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TEST DATA FROM
SMALL SOLID PROPELLANT
ROCKET MOTOR PLUME MEASUREMENTS
(FA-21)

(MSFC Test HRWT-38)

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by

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FOREWORD

This report presents test data gathered during NASA Marshall Space Flight Center High Reynolds Number Wind Tunnel Test HRWT-38 (Shuttle Test FA-21), relating detailed definition of the test hardware and the test conditions. The work was conducted for Marshall Space Flight Center (MSFC) in response to requirements of Contract NAS8-29751.

The NASA Technical Coordination for this study was provided by Mr. Kenneth L. Blackwell of the Experimental Aerodynamics group of the MSFC Systems Dynamics Laboratory, ED-32.

SUMMARY

An experimental program produced a reliable, parametric set of measurements in the exhaust plumes of solid propellant rocket motors. One rocket nozzle geometry ($\epsilon = 7.6$, $\Theta_n = 15°$) and one design chamber pressure (1000 psia) were used throughout. Plume measurements included pressures, temperatures, forces, heat transfer rates, particle sampling, and high-speed movies. Approximately 210,000 digital data points and 15,000 movie frames were acquired. Measurements were made at points in the plumes via rake-mounted probes, and on the surface of a large plate impinged by the exhaust plume. Parametric variations were made in pressure altitude (50K, 100K, 112K feet), propellant aluminum loading (2%, 10%, 15%), impinged plate incidence angle (30°, 45°, 60°, 90°), and distance from nozzle exit to plate or rake (X/D = 5, 12, 16, 20). Reliability was incorporated by continual use of repeat runs.

This challenging program with the largest propellant charge used to date at the MSFC Experimental Aerophysics Facilities involved several potential difficulties: new test facility, severe test environment, ambitious amount of instrumentation. The P_c level was consistently less than design for the 2% and 10% Aℓ propellants. Instrumentation damage was frequent at X/D = 5. However, the program goal was satisfied and 90 runs were performed in 46 working days. A routine operation of 3-4 runs/day was developed.

This document begins with description of the test setup of the various hardware items, and an account of the test procedures. The test results are discussed, along with accuracy of the data. Format of the data presentation is detailed. The complete data are presented in Appendices.

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NOMENCLATURE

A	Area
abs	Absolute
Aℓ	Aluminum
Alt	Altitude
atm	Atmosphere
Btu	British thermal unit
CRT	Cathode ray tube
D,dia	Diameter
F	Force
FS	Full scale
ft	Feet
g	Gravitational acceleration
HCℓ	Hydrochloric acid
Hg	Mercury
HRWT	High Reynolds Number Wind Tunnel
Hz	Hertz
ign	Igniter
in	Inch
K	Kilo (i.e., $*10^3$)
lb,#	Pound
mm	Millimeter
MOC	Method of Characteristics
msec	Millisec
MSFC	Marshall Space Flight Center
NG	No good
P	Pressure
P_{xx}	P at xx (see Fig. 5)
$\dot{Q}$	Heat transfer rate
Q_{xx}	$\dot{Q}$/A at xx (see Fig. 5)
psi	Pounds/sq. in. (a = absolute, d = difference)
R	Radius
Re	Rhenium
RTV	Room temperature vulcanizing
sec	Second
S/N	Serial number
sq	Square
SSLV	Space Shuttle Launch Vehicle
t	Time
T_{xx}	Temperature at xx (see Fig. 5c)
T/C	Thermocouple
TWT	Trisonic Wind Tunnel
W	Tungsten
X	Axial distance (see Fig. 1, 5); also, unknown quantity
Y	Distance along plate (see Fig. 5e)

Greek

ε	A/A_*
Θ_N	Nozzle wall half-angle
σ	Standard deviation
ψ	Plate incidence (see Fig. 5e)
℄	Centerline

Subscripts

c	Chamber
n	Nozzle
∞	Ambient
*	Throat

2. INTRODUCTION

Solid propellant rocket motors are common items on space vehicles. There has been continuing effort to produce more accurate analyses of plumes of such rocket motors. The traditional method for evaluating the utility of analyses is to compare analytically-predicted properties with measured values and, of course, this method has been applied to these analyses. However, to date there have been several shortcomings regarding this approach:

1. Measured values of plume properties are scarce.
2. Measured values have not been acquired with enough repeat cases to provide high confidence in their reliability.
3. Data are not available for parametrically varied conditions.

An experimental program was conducted to overcome many of these shortcomings. The specific aim of this program was to increase confidence in a particular recently-developed analysis of solid propellant rocket motor exhaust plumes (Ref.1) for Space Shuttle applications. The overriding consideration was to acquire parametric data of the utmost reliability. Extensive use was made of repeat data points to enhance reliability.

To achieve the program aim, a variety of test-specific hardware and facility provisions were required. There were three categories of hardware: (1) the rocket motors to produce the plumes; (2) the plume instrumentation; and (3) the auxiliary equipment to position the motors relative to this instrumentation. A new facility was provided by adding a vacuum capability, supplying instrumentation, and enhancing personnel access for the 50-foot diameter sphere which is the exhaust receiver for the MSFC High Reynolds Number Wind Tunnel (HRWT).

There were several unique and challenging aspects to this program. It was the first use of this modified facility, the first use of solid propellants at the HRWT, and the largest propellant charge used to date at the Experimental Aerophysics facilities. The planned measurements within the severe rocket exhaust environment (pressures, temperatures, heat transfer rates, forces, particle sampling, and high speed movies) were not strictly conventional. Careful attention to a great many considerations was required to accomplish the program aim. The test variables were propellant aluminum content, plume instrumentation, and pressure altitude. One nozzle design was used throughout. A nozzle calibration phase (with air, in the 14-inch TWT) preceeded the basic test of rocket motors in the HRWT 50-foot sphere.

This program was denoted FA-21 by the SSLV Project, and HRWT-38 by the MSFC facility. (The Nozzle Calibration Phase was denoted TWT-633). A total of 90 runs were accomplished. Table 1 presents a capsule of the FA-21 test showing design test conditions. Table 2 shows the overall program schedule and the run rates during the test phase. Details of the test setup, test operations, results, and presentation of data are given in the following sections. (The Nozzle Calibration Phase was quite distinct in all aspects and is treated separately, Appendix A).

3. TEST SETUP

The FA-21 Plume Measurements Test involved the largest solid propellant motors yet used at the MSFC Experimental Aerophysics facilities. Significant facility modifications were required as well as full use of most of the extant facility capabilities and a significant quantity of special-purpose items. In this section the hardware and software are described in categories of facility, rocket motors, auxiliary equipment, instrumentation, and data system. The description includes physical aspects and component operations. Test operations are treated in Section 4 and performance aspects in Section 5.

The basic test setup incorporated an array of plume instrumentation located in the exhaust plume of a small solid propellant rocket motor (Fig. 1). The positions of both rocket motor and plume instrumentation could be varied easily. The hardware design also permitted simple replacement of rocket motors and repair of instrumentation.

3.1 TEST FACILITY

This Plume Measurement Test was conducted in the 50-foot-diameter sphere of the MSFC High Reynolds Number Wind Tunnel (HRWT). Reference 2 describes the HRWT. This sphere was built as a receiver for the HRWT exhaust, to attenuate sound and collect the Mylar diaphragm debris. For the FA-21 program three additional provisions were necessary: (1) vacuum capability, (2) manways, and (3) accommodation of rocket motor and instrumentation. Figure 2 depicts this facility.

The vacuum capability was provided via a 12-inch-diameter line from the sphere (connected near the 45° elbow in the 7-foot-diameter perforated duct from the HRWT test section) to pumps in Building 4734. These pumps also serve the 14-inch TWT.

The key manway is the original 24-inch-diameter manhole, located about 11 feet above ground. Outside, a platform (about 4 x 6 feet) was added adjacent to the manhole, with a stairway for access. Inside, a smaller platform (about 4 x 4 feet) was added with an abbreviated stairway. During welding of supports for the rocket motor and plume instrumentation inside the sphere, a lumber scaffold was erected. This scaffold was retained for the test and although not elegant in design, proved very useful for access to the instrumentation. For accommodation of the rocket motor and plume instrumentation, supports were provided on the sphere floor and along the 7-foot-diameter perforated duct.

The sphere was sealed from the HRWT test section by Mylar diaphragms as used in normal HRWT operations. The 12-inch-diameter line at the sphere base, originally used to convey Mylar debris to a trash container, was disconnected from the trash container and sealed. Another 12-inch diameter fitting was added on the south-west side about 15 feet above ground for potential use of an extant low-throughput, very-high-vacuum pump. It was sealed and not used for this program. The controlled venting system atop the sphere was retained and used throughout this program. The facility data system, described below (Section 3.5), was used in its conventional manner.

3.2 ROCKET MOTORS

The rocket motors to produce the plumes were the key ingredient in this test program (Fig. 3). This design has been used frequently in U. S. Army Missile Command Programs. The metal components (detailed on MSFC Drawing 80M42754) were reusable. Molybdenum was used for the throat insert and steel for the remainder. The case provided for attachment to the facility thrust structure stand, which in turn provided alignment with the plume instrumentation equipment.

Thirty complete rocket motor assemblies were manufactured plus ten extra propellant cases and one dummy (solid aluminum) case. Measured dimensions of each nozzle were determined by procedures detailed in Section4.1e (Table 3).

Three propellant compositions were used: 2%, 10%, and 15% aluminum content (Table 4). It was desired to provide P_c = 1000 psia for at least 200 msec. To facilitate fabrication the grain dimensions for the three propellant compositions were identical. The variation of aluminum content would yield different burn rates. These different burn rates coupled with identical grain geometry and identical nozzle throat diameters would produce different chamber pressures (P_c) and different operating times for each composition. In an attempt to equalize P_c and operating time, trace amounts of burn rate catalyst were added to the 2% and 10% $A\ell$ compositions. The results were not completely satisfactory, as discussed in Section 5.2a.

The propellant was bonded to the case. The igniter was a separate component installed in the nozzle converging section as a part of the motor assembly procedure. Details of this procedure are in Section 4.1b.

The events during motor operation are shown in Fig. 3b. The duration of valid data was typically approximately 1/5 second. This brief time is consistent with previous similar programs (Ref. 3) which produced acceptable data, but constrained instrumentation (Section 3.4). The estimated exhaust products are presented in Table 4. The peak thrust of these motors was less than 400 pounds. The firing control box was that used previously (Ref. 3); a 28 volt d.c. electrical power supply was used, rather than batteries.

3.3 AUXILIARY EQUIPMENT

The auxiliary equipment supported and positioned the rocket motor and plume instrumentation (Fig. 1, MSFC Drawing 80M51454). The motor support was comprised of a stand with a compound drive permanently installed. This stand was supported from the cell floor on three studs so that the stand axis could be tilted in any direction (up to about 7°) or relocated vertically (through a range of about 2 inches). The compound drive had two orthogonal axes in a nominally-horizontal position. Each axis had 12 inches of motion, controlled by handwheels.

The core of the plume instrumentation support was a fixed mounting block (supported from the 7-foot-diameter perforated duct), 11 feet above the cell floor and about 1 foot west of the vertical axis of the motor support stand. A vertically-oriented extension plate was attached to this mounting block. The lower edge of the plate could be located at any 6 inch increment below the bottom of the mounting block, from flush to 48 inches. A 12 inch drive (handwheel controlled) was attached to this extension plate with drive axis vertical. Thus the combination of extension plate and drive provided infinitely-variable position over a 60 inch vertical range. Upon the sliding plate of the 12 inch drive, items were attached to directly support the plume instrumentation (rake or plate).

All of the above support items were made of carbon steel, painted where practical. Conventional machine oil, which required frequent reapplication, protected the unpainted surfaces from the rocket exhaust.

There were three items of equipment used to establish the proper alignment between the rocket nozzle and the plume instrumentation. One item was a special jig which fitted into the rocket nozzle. The other two items were a standard plumb bob and a bubble level. The procedure to use these items to establish proper alignment is described in Section 4.1a.

3.4 INSTRUMENTATION

Because of the relatively brief motor operating time of 1/4 second, it was important that the instrumentation have rapid response characteristics. There were two groups of instrumentation associated with this program, according to general locations: motor and plume. All of the motor instrumentation was pressure measuring equipment. For the plume group, a variety of instrumentation types were used: pressures, temperatures, forces, heat transfer rates, particle samplers, and movies. In addition, the cell pressure was measured using a dial gage tapped into the tunnel inside the HRWT building.

a. Motor - The motor chamber pressure locations are shown in Fig. 3 and the nozzle pressure locations in Fig. 4. Note the redundant measurement of P_C. All the pressure pickups and external lines were attached to each motor as part of the motor installation procedures (Section 4.1a). The motor pressure transducer diaphragms were protected against high heating with a coat of RTV rubber.

b. Rake and Plate Instrumentation - The plume instrumentation is shown in Fig. 5. There were two major items: a rake and a plate. The transducers (Table 5), which convert physical to electrical signals, could be used on both. Either item could be positioned at a variety of longitudinal locations, and the plate could be rotated to several inclinations. Rake and plate positions were selected based on the expected locations of various phenomena of interest and a desire to parametrically vary the height.

Alignment of the plume instrumentation with the rocket nozzle was critical; procedures are detailed in Section 4.1a. The goal of rake alignment was to array the probe tips at specified spacing along a straight line which was orthogonal to the rocket nozzle centerline and at a specified distance from the nozzle exit plane (Figs. 1, 5b). The rake could accommodate pressure, heat rate, temperature, and force gage probes at minimum spacings of 1/2 inch. Probe locations were varied as test conditions and unexpected developments dictated. The force gage, however, had a 2 or 3 inch spacing from the centerline probe so that its large bow shock would not interfere with adjacent gages and still be near enough to the centerline to measure particle as well as gas impingement forces.

The plate could incorporate pressure and heat transfer rate gages (Fig. 5d) and the particle sampler. Because alignment and spacing of gages were fixed (Fig. 5f), the positions were not varied and gage locations were chosen to give a cross-section of the plume. Plate incidence angles (ψ) were also essentially fixed (15° increments from 15-90°). It was possible, although not very practical, to shim the plate support structure to adjust the angle. At installation the plate was shimed to provide $\psi = 90° \pm 0.1°$. Subsequently ψ was monitored for each setup (exhibiting a tolerance of $\pm \frac{1}{2}°$), but no further adjustments were attempted. The plate was originally rotated so that at 45° it was somewhat parallel to the 7-foot-diameter perforated duct (east end up). However, for X/D = 5 the motor mount east-west hand crank interfered with the plate. To obtain the smaller height needed, the plate was rotated with the east end down (Fig. 5e).

For both rake and plate special consideration was given to the sizing and protection of the pressure transducers. Those located in the severest heating area - the centerline and adjacent probes - were protected like the motor transducers - with RTV rubber on the diaphragm. Transducer sizes were selected for expected or observed pressures and availability.

The temperature measuring device was a W-.05Re/W-.26Re thermocouple, of 0.001 inch diameter wire, installed in a special probe (Fig. 5a). Heat rate measurement came from Medtherm, Inc., slug calorimeters with a nominal upper flux level of 600 Btu/(ft^2-sec).

c. Particle Sampler and Movies - Particle sampling equipment was built specially for this program (MSFC Drawing 80M42811, Fig. 5g). This equipment used a rotating disk upon which particles were acquired in a wax base, plus a drive motor and a slotted shield to limit the spatial extent of sampling. Particles arriving at the shield entered the slot and impinged on the wax. The rotation of the disk beneath this slot caused the particles to be arrayed on the wax in an arc which provided a time history, and the length of the slot provided a radial distribution. The disk was rotated at a speed such that the rocket motor start-up and tail-off particles would not overlap each other yet still cover most of the disk.

High speed motion pictures (approximately 1500 frames/sec) were acquired using a camera in the sphere. These movies relied on the illumination provided by the hot exhaust plume. The camera was encased in a polyethylene sheet for protection from the environment. Operating time for the camera was approximately 4.5 seconds for each test run.

Figure 6 shows photographs of typical installed instrumentation.

3.5 DATA SYSTEM

The data system concept was conventional for this facility, but adapted to the special features of this specific program (Fig. 7). Central to this system was an on-line capability which provided digital and analog histories of all measured parameters within minutes of completing a run. The core elements in this capability were the Hewlett Packard data acquisition system and Tektronix cathode ray tube computer terminal. For this test up to 28 channels were used, taking data at 200 frames/sec for 500 msec (recording a total of 100 records per channel per run) The channel assignments for all of the instrumentation devices are given in Table 6.

The data recording system and rocket motor firing were both initiated using the firing control box. Upon activation of the firing switch, a start signal was given to the data system immediately, and the firing current was released to the igniter after a specified delay. The movie camera start signal was manually coordinated with activating the firing switch. This procedure is detailed in Section 4.1b.

4. TEST OPERATIONS

The goal of this program was to acquire parametric, reliable test data for comparison to Ref. 1 predictions. In support of this goal, nozzle calibrations with air (discussed in Appendix A) were accomplished well in advance of the primary rocket firing test phase. Test procedures were selected to achieve the maximum operational efficiency consistent with safety, incorporating the experience of prior related tests as much as practical. Test conditions were chosen to investigate a broad range of typical shuttle operations and to better define certain unexpected phenomena uncovered during the test. This discussion first treats the test procedures and next the design test conditions (exact test conditions are presented in Section 6.4 and Appendices B and C). Then a detailed run log is provided, with remarks on anomalies of individual runs.

4.1 TEST PROCEDURES

The test procedures were selected to achieve the maximum operational efficiency consistent with safety. The experience available from prior related tests was used as much as practical. Ref. 4 outlines the safety practices used during the test.

The nominal run procedure is shown in Table 7. Each run required most of the steps shown, and the initial run after each instrumentation change required all of these steps to be followed. After an initial learning period - approximately three weeks - tunnel personnel could perform four runs daily, assuming no major instrumentation changes. Normal procedure was to end the daily run sequence with a loaded motor in the sphere and the manhole covered. This step permitted a few people to perform a run before the full crew arrived: one person turned on the vacuum pumps early the following morning to establish the desired sphere pressure by 7:00, then with two more personnel a run was fired, and the sphere vented and purged in time for the regular crew to help set up the next run at 7:45-8:00.

a. Instrumentation Preparation - The most involved preparation process was the positioning and alignment of the plume instrumentation. These items were repositioned at the regular instrument configuration changes called for in the test matrix, and as necessary to account for unexpected phenomena; e.g., severe heating, suspected plume shear layer, and instrumentation failure.

The original alignment of the rake probes was accomplished in the tunnel model shop using an optical measurement device. A high accuracy could be assured by this device. Due to expediency, all subsequent probe changes were made in the sphere using the method detailed in Table 8.

The height above the nozzle exit was specified in the run matrix as X/D. Using the diameters of the specific nozzles planned for that series of runs, design heights were calculated prior to an instrumentation X/D change using the following equation:

$$X = (X/D)_{specified} \left(\frac{\sum_{i=S/N_1}^{S/N_f} D_i}{n} \right) \qquad (1)$$

where $(X/D)_{specified}$ is the X/D of the next series of run, i is the nozzle serial number, S/N_1 is the first and S/N_f the final nozzle serial number of this series, and n is the number of nozzles in the series. The design height thus was a function of the average diameter of nozzle exits to be used in the series. This height was adjusted roughly by positioning the mounting block extension in six inch increments. Final adjustment used the vertical hand crank to correctly position the probe tips as measured by a ruler from the nozzle exit plane to the center probe. Estimated accuracy of alignment is given in Table 9.

The impingement plate was aligned in much the same fashion (Fig. 5e). It was important to first adjust the plate incidence angle because the center of the rotation was not on the instrumented surface, and thus a change in this angle also changed the height of the plate above the nozzle.

There were several steps to prepare for particle sampler use. First, the disk was covered with aluminum foil, aluminum tape was wrapped around the perimeter, and wax was poured into the resulting enclosure. The disk was then mounted to the motor shaft, and the cover plate was clamped over the disk and to the impingement plate using C-clamps (Fig. 6d). The plate was at $\psi = 90°$ with the height and plumb adjusted as above, except: (1) the height was measured to the cover plate, and (2) the plumb bob string was held to the narrow end of the cover plate slot (Fig. 5g). One exception was Run No. 30/1 in which the center of the cover plate instead of the narrow end of the slot was centered over the nozzle. Reinstalling the cover plate at the beginning of each run could stop the disk's movement. Such a stalled disk caused the motor to draw a high current of 0.5-0.6 amp (normal current was 0.1 amp); a check of the current was made to detect this situation.

b. Pre-Fire - Firing preparation consisted of obtaining an igniter and a motor of the correct aluminum content and installing them. The igniter leads emerging from the nozzle were initially connected only to the binding posts of the shunt box (a box placed in the ignition circuit which allowed the loading personnel to short circuit any current). During Run No. 4/1 (X/D = 5) the igniter plug, upon exiting the nozzle, struck the rake, ruined one probe, and damaged three others (Section 5.2c). Subsequent igniter leads were pulled tightly from the nozzle lip and tied to a motor assembly bolt to impart a side force on the plug and thus avoid striking the rake. The leads were then connected to the shunt box. This procedure was apparently successful because only on one other run did it appear that the plug damaged the rake.

In the control room, the procedure called for the computer operator to check the instrumentation readings about 5 to 10 minutes before firing. At 30 to 60 seconds before firing, the computer operator again checked for normal readings and stored the pre-fire zero counts (Section 6.1). The particle sampler motor power supply was turned on and the camera speed brake plugged in. Upon reaching the desired sphere pressure, the computer operator started the camera and approximately three seconds later the test engineer fired the run. The three second lag allowed the reels to reach a constant speed, leaving 1.5 seconds to record the run. For runs without movies the test engineer fired the igniter when the sphere pressure dial gage indicated the correct pressure.

To assure that the computer covered the entire run, a delay was built into the firing curcuit box (after Run No. 6/2) so that the computer data acquisition system began recording 25 to 30 msec before the igniter fired. A low rumble and immediate sphere pressure rise indicated that the motor had successfully fired. If such indications were not obtained, the control room igniter circuitry was checked and the computer recycled for another try. If ignition was not obtained then, the sphere was vented and the motor dismantled and checked.

c. Post-Fire - After firing, the gage readings were checked to see that they returned to approximately the pre-fire values. Those that did not were inspected for damage at the first opportunity.

The sphere was vented originally by admitting atmospheric pressure through opening the vent valve. Much dust filled the air and HCℓ odor was evident. To improve sphere conditions later runs were vented, pumped down to approximately 200 mm Hg, vented, pumped down to 200 mm Hg again, and vented again. This procedure took about 40 minutes and was replaced by an improved procedure whereby the sphere was vented and at the same time the valve to the vacuum line was left open. When atmospheric pressure was reached the vent was closed and the sphere evacuated to 400 mm Hg. Again, the sphere was vented with the vacuum line open. Only 20 minutes were used this way.

During venting the data were examined. Pressure traces were used to identify clogged taps; and adjacent positions, previous runs, and predicted values were checked to determine if data were reasonable and consistent.

d. Recovery - For the first few runs the centerline rake pressure probe and the two chamber pressure leads were blown out after each run. It was found that the centerline probe contained very little debris even after a 15% Aℓ run and the practice of automatically cleaning them was abandoned. The chamber pressure leads, however, always contained sufficient dust and debris to justify cleaning after every run. Often shop air was insufficient and piano wire was run through the leads to dislodge thick clogs.

The heat rate gages were cleaned by washing the exposed surface with electrical component solvent and sometimes rubbing the surface with wet pumice. On various occasions - particularly after 10% or 15% runs - it was necessary to lightly scrape the gage to remove encrusted debris.

The plate was thoroughly scraped after each impingement run because the nickel plating peeled off and a crust of exhaust products made the surface very rough. It was necessary to use a file and sometimes quite a bit of force to remove irregularities. Finally the entire surface was wiped with a cloth or paper towel to remove dust.

After particle sampling runs, the disk was removed; the aluminum tape was stripped from the steel disk perimeter; and the wax with the aluminum foil was removed, marked, and stored. Availability of three disks prevented the wax pouring operation from delaying the test.

e. Calibration - The pressure transducers and force gage required calibration for proper operation. In all cases, "calibration" meant establishing the transducer output at specified pressure levels, where that pressure was determined by a large dial gage. The general scheme for pressure transducers was to use a vacuum pump to calibrate the plume instrumentation and to use high pressure air to calibrate the motor instrumentation. Communication between personnel in the sphere and control room was maintained by portable transceivers. Recalibration was performed each Monday morning for all gages and as necessary when individual transducers were replaced by uncalibrated ones.

The variety of transducers (Section 3.4) necessitated somewhat different calibration and equipment (Fig. 8). The Statham P_c and Kistler transducers required an adapter connected to a high pressure line. The impingement plate required a special sling and chain hoist since pressure transducers on the plate (all Statham) were inaccessable, and the plate had to be unbolted and lowered by this special equipment. The pressure transducers were then disconnected from the tap leads and reconnected to tubing for conventional application of specified pressures.

Kistler transducers needed a unique calibration procedure. Because they were piezoelectric, their electric output vanished under a continuous pressure. It was therefore necessary to install a quick-acting valve to suddenly load the transducers and then record the instantaneous values for the calibration curves.

The force gage was also a piezoelectric device and had to be calibrated by a sudden change in force. Experience at this facility showed these devices to be linear and only two points were used in calibration, 0 and 1 pound. The gage was clamped with the flat surface up and carefully leveled. A one pound weight was then quickly removed and the instantaneous voltage output was recorded to generate the calibration curve.

Continuity checks of all instrumentation were made after calibration and major instrumentation changes. The pressure gages were checked in conventional manner by applying vacuum sequentially to each probe or tap. Heat - either a match flame or hot air "gun" held several inches below the device - was applied to heat rate gages and thermocouples.

Prior to testing, the values of all nozzle dimensions were measured. A technique used previously for determining these values was to make RTV castings of the interior then measure the RTV dimensions. This allowed quick and easy measurement of otherwise difficult parmeters such as the throat radius of curvature (R_c). This technique was tried using several different brands of RTV and curing techniques, but shrinkage was experienced on all castings, and the casting diameters were smaller than the actual diameters as measured with hole gages. Eventually all the physical measurements except R_c were made using the actual nozzle and standard laboratory gages (Table 3). Measurements of R_c were not practical except via the RTV castings. The castings of 12 nozzles were checked and found acceptable; and further R_c measurements were not made. Other measurements, however, were estimated to be quite accurate (.001 in.).

f. Motor Refurbishment and Reloading - The motor hardware refurbishment procedure was developed to provide: (1) clean nozzles for subsequent runs, and (2) clean motor cases for propellant reloading. This service was provided by the Fabrication Division (ET39) of MSFC Test Laboratory. The primary method was blasting by glass beads using commercial equipment. Some use was made of certain solvents prior to bead blasting, such as weak $HC\ell$ solution and hot (190°F) caustic soda bath. After such treatment rapid rusting occurred if the surfaces were not protected by an oil coating. The time required for this service varied depending on the total work load but averaged about two days for a set of ten cases and ten nozzles.

The propellant reloading procedure was performed by the Propellant Chemistry Branch (DRSMI-RKC) of U. S. Army Missile Research and Development Command (formerly Army Missile Command). Batches of 10 or 20 cases were reloaded in 7-8 calendar days.

4.2 TEST CONDITIONS

Test conditions were selected to provide data to increase confidence in the utility of the Ref. 1 analysis of solid propellant rocket motor exhaust plumes, especially for conditions appropriate to the Space Shuttle. An extensive use was made of repeat points to provide highest confidence in the data.

The original plan called for 3 runs at each condition, but repeatability was adequate with only 2 runs (Section 6.2). The cases for which only one run was made resulted from either: (1) discovering adverse instrumentation performance (Run No. 35/1, 36/1), or (2) shortage of motors (Run No. 9/1, 44/1). Run Nos. 41/1 and 42/1 were intended to have been performed at X/D = 12 but inadvertently took place at X/D = 20.

As unexpected phenomena were uncovered during the test, investigations were incorporated to properly define them. Some balance was required to remain within the constraint of 90 motors and the desire for timely test completion. The runs at X/D = 12 and 16 were of such nature, investigating a suspected shear layer noted in the earliest runs at X/D = 20.

The facility, motor, and plume instrumentation design conditions are summarized in Table 1, a total of 90 runs. Exact values varied with time during a run; the complete time histories are in Appendices B and C. Summaries of the values averaged over a time interval selected as most appropriate for each run are in Section 6.4. The 1963 Patrick AFB atmosphere was used to choose sphere pressures for selected altitudes.

4.3 RUN LOG

During the test, several logs were kept: (1) a run log to record test configuration, design test conditions, and brief remarks on anomalies; (2) a detailed test log as a source document; (3) a log of propellant and igniter inventories; and (4) the standard Operators Log maintained by the HRWT staff. The run log is reproduced in Table 10. The effects on test conduct and resulting data, due to anomalies noted in the run log, are detailed in the test log and discussed in Section 5.

Run numbers were assigned sequentially as runs were completed, beginning with 1/1. Repeat runs were denoted X/2, X/3, etc. However, some of the repeat runs were not performed immediately after their respective initial run. Specifically: Run No. 6/3 was performed after 11/2, Run Nos. 14/2 and 14/3 were performed after 27/2, and Run Nos. 43/2 and 43/3 were performed after 45/2. Nozzle calibration run numbers begin with 1/0, and repeat runs were denoted X/1, etc. As the test setup and goals of this element are distinct, this redundancy should not cause confusion.

5. RESULTS

The goal of this program was to acquire parametric, reliable test data for comparison to Ref. 1 predictions. Success depended upon the performance of the equipment, procedures, and personnel involved. All of these elements performed well and the goal was met. Approximately 210,000 digital data points were recorded. This discussion treats the resulting performance of the various hardware items separately, including how improved procedures evolved. (The data system performed so well that no separate discussion was needed.) The section concludes with a discussion of the resulting performance of the combination of equipment and remarks on overall run rates. (Results of the nozzle calibration phase are in Appendix A.)

5.1 TEST FACILITY

The facility was developed specifically for this test by modifying an extant structure (Section 3.1), and this test was the first use of this modified structure. Performance of this facility for this test could be measured in terms of:

1. Time required to acquire a specified pressure altitude.
2. Ability to precisely maintain a specified pressure altitude.
3. Maximum obtainable pressure altitude.
4. Ease of performing test setup and routine equipment changes within the facility.

The first three items may be evaluated objectively and quantitatively, while the last item can only be evaluated subjectively.

The time required to pump down to specified pressure altitudes is shown in Fig. 9. The ability to maintain a particular pressure altitude was not critical to this test, because the test procedure was to fire as the desired pressure was reached while in continuous-pumping mode. The maximum demonstrated pressure altitude was about 114,000 ft (4.6 mm Hg abs.). This limit appeared to result from leaks of outside air into the sphere, rather than from pump limits, as the pump specification calls for operation down to 3 mm Hg abs.

The utility of this facility for performing test setup and change was adequate. There were several features that caused initial concern: rather modest manhole dimensions, multi-bolt manhole securing, ascending and descending stairs, maneuvering on and around the scaffold, and exposure to the elements. Each of these features did cause some degree of delay in day-to-day operations; however, no gross inefficiencies can be attributed to them.

5.2 ROCKET MOTORS

The propellant compositions were developed specifically for this test. Metal hardware, whose design had previously been used successfully, was used without modification. Performance could be measured in terms of:

1. P_c history: level, smoothness, duration, reproducibility.
2. Hardware durability.
3. Ease of assembly, attachment, refurbishment.

Some objective, quantitative evaluations may be made of the first two items, but a considerable degree of subjective evaluation will be necessary on all three items.

a. P_c History - Chamber pressure was measured by duplicate instrumentation (Section 3.4a) and agreement between these two measurements was excellent, (Fig.10a). The complete P_c histories, although acceptable, were disappointing. First, the P_c levels did not generally meet the design value of 1000 psia. There was a clear effect of $A\ell$ content (Fig. 10b). This situation was attributed to inadequate performance of the burning rate additives in the 2% and 10% $A\ell$ compositions. Since the propellants for all 90 motors had been prepared before this testing phase, it was not practical to correct this deficiency.

Smoothness (i.e., the degree to which the P_c remains constant over the duration) was not ideal (Fig. 3b, 10c). All motors showed a significant initial spike and a small terminal spike. However, it was the character of the P_c history between these spikes that was important. The 10% $A\ell$ propellant was best, producing a variation in P_c less than $\pm 3\%$ of the average for approximately 150 msec. Most of the first 10 2% $A\ell$ were equally good; however, the last 20 2% $A\ell$ motors showed a significant hump. Because of this hump, the variation in P_c over an interval of 150 msec exceeded $\pm 10\%$ of the average. The time interval for which a $\pm 3\%$ variation occurred was generally less than 80 msec. The 15% $A\ell$ motors showed a generally progressive burning characteristic, having a plateau of about 60-80 msec with $\pm 3\%$ variation in P_c. Because of the general lack of smoothness, the summary data presented in Section 6 was generally taken for 50 msec intervals.

Duration was coupled to P_c level, with the higher P_c levels having shorter operating times. Duration between the end spikes ranged from 150 to 250 msec. These values in themselves were not as important as the time interval of acceptable smoothness just discussed. Reproduceability from run to run was adequate (Fig.10c). The 10% $A\ell$ motors were best in this respect, with the 15% $A\ell$ next best. There was no ignition lag like that which had decreased reproducibility in the Ref. 3 and 5 tests.

The nozzle calibration with air (Appendix A) indicated that measured P_n/P_c did not match predicted values as closely as desired with air. Thus with the rocket exhaust gas some mismatch might also be expected.

b. Durability - Hardware durability was quite satisfactory. No basic hardware items were damaged or even markedly deteriorated during the test. (One nozzle pressure tap fitting was damaged). One set of firing head, nozzle retainer, and bolts was used for all 90 firings. Most nozzles were used 3 times (S/N-1 was used 4 times, S/N-29 only twice). Measurements of throat diameter indicated a slight increase (approx. .001 in.) after one firing but no subsequent change. In fact the difference in measurement between hot and cold days was as great as the nozzle-to-nozzle and run-to-run differences.

Results of the nozzle cleanup process are shown in Fig. 11. The significant slag deposits are evident in Fig. 11a, where it is seen that the slag deposits increased noticeably with aluminum content. However, the refurbishment process produced a nozzle as clean as new (Fig.11b). With the 10% and 15% $A\ell$ propellants, slag could be found covering the wall pressure ports in the nozzle exit cone. As discussed below (Section 5.4a), this deposit affected the quality of nozzle wall pressure measurements.

c. Handling - The ease of handling the motor items was adequate. No notable difficulty was encountered with the metal components, after some initial trouble with the nozzle pressure tap was cured by a redesign of the fitting. The mounting of each nozzle to the remainder of the motor produced assemblies whose alignment with the plume instrumentation was essentially constant, so that re-alignment from run to run was not needed. A difficulty was encountered regarding igniter installation. For the first few runs, vacuum grease was applied on the rubber plug where it sat in the nozzle throat (Fig. 3a) to ensure holding sea level pressure within the motor case when the sphere pressure was reduced, and thus facilitate ignition. However, two instances occurred in trying to perform Run No. 2/2 where the igniter assembly apparently was forced out through the nozzle upon initial activation of the igniter. The lubrication action of the vacuum grease was suspected to have permitted these events. On the third attempt at Run No. 2/2, this grease was omitted and successful ignition obtained. Thereafter no grease was used for the igniter/nozzle junction.

There was another igniter-related problem. The aft-end igniter design resulted in all igniter debris being expelled toward the plume instrumentation. The rubber plug portion of the igniter tended to travel essentially along the projected nozzle centerline. On two instances, some of the rake instrumentation was destroyed (Fig. 12) but no motor damage occurred. Efforts to deflect it by tying the trailing ignition wires to one side of the nozzle were evidently successful (Section 4.1b).

5.3 AUXILIARY EQUIPMENT

The auxiliary equipment was designed specifically for this test to support and position the rocket motor relative to the plume instrumentation (Fig. 1). The durability of these items was excellent. Although significant rusting was experienced on some unpainted surfaces, no detrimental effects on testing were encountered. Rigidity of the system appeared to preclude any relative motion between motor and plume instrumentation due to motor firing.

