)	28 Aug 73	106	102	PT4-5	0010	0021
RA 168 (PFRT 9)	13 Sep 73	106	102	PT4-5	0010	0025

NR - Not Recorded

NA - Component Not Used on this Test

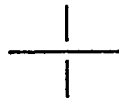
SYMBOLS

PLUMBING

LINES



INTERSECTION OF LINES

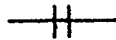


CROSS-OVER OF LINES



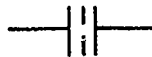
CAP

CONNECTION TYPES



FLANGED ENDS

MISCELLANEOUS



ORIFICE



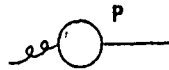
PRESSURE GAGE

SYMBOLS (Continued)



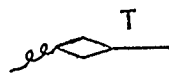
VENT

TRANSDUCER (PRESSURE)



NORMAL (GAGE)

TRANSDUCERS (TEMPERATURE)



THERMOCOUPLE

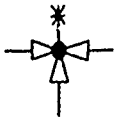
SYMBOLS (Continued)

VALVES



GATE

* ACTUATOR SYMBOL COMBINED WITH VALVE SYMBOL AT THIS POINT.



GLOBE, 3-WAY



ACTUATOR, MANUAL



GLOBE, ANGLE



ACTUATOR, PNEUMATIC
SPRING CLOSING



CHECK



ACTUATOR, SOLENOID

SYMBOLS (Continued)

RELIEF VALVES



ANGLE

REGULATOR



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University of Southern California, 1966.

Reports and papers published:

"Evaluation of a Rocket Engine System Using Metallized Gelled Propellants,"
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Propellants," AFRPL-TR-68-5, Jan 68

"Recent Advances in Transpiration Cooling," presented at 10th Liquid
Propulsion Symposium, Las Vegas, Nevada, 19-21 Nov 68

"Trends in the Fabrication of Liquid Rocket Thrust Chambers" presented
at AGARD Propulsion and Energetics Panel Symposium on Advanced
Technology for Production of Aerospace Engines, London, England,
6-10 Apr 70

"Materials Application to Transpiration Cooling," presented at Air Force
Materials Symposium, Miami, Florida, 18-20 May 70

"Thermal Fatigue in Non-Tubular Thrust Chambers," (co-author),
presented at Space Transportation System Propulsion Technology Confer-
ence, NASA Marshall Space Flight Center, Huntsville, Alabama, 6 & 7
Apr 71

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