The ease of positioning the plume instrumentation relative to the motor nozzle was very satisfactory. For the motor stand, no further adjustment was needed after the initial alignment. The alignment of the mounting block (welded to the perforated duct), was excellent. Some shimming was required in the initial alignment of the plume instrumentation support, but run-to-run changes were accomplished without further shimming. A sling was devised to support the plate during transducer changes, and greatly facilitated what might otherwise have been a tedious, time-consuming operation. Some rework of the nozzle alignment jig was required to accommodate the igniter wires.

5.4 INSTRUMENTATION

There were two groups of instrumentation used in this test, categorized according to general locations: motor and plume. Their satisfactory performance was a significant factor in the timely and beneficial completion of this test program. The plume equipment was the heart of this test program. Motor P_c instrumentation monitored the controlling independent parameter of the plume, and nozzle wall pressures checked this. Instrumentation is discussed as motor pressures, the rake and plate, plume pressures, plume heat rates and temperatures, plume force gage, and miscellaneous instrumentation (particle sampler and movies).

a. Motor Pressure Instrumentation - Performance of this equipment was satisfactory. Durability of the transducers was excellent: one set of nozzle pressure transducers was used throughout the test, and each P_c transducer was replaced only once. This durability was considerably better than previous solid propellant rocket motor tests (Ref. 3, 5). The reasons are surmised to be: (1) lower P_c, and (2) better protection of diaphragm due to better RTV application and longer, convoluted plumbing. The pre-ignition values of P_c did not always match the expected atmospheric value, nor did the post-burnout values match sphere pressure. This result was ascribed to lack of accuracy of these high-range transducers at such low pressures (Section 6.2). The nozzle wall pressure ports experienced a significant amount of plugging (Section 5.2b, Fig. 11). Initially, specific notations were kept but this plugging occurred so frequently that run log notes were later omitted. Rather, the P_n history reliably indicates plugging by its marked deviation from the P_c history.

b. Rake and Plate - The basic instrumentation items (rake probes, plate) performed well. Thirty-six (36) runs were made with the rake equipment. There was noticeable erosion of tips of the rake pressure probes at X/D = 5. This repeatable phenomenon removed about .09 - .10 inches from the centerline (P_1) probe, .03 - .06 inches from tne next (P_2) probe, .01 - .02 inches from the third probe (P_3), and a negligible amount from other probes. Generally, these were refurbished by hand filing, then realigned to position all probe tips in a plane. During the early runs several probes were dismantled and blown out to decide if the particle flux were clogging the pressure tubes. There was almost no clogging except in cases where severe probe damage occurred. The pressures measured by these probes consistently indicated axial symmetry, so that in later rake runs few or no checks were called for.

The plate was used on 54 runs (44 for plate surface pressures and heat rates and 10 for particle sampling). The nickel surface plating on this plate deteriorated rapidly due to flaking and peeling. Loose material was removed between runs to provide the smoothest practical surface. After 3-5 runs, essentially all of the plating in the central plate area was gone. Fortunately, the low-carbon steel plate showed almost no further deterioration once this nickel plating had been removed. It was concluded that the minor surface irregularities did not affect the measured pressures and heat rates. There was an anomaly in the plate data at ψ = 90°. For this inclination there should be symmetry about the extended nozzle centerline. However, the data in the region 6-9 inches from center show a distinct, consistent lack of symmetry (Fig. 13) in which the peak readings on the west side were closer to the center than the peak east side readings. It was first thought that there might be geometric misalignment, but extensive measurements showed this was not the case. The maximum misalignment was estimated to be about 2/3° of inclination and 0.02 inches, and a check of transducers by serial number revealed no reason to suspect any consistent malfunction. It was concluded that the nozzles were not likely causes, because on rake runs with these same nozzles, no such asymmetry was measured. Discoloration of the plate itself seemed to confirm the asymmetry-- although the core region was centered, there were smokey arcs (about 2 inches wide) coinciding with the peak pressure readings with the west one 2-3 inches closer to center than the east one. Possibly, detailed analysis of the movies could provide more information. However, at this writing no cause has been identified, and this puzzling phenomenon is reported as it was recorded.

c. Plume Pressure Instrumentation - A significant number of pressure transducers were mounted on either the rake or plate for every shot. In general they performed satisfactorily. The originally-selected transducers for low-pressure measurements, Setra Model 237, did an admirable job while they lasted. However, an accident during initial pre-installation calibration permitted vacuum pump oil to enter the reference pressure ports of all 16 available transducers, with unfortunate results. Although all items were cleaned, only 8 were functional for the initial rake installation; and there was a continuing decline in the quantity of functioning devices. The inverted (diaphragm down) position required for use on the rake evidently accelerated the harmful effects of this oil. The requirement to replace Setras with Stathams involved a good deal of activity: (1) swap transducers, (2) adjust channel assignments to position all Setras onto a sequential group of data channels, with a similar sequential group for Stathams (required by data reduction program), and (3) adjust data reduction program for reduced number of Setras and increased number of Stathams. Additional activity was needed to replace a Setra which was one of a pair checking axial symmetry (such as P_{11} and P_{41} on Run No. 1/1) because both transducers were then replaced (so that such symmetry checks would be made with identical transducers). Note that these difficulties were not due to the transducer design but resulted from the limited number of functional Setras relative to the number of desired probes. The Statham pressure transducers performed well in this severe environment. On the average each Statham was replaced once. The need for replacements was not clearly related to position within the plume.

Clogging was detected by an examination of the pressure history traces. A continuous rise in pressure (or no rise at all) indicated the probe was clogged at the beginning, and its data were ignored. A slow decrease in pressure after burnout indicated the probe was clogged during the run, and its data normally were good. The probes that held the transducers performed well and rarely clogged.

d. Plume Heat Rates and Temperatures - The heat transfer rate gages performed satisfactorily. Several of these items were mounted for every run. One gage was destroyed on Run No. 4/1 due to excess heat load near the centerline at X/D = 5. For subsequent runs at X/D = 5 the remaining heat gages were moved adequately far outboard to ensure survival.

The gages used were designed for a maximum input rate of 600 Btu/(ft^2-sec) sec., which was acceptable for almost all measurements made. One value (Run No. 6/1) in Table 16, however, was over 800 Btu/(ft^2-sec) and should be used with caution. Values below 10 Btu/(ft^2-sec) should also be used with caution. Those below 4-5 Btu/(ft^2-sec) should probably be disregarded because the resolution (indicated by erratic traces) is insufficiently accurate.

The thermocouple probes initially performed poorly. The first design did not include the solid spacer shown in Fig. 5a and had only one vent. This design apparently allowed the thermocouple to touch the interior wall of the probe and thus not measure the true gas temperature. The improved design was installed prior to Run No. 6/1 and measured 5237 °R during the run. This value compared favorably with pretest estimates of approximately 5500 °R, but the temperature history was very erratic and the reading was probably erroneous. The probe was damaged during this run due to the severe conditions (X/D = 5, 15% $A\ell$, 50 Kft altitude). Replacement thermocouples were used in less severe environments and did not register more than 2200 °R.

e. Plume Force Gage - The force measuring device was used for 23 runs and performed acceptably. Durability was excellent. However some electronic drift occurred after taking the pre-fire zero. This drift caused a non-zero reading in the interval between data system start and motor ignition, and required correcting the printed data (Section 6.1, 6.3). Comparing measured forces to corresponding pressures (Table 11) indicates that the particles generally made a significant contribution to forces and not to pressures, i.e., $F/\int PA>1$. This result qualitatively documents the validity of the many pitot pressures measured in this test. A quantitative assessment is beyond the scope of this document, primarily because it would require detailed definition of the particle flux.

Furthermore, the Table 11 trends are not unambiguous. There are several possible reasons. Note that this force gage measured the sum of: (1) the particle momentum change to the metric gage element, and (2) the integral of ΔP across that element (Fig. 14). In ideal circumstances the pressure forces would be nearly balanced, and of magnitude considerably less than the particle force, so that the force gage value would be taken to equal the particle force. No data were taken to confirm this approach, and certain phenomena may have worked to invalidate it. For instance, the labyrinth seal design was intended to minimize movement of air between exterior and interior of the probe. Thus the interior (P_{core}) was expected to be at sphere ambient pressure, while the exterior (P_{face}) was at the pitot-probe measured pressure, and P_{edge} might be at some intermediate value. Also, at 50,000 feet, the predicted plume edge and lip shock impinged the force probe. Such impingement could produce complicated pressure fields. For these reasons it is recommended that the force gage values be regarded as qualitative rather than quantitative.

f. Particle Sampler and Movies - The miscellaneous instrumentation includes the particle sampler and the movies. Actual analysis of the entrapped particles has not been accomplished, so that evaluating the performance of the particle sampler will focus on mechanical operation. This equipment performed very well, especially considering that it had been designed with minimum experience in this topic, and practically no development.

The angular velocity versus power supply voltage was calibrated outside the sphere. This calibration indicated that a control room power of 12.5 volts would provide 11 volts to the sampler motor yielding a 2.5 rps disk velocity. This should have exposed 75% of the surface in 300 msec. In Run No. 30/1, the first particle run, only about 40% of the surface was covered. The power supply was increased to 14.7 volts (its maximum) which produced 13.2 volts in the sphere, and subsequent runs covered approximately 60% of the disk. (The disk, however, rotated as long as the power was on, which was usually several minutes. Stray particles may have been picked up after burnout).

On one run (No. 4/2), the wax base was mounted downstream of the rake as a "piggy-back" verification, with the disk stationary. White candle-wax base was used (except Run No. 38/2 which used red tunnel wax) and was generally satisfactory. However, at X/D = 12 with the higher aluminum content propellants, there was significant melting and splashing of the wax. For this reason repeat points were not obtained for Run Nos. 35/1 and 36/1. The aluminum foil backing for the candle wax proved very beneficial, greatly facilitating handling and storage. A total of 10 runs were devoted to this activity.

The high speed movie camera performed very satisfactorily so that no comments are needed. Movies were obtained on 58 runs, producing a total of about 15,000 frames. The results are most interesting. It is expected that considerable benefit to the subsequent analytical tasks will be available from these movies. Movie speed was not precisely defined so that use of the movies may need correlation to P_c history for detailed analysis.

5.5 PERFORMANCE OF COMBINED EQUIPMENT

The resulting performance of instrumentation measuring the exhaust plumes of the rocket motors operating in the test facility is discussed here, along with overall run rates. Overall performance was very satisfactory, especially since this was the first use of the facility, and led to a timely and beneficial completion of this test program. The program goal of parametric, reliable test data was satisfied.

The sphere size was quite adequate for these motors; there was no indication that the scaffold, perforated duct, nor other sphere component affected the exhaust plume. Likewise, there was no evidence of permanent damage to the sphere from the exhaust. There was minor scorching of the wooden scaffold, which appeared due to the plate deflecting the exhaust onto part of the scaffold. The X/D = 5 position imposed a severe environment to the rake components, and was probably the closest practical location with this hardware. In general, however, all hardware endured satisfactorily or was repairable. Originally there were 15 pitot probes available. Although some damage was incurred, at least 12 operable pitot probes were always available. As a result of a sustained repair effort, at the conclusion of this test program there were again 15 available.

In general, the measured data agreed with the pre-test predictions, (Ref. 6). However, P_c was generally lower than the design value of 1000 psia, upon which the predictions had been made. Consequently, the plumes were not as large as predicted. This situation made the X/D = 20 position less than completely satisfactory and resulted in investigations at intermediate axial positions. The fact that P_c was a function of aluminum content of the propellant complicated comparisons with predictions, due to having two variables changing simultaneously.

This test was quite unique and differed in most respects from previous programs at the Experimental Aerophysics facilities. Ready comparison of this test's experience to conventional programs in terms of installation time, model change time, etc., is not straightforward. However, the most appropriate description might include: (1) facility modifications, (2) auxiliary equipment installation, (3) instrumentation build-up and installation, and (4) testing. Facility modification took place intermittently over a 3-month period. The actual welding and aligning of the auxiliary equipment required about half a month with an additional half a month of preparation beforehand. Instrumentation build-up took about a month with an additional month of installation, calibration, and checkout. The testing phase, from first shot to last, was 9½ weeks. Ninety runs were performed at an average rate near 2/day. The greatest number of runs on one day was 6; this productivity was possible because 4 of these runs were at 50,000 feet, for which pumping time was brief. In the latter portion of the test, it became routine to perform 3-4 runs/day.

6. DATA

An extensive body of data was acquired in this test program. These data were in the form of time histories of a variety of physical parameters for the complete duration of rocket motor operation. It was decided that summaries of the data and samples of each type of data would be of general interest while the complete collection might be of more limited interest. The data presentation is organized for this anticipated usage.

A certain time interval was selected to represent each shot. This selection method is discussed in the first sub-section below along with the standard HRWT data reduction steps. Next is presented the estimated overall accuracy of the data. Then the format of presenting the various data is explained along with samples. This section concludes with the data summaries. The complete time histories are presented in Appendices B and C. (All of the nozzle calibration data are in Appendix A).

6.1 DATA REDUCTION

There were three steps involved in producing the desired engineering units and ratios for the data summaries: convert from counts to engineering units, select a representative time interval, then average the values over this interval.

The first step was performed for the pressure data of each time frame for each channel, using:

$$\text{Engrg. unit} = \text{Ref. engrg. unit value} + \frac{\text{counts} + \text{zero counts}}{\text{sensitivity}} \qquad (2)$$

where the "zero counts" were obtained immediately prior to each run, and "sensitivity" (counts/engrg. unit) was obtained from weekly or more frequent calibrations. The "Ref. engrg. unit value" was the design sphere pressure (corresponding to the design altitude). For the temperature data a similar procedure was used but the reference value and sensitivity were constants throughout the test, taken from published literature. For the force gage the reference value was zero. Heat transfer rate data was computed from the slope of the temperature history and the calibration constant supplied with the individual gage:

$$\underset{(\text{Btu/ft}^2\text{-sec})}{\dot{Q}/A} = \underset{(\text{Btu/ft}^2\text{-}^\circ\text{R})}{(\text{Calibration Constant})} \times \underset{(^\circ\text{R/sec})}{\Delta T/\Delta t} \quad (3)$$

Originally $\Delta T/\Delta t = (T_i - T_{i-1})/(t_i - t_{i-1})$ for a 5 msec interval. Beginning with Run No. 28/1 a moving mean smoothing computation was incorporated to provide a more comprehensive value of $\Delta T/\Delta t$.

The resulting digitized data were tabulated (Appendix C) and plotted (Appendix B). Because of the electronic drift experienced on the force gage (Section 5.4e), the tabulated force data require correction:

$$F_{corr.} = F_{tabulated} - 1/5 \sum_{t=5}^{25\ msec} (F_t)_{tabulated} \quad (4)$$

The plotted data were corrected for this drift (Section 6.3).

The second step was to select a time interval during each run that would appropriately represent that run. The goal was to identify a 50 msec (or longer) interval during which P_c was acceptably smooth. This step was performed by subjective evaluation of the plotted P_c history. The acceptability of this selected interval was verified by the fact that the standard deviation from the P_c averaged over this interval varied from 0.1% - 3% and averaged approximately 1/2 - 3/4%.

The third step was to average the data for each channel for this selected time interval. After this time averaging step, the duplicate P_c values were again averaged to produce the single most representative P_c value for that run:

$$\overline{P}_c = \frac{1}{2} (\overline{P}_{c_{Kistler}} + \overline{P}_{c_{Statham}}) \tag{5}$$

There were some instances where one of the duplicate P_c measurements was suspect; for these cases the other P_c value was used for $\overline{P}_c$ and denoted in the run log. Next all of the other pressures were ratioed to this $\overline{P}_c$. For Run No. 1/1 no P_c data were obtained; so the average P_c of Run Nos. 1/2 and 1/3 were used:

$$\overline{P}_{c_{Run\ No.\ 1/1}} = \frac{1}{2} (\overline{P}_{c_{Run\ No.\ 1/2}} + \overline{P}_{c_{Run\ No.\ 1/3}}) \tag{5A}$$

6.2 DATA ACCURACY

The accuracy of the data determines the degree to which any comparison with Ref. 1 predictions may be accepted. The accuracy of data generally may be assessed by three methods. First, the accuracy of each component or step used in the measuring process may be determined, and the cumulative effect summed. Second, measured data may be compared to equivalent data acquired elsewhere. Third, measured data may be compared to theory. These last two methods are not available for this program - it was the lack of data and theory that neccessitated this test. Repeatability among data of this test may be a partial substitute for the second listed method. This section begins with an estimation of accuracy of the data from cumulative tolerances of the various data measuring, recording, and reducing equipment. Next thermocouple response time and repeatability are examined.

The accuracy as affected by cumulative tolerances may be explained by referring to Eqn. 2 and Fig. 7. (It is generally accepted that digital processing equipment---computer and terminal---have negligible errors). The reference values and sensitivities were determined by visual readings during calibrations.

Counts were the resultant of operations by the transducer and the electronic processing equipment:

Counts = (Pressure sensed by transducer) * (Transducer mv/psi conversion) * (Computer counts/mv conversion) (6)

Thus, Eqn. 2 may be modified to emphasize accuracy:

$$\text{True physical value} \pm \varepsilon_1 = \text{Ref. value} \pm \varepsilon_2 + \frac{\text{counts} \pm \varepsilon_3 + \text{zero counts} \pm \varepsilon_4}{\text{sensitivity} \pm \varepsilon_5} \quad (2A)$$

where

$$\text{counts} \pm \varepsilon_3 = (\text{Pressure})*(\text{mv/psi conv.} \pm \varepsilon_6)*(\text{counts/mv conv.} \pm \varepsilon_7) \quad (6A)$$

Estimations of the resultant range of error in the computed physical value (ε_1) are summarized in Table 12. The effect of these cumulative tolerances was seen in the duplicate P_C measurement (Fig. 15). In many cases, there was a distinct $(\Delta P_C)_1$, with P_{C1} (Kistler) being higher. In almost all cases there was a $(\Delta P_C)_2$, but P_{C1} was not always higher and there definitely was not a general trend of $(\Delta P_C)_1 = (\Delta P_C)_2$. The magnitude of these differences was consistent with Table 12.

As mentioned in Section 5.4d thermocouple data for Run Nos. 1/1-5/2 are incorrect. Subsequent data also appear suspect for several reasons: unrealistically low values and (in 8 cases) inadequate response times. As shown by the temperature histories, all runs exhibited a response time lag of 80-100 msec; but runs after 5/2 (except Run Nos. 41/1-45/2) came to steady state and had temperatures of approximately 1900°R. These temperatures are judged to be low; they should be near the stagnation temperature of approximately 5500°R. Reradiation and conduction losses in the thermocouple, mixing and cooling in the plume, and other causes could have prevented the thermocouples from indicating the expected temperature; however, it is not possible to accurately predict such effect. At 112,000 feet (Run Nos. 41/1-45/2) steady-state was not reached and the data shown are the highest values reached for each run. The recorded temperature data are therefore presented for completeness and should be used only as lower limits.

As mentioned in Section 5.4e, the force data exhibited drifts in zero values immediately prior to firing. As a result these data should be regarded as qualitative.

A key element in this program was the inclusion of a number of repeat runs adequate to lend high confidence to the data. As mentioned in Section 4.2, the only cases for which only one run was made were a result of discovering adverse instrumentation performance or shortage of motors. Figure 16 shows the degree to which parameters (P_c, P_n, P/P_c, $\dot{Q}/A$, T, F) for each repeat run agreed with the original values. The P_c and P_n repeatability is acceptable though not as good as initially estimated; however, the plume measurements show very satisfactory repeatability. In fact repeatability evident in the majority of $\dot{Q}/A$, T, and F measurements is better than expected, especially when considering the rather non-standard nature of this instrumentation. The indicated repeatability documents the fundamental accuracy of the FA21 data, and strengthens confidence in these data.

6.3 DATA PRESENTATION FORMAT

The time histories of the measured parameters were recorded in two forms: digital tabulations and CRT plots of these digital data. This section describes the manner in which these data are presented; the complete sets of data are presented in appendices. Tables 1 and 10 can be used as indices to the data.

The digital tabulations (Table 13) are presented in a conventional manner.

Nomenclature is that used throughout this report. The arrangement of columns is by channel number. On the rake this pattern generally follows radial probe positions from centerline outward. On the plate it follows pressure port positions from east to west, then heat gage positions also from east to west. (See Table 6 for details of channel assignments). The complete set of digital data is in Appendix C, in run number sequence. Note that the print format adjusts to the left when "zero" appears in a column. Also, the force data needs correction (Section 6.1, Eqn. 4).

The CRT plots (Fig. 17) are likewise of conventional format and consistent nomenclature, with several per axis for compactness. The HRWT printer did not always operate at constant speed, thus causing some variation in the vertical scale from sheet to sheet. Any such mismatch was corrected in the plots for each given run number. However, the variations from run to run were not necessarily accounted for. In comparing from run to run, the ticks along the vertical axis should be used rather than superposition. The complete set of CRT plots is in Appendix B, in run number sequence. The drift in the force data (Section 6.1) was corrected in these plots.

Note that in both Appendices B and C, the complete sets of recorded data are included without editing. Refer to Section 5 and Table 10 for comments on anomalies.

The high speed movies comprise a potentially valuable collection of information (Fig. 18). The movies are in color and show even more detail than can be seen in Fig. 18. They are available via the authors or the MSFC facility. The movies present the scene as viewed looking north, but the Fig. 18 example shows a reversed image, as if viewed looking south.

6.4 SUMMARY DATA

The complete time histories were inspected to select a time interval during each run that would appropriately represent that run, and the data were averaged for this interval, as described above (Section 6.1). These averages are tabulated for the nozzle, plate, and rake in Tables 14-16. The force data in these summaries were corrected per Eqn. 4 (Section 6.1). Data evaluated to be erroneous, per the discussion in Section 5 and Table 10 or by inspection of the Appendix B plots, were omitted.

The data from Tables 14-16 are plotted in Figs. 19-21, respectively. Although some anomalous points seem indicated, all of the Table 14-16 data were plotted for completeness. The unusual appearing data were plotted with dashed symbols for emphasis.

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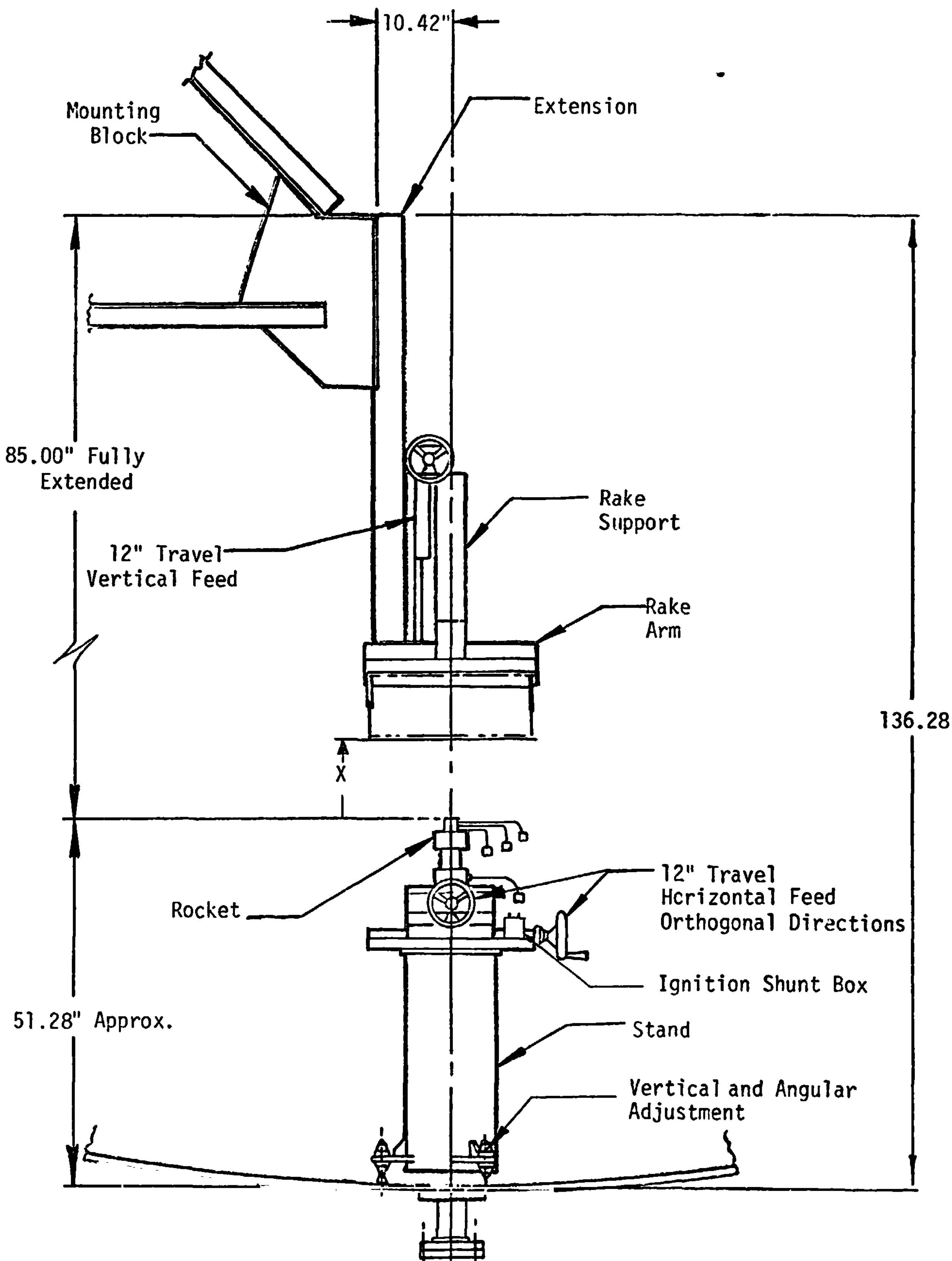
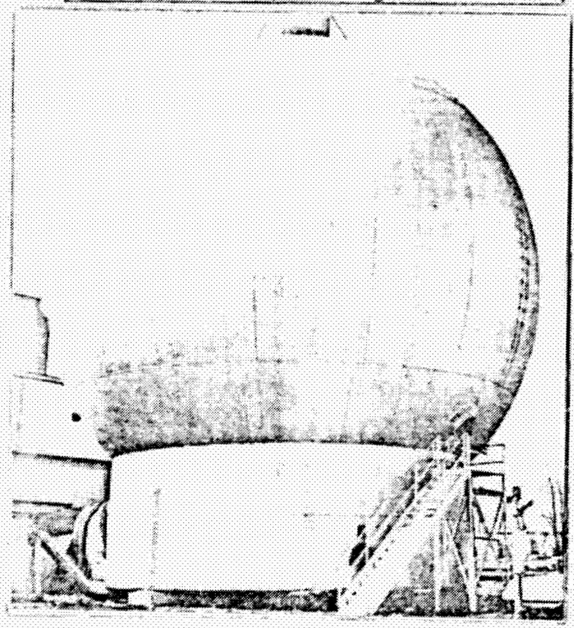
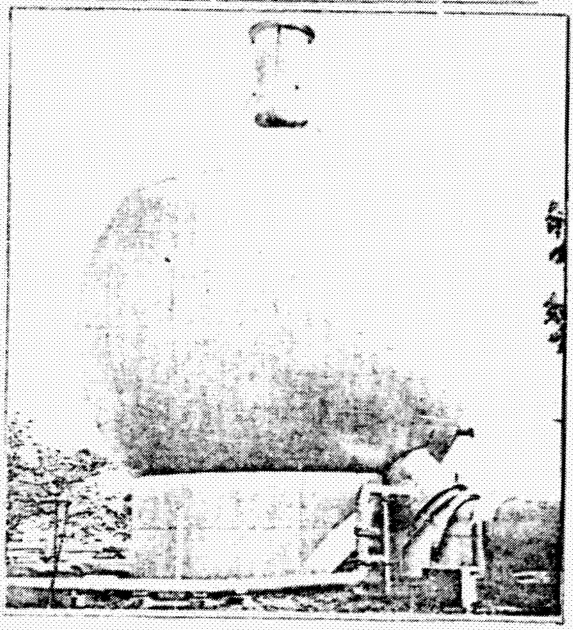


Fig. 1 Test Setup

a. Exterior (looking North-West)



b. Exterior (looking South-East)



c. Interior

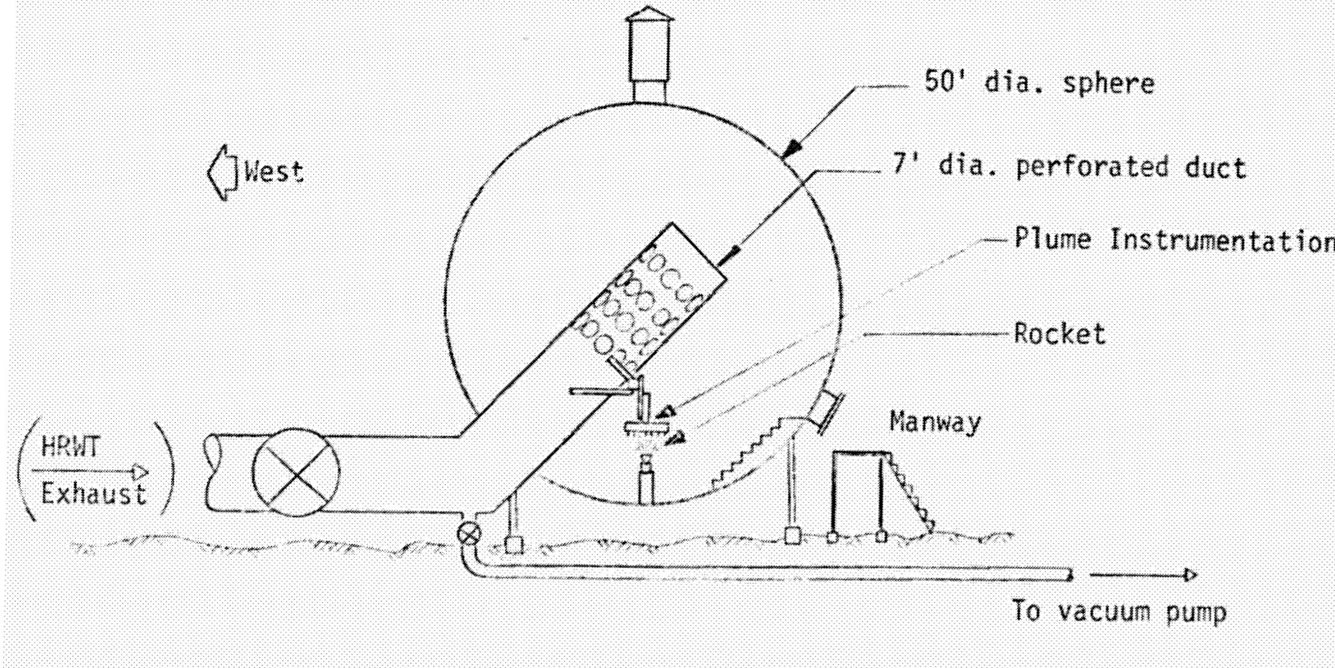


Fig. 2 Test Facility

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a. Physical Characteristics

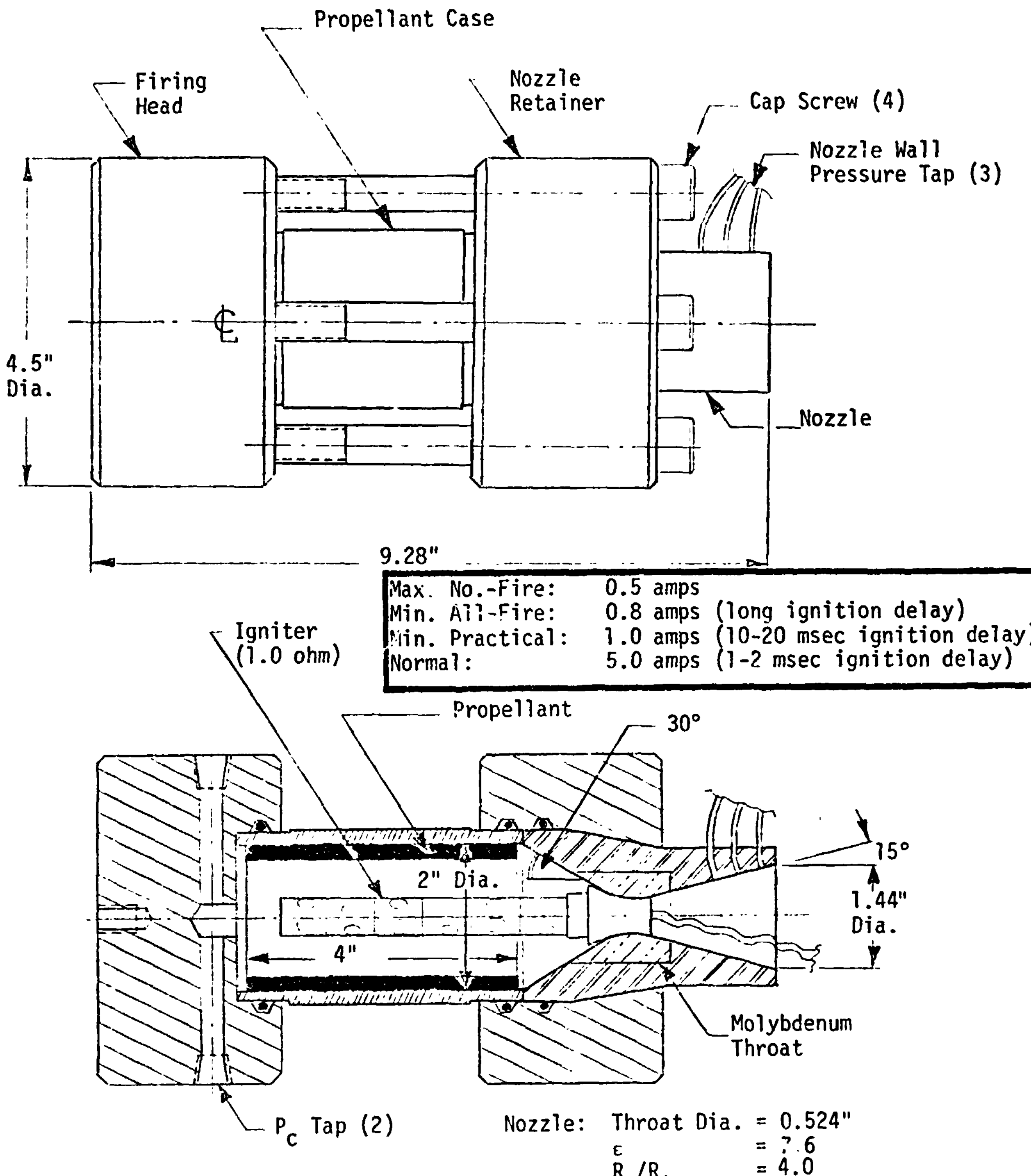


Fig. 3 Rocket Motor

b. Operational Characteristics

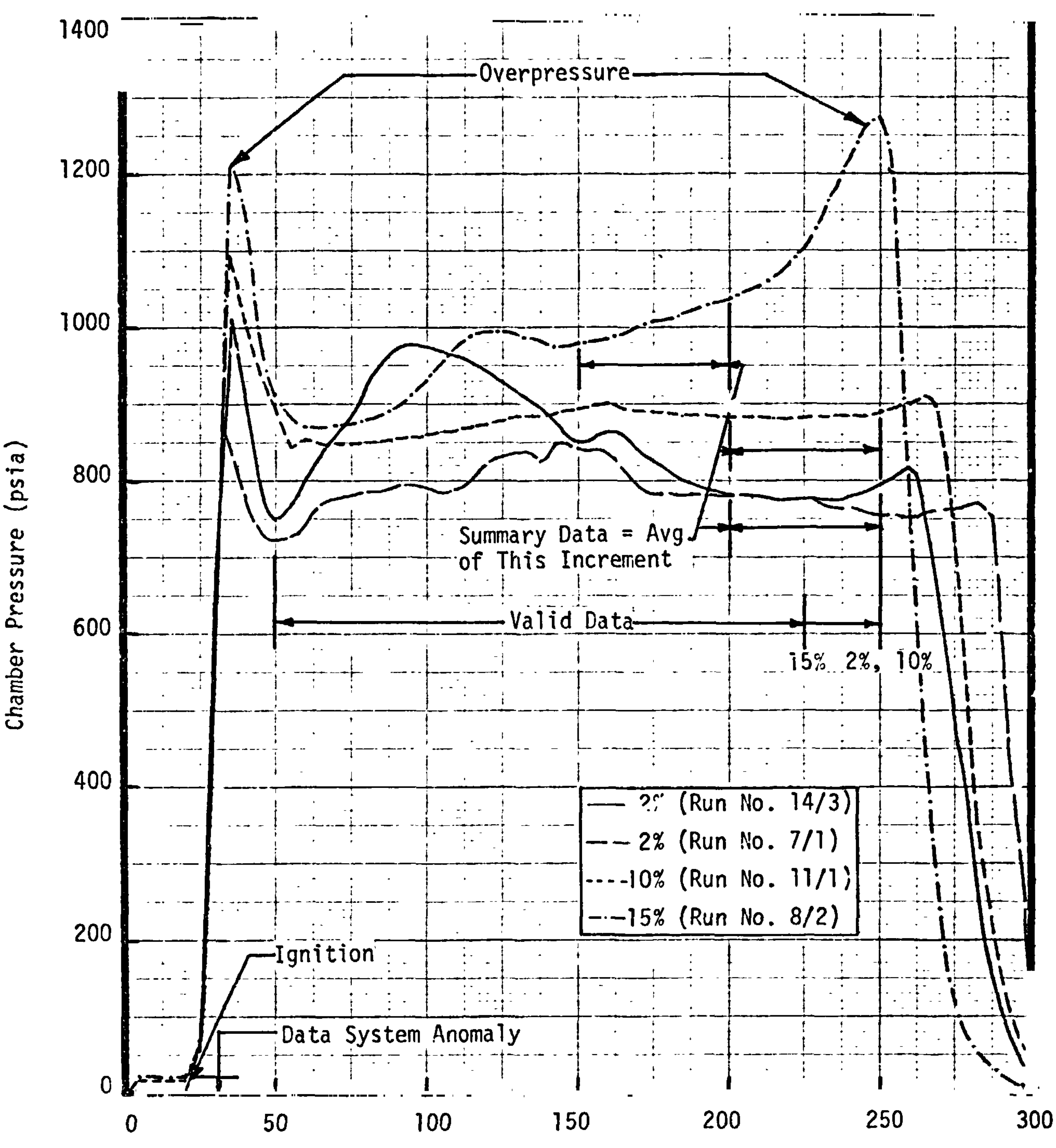
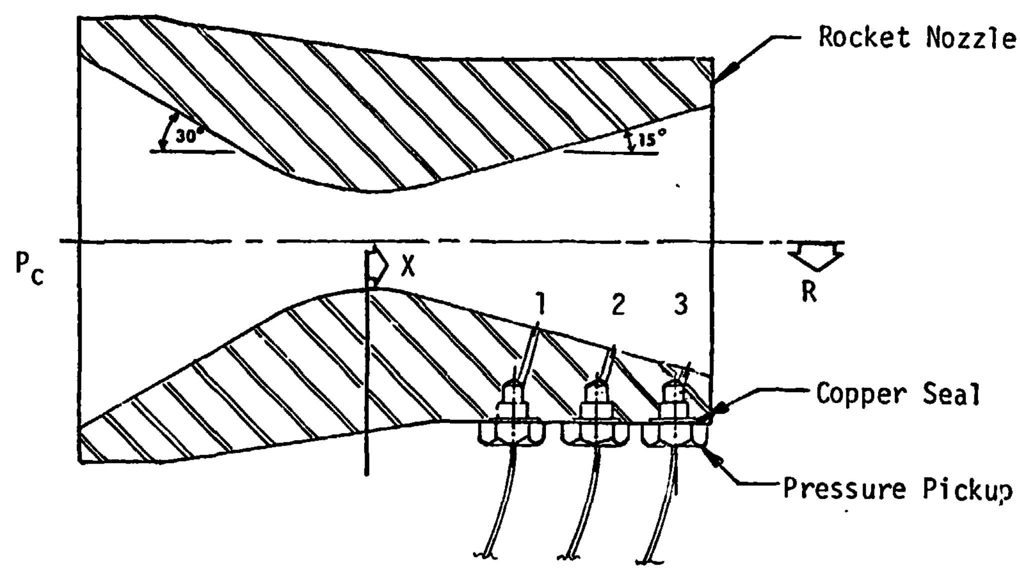


Fig. 3 (Concluded)

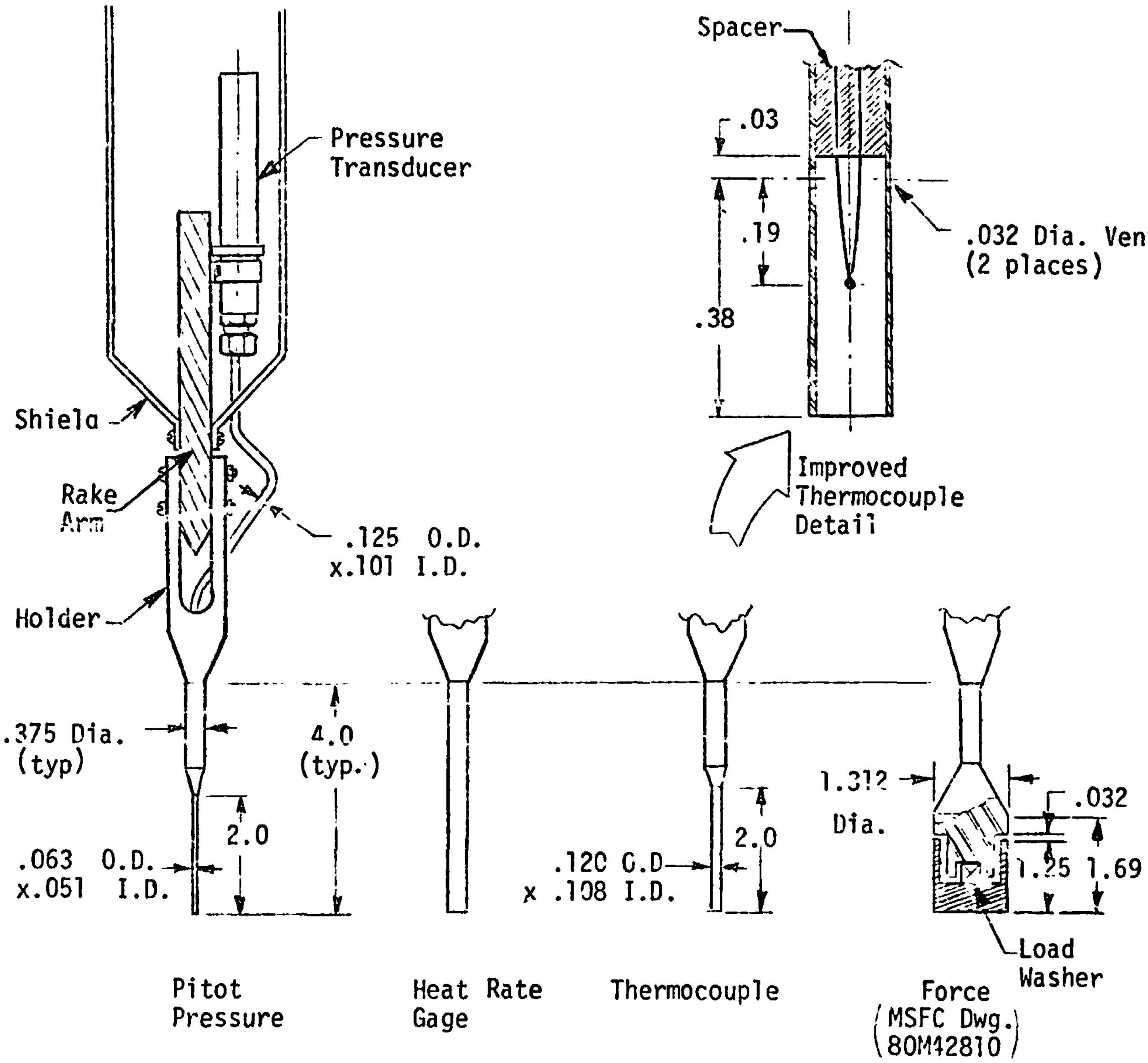


Design Values (See Table 3 for measured values)

Nozzle Pressure No.	X (in.)	R (in.)	A/A*
P_{n1}	.888	.463	3.170
P_{n2}	1.288	.570	4.808
P_{n3}	1.688	.677	6.786

Fig. 4 Nozzle Instrumentation

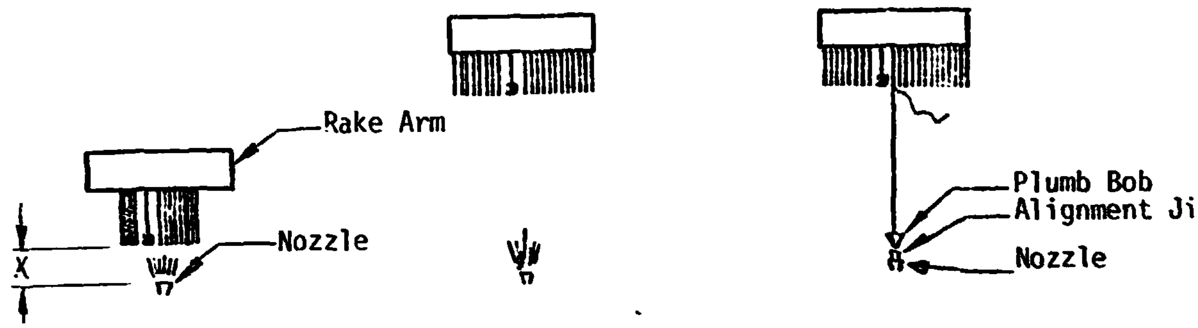
a. Rake Probe Designs



All dimensions in inches.

Fig. 5 Plume Instrumentation

b. Rake Positions



X/D = 5 X/D = 20 Alignment

c. Rake Probe Combinations

East — West

Radial Position, inches: -12 -10 -8 -6 -4 -2 0 2 4 6 8 10 12

Position No.: 55 51 47 43 39 35 1 5 9 13 17 21 25

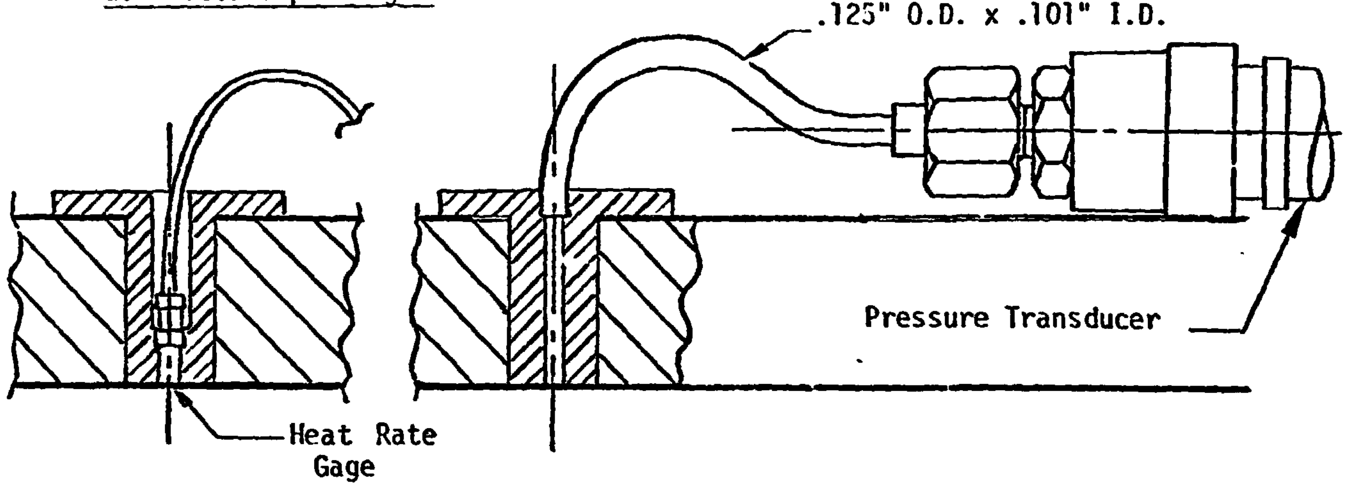
Config. No.	X/D	Probes (East → West)
1	20	P Q T Q T Q P T Q P Q P P P P P P P P P P P P
6A	16	Q Q Q T Q F P P P P P P P P P P PPPP
6B	↓	Q Q Q T Q F P P P P P P P P P !· PPP
4	12	Q Q Q T Q F P P P P P P P P P PPPPPP
9	12,20	Q T Q F P P PPPPPPPPPPPPP
2A	5	PQ Q QPTQPQPPPPPPPPPPPP
2B		PQ Q QPT P PPPP ·P PPPP
2C		P Q Q QPTQP PPPP PP PPP P
3		P P P PPPP PPPP
5A		PQQTQQ F PPPPPPPPPPPPPPP
5B	↓	QQTQQ F PPPPPPPPPPP

℄

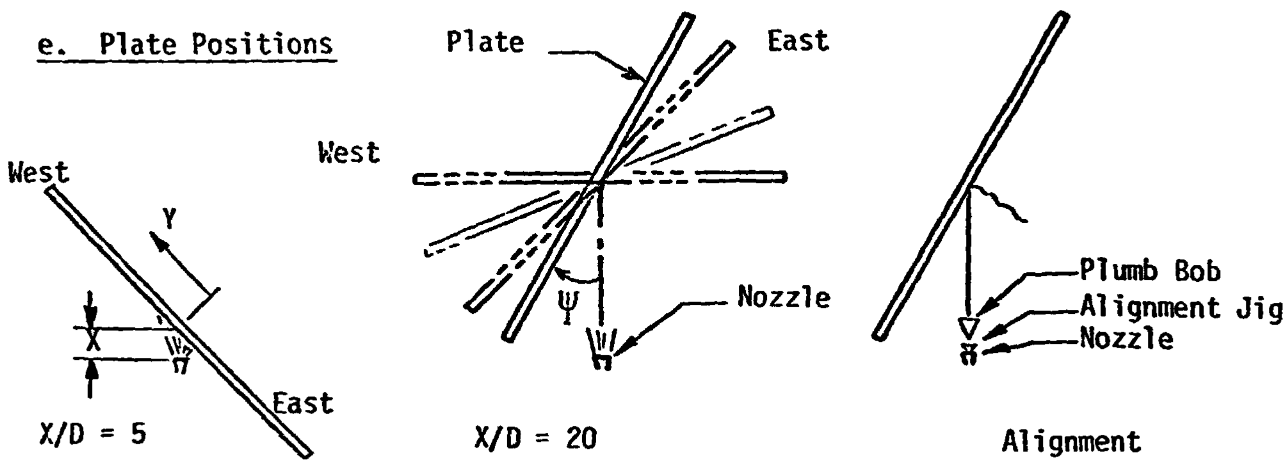
F - Force
P - Pitot Pressure
Q - Heat Rate Gage
T - Thermocouple

Fig. 5 Continued

d. Plate Tap Designs



e. Plate Positions



f. Plate Tap Combination (P = Pressure, Q = Heat Rate Gage)

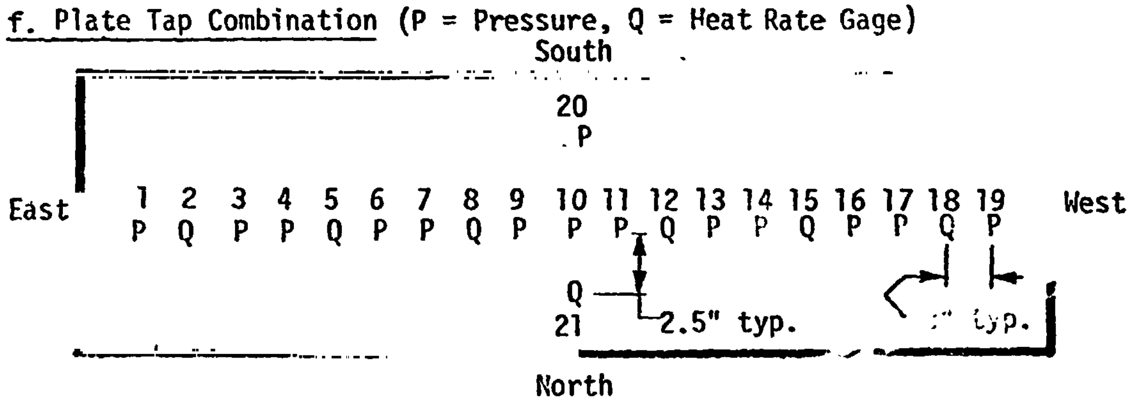


Fig. 5 (Continued)

g. Particle Sampling

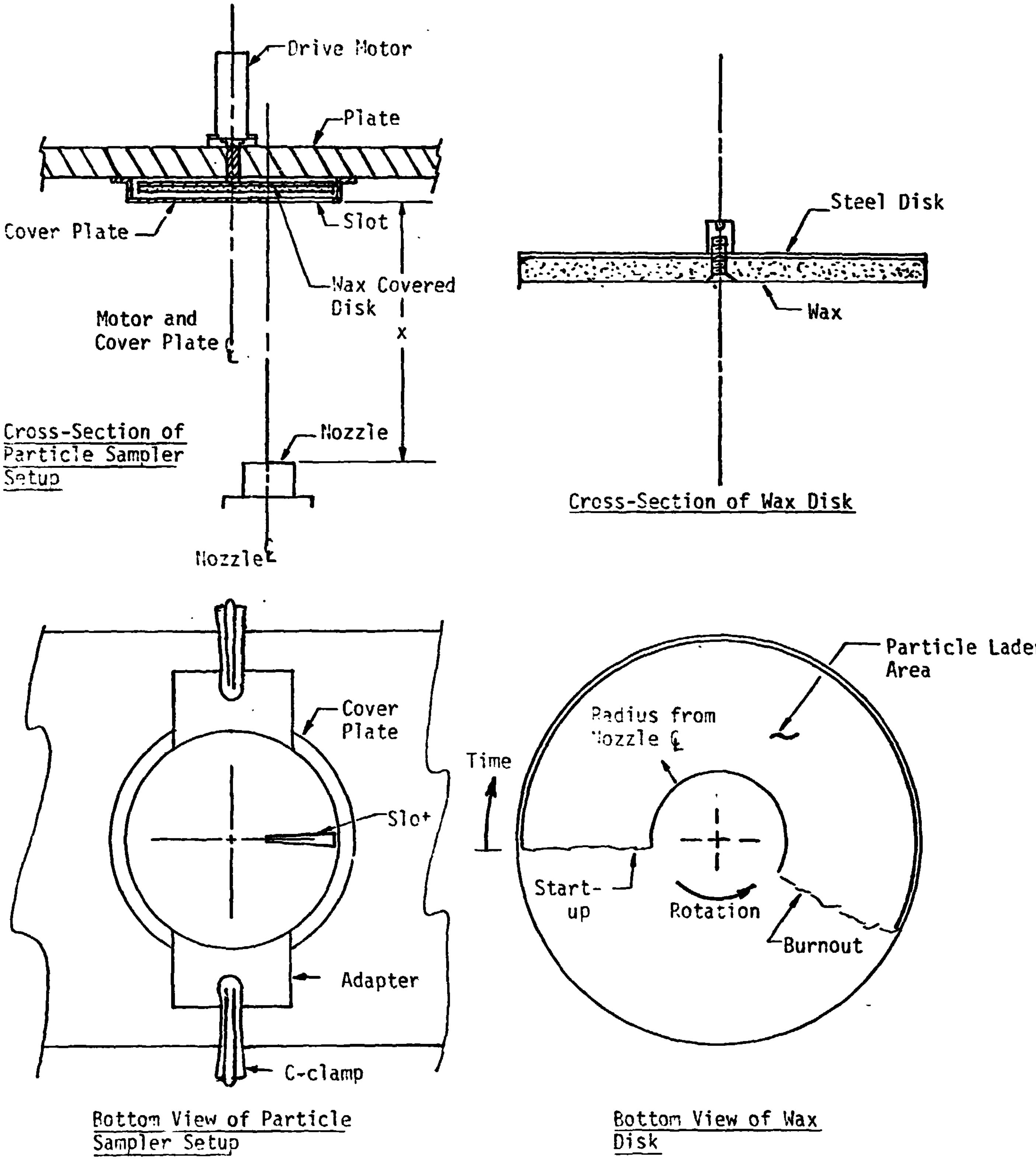
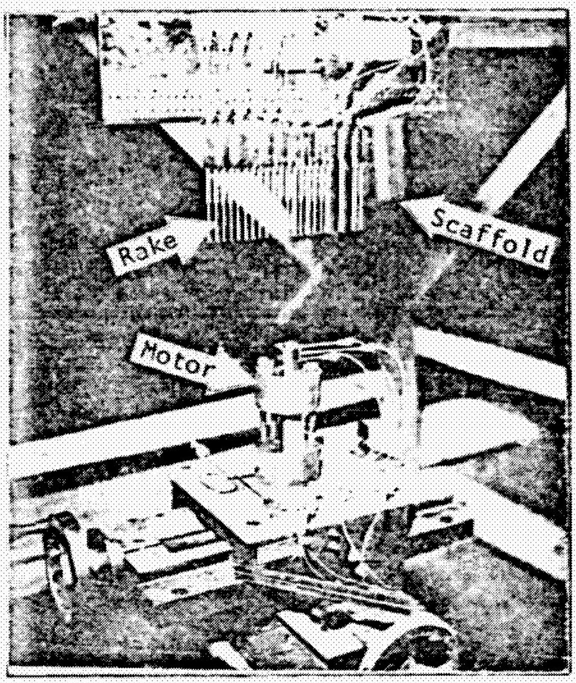
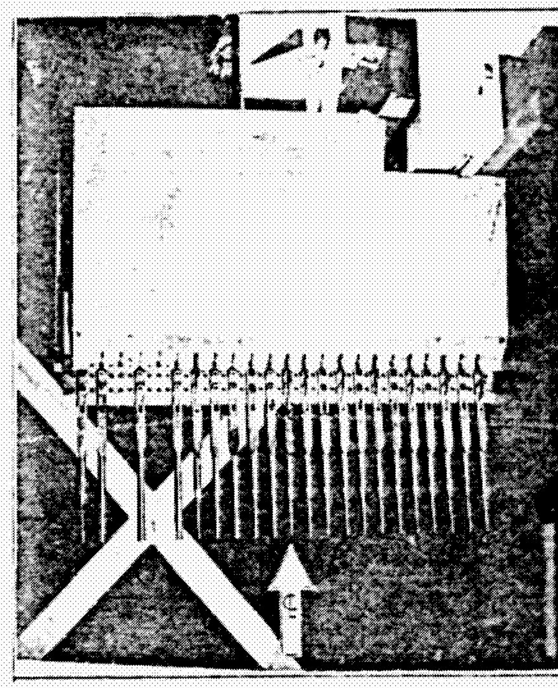


Fig. 5 (Concluded)

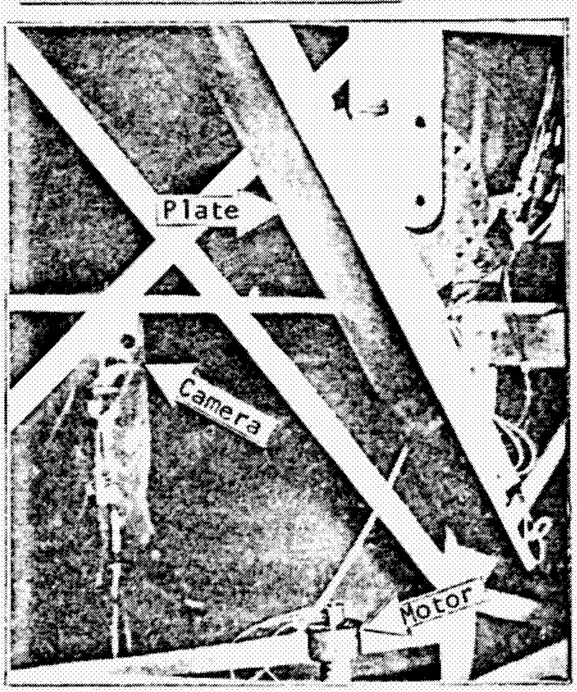
a. Overall View (looking North-East)



b. Rake (looking South)



c. Plate (looking South)



d. Particle Sampler (on Plate)

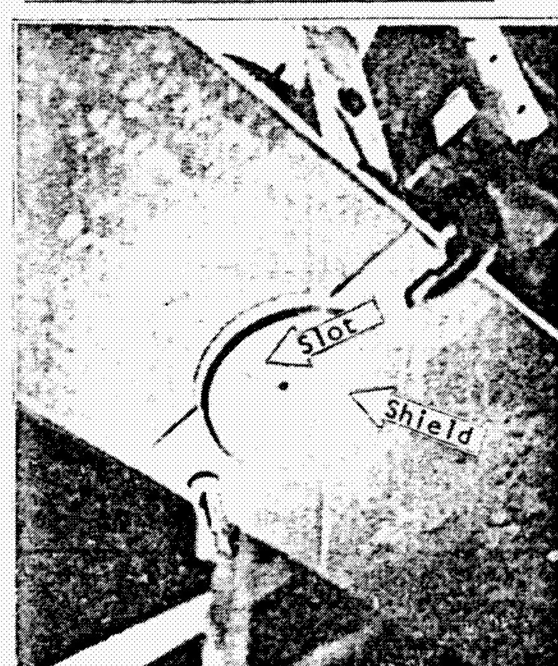


Fig. 6 Instrumentation Installation Photographs

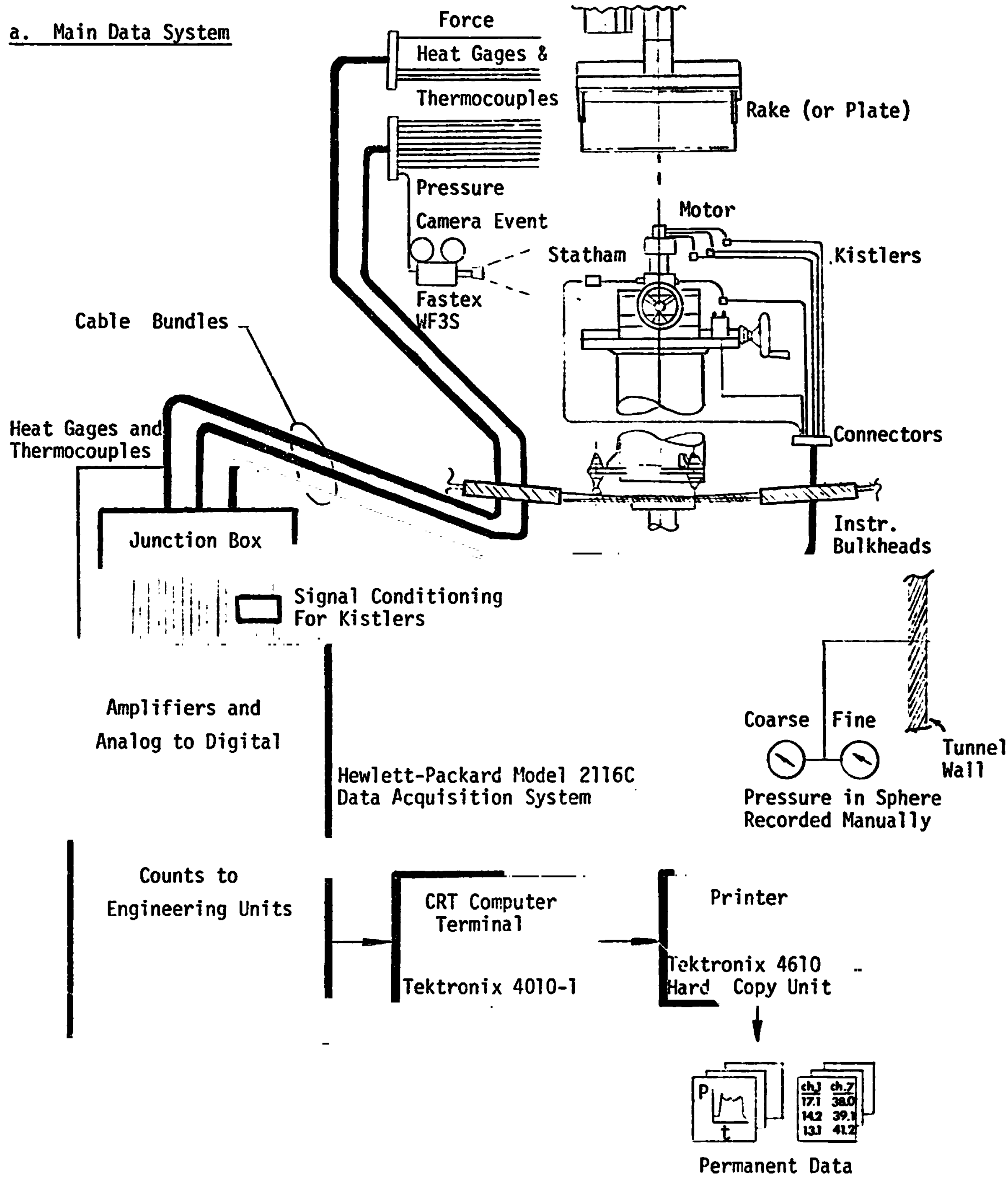


Fig. 7 Data System Schematic

b. Peripheral System

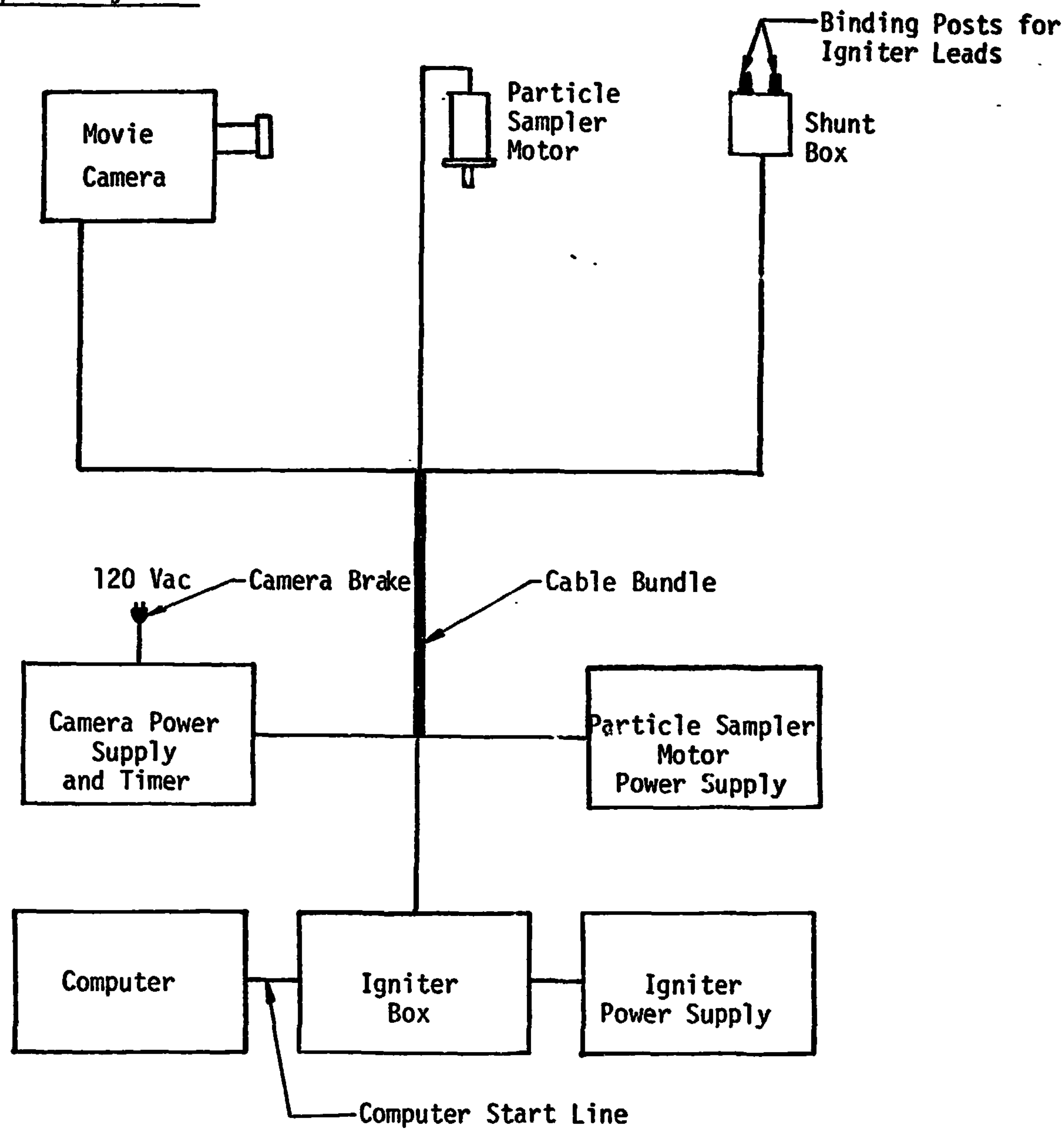
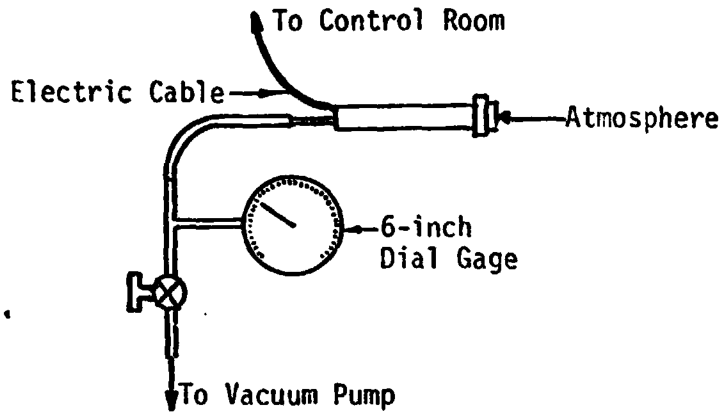


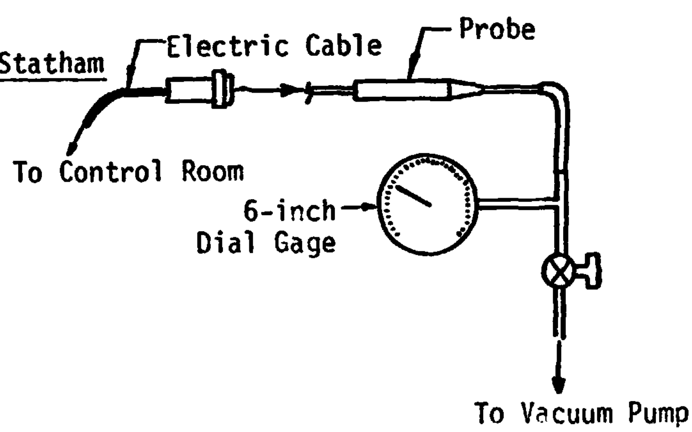
Fig. 7 (Concluded)

a. Setra



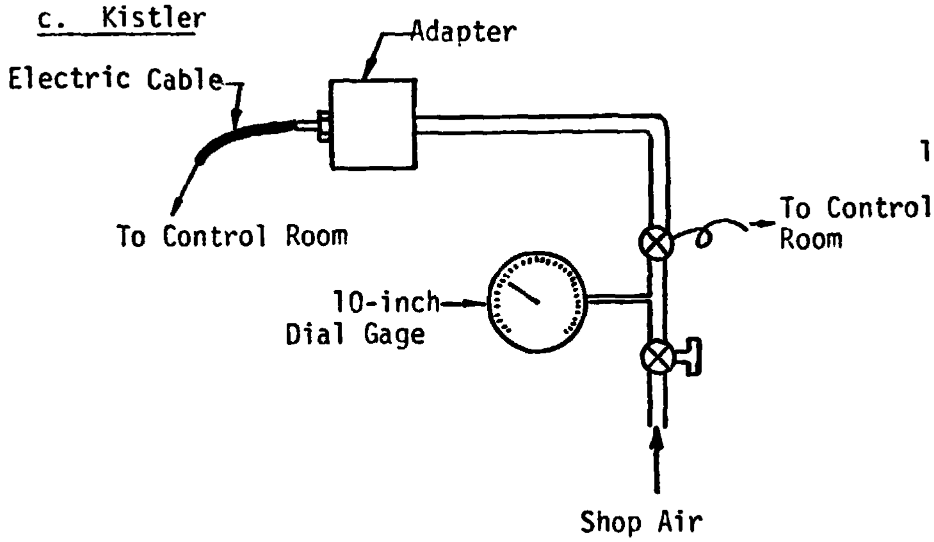
Range	Calibration Points
1 psid	-10,-20,-30,-40, -50 mm Hg gage

b. Statham



Range	Calibration Points
5, 10 psia	0,1,2,3,4,5 psia
15 psia	0,5,10 psia, atm. (0, atm).*
1500 psia	0, 1000 psia

c. Kistler



Range	Calibration Points
75 psia	0,15,30,45,60 psia (0,50 psia).*
1000 psia	0, 1000 psia

* Later abbreviated calibration justified by high linearity evident in earlier multi-point calibration.

Fig. 8 Calibration Setup

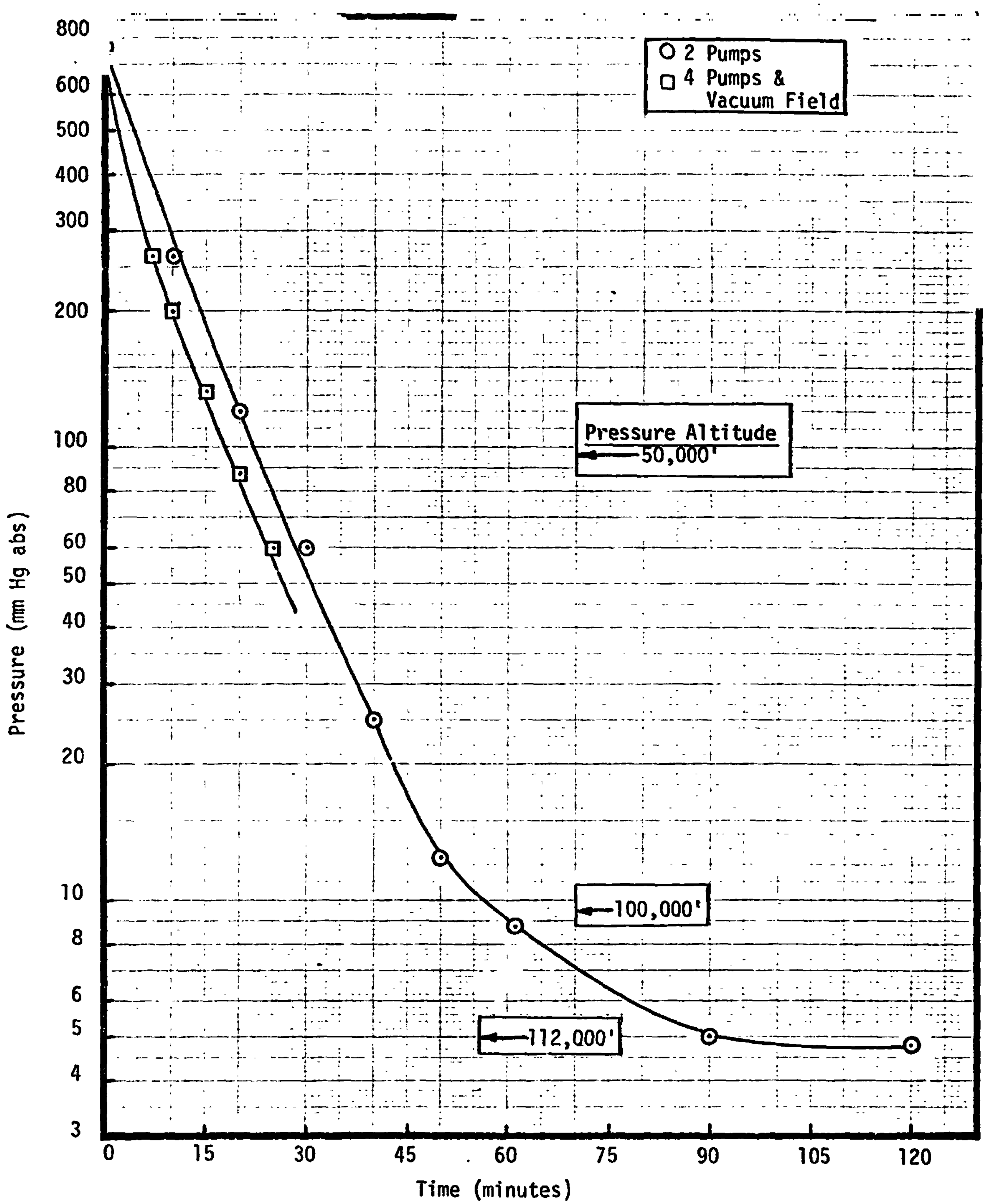
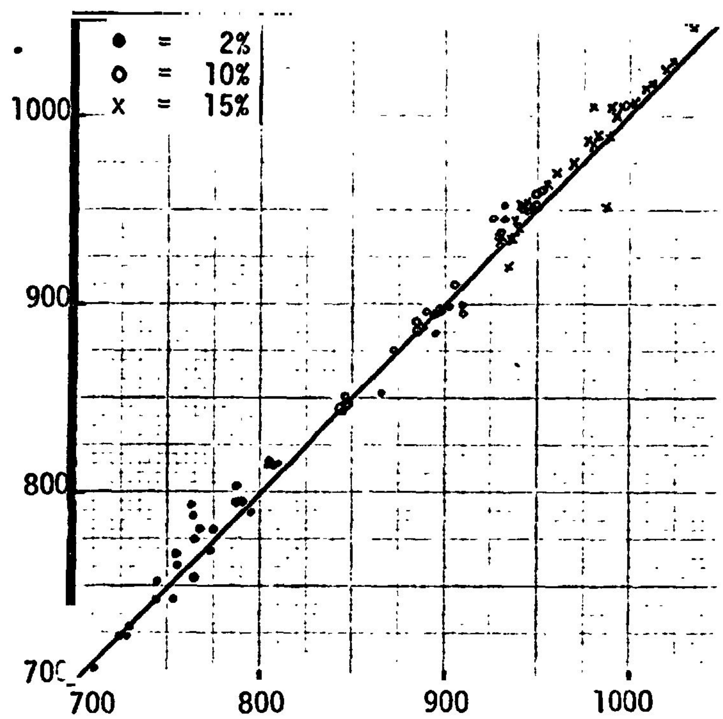
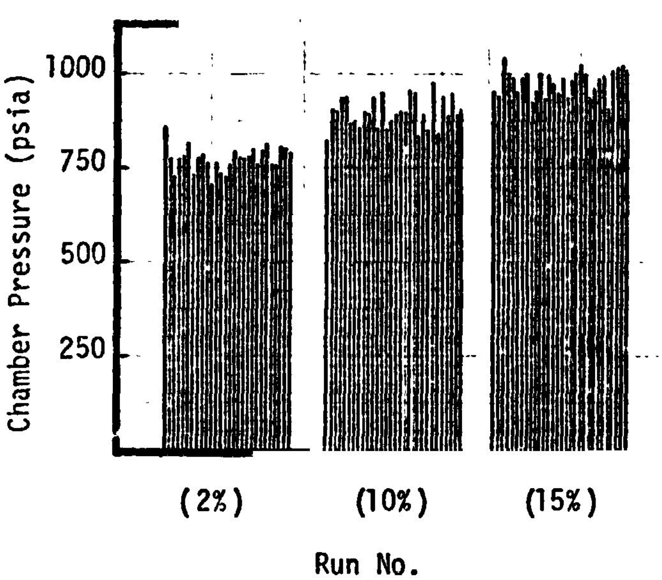


Fig. 9 Sphere Pump-Down Performance

a. Comparison of P_c Measured by Statham and Kistler Gages



b. Variation of P_c During Test From Summary Data (averaged over selected time interval).



		Aluminum Content		
		2%	10%	15%
P_c	Max.	860	957	1050
	Min.	709	826	928
	Avg.	773	899	979
	σ	32.8	37.6	37.1
	σ/Avg.	4.2%	4.2%	3.8%

Fig. 10 Rocket Motor Performance

c. P_c History Reproducibility

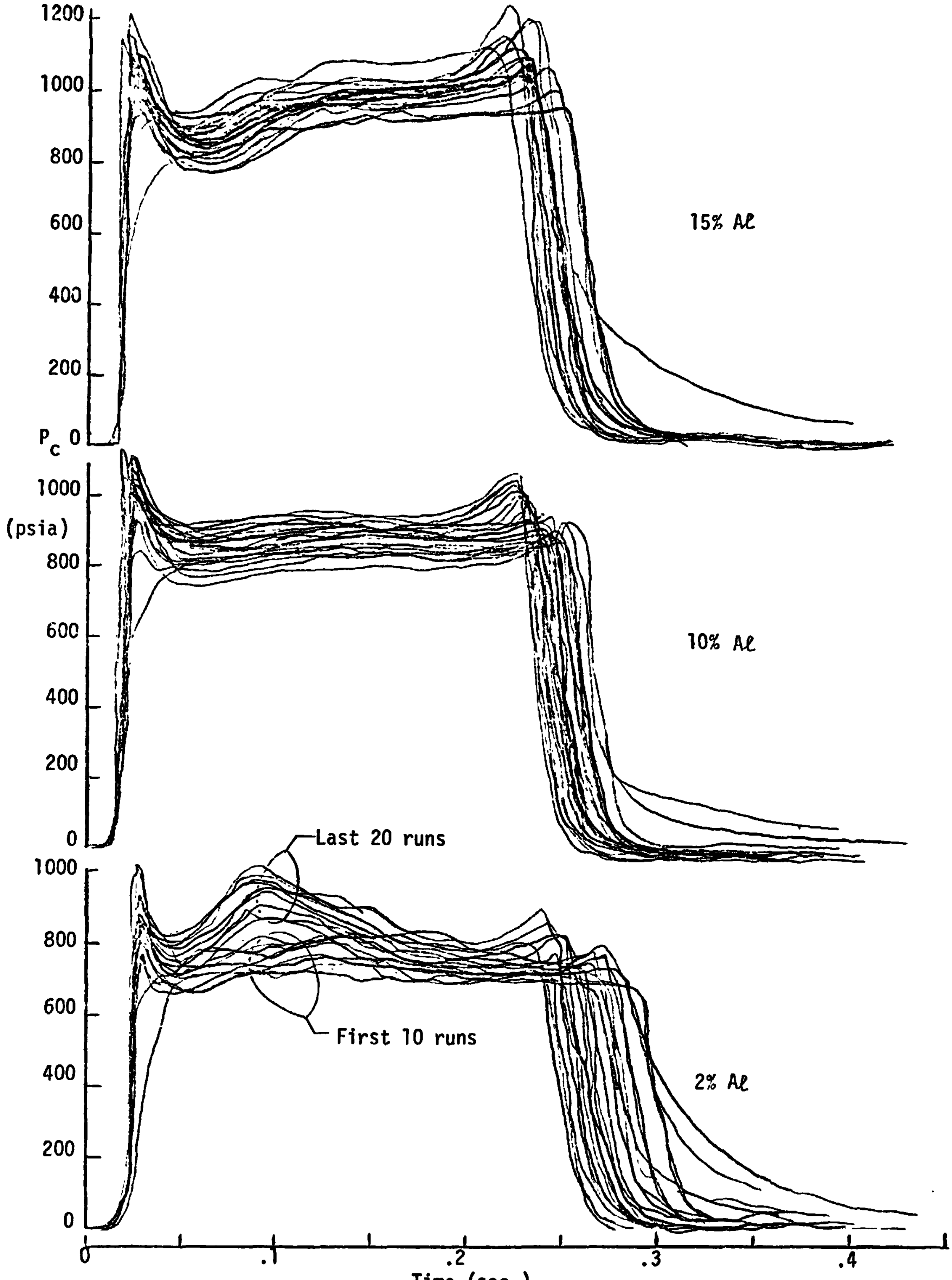
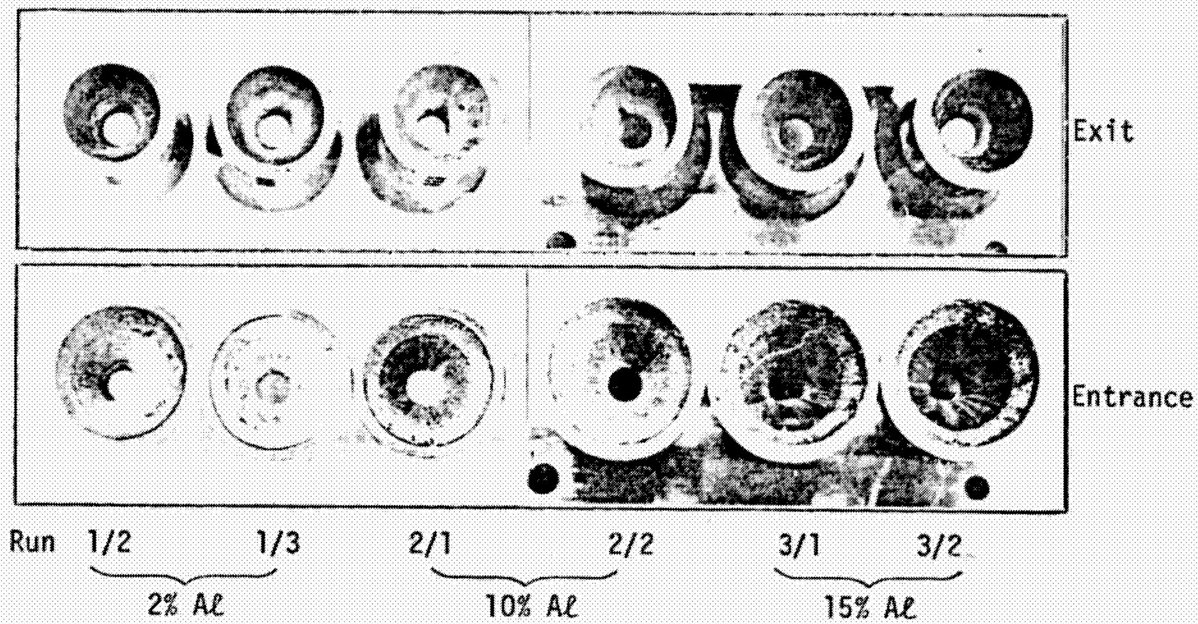


Fig. 10 (Concluded)

a. Post-Fire Condition



b. After Refurbishment

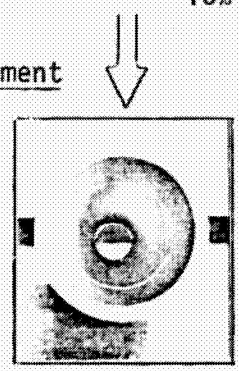


Fig.11 Nozzle Post-fire and Refurbishment Conditions

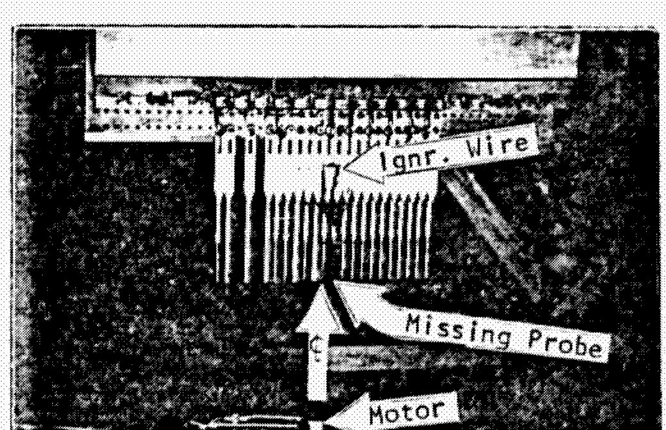


Fig.12 Rake Damage After Run No. 4/1

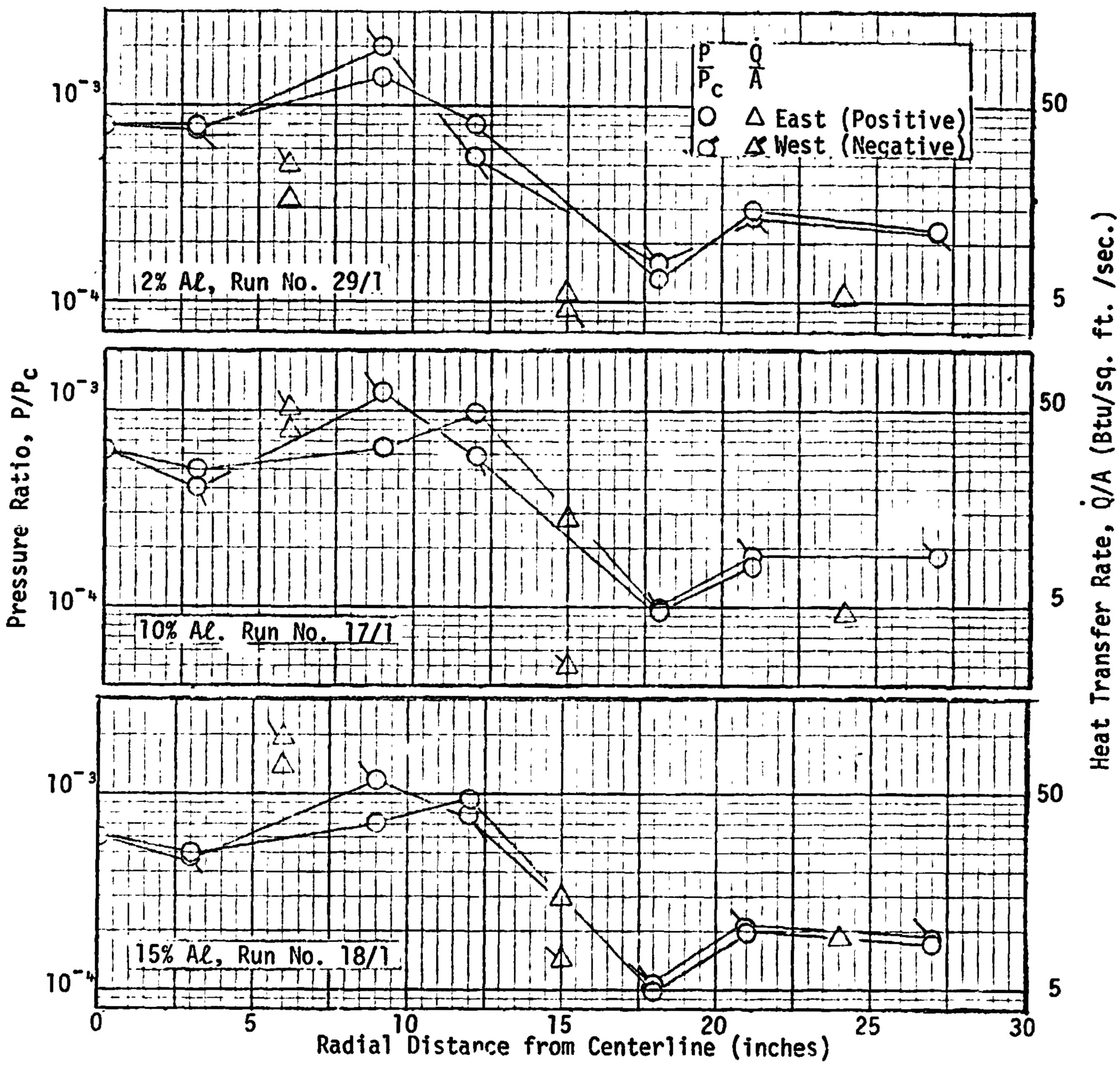


Fig. 13 Plate Data Anomaly at $\psi = 90°$

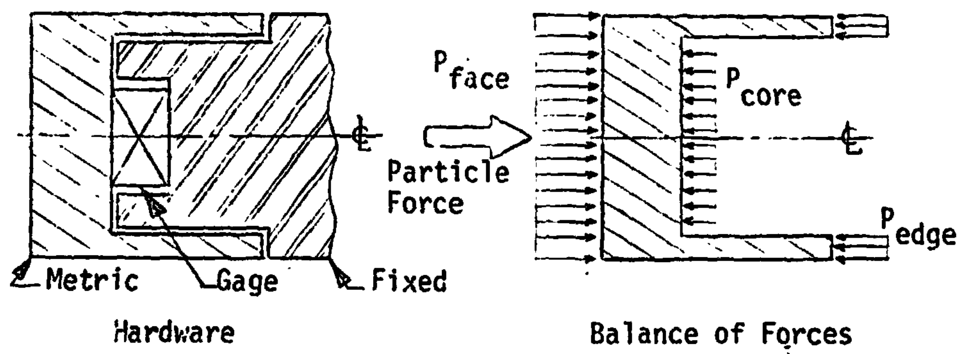


Fig. 14 Force Measurement

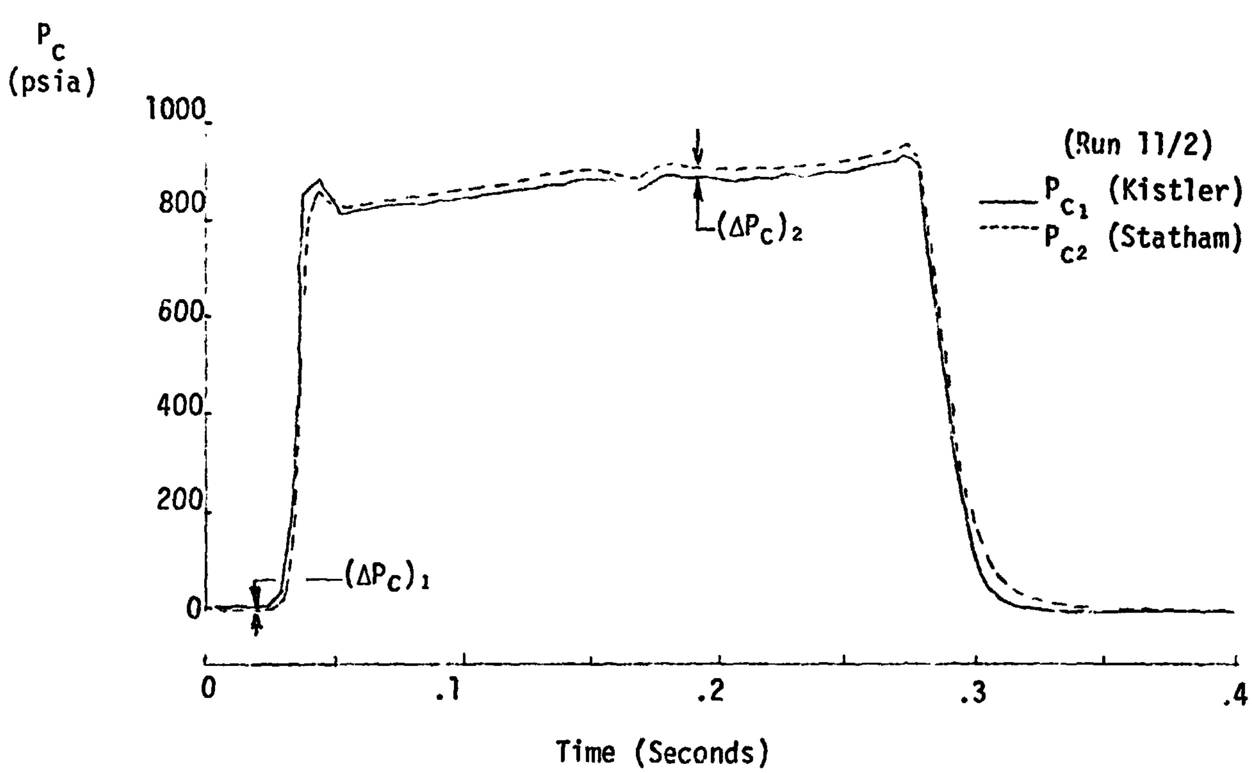


Fig. 15 P_c Accuracy

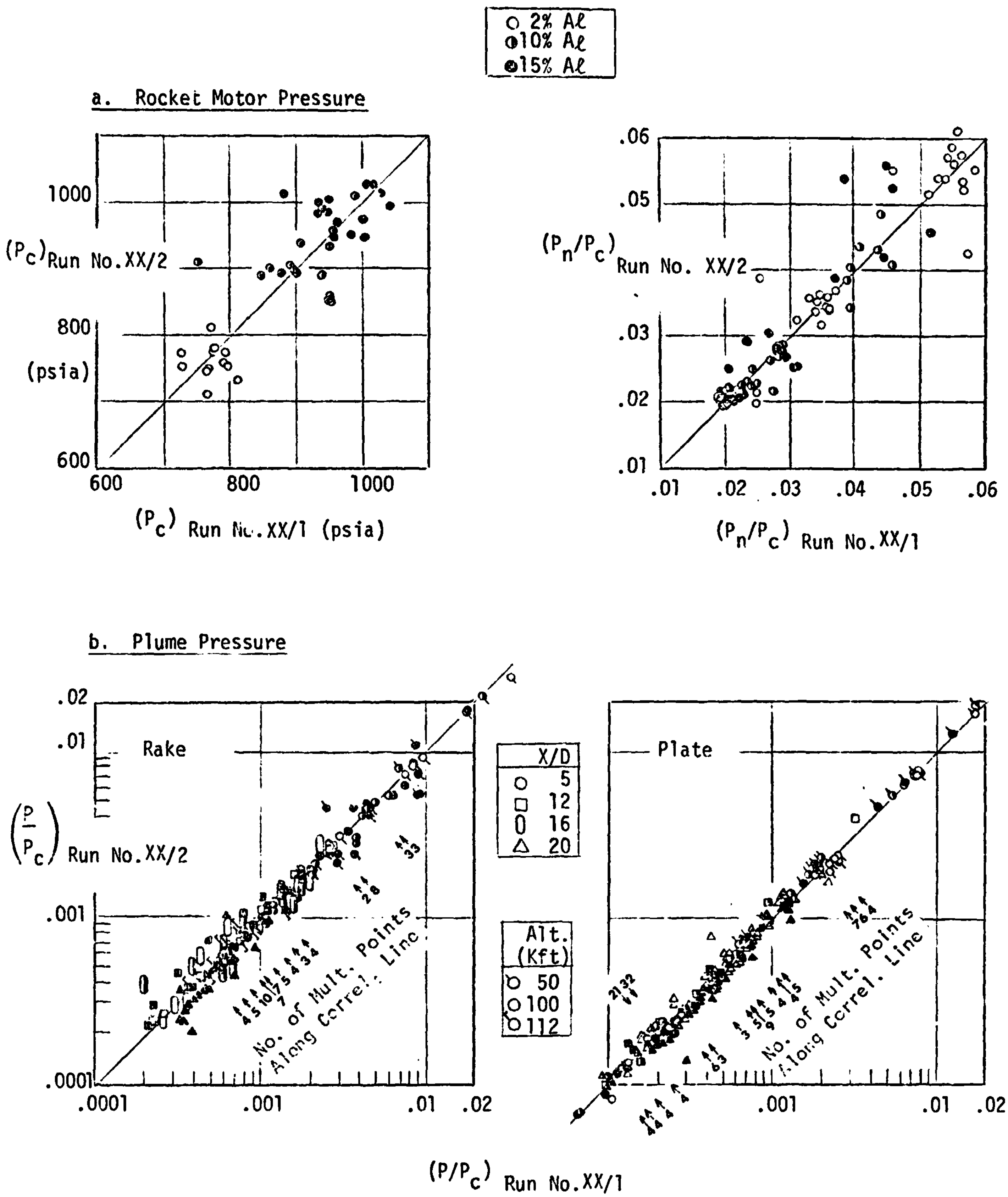
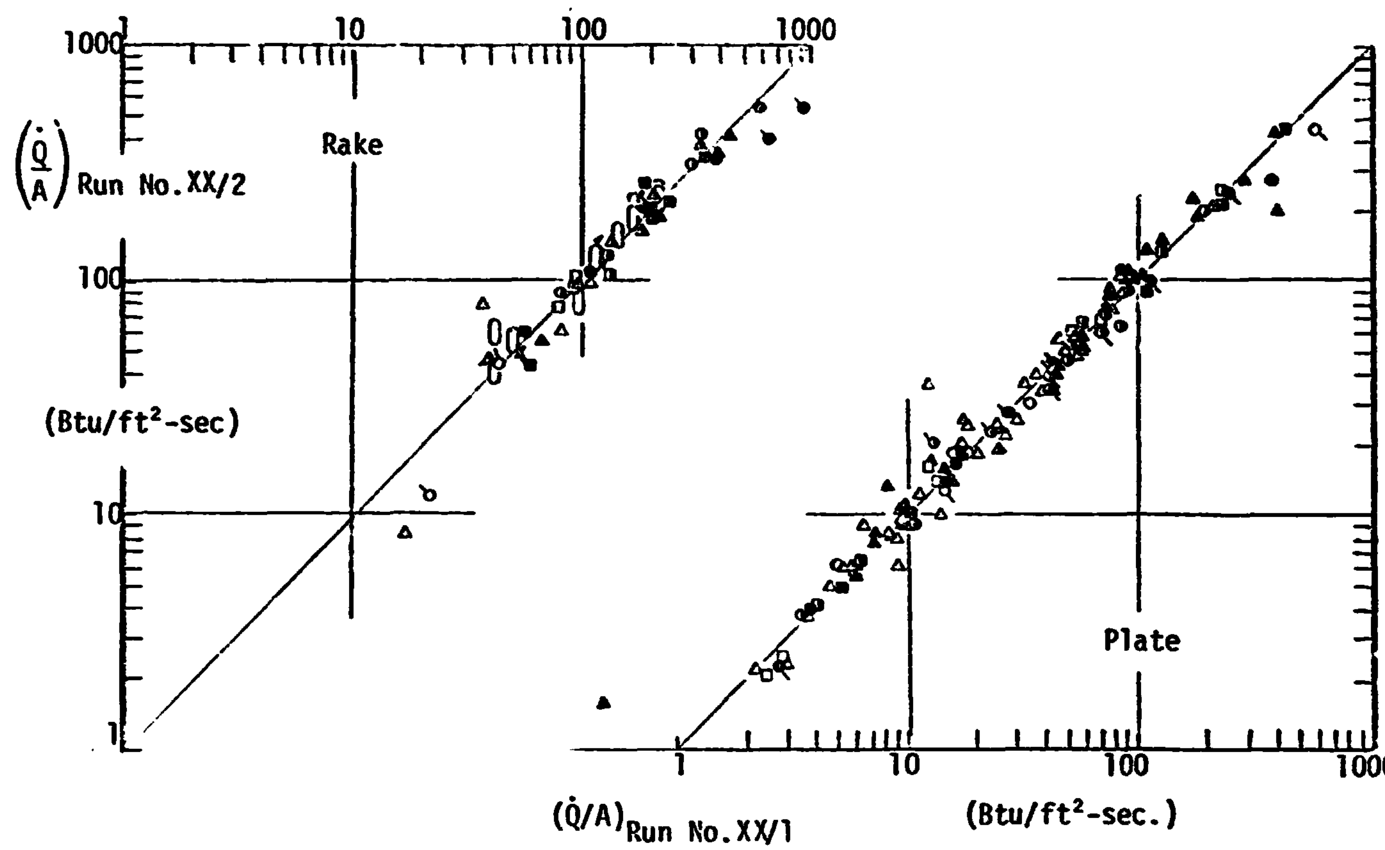
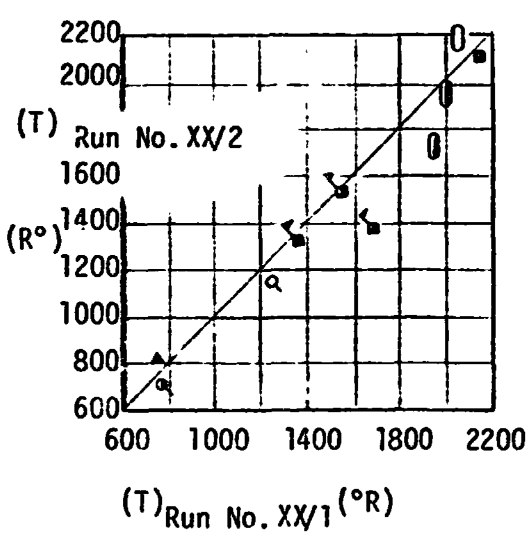


Fig. 16 Repeatability

c. Plume Heat Rate



d. Temperature



e. Force

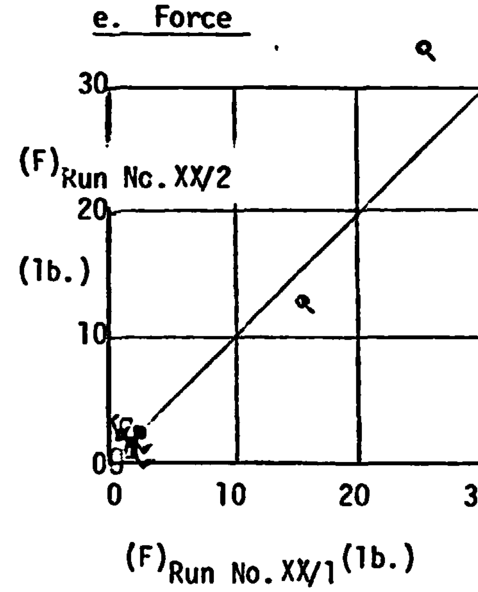


Fig. 16 (Concluded)

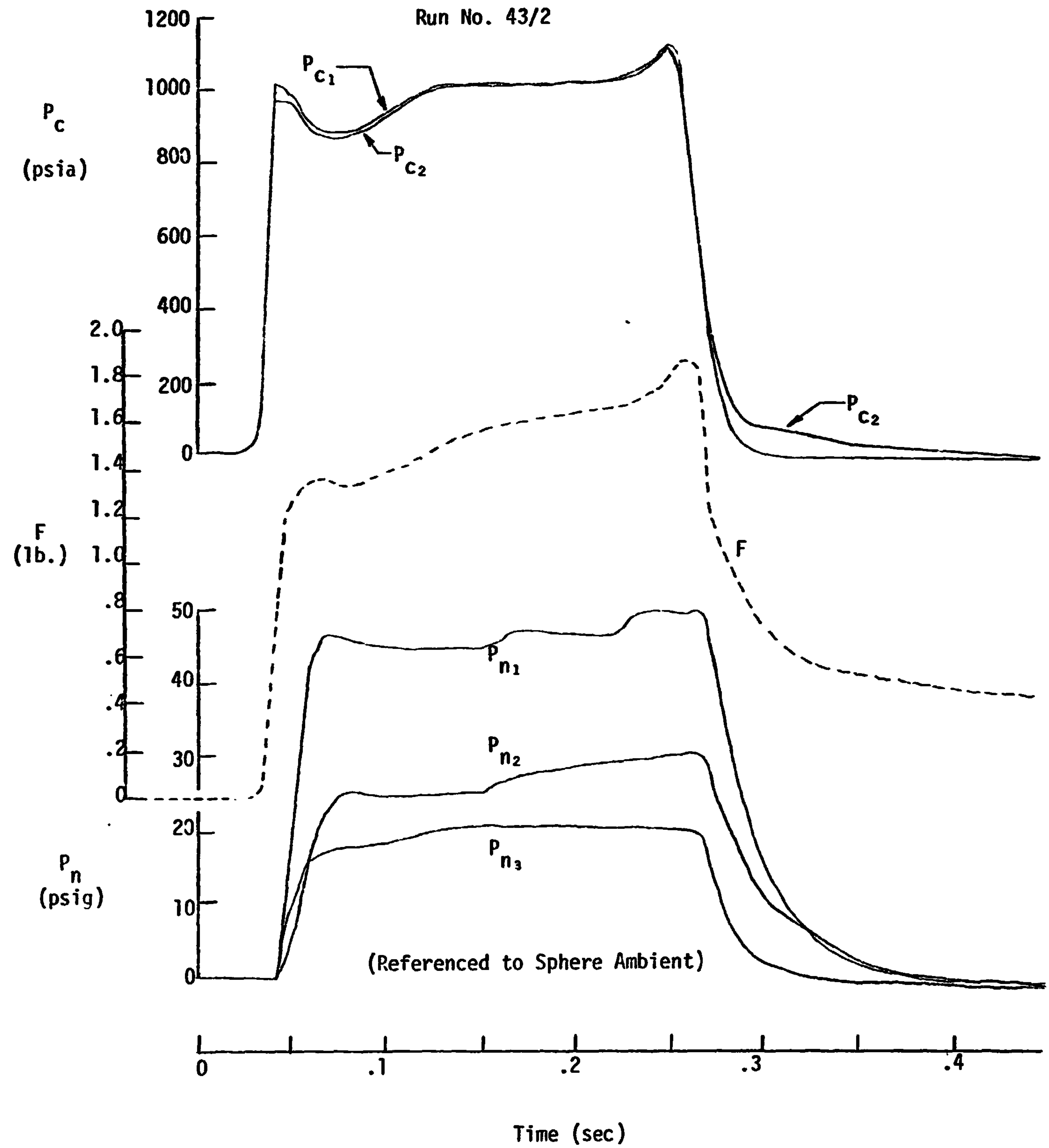


Fig. 17 Examples of CRT Plots

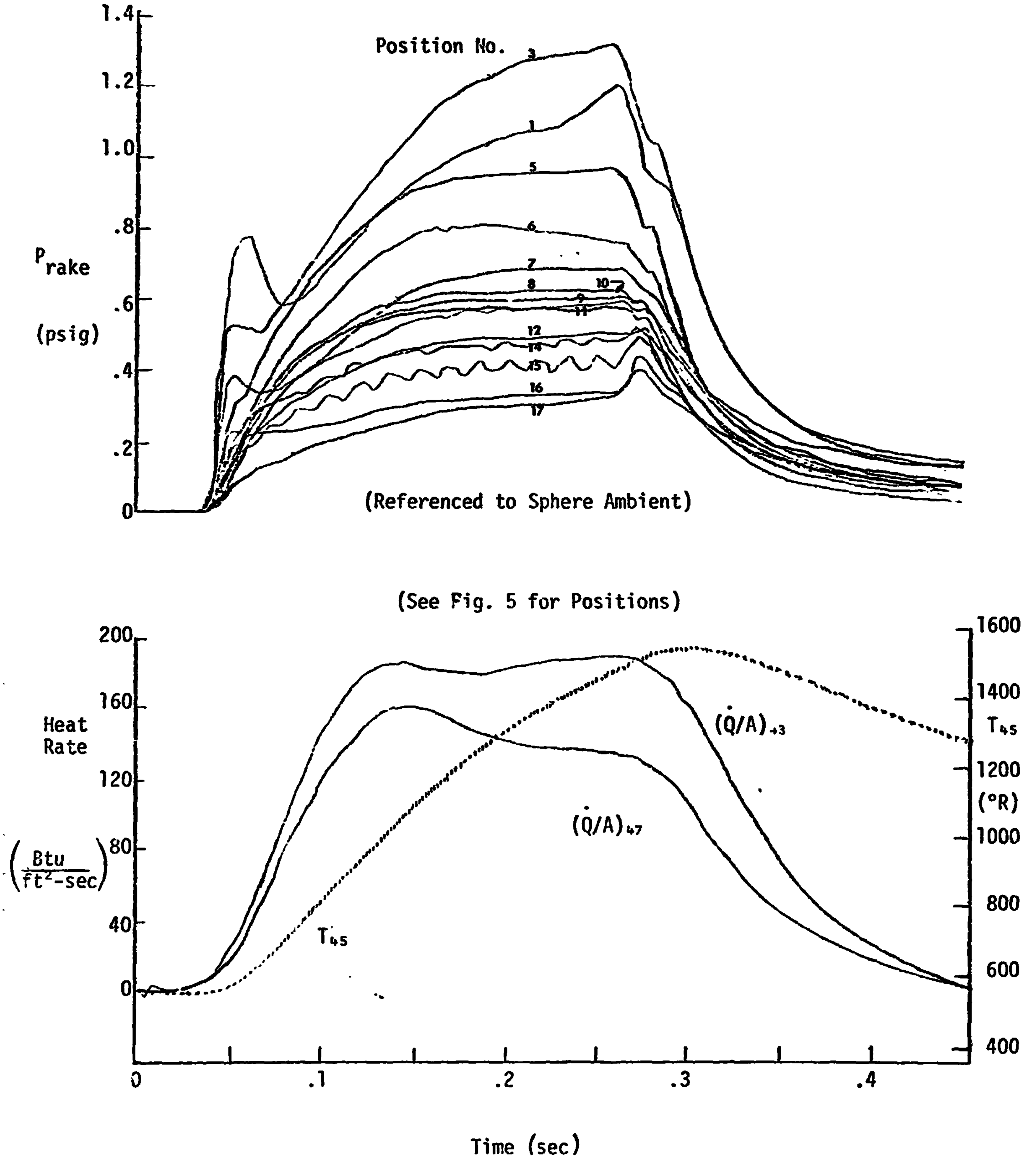


Fig. 17 (Concluded)

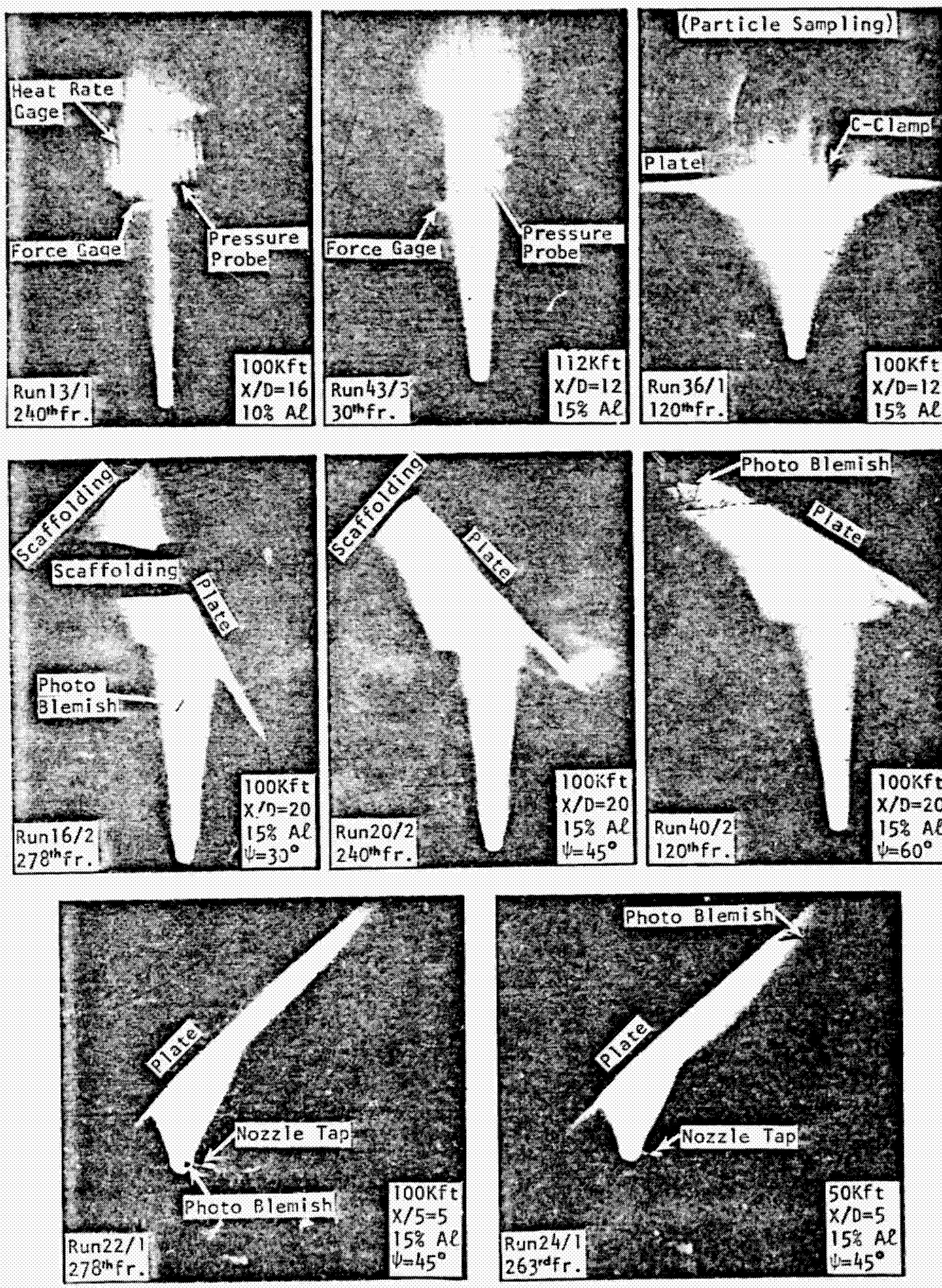


Fig. 18 Examples of High-Speed Movies

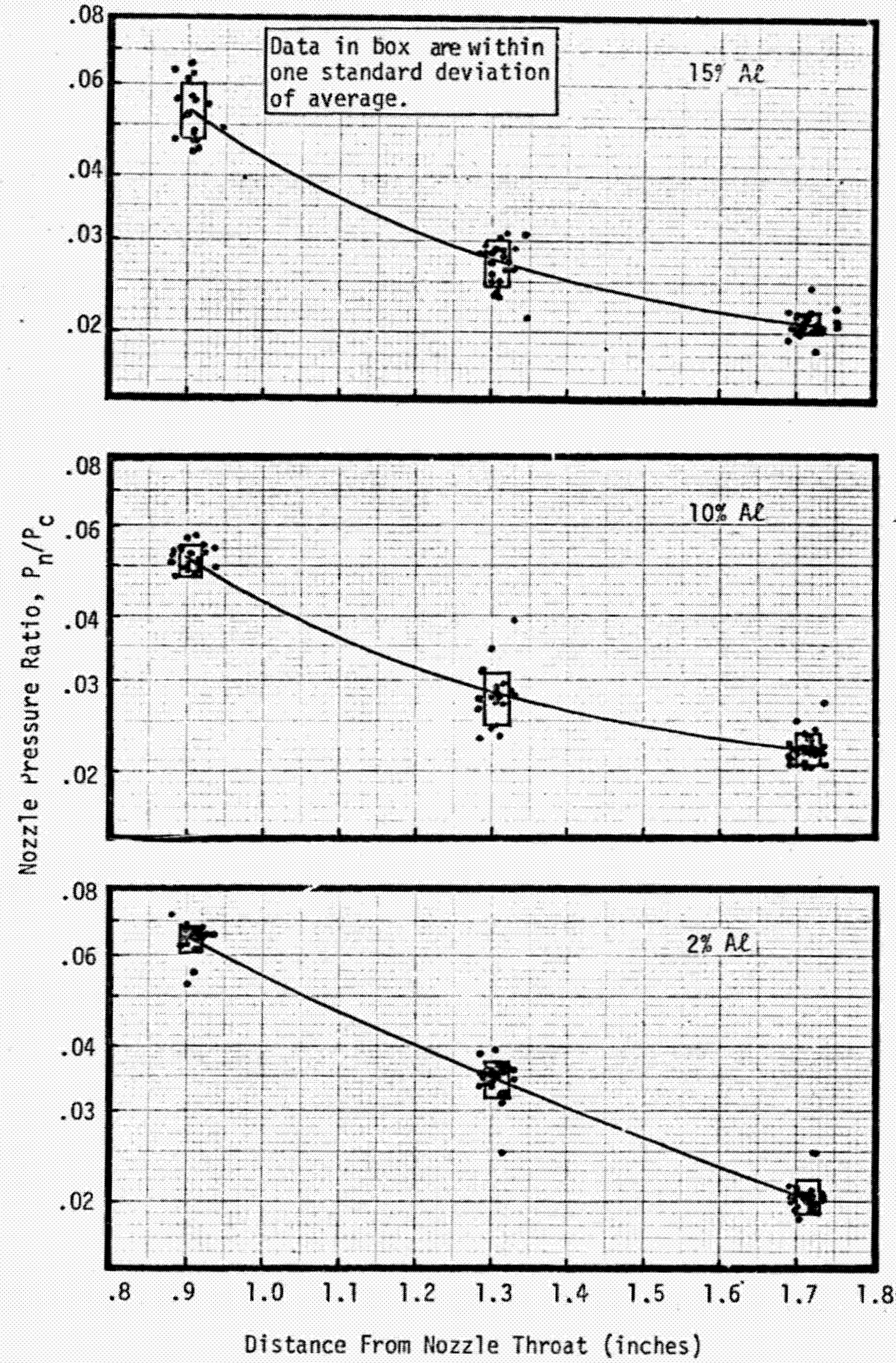


Fig. 19 Nozzle Data Summary

a. X/D = 5, 50,000', ψ = 45°

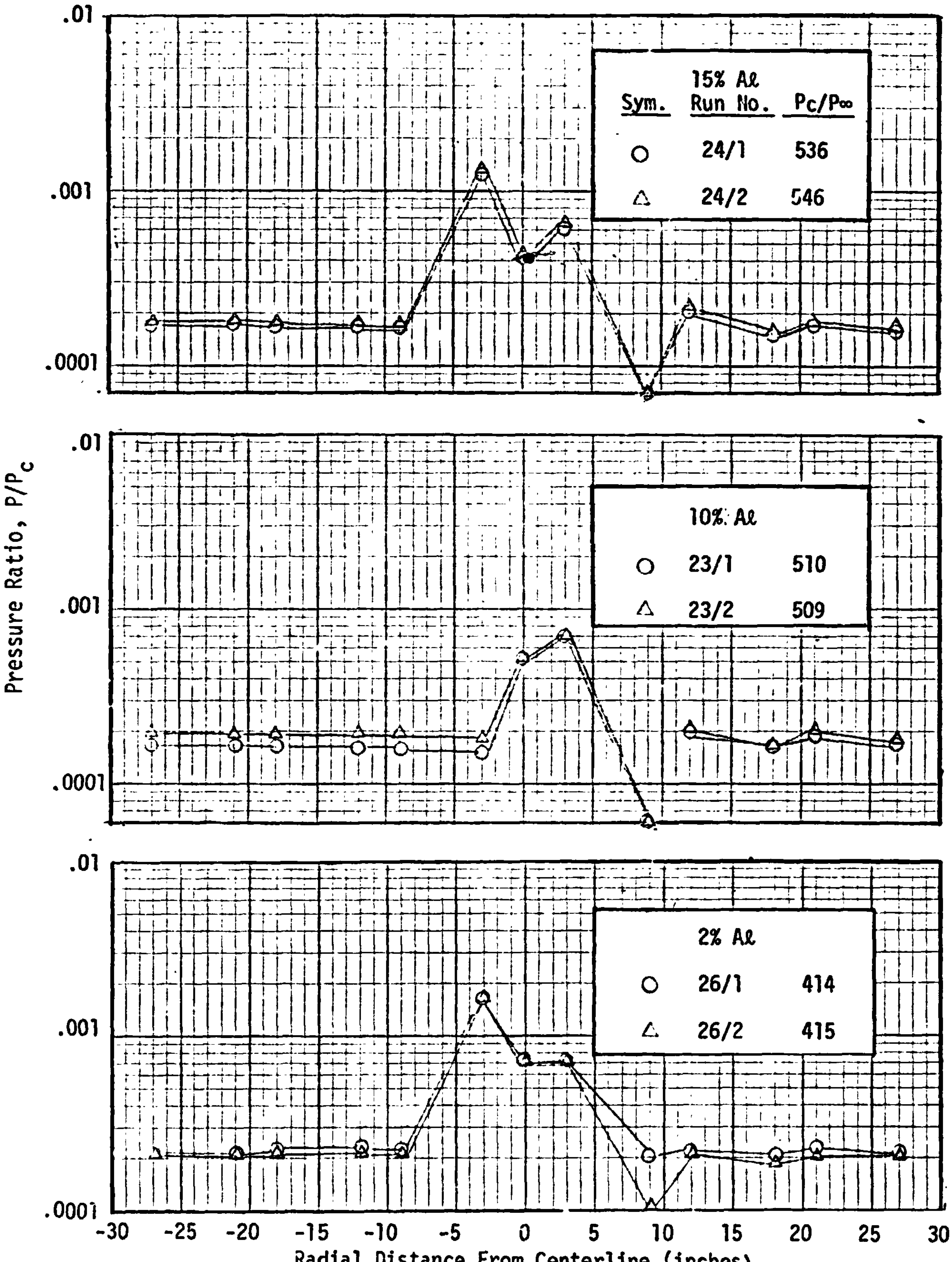


Fig. 20 Plate Data Summary

b. X/D = 5, 100,000', ψ = 45°

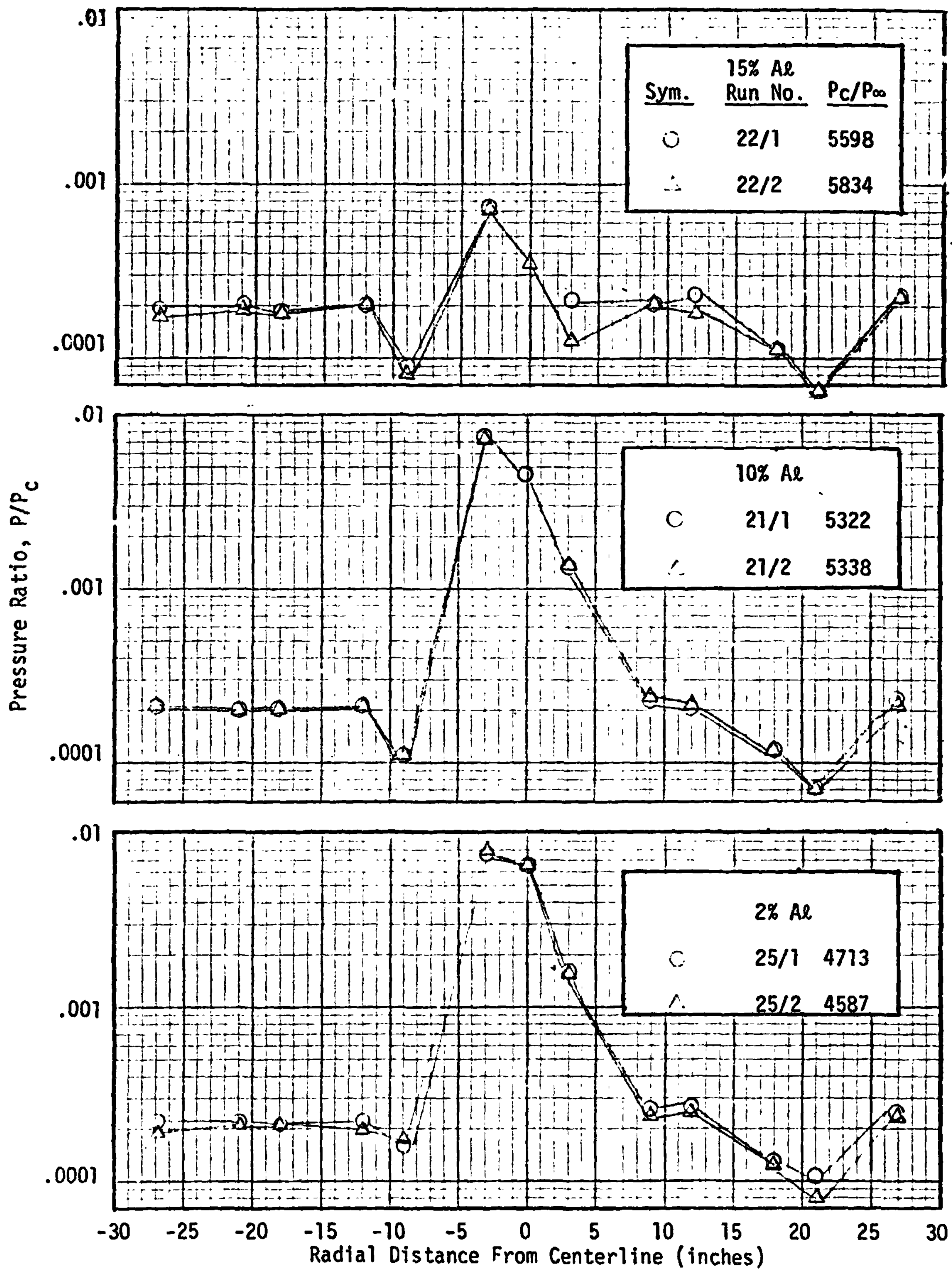


Fig. 20 (Continued)

c. X/D = 12, 100,000', ψ = 45°

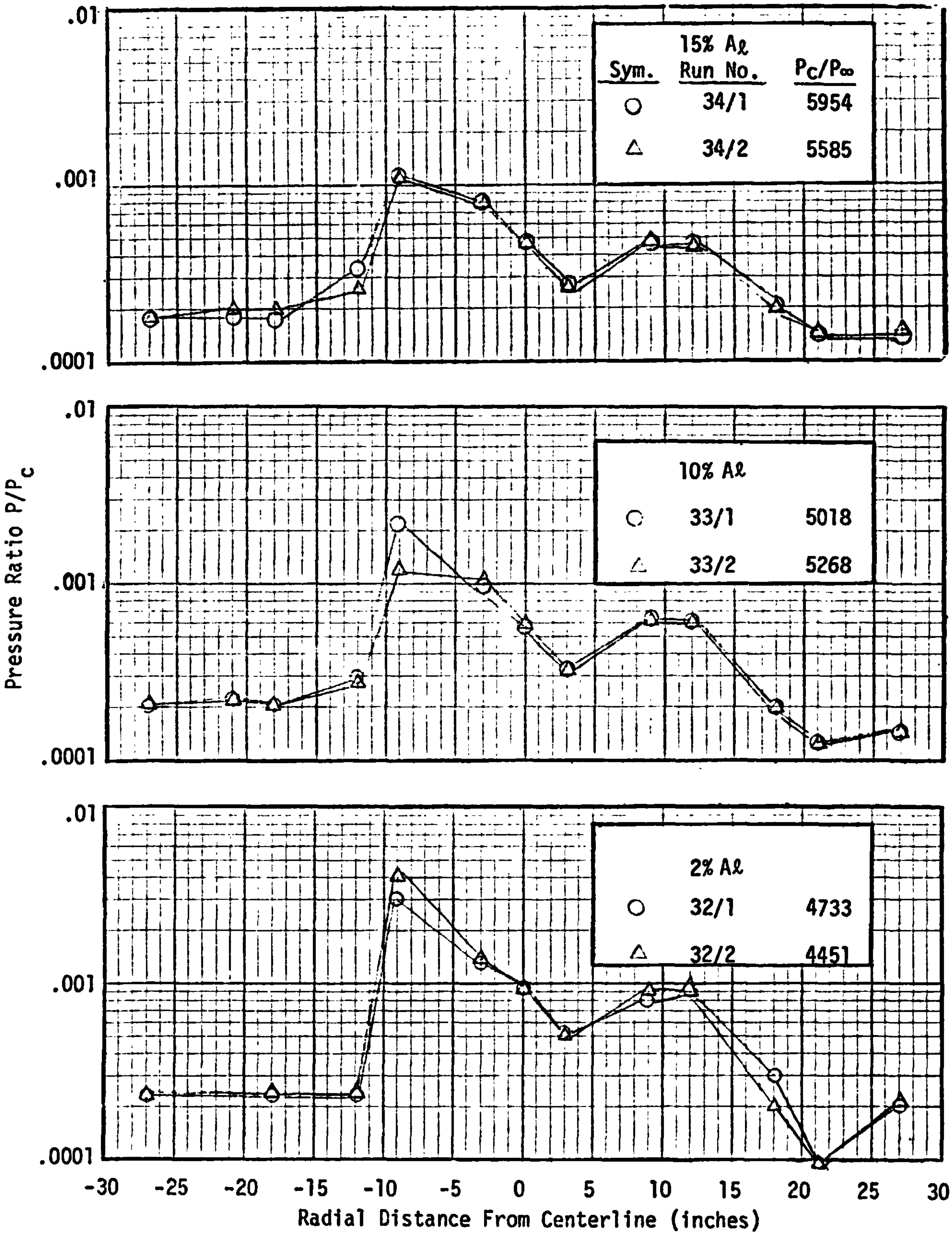


Fig. 20 (Continued)

d. X/D = 20, 100,000', ψ = 45°

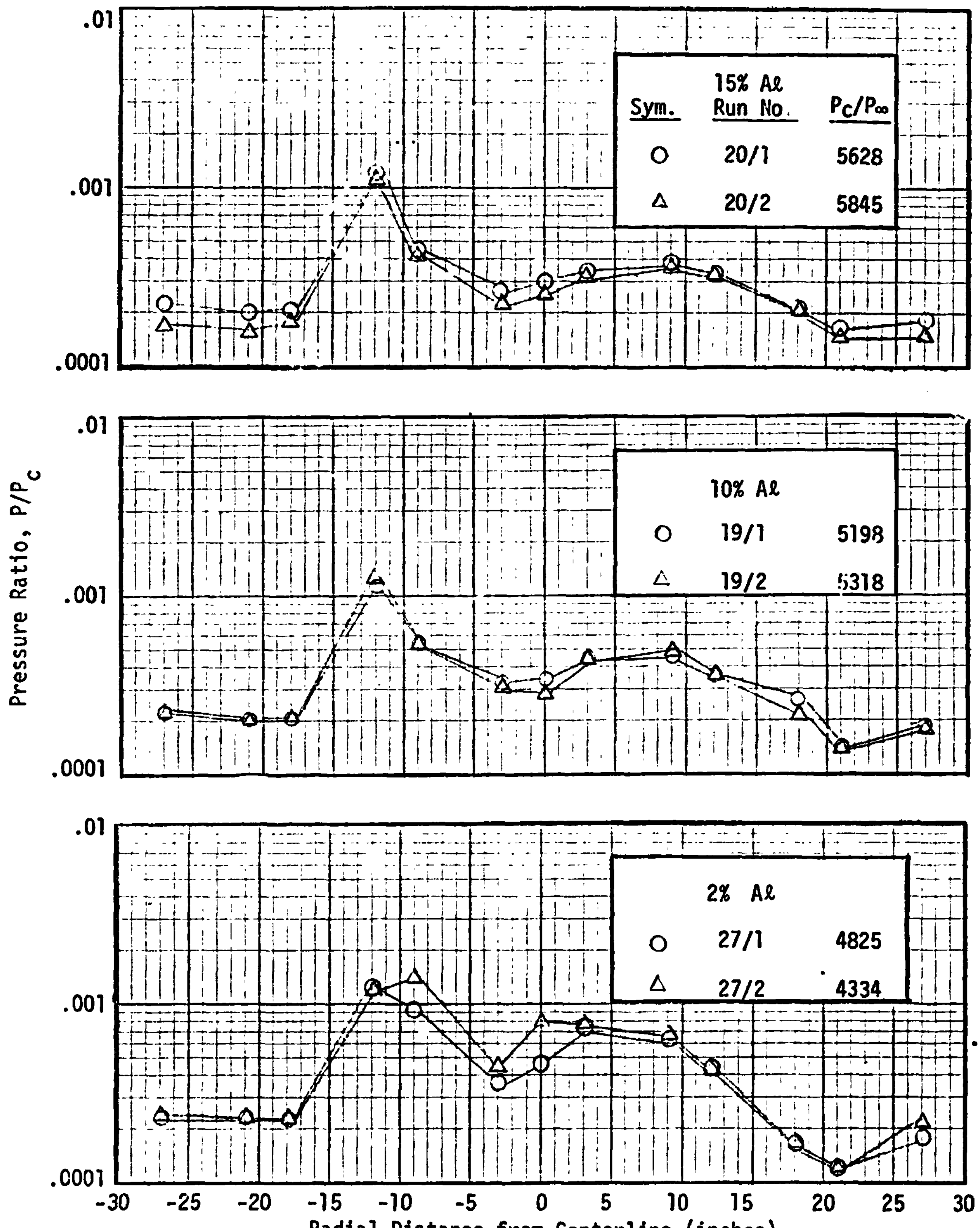


Fig. 20 (Continued)

e. X/D = 20, 100,000', ψ = 30°

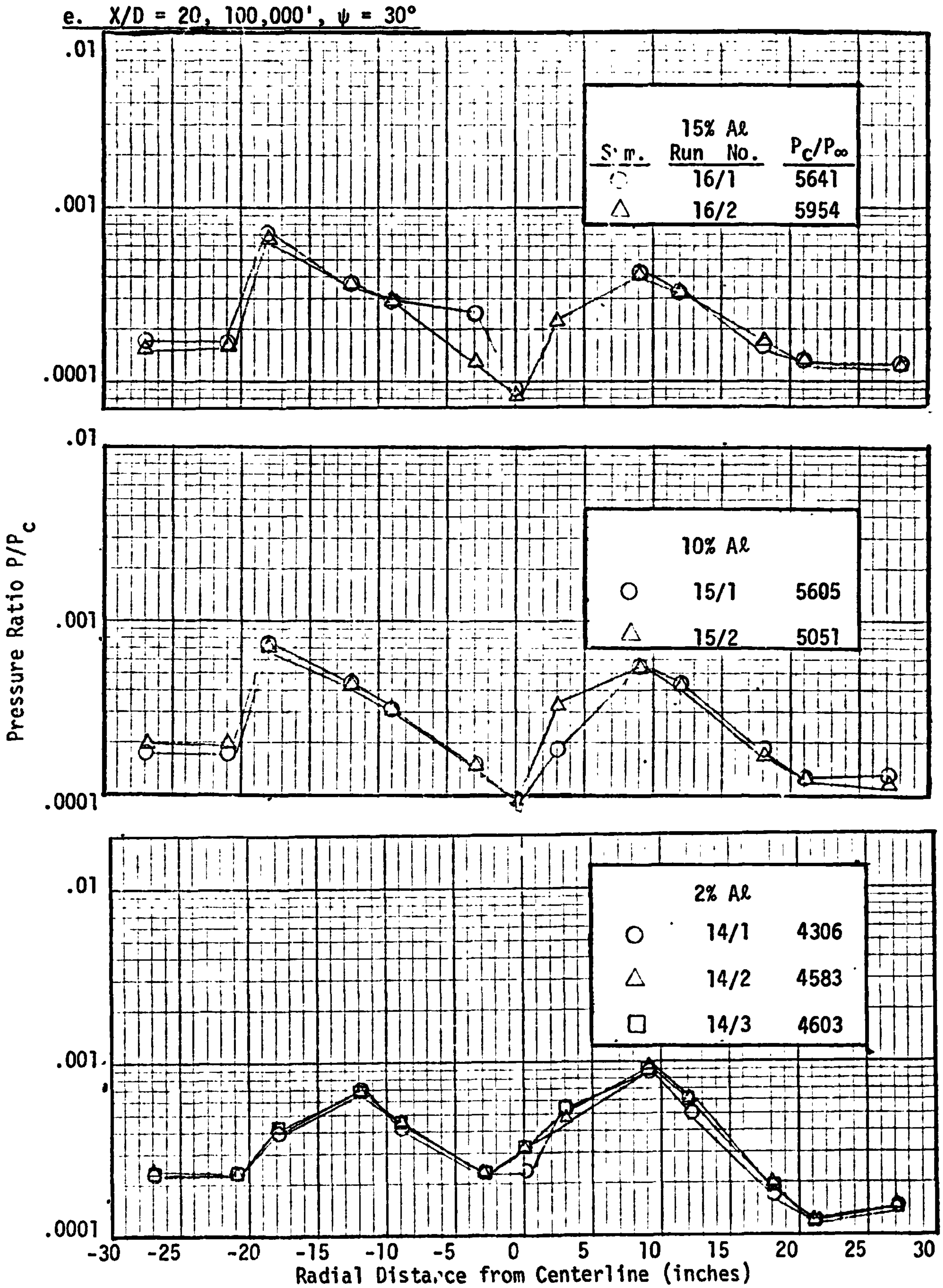


Fig. 20 (Continued)

f. X/D = 20, 100,000', ψ = 60°

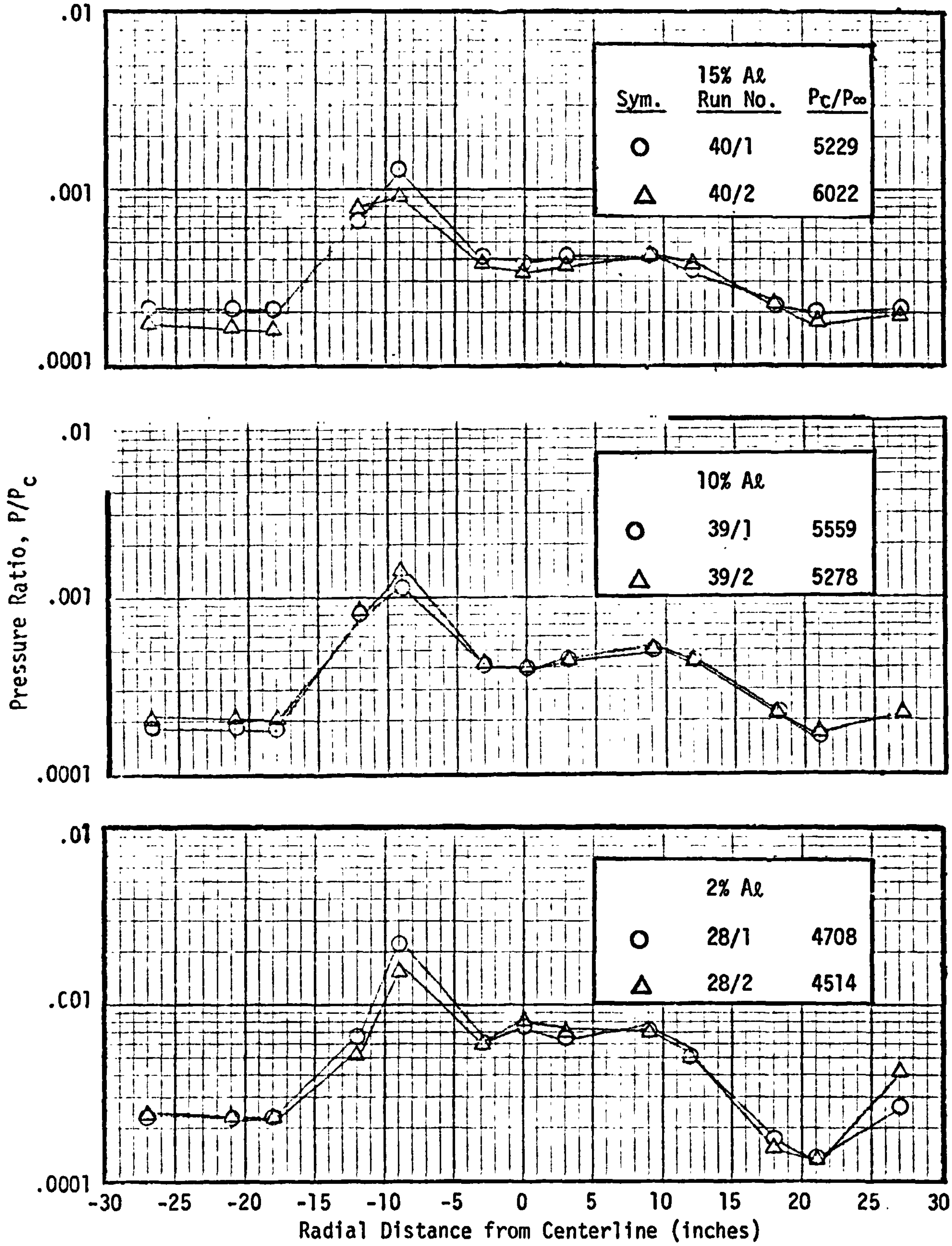


Fig. 20 (Continued)

g. X/D = 20, 100,000', ψ = 90°

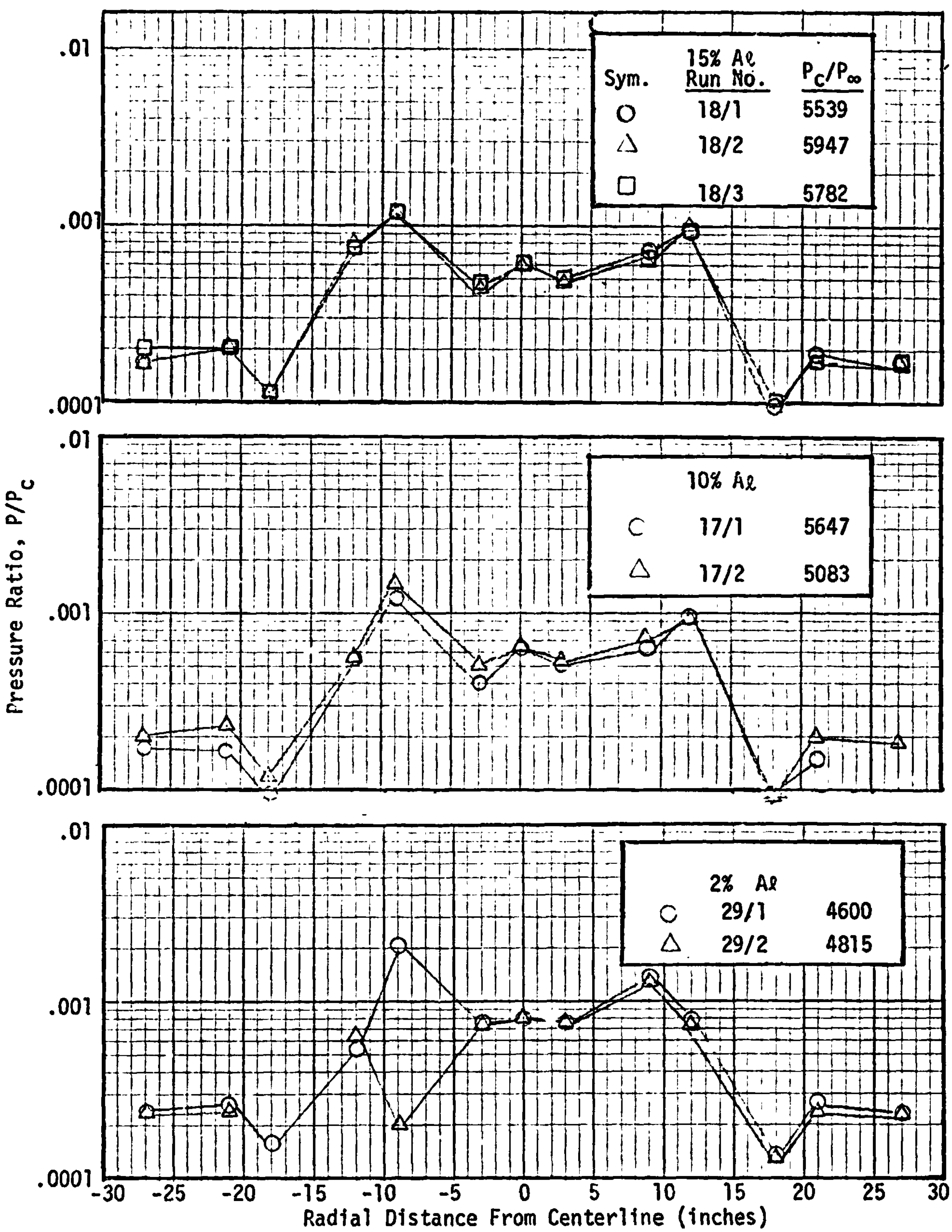


Fig. 20 (Concluded)

a. X/D = 5, 50,000'

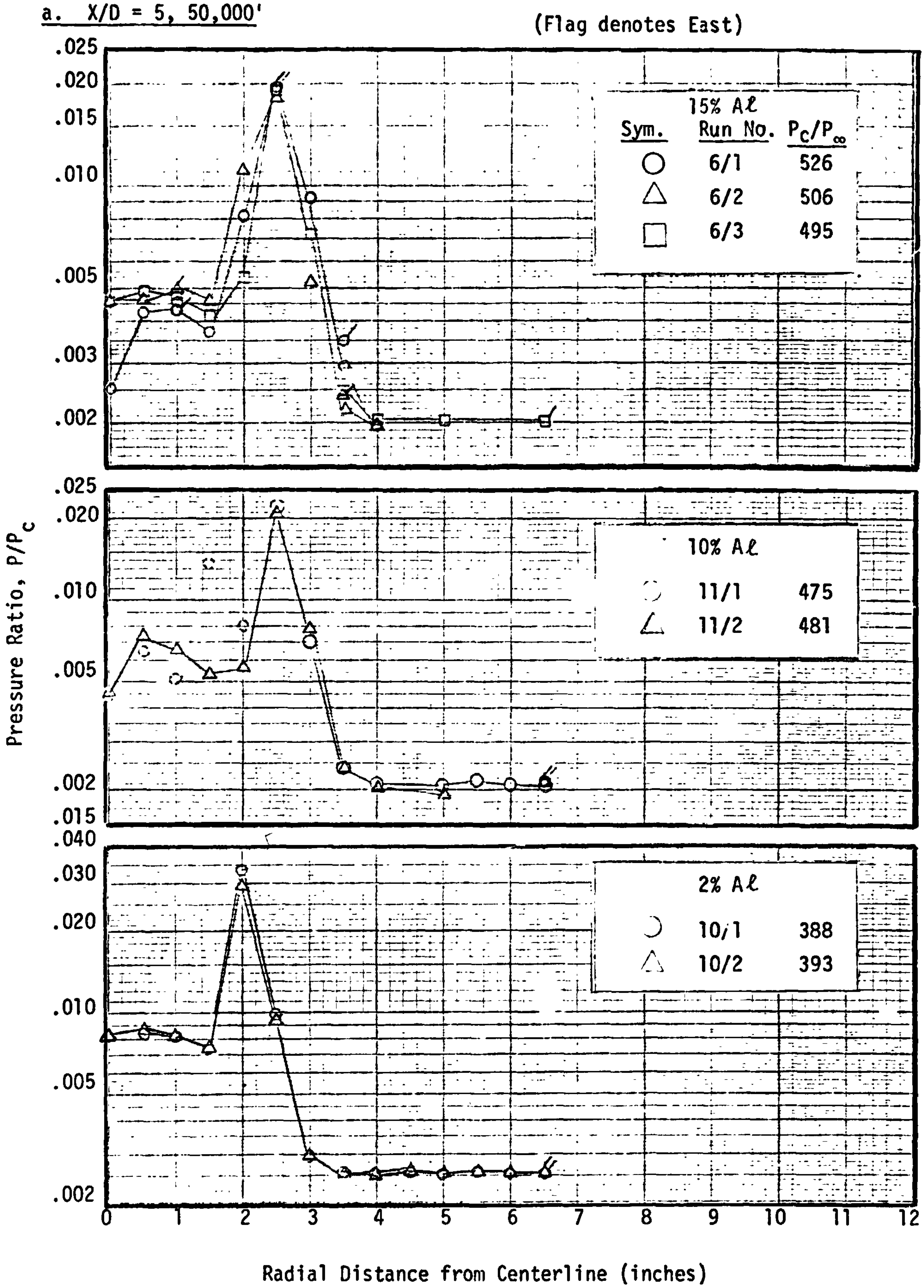


Fig. 21 Rake Data Summary

b. X/D = 5, 100,000'

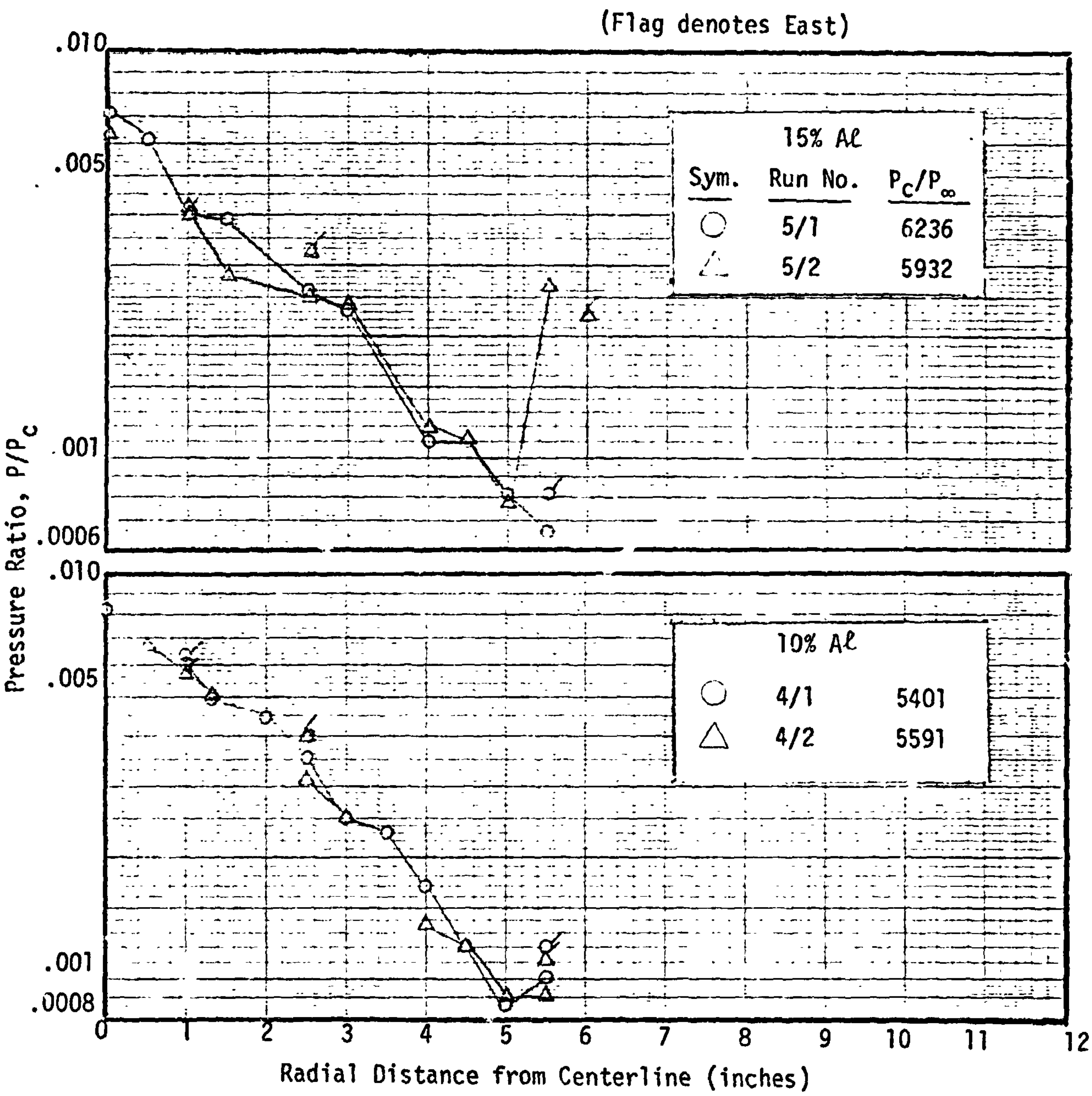


Fig. 21 (Continued)

c. X/D = 12, 100,000'

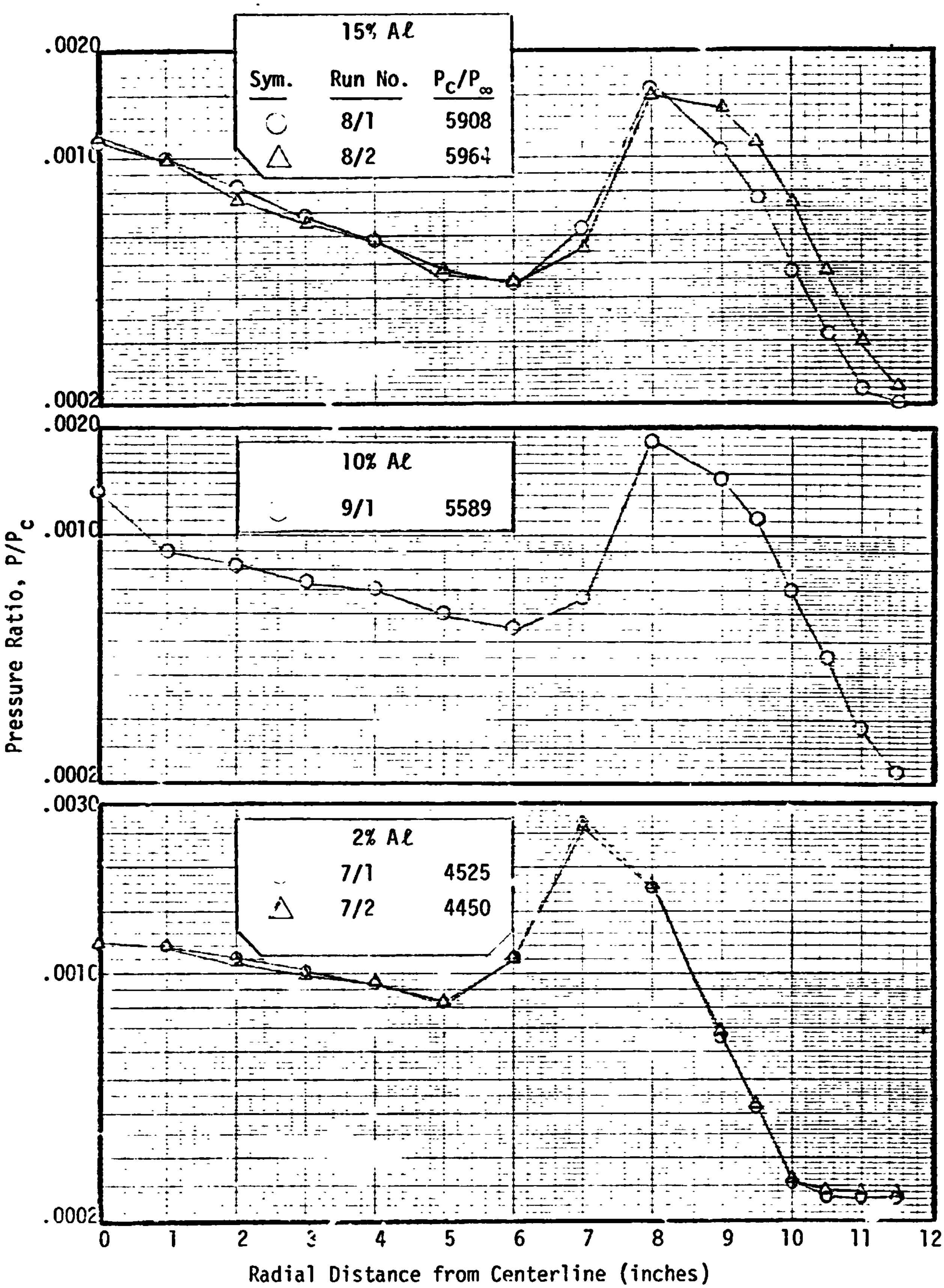


Fig. 21 (Continued)

d. X/D = 12, 112,000'

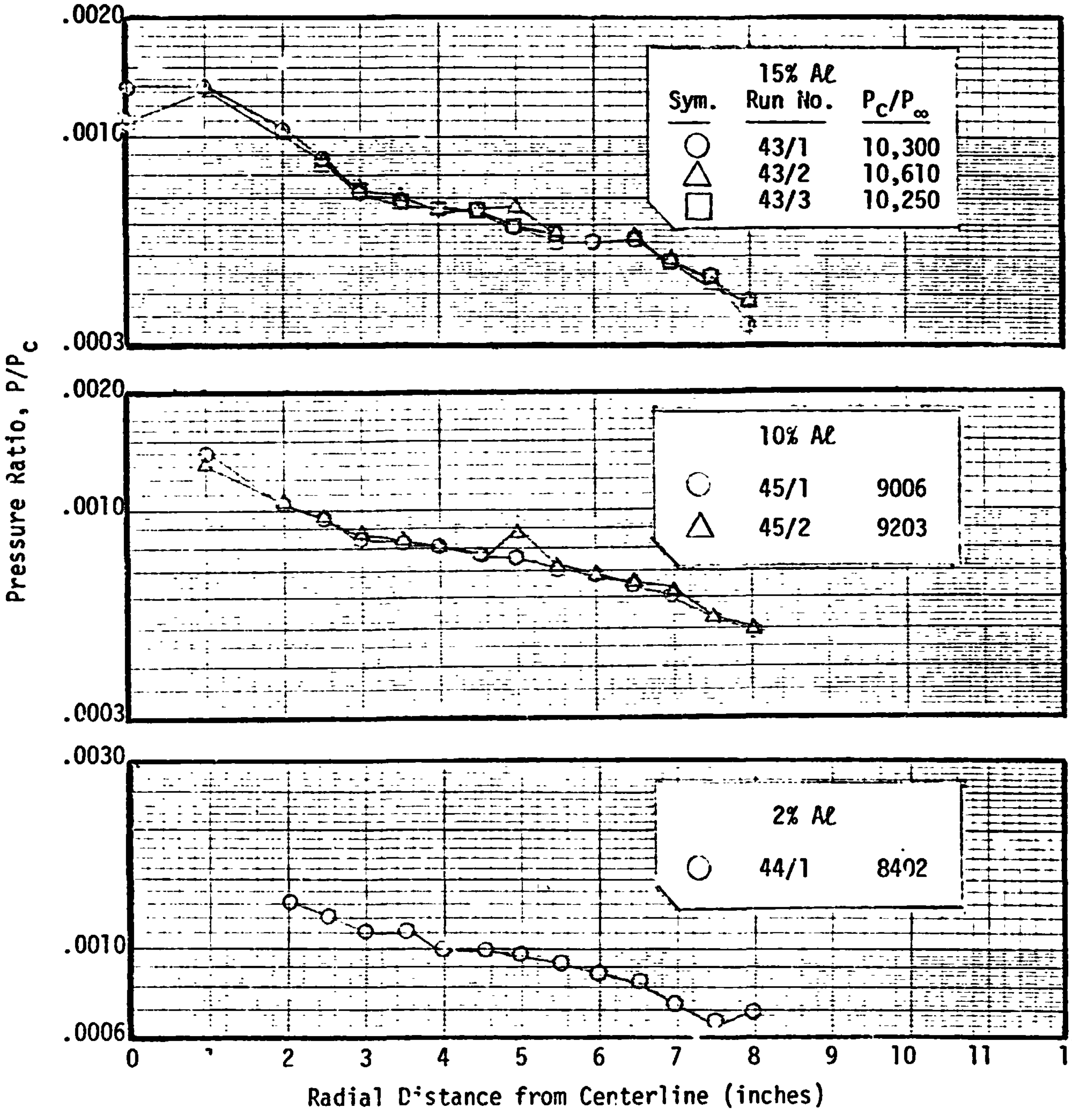


Fig. 21 (Continued)

e. X/D = 16, 100,000'

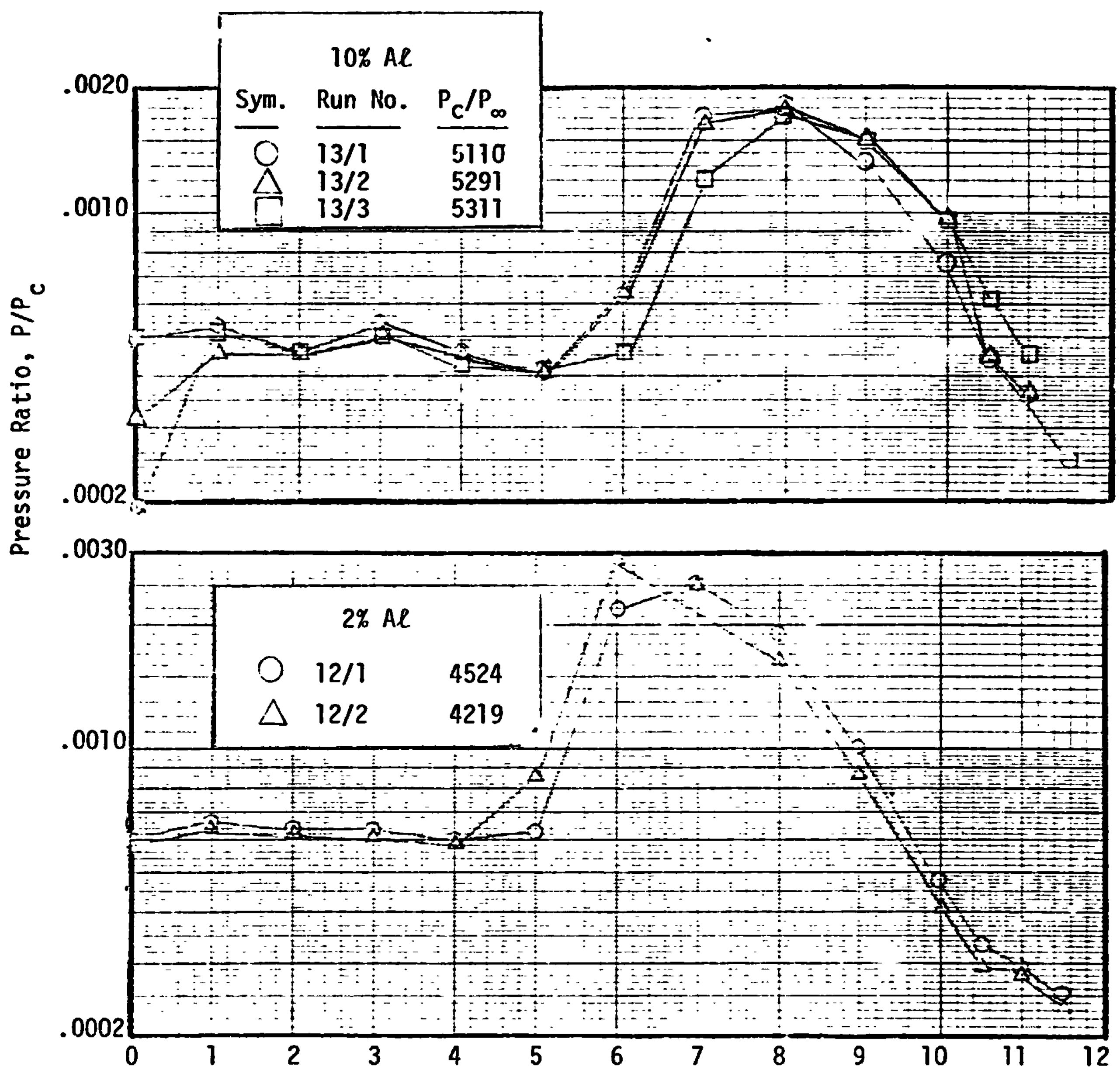


Fig. 21 (Continued)

f. X/D = 20, 100,000'

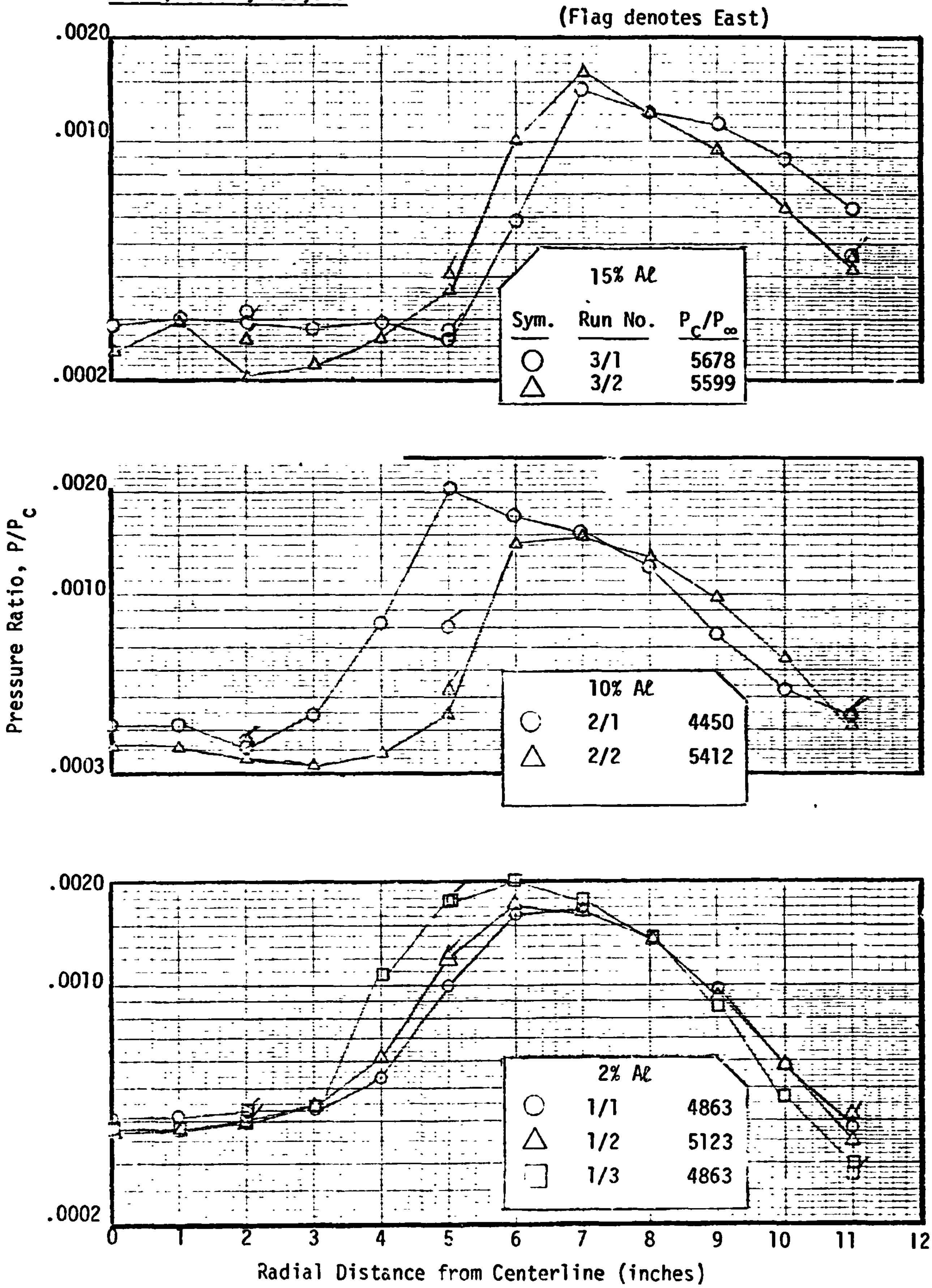


Fig. 21 (Continued)

g. X/D = 20, 112,000'

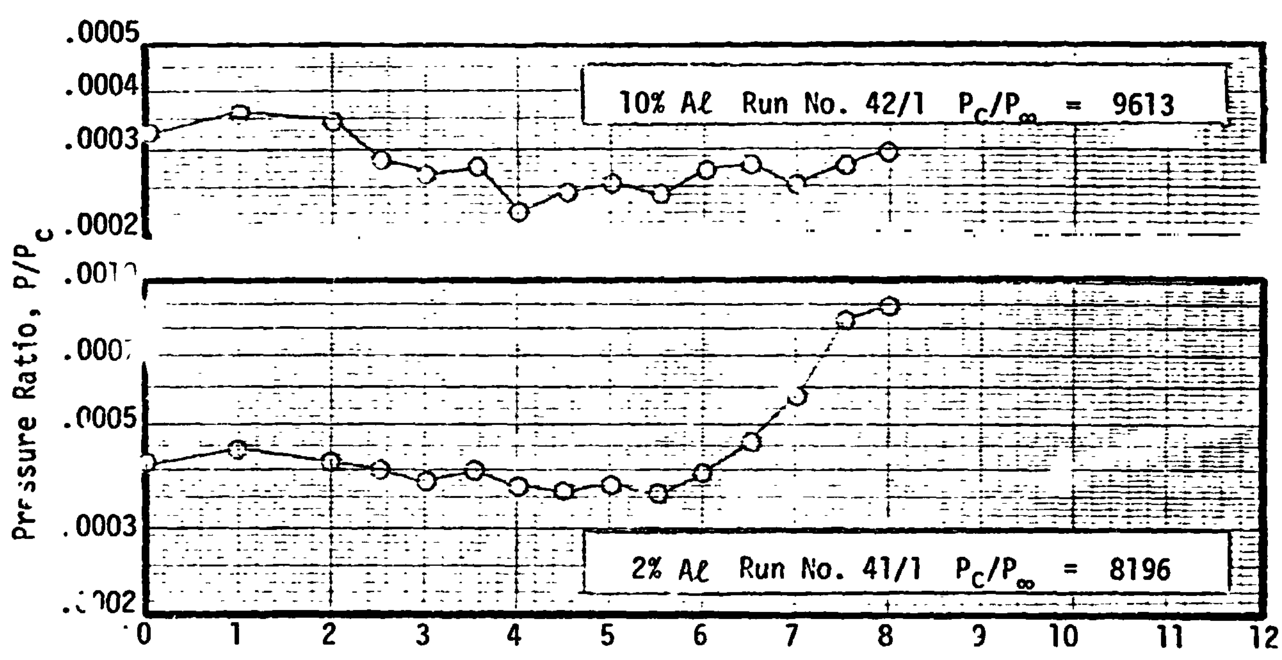


Fig. 21 (Concluded)

TABLE 1

CAPSULE OF FA-21 (HRWT-38) TEST

a. Summary (Showing Altitudes in Feet)
(No. of runs in parentheses)

	X/D = 5	X/D = 12	X/D = 16	X/D = 20	
Plate (ψ = 45°)	50K (6) 100K (6)	 100K (6)		 100K (26) (+ψ=30°,60°,90°)	6 38
Rake	50K (7) 100K (4)	 100K (5) 112K (6)	 100K (5)	 100K (7) 112K (2)	7 21 8
Particle		100K (4)		100K (6)	10
	23	21	5	41	90

b. Details (Showing Run Nos.)

Design P_c = 1000 psia

	X/D=5			X/D=12			X/D=16		X/D=20		
	2%	10%	15%	2%	10%	15%	2%	10%	2%	10%	15%
Plate ψ = 30°									14 ●●●	15 ●●	16 ●●
ψ = 45°	25 ●● 26 ▲▲	21 ●● 23 ▲▲	22 ●● 24 ▲▲	32 ●●	33 ●●	34 ●●			27 ●●	19 ●●	20 ●●
ψ = 60°									28 ●●	39 ●●	40 ●●
ψ = 90°									29 ●●	17 ●●	18 ●●●
Rake	10 ▲▲	4 ●● 11 ▲▲	5 ●● 6 ▲▲▲	44 ♦ 7 ●●	45 ♦♦ 9 ●	43 ♦♦♦ 8 ●●	12 ●●	13 ●●●	41 ♦ 1 ●●●	42 ♦ 2 ●●	3 ●●
Particle				31 ●●	35 ●	36 ●			30 ●●	37 ●●	38 ●●

♦ 112,000 feet pressure altitude
● 100,000 feet pressure altitude
▲ 50,000 feet pressure altitude

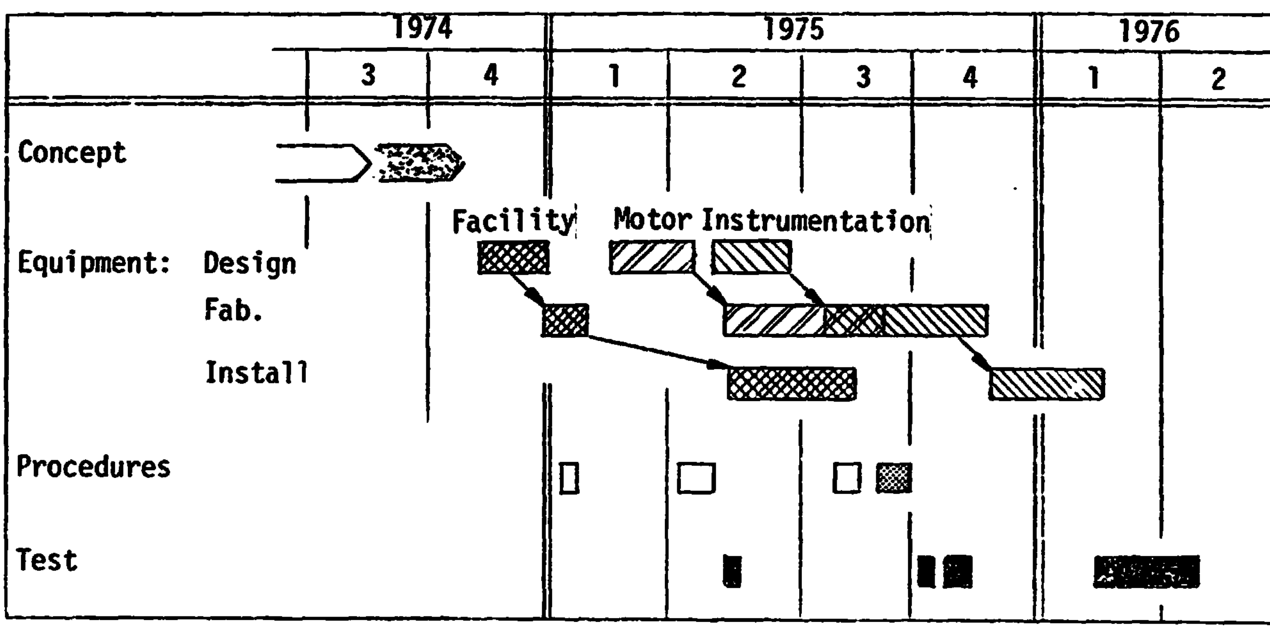
Runs were performed in Run No. Sequence, except:

1. 6/3 occurred after 11/2.
2. 14/2, 14/3 occurred after 27/2.
3. 43/2, 43/3 occurred after 45/2.

TABLE 2

SCHEDULE

a. Overview



Open = Preliminary
Shaded = Final

b. Test Phase

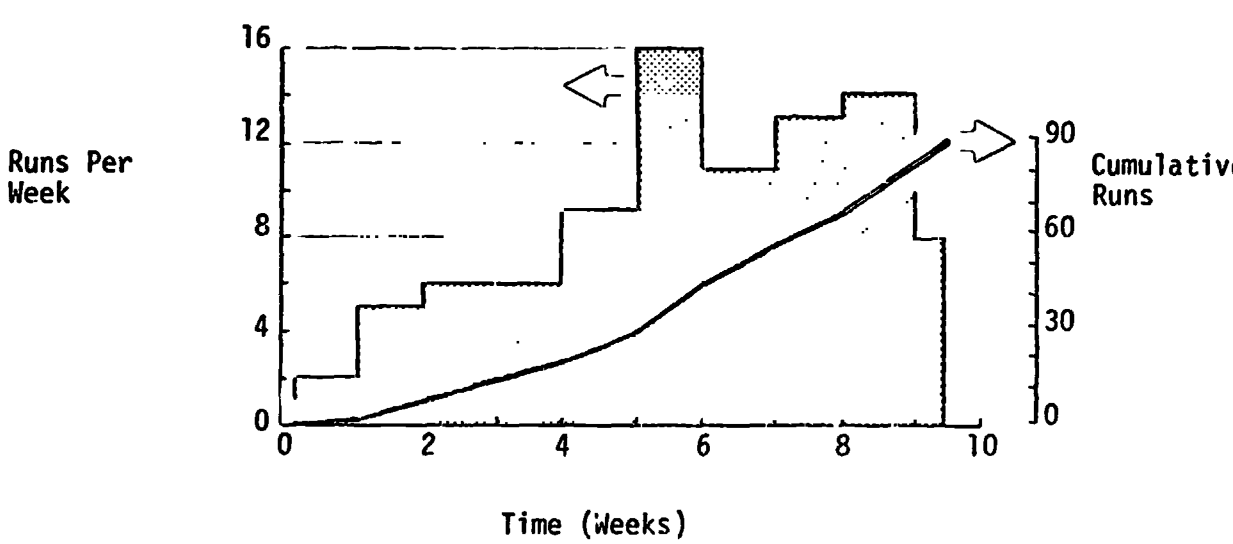
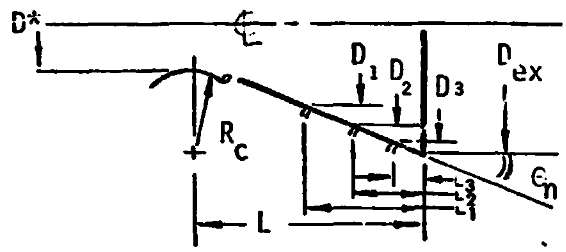


TABLE 3

MEASURED NOZZLE DIMENSIONS

Dimensions In Inches



$\varepsilon = A/A_* = (D/D_*)^2$

NOZ. S/N	Overall: θ_n ①	L ①	D_* ①	D_{ex} ①	ε	Wall Pressure Taps: L_1 ①	D_1	ε_1	L_2 ①	D_2	ε_2	L_3 ①	D_3	ε_3
1	15°01'	1.871	.5235	1.445	7.619	.95[illegible]	.930	3.159	.555	1.147	4.803	.147	1.366	6.810
2	14°57'	1.851	.5235	1.442	7.587	.951	.934	3.184	.550	1.148	4.811	.145	1.365	6.794
3	14°59'	1.840	.5230	1.444	7.623	.956	.932	3.178	.557	1.146	4.800	.149	1.364	6.804
4	15°02'	1.883	.5230	1.440	7.581	.946	.932	3.175	.554	1.142	4.771	.147	1.361	6.772
5	15°01'	1.857	.5235	1.441	7.577	.957	.928	3.139	.552	1.145	4.783	.148	1.362	6.765
6	15°07'	1.885	.5235	1.442	7.587	.958	.924	3.118	.555	1.142	4.760	.151	1.360	6.753
7	14°58'	1.871	.5230	1.444	7.623	.965	.928	3.149	.562	1.144	4.781	.152	1.363	6.789
8	15°02'	1.855	.5240	1.446	7.615	.960	.930	3.152	.556	1.147	4.794	.148	1.367	6.801
9	15°-	1.861	.5240	1.440	7.552	.947	.933	3.167	.555	1.143	4.755	.143	1.363	6.770
10	14°59'	1.841	.5235	1.442	7.587	.959	.929	3.147	.559	1.143	4.765	.151	1.361	6.761
11	15°-	1.899	.5235	1.442	7.587	.955	.930	3.157	.552	1.146	4.794	.147	1.363	6.781
12	15°02'	1.862	.5240	1.442	7.573	.955	.929	3.143	.552	1.145	4.779	.149	1.362	6.756
13	15°02'	1.845	.5235	1.447	7.640	.953	.935	3.191	.552	1.150	4.830	.146	1.369	6.834
14	15°03'	1.865	.5230	1.441	7.591	.950	.930	3.163	.551	1.145	4.790	.146	1.362	6.787
15	14°55'	1.871	.5230	1.443	7.613	.960	.932	3.172	.558	1.146	4.799	.153	1.361	6.777
16	15°-	1.858	.5230	1.443	7.613	.949	.934	3.192	.550	1.148	4.820	.143	1.366	6.825
17	15°-	1.860	.5230	1.441	7.591	.957	.928	3.149	.555	1.144	4.781	.149	1.361	6.773
18	14°58'	1.878	.5230	1.437	7.549	.963	.922	3.109	.563	1.136	4.718	.154	1.355	6.709
19	15°01'	1.862	.5235	1.446	7.630	.964	.929	3.148	.563	1.144	4.775	.151	1.365	6.799
20	14°59'	1.840	.5235	1.441	7.577	.949	.933	3.176	.553	1.145	4.784	.138	1.367	6.820
21	15°08'	1.849	.5230	1.446	7.644	.957	.928	3.151	.560	1.143	4.777	.154	1.363	6.789
22	15°04'	1.874	.5235	1.443	7.598	.968	.922	3.101	.553	1.145	4.786	.150	1.362	6.771
23	14°59'	1.855	.5230	1.441	7.591	.937	.939	3.227	.538	1.153	4.860	-	-	-
24	14°55'	1.869	.5230	1.443	7.613	.960	.932	3.172	.558	1.146	4.790	.148	1.364	6.803
25	14°56'	1.850	.5230	1.440	7.581	.949	.934	3.188	.550	1.147	4.807	.150	1.360	6.762
26	15°05'	1.851	.5230	1.438	7.560	.954	.924	3.120	.559	1.137	4.724	.152	1.356	6.723
27	15°01'	1.885	.5230	1.444	7.623	.963	.927	3.144	.560	1.144	4.781	.150	1.364	6.797
28	15°02'	1.844	.5230	1.445	7.634	.964	.927	3.143	.558	1.14[illegible]	4.795	.152	1.363	6.795
29	14°59'	1.869	.5235	1.441	7.577	.959	.928	3.140	.550	1.147	4.797	.147	1.362	6.772
30	14°59'	1.857	.5230	1.442	7.602	.949	.934	3.189	.552	1.147	4.806	.146	1.364	6.800

For S/N 1 - 12, R_c = 1.00 - 1.02 with average value of 1.01.

① Measured (other values were computed).

TABLE 4

PROPELLANT COMPOSITION AND EXHAUST PRODUCTS

(Mass Percentages)

Propellant Composition

Solids				Other	
	"2%"	"10%"	"15%"		
AL	2.%	10.%	15.0%	11.35%	HTPB (hydroxyl-terminated polybutadiene).
NH_4ClO_4	82.0	74.0	69.0	0.15	MT4 binding agent
				1.00	IPDI curing agent
				3.50	Plasticizer
	84.0%	84.0%	84.0%	16.00%	

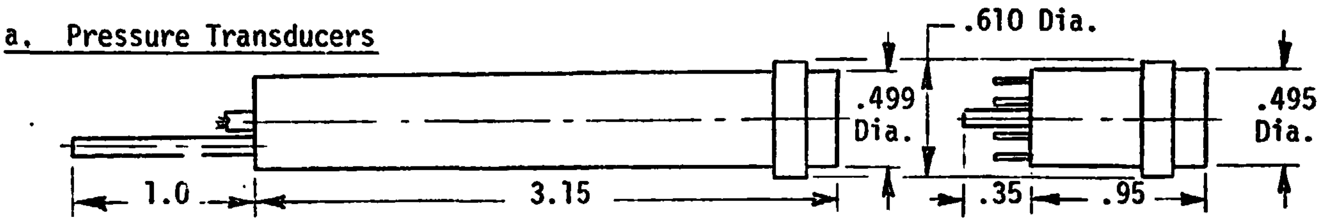
Estimated Rocket Exhaust Products

Product	% Aluminum		
	2%	10%	15%
Al_2O_3	4	19	28
H_2O	22	13	6
HCl	25	23	21
H_2	1	2	3
N_2	10	9	8
CO	22	28	31
CO_2	15	6	2
	(99)	(100)	(99)

TABLE 5

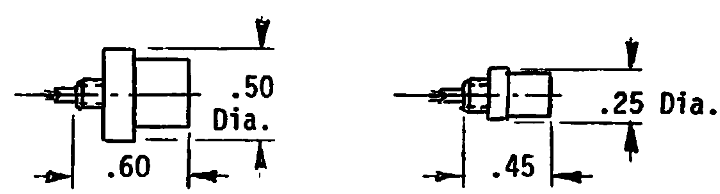
INSTRUMENTATION DEVICE CHARACTERISTICS

a. Pressure Transducers



Setra Model 237 | Statham Model PA208TC

Kistler



Model 601L | Model 603A

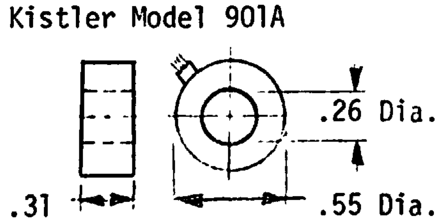
Parameter	(Units)	Statham 5	Statham 15	Statham 1500	Kistler 601L	Kistler 603A	Setra 237
Rated Pressure	(psia)	5	15	1500	.1-300	3000	+ 1 psid
Max. Pressure	(psia)	15	30	3000	1000	5000	100 pos.①
Temp. Limits	(°F)	← -65 - +250 →			← -450 - +500 →		30 - 150
Resolution	(psi)				.10	.05	
Non-Linearity	(%FS)	.75	.75	.75	.50	1.0	.25
Hysteresis	↓	.75	.75	.75			.10
Thermal Zero Shift	(%FS/°F)	.02	.01	.01			.01
Thermal Sensitivity	↓	.02	.01	.01	.01	.01	.015
Accel. Sensitivity	(%FS/g)	.2	.6	.01	.003	.00003	.02
@ Frequency	(Hz)	500	1200	6000			
Resonant Frequency	↓	2500	6000	30K	130K	400K	5000

(All dimensions in inches)

① 5 neg.

b. Load Washer

Kistler Model 901A



Rated Force	3500 lb.
Max. Force	3850 lb.
Temp. Limits	-400 - +500°F
Resolution	.01 lb.
Non-linearity	1%
Temp. Sensitivity	.01%/°F
Rigidity	15 x 10^{-8} in./lb.

TABLE 6
INSTRUMENTATION AND DATA SYSTEM CHANNEL ASSIGNMENTS

Position On Rake (No.)	(In.)	1A Run No 1/1 Ch. Type	1B 1/2-3/2 Ch. Type	2A 4/1 Ch. Type	2B 4/2,5/1 Ch. Type	2C 5/2 Ch. Type	3 6/1,6/2 Ch. Type	4 7/1-9/1 Ch. Type	5A 10/1-11/1 Ch. Type	5B 11/2, 6/3 Ch. Type	6A 12/1-13/1 Ch. Type	6B 13/2-13/3 Ch. Type
24	(West)							20 P_5			19 P_5	
23	11	18 P_5	17 P_5					19			18	18 P_5
22								18			17	17
21	10	17 P_5	16 P_5					17			16	16
20								16				
19	9	16 P_5	15 P_5					15			15 P_5	15 P_5
18												
17	8	10 P_1	14 P_5					14 P_5			14 P_5	14 P_5
16												
15	7	15 P_5	13 P_5					13 P_5			13 P_5	13 P_5
14									19 P_{15}			
13	6	14 P_5	12 P_5			17 P_{15}		12 P_5	18		12 P_5	12 P_5
12				17 P_{15}	17 P_{15}				17			
11	5	9 P_1	11 P_5	16	16	16 P_{15}		11 P_5	16	16 P_{15}	11 P_5	11 P_5
10				15	15	15			15	15		
9	4	13 P_5	9 P_1	14	14	14	14 P_{15}	10 P_5	14	14	10 P_5	10 P_5
8				13			13		13	13		
7	3	8 P_1	8 P_1	12	12	12	12	9 P_5	12	12	9 P_5	9 P_5
6				11	11	11	11		11	11		
5	2	7 P_1	7 P_1	10			10	6 P_5	10	10	8 P_5	8 P_5
4				9	9	9	9		9	9		
3	1	6 P_1	6 P_1	8	8	8	8	7 P_5	8	8	7 P_5	7 P_5
2				7	7	7	7		7	7		
1	℄	5 P_1	5 P_1	6	6	6	6	8 P_5	6	6	6 P_5	19 P_5
32				21 Q								
33	-1	20 Q	20 Q	18 P_{15}	18 P_{15}	18 P_{15}	18 P_{15}					
34				22 Q		22 Q	25 Q					
35	-2	11 P_1	10 P_1	26 T_1	26 T_1	26 T_1	26 T_2	25 F	25 F	25 F	25 F	25 F
36				19 P_{15}	19 P_{15}	19 P_{15}	19 P_{15}					
37	-3	21 Q	21 Q	23 Q	23 Q	23 Q	23 Q					
38							20 P_{15}					
39	-4	25 T_1	25 T_1	24 Q	24 Q	24 Q	24 Q	21 Q	21 Q	21 Q	21 Q	21 Q
40									22 Q	22 Q		
41	-5	12 P_1	18 P_5	25 Q	25 Q	25 Q		26 T_2	26 T_2	26 T_2	26 T_2	26 T_2
42				20 P_{15}	20 P_{15}				23 Q	23 Q		
43	-6	22 Q	22 0			20 P_{15}		22 Q	24 Q	24 Q	22 Q	22 Q
44									20 P_{15}			
45	-7	26 T_1	26 T_1									
46												
47	-8	23 Q	23 Q					23 Q			23 Q	23 Q
48												
49	-9	27 T_1	27 T_1								24 Q	24 Q
50												
51	-10	24 Q	24 Q					24 Q				
52												
53	-11	19 P_5	19 P_5									
54	(East)											
P_{c1} (Kistler)		1	1	1	Constant for remainder of test.							
P_{n1}		2	2	2								
P_{n2}		3	3	3								
P_{n3}		4	4	4								
P_{c2} (Statham)			28	5								

TABLE 6 (Concluded)

Position On Plate (No.)	Position On Plate (In.)	7 ① 14/1-20/2, 27/1-40/2 Ch. Type
	(East) (far)	
1	27	6 P_5
2	24	21 Q
3	21	7 P_5
4	18	8 ↓
5	15	22 Q
6	12	9 P_5
7	9	10 ↓
8	6	23 Q
9	3	11 P_5
10	℄	12 ↓
11	-3	13 ↓
12	-6	24 Q
13	-9	14 P_5
14	-12	15 ↓
15	-15	25 Q
16	-18	16 P_5
17	-21	17 ↓
18	-24	26 Q
19	-27	18 P_5
	(near) (West)	
	(North)	
21	2.5	27 Q
20	-2.5	19 P_5
	(South)	
Camera Events		13

Position On Plate (No.)	Position On Plate (In.)	8A 21/1 Ch. Type	8B 21/2-26/2 Ch. Type
	(West) (far)		
19	27	18 P_{15}	18 P_5
18	24	26 Q	26 Q
17	21	17 P_{15}	17 P_5
16	18	16 ↓	16 ↓
15	15	25 Q	25 Q
14	12	15 P_{15}	15 P_5
13	9	14 ↓	14 ↓
12	6	24 Q	24 Q
11	3	13 P_{15}	13 P_{15}
10	℄	12 ↓	12 ↓
9	-3	11 ↓	11 ↓
8	-6	23 Q	23 Q
7	-9	10 P_{15}	10 P_5
6	-12	9 ↓	9 ↓
5	-15	22 Q	22 Q
4	-18	8 P_{15}	8 P_5
3	-21	7 ↓	7 ↓
2	-24	21 Q	21 Q
1	-27	6 P_{15}	6 P_5
	(near) (East)		
	(North)		
21	2.5	27 Q	27 Q
20	-2.5	19 P_{15}	19 P_{15}
	(South)		
Camera Events		13	13

Position On Rake (No.)	Position On Rake (In.)	9A 41/1-43/1, 44/1 Ch. Type	9B 45/1, 45/2 Ch. Type	9C 43/2, 43/3 Ch. Type
24	(West)			
23	11			
22				
21	10			
20				
19	9			
18				
17	8	20 P_5	20 P_5	20 P_5
16		19 ↓	19 ↓	19 ↓
15	7	18	18	18
14		17	17	17
13	6	16	16	6 P_{10}
12		15	15	15 P_5
11	5	14	14	14 ↓
10		13	13	13
9	4	12	12	12
8		11	11	11
7	3	10	10	10
6		9	9	9
5	2	8	8	8
4				
3	1	7 P_5	7 P_{10}	7 P_{10}
2				
1	℄	6 P_5	6 P_{10}	16 P_5
32				
33	-1			
34				
35	-2			
36				
37	-3	24 F	24 F	24 F
38				
39	-4			
40				
41	-5			
42				
43	-6	21 Q	21 Q	21 Q
44				
45	-7	23 T_2	23 T_2	23 T_2
46				
47	-8	22 Q	22 Q	22 Q
48				
49	-9			
50				
51	-10			
52				
53	-11			
54	(East)			

① For 10 Particle Sampling Runs (30/1-31/2, 35/1-38/2), only motor pressures (Ch. 1-5) were recorded.

P_1 Setra pressure transducer, ± 1.0 psid
P_{XX} Statham pressure transducer, xx psia
Q Heat rate gage, 600 Btu/ft²/sec
T_1 Thermocouple, original design
T_2 Thermocouple, improved design

TABLE 7

TEST PROCEDURE

A. MOTOR PREPARATION (Outside of Sphere)

1. Obtain next S/N nozzle and place in retainer using o-rings (2).
2. Install nozzle pressure taps.

B. SPHERE PREPARATION STEP 1 (As Req'd by Run Schedule)

1. Position plume instrumentation (rake/plate) as required.
2. Verify functioning of instrumentation (span, leak, etc.).
3. Full calibration each Monday a.m.
4. Stack catwalks at west end of scaffold.

C. SPHERE PRFPARATION STEP 2 (Every Run)

1. Check O-ring in firing head.
2. Mount nozzle/retainer/tap assy. on dummy motor in firing head.
3. Connect nozzle and P_c taps to transducers.
4. Remove non-essential personnel and equipment from sphere (see list).

D. MOTOR INSTALLATION

1. In control room, insure firing box safety shunt on "UNARMED".
2. Put on face shield, gloves, ear protectors; get magazine keys and firing box key.
3. Obtain correct loaded % Aℓ propellant case, and igniter (2 people or 2 trips)
4. Set propellant case into firing head (replacing dummy).
5. Set igniter into inside of nozzle, using special pushing tool.
6. Attach nozzle/retainer/igniter assy. to firing head with 4 bolts.
   →motor now live←
7. Recheck alignment of rake/plate to motor using brass jig, level, and plumb bob.
8. Remove all lights except one. (Only one man in cell at this time).
9. Check firing circuit for stray current. (Do not proceed if current detected). Place shunt in shunt box.
10. Place alligator clamp across lower igniter leads near insulation, untwist leads, and attach to shunt box.
11. Remove clamp and shunt, and exit sphere. (Keep head below level of nozzle exit plane while near motor mount).

E. TEST CONDITION

1. Close sphere door.
2. Check continuity of circuit using firing box in control room, w/o moving fire switch.
3. If discontinuous, put on safety equipment and reverse order of motor installation beginning at D-9 above to discover cause.
4. If continuous, turn off fire box, turn shunt to safe position.
5. Depressurize sphere to desired altitude simulation.

TABLE 7 (Concluded)

F. DATA TAKING

1. Check data system--on and ready; turn on all power switches.
2. Take sensitivity reading and pre-fire zeros using computer (within 30-60 seconds of firing).
3. Turn igniter box shunt to "ARMED" and make final continuity check.
4. If discontinuous, proceed as per E-3 above.
5. If continuous, turn key to "ARMED".
6. Turn on power supply to particle sampler motor (particle runs only).
7. Plug in movie camera brake (movie run only).
8. When at desired pressure trigger camera timer (movie run only).
9. Push "FIRE" switch forward (when timer reaches 1.5 second for movie run). Hold for 5 sec.
10. Observe pressure gage for increase in pressure and listen for low rumble.
11. Turn key to "SAFE" and remove; put shunt in "UNARMED" position.
12. Unplug camera brake (movie run only).
13. Turn off particle sampler motor power supply (particle sampling run only).
14. If misfire--no pressure increase; no rumble--proceed as in E-3 above.

G. RECOVERY OUTSIDE SPHERE

1. Close pump valve and vent sphere to atmosphere.
2. Pump down to 200 mm and vent again--do this twice. (Final procedure was to leave pumps on and vent to atmosphere then pump to 400 mm and vent again with pumps on).
3. Open cell door.

H. RECOVERY INSIDE SPHERE

1. Replace lights and scaffolding as needed.
2. Remove nozzle and spent motor (back to step A-1).
3. Inspect hardware and instrumentation for damage, corrosion, excessive dust, burns, etc.
4. Clean motor mount and instrumentation, especially pressure taps/probes.
5. Reapply protective grease as necessary.
6. Detach and blow out both P_c leads - run wire through leads if necessary to dislodge debris.

ESSENTIAL EQUIPMENT LIST

Lantern
Firing box keys
Ammeter
Shunt for firing leads
Igniter pushing tool
Hex wrench for ½-13 cap screw
Brass alignment jig
Level
Plumb bob
Alligator clamp

TABLE 8

PLUME INSTRUMENTATION ALIGNMENT PROCEDURE

A. RAKE

1. Install dummy probe in centerline position.
2. Touch two widely spaced probe tips with steel ruler.
3. Move one probe tip down until ruler is level as determined by bubble level.
4. Bring all other probes down until the tips touch the ruler.
5. Adjust spacing by slightly bending tips or loosening and retightening holding bolts.
6. Adjust height roughly by moving mounting block extension.
7. Place alignment jig in nozzle and check level of nozzle.
8. Adjust motor mount hand cranks until plumb bob centers on jig cross-hairs.
9. Adjust height using mounting block hand crank and measuring distance from nozzle exit center to center probe.
10. Re-check plumb.
11. Remove dummy probe and align centerline probe as in steps 4 and 5.

B. PLATE

1. Adjust plate angle ψ.
2. Proceed as in steps a.6 - a.10 above except that plumb bob string hand-held to center tap.

C. PARTICLE SAMPLER

1. Adjust ψ to 90°.
2. Install disk and clamp cover over it.
3. See that disk rotates freely under power.
4. Proceed as in steps a.6 - a.10 above except plumb bob will have to be hand-held to narrow end of slot and height measured to this point.

TABLE 9

PLUME INSTRUMENTATION ALIGNMENT ACCURACY

Device	Parameter	Estimated Accuracy
Rake	Ruler Level	± 1°
Rake	Tip Height above Ruler Δx (See Below)	± .03 inches
Rake	Probe Tip Spacing	± .03 inches
Rake, plate, sampler	Height above Nozzle Exit	± .03 inches
Rake, plate, sampler	East - West Center	± .02 inches
Rake, plate, sampler	North - South center	± .02 inches
Plate	Plate Incident Angle	± .67°

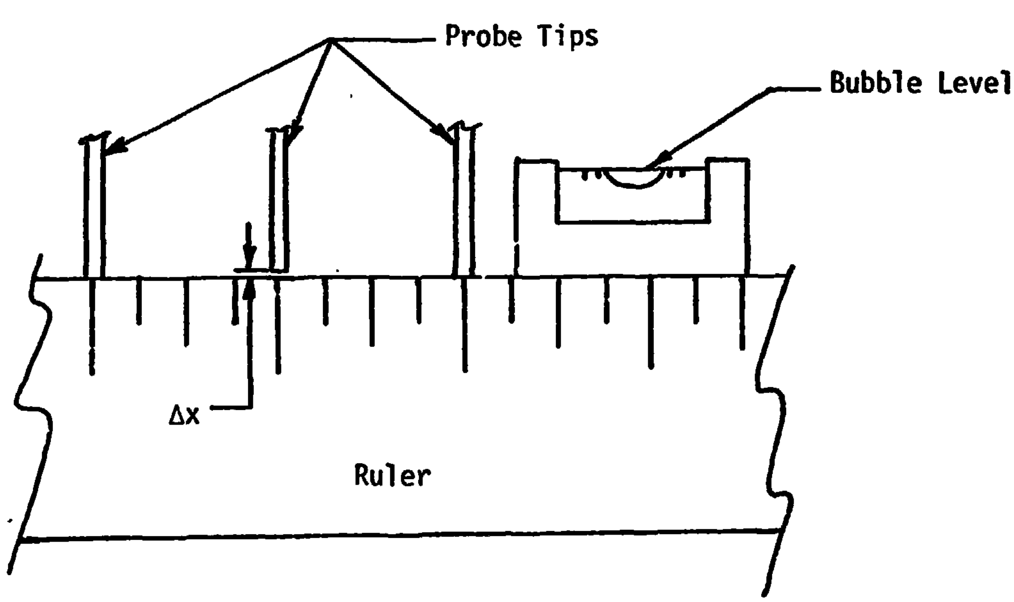


TABLE 10

RUN LOG

CHRONOLOGY				NOM. COND.		ROCKET S/N		ACTUAL CONDITION		INSTRUMENTATN.						REMARKS
SEQ NO.	RUN NO.	DATE	TIME	ALT. (ft)	% AL	NOZ	CASE ①	P_C ② psia	P_∞ mmHg	[illegible]	ψ	X/D	X	③	movie	
1	1/1	2/17	1015	100K	2	1	20A=A	-	8.60	R		20	28.73	1A		P_{41} N.G.; P_{11}, P_{17} overscale.
2	1/2	2/20	1545			2	20A=B	860	8.65	A				1B		P_{C1}, P_{N1-N3} not on (Kistlers).
3	1/3	2/23	1400			3	20A=C	773	8.70	K						
4	2/1	2/24	1040		10	4	19A=A	749	8.70	E						Q_{33} deteriorated.
			1500			5	19A=B									No fire.
		2/25	0900				19A=C									No fire.
5	2/2		1050				19A=D	909	8.68							P_{C1} N.G. (Kistler).
6	3/1		1430		15	6	18A=A	955	8.70							P_{C1} N.G. (Kistler).
7	3/2	2/26	1035			7	18A=B	942	8.70							
8	4/1	3/02	1035		10	8	19A=E	904	8.65			5	7.22	2A		P_1, P_2, Q_{32} destroyed; Q_{34} over-
9	4/2	3/03	1130			9	19A=F	935						2B		P_1 damaged. scale.
10	5/1		1520		15	10	18A=C	1043								
11	5/2	3/04	1125			11	18A=D	992						2C		P_2 destroyed.
12	6/1	3/05	0840	50K		12	18A=E	986	97.0					3		P_1 bent; improved T/C instl.
13	6/2		1305			13	18A=F	949								P_{C1} N. G. (Kistler).
14	7/1	3/10	1605	100K	2	14	20A=D	761	8.70			12	17.30	4		Added force gage.
15	7/2	3/11	0950			15	20A=E	745	8.65							
16	8/1		1215		15	16	18A=G	988								
17	8/2		1440			17	18A=H	998								
18	9/1		1645		10	18	19A=G	940	8.70							
19	10/1	3/12	1535	50K	2	19	20A=E	726	96.9			5	7.21	5A		P_1 N.G.
20	10/2	3/15	1135			20	20A=G	749	98.5							
21	11/1		1340		10	21	19A=H	890	97.0							P_1 destroyed; P_2. P_3. P_4. damaged.
22	11/2		1600			22	19A=I	902						5B		
23	6/3	3/16	0920		15	23	18A=I	928								
24	12/1	3/17	1600	100K	2	24	20A=H	761	8.70			16	23.07	6A	x	P_{C2} plugged; added camera.
25	12/2	3/18	0710			25	20A=I	710								P_{C2} plugged.
26	13/1		0925		10	26	19A=J	860							x	P_1 N. G.
27	13/2		1140			27	19A=B	901	8.8					6B		P_1 plugged.
28	13/3		1420			28	19A=C	894	8.7							Force N. G.
29	14/1	3/22	1200		2	29	20A=J	724		P	30°	20	28.86	7.	x	Q_8, Q_{18} N. G.
30	15/1		1515		10	30	19 =A	943		L					x	Plate plating deteriorating.
31	15/2	3/23	0715			1	19 =B	850	8.70	A					x	Q_{12}, Q_{15} N.G.
32	16/1		0935		15	2	18A=J	949		T					x	
33	16/2		1145			3	18 =A	1002		E					x	
34	17/1		1425		10	4	19 =C	950			90°				x	P_{C1} Incorrect sensitivity
35	17/2	3/24	0715			5	19 =D	855							x	P_{C1} N. G. (Kistler)
36	18/1		0920		15	6	18 =B	932							x	
37	18/2		1125			7	18 =C	1001							x	
38	18/3		1355			8	18 =D	973							x	
39	19/1	3/25	0710		10	9	19 =E	875			45°				x	
40	19/2		0920			10	19 =F	890	8.65						x	P_{C2} N.G.(plugged) (Statham).
41	20/1		1120		15	11	18 =E	947	8.70						x	P_{C2} dirty.
42	20/2		1355			12	18 =F	983							x	
43	21/1	3/26	1015		10	13	19 =G	895				5	7.21	8A	x	Q_{18} N.G.
44	21/2		1510			14	19 =H	898						8B	x	Q_{18} N.G., P_{10} plugged.
45	22/1	3/29	0845		15	15	18 =G	936	8.65						x	P_{10} plugged; no RTV on P_{C2} xdcr.
46	22/2		1110			16	18 =H	983	8.70						x	
47	23/1		1310	50K	10	17	19 =I	957	97.0						x	P_{10} eroded; P_{N2} tap loose.
48	23/2		1450			18	19 =J	954							x	P_{10} eroded; P_{11} over scale.
49	24/1		1625		15	19	18 =I	1005							x	
50	24/2		1750			20	18 =J	1024							x	

TABLE 10

(Concluded)

CHRONOLOGY				NOM. COND.		ROCKET S/N		ACTUAL CONDITION		INSTRUMENTATN.						REMARKS
SEQ NO.	RUN NO.	DATE	TIME	ALT. (ft)	% AL	NOZ	CASE ①	P_c ② psia	P_∞ mmHg	[illegible]	ψ	X/D	X	③	[illegible]	
51	25/1	4/01	1600	100K	2	21	20 =A	730	8.70	PLATE	45°	5	7.21	3B	x	
52	25/2	4/02	0715			22	20 =B	772							x	
53	26/1		1020	50K		23	20 =C	777	97.0						x	
54	26/2		1150			24	20 =D	779							x	
55	27/1		1540	100K		25	20 =E	812	8.70			20	28.84	7	x	
56	27/2	4/05	0935			26	20 =F	729							x	
57	14/2		1155			27	20 =G	771			30°				x	P_{C1} N.G. (Kistler).
58	14/3		1410			28	20 =H	774							x	
59	28/1	4/06	0715			14	20 =I	792			60°				x	Added smoothing to Q data.
60	28/2		0930			30	20 =J	760							x	
61	29/1		1145			1	20 =K	774			90°				x	P_{C2} N.G. (plugged)
62	29/2		1420			2	20 =L	810							x	P_{16} N.G.
63	30/1	4/07	1025			3	20 =M	-							x	Ⓟ; all channels off.
64	30/2		1425			4	20 =N	815							x	Ⓟ; ign. plug hit wax.
65	31/1	4/08	0715			5	20 =O	765				12	17.31		x	Ⓟ N.G., disk did not ro-
66	31/2		1005			6	20 =P	750							x	Ⓟ tate
67	32/1		1425			7	20 =Q	796			45°				x	
68	32/2	4/09	0900			8	20 =R	749							x	P_{17} N.G.
69	33/1	4/12	0850		10	9	19 =A	844							x	
70	33/2		1055			10	19 =B	886							x	
71	34/1		1350		15	11	18 =A	1002							x	
72	34/2	4/13	0710			12	18 =B	940							x	
73	35/1		1010		10	13	19 =C	846	8.65		90°				x	Ⓟ
74	36/1		1225		15	29	18 =C	967	8.70						x	Ⓟ; alignment jig in noz-
75	37/1		1520		10	15	19 =D	950				20	28.85			Ⓟ zle
76	37/2	4/14	0720			16	19 =E	845								Ⓟ
77	38/1		0920		15	17	18 =D	987								Ⓟ; alignment not veri- fied.
78	38/2		1120			18	18 =E	996								Ⓟ; used red wax.
79	39/1		1430		10	19	19 =F	935			60°					P_1 N.G.
80	39/2	4/15	0850			20	19 =G	888							x	
81	40/1		0940		15	21	18 =F	880							x	P_{C2} Appears too low
82	40/2		1230			22	18 =G	1013							x	
83	41/1	4/19	1015	112K	2	23	20 =S	793	5.00	RAKE				9A	x	T_{45} N.G., F not connected
84	42/1		1330		10	24	19 =H	948	5.1						x	T_{45} N.G., F N.G.
85	43/1	4/20	0905		15	25	18 =H	1016	5.1			12	28.84		x	P_9 N.G. ④
86	44/1		1215		2	26	20 =T	812	5.05						x	P_1P_3 damaged
87	45/1		1600		10	27	19 =I	888	5.1					9B	x	P_1 N.G.
88	45/2	4/21	0850			28	19 =J	908	5.1						x	
89	43/2		1155		15	1	18 =I	1026	5.0					9C	x	P_{13} N.G.
90	43/3		1450			30	18 =J	1011	5.1						x	

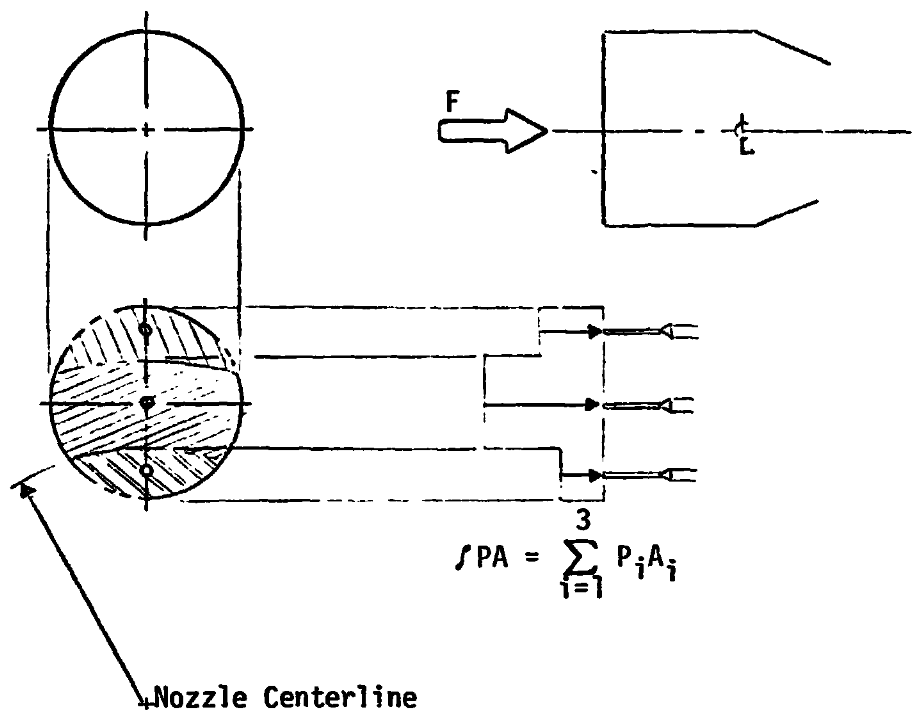
Notes: ① Full S/N = given S/N preceded by "12", i.e., for Run No. 1/1, "1220A = A".
② Average P_{c1} per Eqn. 5 and Tables 14-16.
③ Configuration per Fig. 5 and Table 6.
④ T_{45} did not reach steady state condition.

Ⓟ Particle sampling run.

P_{xx} = Pressure at position xx
Q_{xx} = Heat rate at position xx
T_{xx} = Temperature at position xx
} Position per Fig. 5 and Table 6.

TABLE 11

FORCE MEASUREMENT RESULTS



$$\int PA = \sum_{i=1}^{3} P_i A_i$$

Run No.	Alt. (ft)	X/D	% Al	P_c (psia)	P_c/P_∞	F (lb.)	$\int$PA (lb.)	F/$\int$PA
10/1	50 K	5	2	726	388	25.3	19.5	1.30
10/2			↓	749	393	33.5	18.4	1.82
11/1			10	890	475	15.6	15.7	0.99
11/2			↓	902	481	12.8	12.0	1.07
6/3			15	928	495	8.1	10.9	0.74
7/1	100 K	12	2	761	4525	1.0	1.1	0.91
7/2			↓	745	4450	2.8	1.1	2.55
9/1			10	940	5589	1.6	1.0	1.60
8/1			15	988	5908	2.0	1.1	1.82
8/2			↓	998	5964	2.0	1.1	1.82
12/1		16	2	761	4524	0.55	0.66	0.83
12/2			↓	710	4219	0.38	0.61	0.62
13/1			10	860	5110	0.67	0.56	1.20
44/1	112 K	12	2	812	8402	1.04	1.41	0.74
45/1			10	888	9006	1.46	1.27	1.15
45/2			↓	908	9203	1.15	1.30	0.88
43/1			15	1016	10300	1.21	1.41	0.86
43/2				1026	10614	1.70	1.39	1.22
43/3			↓	1011	10249	1.59	1.21	1.31
42/1		20	10	948	9613	5.2?	0.42	12.4

TABLE 12

CUMULATIVE TOLERANCES

Parameter					Tolerance
Pressures:	Setra	1.0	psid	(Plume Instr.)	.04 psi
	Statham	5,10	psia		.08 psi
	Statham	15	psia		.25 psi
	Statham	1500	psia	P_{c_2}	16 psi
	Kistler	3000	psia	P_{c_1}	11 psi
	Kistler	300	psia	P_n	.5 psi
Force					.03 lb.
Temperature					2%
Heat Transfer Rate					5%

TABLE 13

EXAMPLE OF DIGITAL DATA

Time (ms)	Ch. 1	Ch. 2	Ch. 3	Ch. 4	Ch. 5
5	31.18	.26	0	.16	17.86
10	31.42	.28	0	.19	16.82
15	32.13	.3	0	.21	17.6
20	30.7	.26	0	.16	18.12
25	30.94	.26	0	.17	17.08
30	33.09	.29	0	.19	33.21
35	56.47	.26	0	.16	176.56
40	823.88	3.3	0	1.25	760.11
45	1001.04	15.38	2.59	5.84	1002.07
50	997.31	27.09	6.78	10.01	955.76
55	980.37	34.97	10.54	12.74	945.35
60	942.68	40.5	13.59	14.36	912.31
65	915.01	43.95	15.89	15.23	889.68
70	902.84	45.89	17.59	15.78	880.57
75	900.45	47.11	19.11	16.29	877.45
80	895.68	47.09	20.00	16.52	879.53
85	904.75	47.41	21.25	17.03	883.43
90	908.09	47.37	21.85	17.32	886.03
95	913.57	47.11	22.17	17.66	890.72
100	918.35	46.74	22.21	17.96	897.22
105	922.64	46.44	22.23	18.27	900.86
110	928.6	46.23	22.34	18.67	905.81
115	933.85	46.07	22.44	19.01	912.57
120	939.34	45.86	22.47	19.28	918.81
125	945.3	45.7	22.54	19.58	924.02
130	948.88	45.58	22.61	19.91	927.14
135	947.69	45.42	22.6	20.16	928.18
140	948.4	45.28	22.6	20.44	927.4
145	953.17	45.23	22.68	20.72	931.3
150	958.9	45.11	22.68	20.94	938.59
155	963.43	45.01	22.65	21.17	941.71
160	964.86	44.97	22.69	21.44	942.75
165	962.24	44.9	22.69	21.64	941.45
170	956.99	44.79	22.61	21.77	937.29
175	955.56	44.75	22.6	21.91	934.42
180	954.84	44.7	22.61	22.04	934.94
185	953.17	44.6	22.53	22.09	935.2
190	952.22	44.54	22.48	22.17	932.34
195	952.94	44.51	22.47	22.26	932.6
200	951.5	44.43	22.4	22.28	933.12
205	950.55	44.35	22.33	22.29	931.3
210	952.46	44.34	22.37	22.35	932.34
215	952.7	44.3	22.34	22.37	933.9
220	951.27	44.22	22.27	22.3	932.6
225	952.22	44.19	22.27	22.32	932.6
230	954.84	44.17	22.27	22.3	935.46
235	957.71	44.08	22.18	22.2	940.67
240	963.19	44.03	22.17	22.17	944.05
245	972.02	44.02	22.17	22.16	952.9
250	983.23	43.96	22.12	22.1	966.16

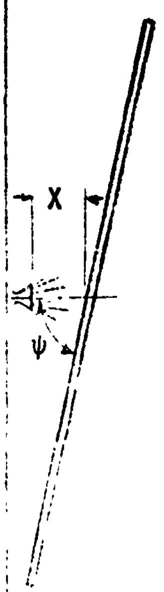
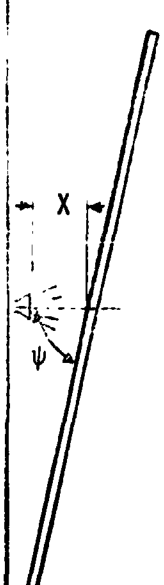
Time (ms)	Ch. 1	Ch. 2	Ch. 3	Ch. 4	Ch. 5
255	1002.31	43.9	22.07	22.05	982.55
260	1029.75	43.91	22.11	22.09	1009.87
265	1047.16	43.87	22.09	22.09	1026
270	937.91	43.81	22.03	22	909.71
275	675.74	43.8	22.05	21.56	655.53
280	430.27	43.74	22.03	20.48	430.48
285	258.99	43.53	21.86	19.07	330.58
290	155.23	43.3	21.71	17.69	280.43
295	94.39	43.08	21.58	16.43	262.94
300	57.42	42.79	21.35	15.21	247.07
305	37.14	42.49	21.11	14.13	232.5
310	27.36	42.25	20.94	13.17	219.23
315	21.64	41.95	20.72	12.26	208.04
320	17.34	41.64	20.46	11.39	197.11
325	16.63	41.36	20.26	10.65	185.93
330	15.44	41.1	20.05	9.94	177.08
335	13.53	40.76	19.74	9.3	168.5
340	13.05	40.47	19.53	8.79	159.39
345	13.77	40.21	19.34	8.35	151.84
350	12.33	39.89	19.06	7.89	145.6
355	11.62	39.58	18.82	7.49	137.8
360	13.05	39.33	18.64	7.14	131.55
365	12.81	39.01	18.41	6.79	126.35
370	12.1	38.68	18.16	6.43	120.62
375	13.05	38.4	17.99	6.16	114.38
380	13.53	38.09	17.8	5.86	110.48
385	12.1	37.74	17.53	5.55	106.06
390	12.33	37.44	17.33	5.29	100.85
395	12.81	37.15	17.17	5.07	96.69
400	12.1	36.81	16.9	4.79	93.57
405	11.62	36.51	16.7	4.56	88.88
410	13.05	36.26	16.55	4.38	84.98
415	12.57	35.96	16.36	4.16	82.38
420	12.1	35.65	16.12	3.97	78.48
425	13.05	35.4	15.99	3.83	74.58
430	13.53	35.14	15.84	3.67	72.75
435	12.33	34.82	15.6	3.48	70.15
440	12.57	34.57	15.47	3.35	66.51
445	13.05	34.32	15.33	3.23	63.91
450	12.1	33.99	15.09	3.06	62.35
455	11.62	33.71	14.93	2.93	58.71
460	13.05	33.48	14.82	2.84	56.62
465	12.57	33.19	14.65	2.72	55.32
470	12.1	32.89	14.46	2.6	52.72
475	13.53	32.66	14.38	2.54	50.12
480	13.53	32.39	14.24	2.46	49.08
485	12.33	32.09	14.04	2.34	47.26
490	12.81	31.82	13.92	2.28	44.92
495	13.53	31.58	13.82	2.21	43.62
500	12.33	31.26	13.6	2.1	42.31

TABLE 14

NOZZLE DATA SUMMARY

% Al	Run No.	P_c (psia)	P_{n1}/P_c	P_{n2}/P_c	P_{n3}/P_c
2	1/1	816	-	0.0249	0.0248
	1/2	860	-	-	-
	1/3	773	-	0.0387	0.0213
	7/1	761	0.0612	0.0311	0.0196
	7/2	744	0.0616	0.0325	0.0205
	10/1	726	0.0668	0.0333	0.0205
	10/2	749	0.0624	0.0330	0.0196
	12/1	761	0.0672	0.0357	0.0248
	12/2	709	0.0524	0.0337	0.0193
	14/1	724	0.0557	0.0327	0.0193
	14/2	771	0.0655	0.0359	0.0207
	14/3	774	0.0719	0.0356	0.0206
	25/1	792	0.0623	0.0347	0.0200
	25/2	771	0.0636	0.0321	0.0191
	26/1	776	0.0641	0.0367	0.0199
	26/2	779	0.0673	0.0365	0.0204
	27/1	811	0.0683	0.0349	0.0208
	27/2	729	0.0653	0.0362	0.0213
	28/1	792	0.0646	-	0.0209
	28/2	759	0.0687	0.0394	0.0205
	29/1	773	0.0665	0.0357	0.0197
	29/2	810	0.0635	0.0341	0.0185
	30/1	-	-	-	-
	30/2	810	0.0658	0.0359	0.0204
	31/1	762	0.0650	0.0354	0.0201
	31/2	750	0.0660	0.0345	0.0202
	32/1	796	0.0664	0.0348	0.0194
	32/2	749	0.0678	0.0358	0.0202
	41/1	792	0.0635	0.0353	0.0202
	44/1	812	0.0635	0.0338	0.0205
		Avg.	0.0645	0.0346	0.0205
		σ	0.0039	0.00	0.0014
		σ/Avg.	6.1%	7.8%	6.8%
10	2/1	748	0.0538	0.0391	0.0271
	2/2	908	0.0582	0.0344	0.0217
	4/1	903	0.0493	0.0241	0.0222
	4/2	935	0.0486	0.0246	0.0222
	9/1	940	0.0516	0.0271	0.0241
	11/1	890	-	0.0316	0.0222
	11/2	902	0.0531	-	0.0215
	13/1	859	-	-	0.0248
	13/2	900	0.0530	-	0.0223
	13/3	893	0.0527	0.0232	0.0210
	15/1	943	-	-	0.0236
	15/2	849	0.0577	0.0295	0.0220
	17/1	950	0.0496	0.0280	0.0204
	17/2	855	0.0505	0.0286	0.0220
	19/1	874	0.0501	0.0272	0.0230
	19/2	889	0.0532	0.0263	0.0225

% Al	Run No.	P_c (psia)	P_{n1}/P_c	P_{n2}/P	P_{n3}/P_c
10	21/1	895	0.0544	-	0.0221
	21/2	898	-	-	0.0213
	23/1	956	-	-	0.0202
	23/2	954	-	-	0.0217
	33/1	844	0.0480	0.0279	0.0215
	33/2	886	0.0474	0.0278	0.0213
	35/1	846	0.0540	-	0.0216
	37/1	951	0.0491	-	0.0227
	37/2	843	-	0.0279	0.0227
	39/1	935	0.0489	0.0276	0.0204
	39/2	888	-	0.0313	0.0206
	42/1	948	0.0483	0.0233	0.0202
	45/1	888	0.0552	0.0283	0.0217
	45/2	907	0.0503	0.0267	0.0204
		Avg.	0.0513	0.0282	0.0220
		σ	0.0039	0.0038	0.0015
		σ/Avg.	7.6%	13.3%	6.7%
15	3/1	955	0.0552	0.0289	0.0202
	3/2	942	0.0629	-	0.0244
	5/1	1043	0.0468	-	0.0221
	5/2	992	0.0493	0.0212	0.0207
	6/1	986	0.0488	0.0232	0.0213
	6/2	949	0.0641	0.0294	0.0215
	6/3	928	-	0.0266	0.0201
	8/1	987	-	0.0238	0.0216
	8/2	997	-	0.0235	0.0213
	16/1	949	0.0616	0.0283	0.0197
	16/2	1002	0.0566	0.0284	0.0194
	18/1	932	0.0546	0.0265	0.0205
	18/2	1000	0.0662	0.0305	0.0203
	18/3	972	0.0519	0.0250	0.0207
	20/1	946	-	0.0310	0.0227
	20/2	983	0.0469	0.0250	0.0213
	22/1	936	-	-	0.0220
	22/2	981	-	-	0.0215
	24/1	1004	0.0533	0.0259	0.0206
	24/2	1023	-	-	0.0200
	34/1	1001	-	-	0.0210
	34/2	939	0.0445	-	0.0215
	36/1	962	0.0559	0.0307	0.0184
	38/1	970	0.0466	-	0.0215
	38/2	996	-	0.0281	0.0192
	40/1	879	-	0.0285	0.0205
	40/2	1013	0.0567	0.0271	0.0204
	43/1	1015	-	0.0284	0.0214
	43/2	1026	0.0467	0.0288	0.0208
	43/3	1010	0.0484	0.0289	0.0207
		Avg.	0.0536	0.0272	0.0209
		σ	0.0065	0.0026	0.0011
		σ/Avg	12.2%	9.7%	5.4%

Posn. (in.)		ψ = 45°									
		X/D = 5						X/D = 12			
		2% ①	10% ①	15% ①	2%	10%	15%	2%	10%	15%	2%
	Run No.	26/1	23/1	24/1	25/1	21/1	22/1	32/1	33/1	34/1	27/1
	time (ms)	200-250	160-210	150-200	200-250	175-225	160-210	185-235	175-225	165-200	200-250
	P_c (psia)	776.8	956.7	1004.78	792.9	895.4	936.4	796.3	844.3	1001.8	811.7
	P_c/P_∞	414.1	510.0	535.6	4713.0	5321.7	5597.6	4732.9	5018.0	5954.3	4824.6
	27 (far)	.002294	.001832	.001739	.000260	.000222	.000226	.000204	.000165	.000149	.000184
	24	-	-	-	-	-	-	2.4	6.4	10.0	2.4?
	21	.002411	.001901	.001822	.000103	.000070	.000067	.000097	.000141	.000152	.000127
	18	.002198	.001709	.001621	.000132	.000129	.000116	.000202	.000204	.000201	.000178
	15	42.7	39.2	41.9	4.9	10.1	16.3	13.4	13.9	16.7	5.7
	12	.002391	.002018	.001836	.000282	.000203	.000240	.000919	.000600	.000460	.000435
	9	.002198	.000617	.000699	.000265	.000235	.000208	.000818	.000644	.000420	.000634
	6	40.7	66.2	111.6	15.5	48.0	88.9	14.1	55.1	111.0	18.2
	3	.007390	.007116	.006714	.001875	.001444	.001296	.000542	.000357	.000284	.000738
	¢	.007320	.005315	.004442	.006545	.004614	-	.000930	.000580	.000484	.000438
	-3	.017103	.017490	.012649	.007748	.007814	.007469	.001410	.000999	.000815	.000382
	-6	14.7	23.0	27.9	31.7	80.1	87.6	50.4	130.9	219.1	24.0
	-9	.002249	.001825	.001744	.000179	.000103	.000097	.003065	.001285	.001197	.000912
	-12	.002251	.001821	.001740	.000227	.000212	.000204	.000233	.000292	.000336	.001153
	-15	-	2.7	-	-	3.5	3.8	2.8	4.0	5.4	8.7
	-18	.002254	.001828	.001739	.000229	.000201	.000194	.000225	.000206	.000188	.000223
	-21	.002253	.001822	.001739	.000241	.000200	.000204	-	.000220	.000189	.000223
	-24	-	-	-	-	-	-	-	-	-	-
	-27 (near)	.002259	.001832	.001747	.000225	.000201	.000194	.000221	.000202	.000186	.000224
	2.5 (N)	528.5?	126.5	243.5	69.9	193.4	376.1	66.9	226.8	413.3	31.6
	-2.5 (S)	.016135?	.006625	.005302	.003283	.002934	.002729	.000827	.000577	.000468	.000435
	Run No.	26/2	23/2	24/2	25/2	21/2	22/2	32/2	33/2	34/2	27/2
	time (ms)	215-250	150-190	160-210	150-200	175-225	160-210	185-235	175-225	175-225	200-250
	P_c (psia)	779.3	954.1	1023.9	771.75	898.1	981.6	748.9	886.3	939.6	729.2
	P_c/P_∞	415.4	508.6	545.8	4587.0	5338.0	5834.4	4451.0	5267.6	5584.6	4334.0
	27 (far)	.002145	.001992	.001878	.000240	.000219	.000215	.000233	.000144	.000178	.00022_
	24	-	-	-	-	-	-	2.1	6.2	10.3	1.9?
	21	.002268	.002069	.001955	.000082	.000070	.000067	.000098	.000139	.000165	.000124
	18	.001827	.001859	.001721	.000131	.000127	.000116	.000193	.000219	.000191	.000173
	15	41.1	35.0	44.8	6.3	9.2	17.1	17.9	14.0	18.6	6.0
	12	.002188	.002299	.002093	.000265	.000226	.000196	.000908	.000596	.000471	.000445
	9	.001022	.000698	.000765	.000259	.000245	.000209	.000962	.000564	.000496	.000682
	6	38.8	59.9	98.6	19.3	46.4	91.2	15.1	64.5	90.2	25.7
	3	.007293	.007268	.006769	.001899	.001524	.001316	.000551	.000346	.000285	.000774
	¢	.007263	.005533	.004650	.006532	-	.003828	.000937	.000595	.000469	.000787
	-3	.017339	.019096	.013135?	.007900	.007599	.007416	.001394	.001028	.000829	.000459
	-6	13.1	22.9	27.8	30.6	62.5	110.1	60.0	137.2	211.9	25.4
	-9	.002111	.001966	.001877	.000190	.000109	.000086	.004007	.001231	.001184	.00150[illegible]
	-12	.002105	.001995	.001872	.000217	.000217	.000202	.000244	.000285	.000293	.001257
	-15	-	2.3	3.5	-	3.8	4.1	2.5	4.2	4.9	7.6
	-18	.002111	.002006	.001875	.000220	.000207	.000186	.000244	.000209	.000200	.00024[illegible]
	-21	.002104	.001997	.001872	.000229	.000211	.000193	-	.000211	.000200	.000252
	-24	-	-	-	-	-	-	-	-	-	-
	-27 (near)	.002115	.002000	.001879	.000221	.000204	.000188	.000241	.000207	.000197	.000251
	2.5 (N)	459.3?	205.1	243.6?	71.0	197.0	276.2	66.6	239.7	419.2	37.5
	-2.5 (S)	.016894	.006717	.005411	.003343	.003025	.002436	.000833	.000573	.000471	.000682

① 50,000 ft. (Otherwise, 100,000')

FOLDOUT FRAME

TABLE 15
PLATE DATA SUMMARY

						ψ = 30°				ψ = 60°				
	X/D = 12		X/D = 20											
%	10%	15%	2%	10%	15%	2%		10%	15%	2%	10%	15%	2%	
/1	33/1	34/1	27/1	19/1	20/1	14/1	14/3	15/1	16/1	28/1	39/1	40/1	29/1	
-235	175-225	165-200	200-250	175-225	185-235	200-250	200-250	180-230	175-200	225-260	160-210	175-225	200-250	1
.3	844.3	1001.8	811.7	874.6	946.9	724.4	774.4	943.0	949.1	792.1	935.3	879.8	773.9	
..9	5018.0	5954.3	4824.6	5198.4	5628.3	4305.6	4602.5	5604.6	5640.9	4707.9	5559.4	5229.4	4599.8	
204	.000165	.000149	.000184	.000196	.000192	.000167	.000169	.000117	.000135	.000285	-	.000232	.000239	
.4	6.4	10.0	2.4?	6.0	10.0	-	2.4?	4.3?	5.5	2.2	5.7	7.9	5.4	
097	.000141	.000152	.000127	.000162	.000183	.000110	.000121	.000138	.000148	.000129	.000171	.000207	.000288	.
202	.000204	.000201	.000178	.000212	.000233	.000178	.000195	.000196	.000183	.000179	.000224	.000218	.000138	.
4	13.9	16.7	5.7	9.0	14.4	6.8	9.8	18.9	21.3	8.6	10.9	13.4	5.7	.
919	.000600	.000460	.000435	.000377	.000341	.000504	.000599	.000432	.000323	.000511	.000438	.000378	.000795	.
18	.000644	.000420	.000634	.000478	.000387	.000875	.000943	.000544	.000421	.000739	.000497	.000438	.001446	.
1	55.1	111.0	18.2	52.0	86.9	-	26.8	52.2	74.2	26.0	54.1	85.5	16.7	.
542	.000357	.000284	.000738	.000458	.000353	.000546	.000509?	.000193?	.000263	.000659	.000450	.000420	.000791	.
930	.000580	.000484	.000438	.000334	.000302	.000242	.000316	.000095	.000090	.000759	.000399	.000390	.000794	.
410	.000999	.000815	.000382	.000314	.000272	.000236	.000245	.000159	.000137	.000609	.000439	.000417	.000767	.
.4	130.9	219.1	24.0	98.0	176.9	11.4	35.8	70.2	93.1	35.9	74.4	120.3	24.6	.
65	.001285	.001197	.000912?	.000553	.000466	.000418	.000461	.000339	.000299	.002232	.001178	.001400	.002006	.
233	.000292	.000336	.001153	.001181	.001308	.000699	.000675	.000443	.000386	.000627	.000809	.000668	.000543	.
.8	4.0	5.4	8.7	18.4	43.8	46.7	56.9	42.4	56.8	3.7	8.2	7.7	4.7	.
225	.000206	.000188	.000223	.000215	.000209	.000400	.000441	.000747	.000709	.000236	.000197	.000216	.000161	.
•	.000220	.000189	.000223	.000209	.000201	.000237	.000233	.000186	.000184	.000239	.000198	.000215	.000274	.
•	-	-	-	-	-	-	-	-	0.5	-	-	-	-	
221	.000202	.000186	.000224	.000224	.000213	.000243	.000238	.000181	.000183	.000239	.000195	.000214	.000233	.
9	226.8	413.3	31.6	84.3	171.2	17.4	18.9	81.5	135.3	44.2	203.1	274.3	53.3	
827	.000577	.000468	.000435	.000340	.000314	.000215	.000316	.000101	.000100	.000701	.000399	.000394	.000754	.
/2	33/2	34/2	27/2	19/2	20/2	14/2		15/2	16/2	28/2	39/2	40/2	29/2	
-235	175-225	175-225	200-250	175-200	175-225	200-250		200-250	160-210	225-260	165-215	175-225	200-250	2
9	886.3	939.6	729.2	889.5	983.4	771.0		849.9	1001.8	759.9	888.1	1013.1	810.1	
.0	5267.6	5584.6	4334.0	5317.5	5845.0	4582.6		5051.3	5954.4	4514.3	5278.4	6021.7	4814.8	
33	.000144	.000178	.000220	.000190	.000164	.000172		.000118	.000131	.000300	.000230	.000199	.000230	.
1	6.2	10.3	1.9?	6.5	9.0	3.0?		4.1?	5.7?	2.1	6.4	8.0	6.2	.
098	.000139	.000165	.000124	.000162	.000156	.000120		.000133	.000145	.000127	.000187	.000185	.000242	.
93	.000219	.000191	.000173	.000217	.000206	.000206		.000177	.000181	.000166	.000226	.000234	.000119	.
9	14.0	18.6	6.0	10.4	14.1	9.2		15.4	24.4	6.1	12.0	17.4	5.6	
908	.000596	.000471	.000445	.000387	.000316	.000647		.000400	.000331	.000491	.000444	.000397	.000704	.
962	.000564	.000496	.000682	.000482	.000363	.000989		.000567	.000409	.000731	.000512	.000425	.001317	
1	64.5	90.2	25.7	51.8	100.5	28.7		45.8	79.4	22.0	47.0	110.5	18.6	
551	.000346	.000285	.000774	.000444	.000329	.000485		.000346?	.000221	.000698	.000465	.000366	.000766	
937	.000595	.000469	.000787	.000290	.000263	.000346?		.000095	.000083	.000790	.000419	.000323	.000780	.
394	.001028	.000829	.000459	.000303	.000244	.000250		.000158	.000134	.000607	.000435	.000379	.000757	.
	137.2	211.9	25.4	100.2	183.4	37.9		62.6	112.2	39.1	75.4	149.7	23.5	
07	.001231	.001184	.001504?	.000518	.000419	.000461		.000341	.000292	.001675	.001505?	.000952	.001940	.
44	.000285	.000293	.001257	.001435	.001104	.000685		.000443	.000376	.000516	.000870	.000789?	.000629	.
	4.2	4.9	7.6	26.7	43.4	50.4		65.6	53.5	3.7	8.5	14.8	5.1	
44	.000209	.000200	.000249	.000215	.000185	.000444		.000665	.000673	.000243	.000211	.000186	-	
	.000211	.000200	.000252	.000208	.000175	.000237		.000206	.000181	.000245	.000212	.000185	.000256	.
	-	-	-	-	-	-		-	1.6	-	-	-	-	
41	.000207	.000197	.000251	.000224	.000188	.000241		.000204	.000177	.000246	.000209	.000182	.000226	.
	239.7	419.2	37.5	97.8	221.7	20.6		89.1	153.8	58.9	201.4	262.8	50.5	
33	.000573	.000471	.000682	.000297	.000268	.000316		.000109	.000090	.000730	.000427	.000315	.000751	.

P - Pressure Ratio, P/P_c (<.1)
Q - Heat Rate in Btu/ft^2/sec(>1.)

TABLE 15
PLATE DATA SUMMARY

	ψ = 30°				ψ = 60°			ψ = 90°			
	X/D = 20										
	2%		10%	15%	2%	10%	15%	2%	10%	15%	
	14/1	14/3	15/1	16/1	28/1	39/1	40/1	29/1	17/1	18/1	18/3
.35	200-250	200-250	180-230	175-200	225-260	160-210	175-225	200-250	175-225	150-200	150-200
9	724.4	774.4	943.0	949.1	792.1	935.3	879.8	773.9	950.1	931.9	972.8
.3	4305.6	4602.5	5604.6	5640.9	4707.9	5559.4	5229.4	4599.8	5647.1	5538.9	5782.2
92	.000167	.000169	.000117	.000135	.000285	-	.000232	.000239	-	.000180	.000185
	-	2.4?	4.3?	5.5	2.2	5.7	7.9	5.4	4.6?	9.0	9.0
83	.000110	.000121	.000138	.000148	.000129	.000171	.000207	.000288	.000164	.000196	.000179
33	.000178	.000195	.000196	.000183	.000179	.000224	.000218	.000138	.000094	.000099	.000110
	6.8	9.8	18.9	21.3	8.6	10.9	13.4	5.7	14.1	15.0	15.0
1	.000504	.000599	.000432	.000323	.000511	.000438	.000378	.000795	.000993	.000938	.000984
7	.000875	.000943	.000544	.000421	.000739	.000497	.000438	.001446	.000642	.000717	.000663
	-	26.8	52.2	74.2	26.0	54.1	85.5	16.7	40.1	73.2	86.2
3	.000546	.000509?	.000193?	.000263	.000659	.000450	.000420	.000791	.000505	.000504	.000499
2	.000242	.000316	.000095	.000090	.000759	.000399	.000390	.000794	.000634	.000609	.000608
72	.000236	.000245	.000159	.000137	.000609	.000439	.000417	.000767	.000409	.000481	.000484
	11.4	35.8	70.2	93.1	35.9	74.4	120.3	24.6	51.2	96.3	109.3
66	.000418	.000461	.000339	.000299	.002232	.001178	.001400	.002006	.001236	.001236	.001169
	.000699	.000675	.000443	.000386	.000627	.000809	.000668	.000543	.000566	.000767	.000764
	46.7	56.9	42.4	56.8	3.7	8.2	7.7	4.7	2.5	7.3	7.9
	.000400	.000441	.000747	.000709	.000236	.000197	.000216	.000161	.000097	.000117	.000110
1	.000237	.000233	.000186	.000184	.000239	.000198	.000215	.000274	.000189	.000207	.000209
	-	-	-	0.5	-	-	-	-	-	-	-
13	.000243	.000238	.000181	.000183	.000239	.000195	.000214	.000233	.000189	.000187	.000203
	17.4	18.9	81.5	135.3	44.2	203.1	274.3	53.3	245.1	395.9	427.9
4	.000215	.000316	.000101	.000100	.000701	.000399	.000394	.000754	.000473	.000499	.000488
	14/2		15/2	16/2	28/2	39/2	40/2	29/2	17/2	18/2	
5	200-250		200-250	160-210	225-260	165-215	175-225	200-250	200-225	175-200	
	771.0		849.9	1001.8	759.9	888.1	1013.1	810.1	855.2	1000.6	
	4582.6		5051.3	5954.4	4514.3	5278.4	6021.7	4814.8	5083.0	5947.0	
	.000172		.000118	.000131	.000300	.000230	.000199	.000230	.000199	.000176	
	3.0?		4.1?	5.7?	2.1	6.4	8.0	6.2	8.5	10.5	
	.000120		.000133	.000145	.000127	.000187	.000185	.000242	.000207	.000181	
	.000206		.000177	.000181	.000166	.000226	.000234	.000119	.000094	.000102	
	9.2		15.4	24.4	6.1	12.0	17.4	5.6	10.0	16.5	
	.000647		.000400	.000331	.000491	.000444	.000397	.000704	.000902	.001011	
3	.000989		.000567	.000409	.000731	.000512	.000425	.001317	.000762	.000592	
	28.7		45.8	79.4	22.0	47.0	110.5	18.6	35.1	92.1	
	.000485		.000346?	.000221	.000698	.000465	.000366	.000766	.000552	.000481	
3	.000346?		.000096	.000083	.000790	.000419	.000323	.000780	.000676	.000572	
4	.000250		.000158	.000134	.000607	.000435	.000379	.000757	.000514	.000453	
	37.9		62.6	112.2	39.1	75.4	149.7	23.5	50.3	109.2	
	.000461		.000341	.000292	.001675	.001505?	.000952	.001940	.001602	.001228	
	.000685		.000443	.000376	.000516	.000870	.000789?	.000629	.000573	.000799	
	50.4		65.6	53.5	3.7	8.5	14.8	5.1	4.5?	8.5	
	.000444		.000665	.000673	.000243	.000211	.000186	-	.000125	.000112	
	.000237		.000206	.000181	.000245	.000212	.000185	.000256	.000234	.000203	
	-		-	1.6	-	-	-	-	-	-	
	.000241		.000204	.000177	.000246	.000209	.000182	.000226	.000203	.000186	
	20.6		89.1	153.8	58.9	201.4	262.8	50.5	193.7	199.8	
	.000316		.000109	.000090	.000730	.000427	.000315	.000751	.000536	.000472	

...ure Ratio, P/P_c (<.1)

Rate in $Btu/ft^2/sec$ (>1.)

REMTECH INCORPORATED

Posn. (in.)		X/D = 5									
		50,000'							100,000'			
	% AL	2%		10%		15%			10%		15%	
	Run	10/1	10/2	11/1	11/2	6/1	6/2	6/3	4/1	4/2	5/1	5/2
(West) 11												
10												
9												
8												
7												
		002528	.002506	.002087	-			-				
6		002520	.002509	.002102	-			-				.0027
		002580	.002568	.002140	-			-	.001037	.000909	.000550	
5		002539	.002538	.002132	001935			.002044	.000860	.000914	.000814	.0007
		002595	.002567	-	-			-	.001227	.001213	.001132	.0011
4		002559	.002552	.002134	002031	.001954	.001934	.002046	.001748	.001374	.001099	.0011
		002594	.002560	.002439	002445	.002944	.002174	.002471	.002315			
3		002926	.002949	.006969	007828	.009331	.005198	.007168	.002514	.002542	.002322	.002
		009790	.009218	.021740	021164	.019159	-	.018567	.003463	.003055	.002641	.00254
2		032379	.029171	.008098	005624	.008119	.011014?	.005157?	.004225			
		007371	.007310	.013088	005329	.003656	.004622	.004189	.004996	.004992	.003780	.00281
1		008150	.008027	.005085	006621	.004566	-	.004807	.005987	.005696	.004248	.0044
		.008325	.008489	.006453	.007448	.004258	.004582	.004888	-	.006671	.006161	-
℄		-	.008439	.004367	.004692	.002562	.004588	.004607	.008245	-	.007139	.0062
									-			
-1						.004337	.004863		.006197	.005829	.004174	.0041
						893.1	530.1		-			-
-2		25.3#	33.5#	15.6#	12.8#	5236°R	-	8.1#?	1914°R	671°R	1792°R	-
						.019204	.018584		.003922	.003946	.003287	.00322
-3						608.7	396.8		318.9	405.0	557.7	520.8
						.003486	.002358					
-4		42.5	43.6	7.1?	10.2	-	-	11.0?	297.3	310.6	373.3	318.4
		29.1	73.6?	-	-			-				
-5		1245°R	1128°R	767°R	695°R	-		768°R	78.9	87.2	110.0	113.2
		20.3	12.1	-	-			-	.001207	.001102	.000807	
-6		-	-	-	-			-				.0022
		002540	.002528	.002148	-			-				
-7												
-8												
-9												
-10												
-11 (East)												
time (ms)		200-250	210-260	175-225	175-225	140-175	100-150	200-250	100-200	100-200	125-175	125-1
P_c (psia)		726.4	749.1	890.4	902.0	986.4	949.2	928.1	903.5	935.4	1043.2	992.4
P_c/P_∞		388	393	475	481	526	506	495	5401	5591	6236	5932

P - Pre

Q - Hea

FOLDOUT FRAME 1

TABLE 16
RAKE DATA SUMM

X/D = 5		100,000'				100,000'					X/D=12		112,
		10%		15%		2%		10%	15%		2%	10%	
6/2	6/3	4/1	4/2	5/1	5/2	7/1	7/2	9/1	8/1	8/2	44/1	45/1	45/2
						.000231	.000240	.000216	.000200	.000222			
						.000230	.000245	.000289	.000222	.000302			
						.000236	.000245	.000450	.000315	.000488			
						.000258	.000266	.000708	.000472	.000747			
						.000420	.000445	.001133	.000778	.001112			
						.000652	.000700	.001485	.001049	.001380			
						.001772	.001872	.001867	.001592	.001519	.000692	.000489	.0004
											.000664	.000538	.00053
						.002694	[illegible]	.000678	.000634	.000549	.000732	.000612	.00062
	-										.000835	.000665	.00060
	-				.002718	.001006	.001121	.000552	.000436	.000446	.000869	.000679	.0006
	-	.001037	.000909	.000550							.000924	.000702	.0007
	.002044	.000860	.000914	.000814	.000786	.000845	.000846	.000605	.000478	.000486	.000960	.000768	.0008
	-	.001227	.001213	.001132	.001108						.001009	.000767	.0007
01934	.002046	.001748	.001374	.001099	.001192	.000948	.000951	.000708	.000581	.000582	.001040	.000814	.0008
02174	.002471	.002315									.001146	.000854	.0008
05198	.007168	.002514	.002542	.002322	.002402	.001030	.001023	.000746	.000691	.000656	.001140	.000855	.0008
-	.018567	.003463	.003055	.002641	.002548						.001219	.000963	.0009
11014?	.005157?	.004225				.001113	.001138	.000825	.000836	.000760	.001323	.001055	.0010
04622	.004189	.004996	.004992	.003780	.002819								
-	.004807	.005987	.005696	.004248	.004450	.001187	.001191	.000910	.001030	.000983	-	.001408	.0013
04582	.004888	-	.006671	.006161	-								
04588	.004607	.008245	-	.007139	.006285	.001202	.001217	.00?32	.001133	.001158	-	-	-
		-											
04863		.006197	.005829	.004174	.004194								
530.1		-			-								
-	8.1#?	1914°R	671°R	1792°R	-	1.0#	2.8#	1.6#	2.0#	2.0#			
18584		.003922	.003946	.003287	.003224								
396.8		318.9	405.0	557.7	520.8						1.04#	1.46#	1.15#
02358													
-	11.0?	297.3	310.6	373.3	318.4	77.3	77.1	231.?	320.9	316.4			
	-												
	768°R	78.9	87.2	110.0	113.2	-	2172°R	2117°R	2143°R	2108°R			
	-	.001207	.001102	.000807									
	-				.002272	91.1	94.5	200.1	178.1	261.4?	74.8	136.4	101.?
	-												
											1724°R	1556°R	1538°
						91.7	1?3.0	199.5	232.7	214.3	82.0	132.6	138.
						-	-	36.7	54.7	62.6			
0-150	200-250	100-200	100-200	125-175	125-175	225-275	210-260	150-250	175-200	150-200	200-250	190-240	190-
?.2	928.?	903.5	935.4	1043.2	992.4	761.3	744.5	940.4	987.8	997.7	812.4	888.2	907.7
06	495	5401	5591	6236	5932	4525	4450	5589	5908	5964	8402	9006	9203

P - Pressure Ratio, P/P_c (<.1)	T - Temperature in °R
Q - Heat Rate in Btu/ft^2/sec (>1.)	F - Force in lb.

TABLE 16
RAKE DATA SUMMARY

	X/D=12										
	100,000'					112,000'					
	2%		10%	15%		2%	10%		15%		
5/2	7/1	7/2	9/1	8/1	8/2	44/1	45/1	45/2	43/1	43/2	43/3
	.000231	.000240	.000216	.000200	.000222						
	.000230	.000245	.000289	.000222	.000302						
	.000236	.000245	.000450	.000315	.000488						
	.000258	.000266	.000708	.000472	.000747						
	.000420	.000445	.001133	.000778	.001112						
	.000652	.000700	.001485	.001049	.001380						
	.001772	.001872	.001867	.001592	.001519	.000692	.000489	.000481	.000347	.000386	.000393
						.000664	.000538	.000537	.000422	.000421	.000435
	.00[illegible]694	.002746	.000678	.000634	.000549	.000732	.000612	.000622	.000488	.000490	.000488
						.000835	.000665	.000660	.000549	.000563	.000576
.718	.001006	.001121	.000552	.000436	.000446	.000869	.000679	.000684	.000542	-	-
						.000924	.000702	.000711	.000559	.000577	.000573
0786	.000845	.000846	.000605	.000478	.000486	.000960	.000768	.000864	.000589	.000673	.0005[illegible]7
.108						.001009	.000767	.000778	.000611	.000658	.000647
.192	.000948	.000951	.000703	.000581	.000582	.001040	.000814	.000809	-	.000662	.000656
						.001146	.000854	.000863	.000712	.000700	.000690
2402	.001030	.001023	.000746	.000691	.000656	.001140	.000855	.000871	.000724	.000754	.000744
2548						.001219	.000963	.000976	.000888	.000884	.000864
	.001113	.001136	.000825	.000836	.000760	.001323	.001055	.001060	.001054	.001014	-
2819											
4450	.001187	.001191	.000910	.001030	.000983	-	.001408	.001313	.001324	.001308	-
-											
6285	.001202	.001217	.00132	.001133	.001158	-	-	-	.001332	.001130	.001193
.194											
-											
-	1.0#	2.8#	1.6#	2.0#	2.0#						
3224											
.8						1.04#	1.46#	1.15#	1.21#	1.70#	1.59#
.4	[illegible]7.3	77.1	231.[illegible]	320.9	316.4						
.2	-	2172°R	2117°R	2143°R	2108°R						
2272	91.1	94.5	200.1	178.1	261.4[illegible]	74.8	136.4	101.7	196.5	185.6	202.7
						1724°R	1556°R	1538°R	1689°R	1384°R	1350°R
	91.7	103.0	199.5	232.7	214.3	82.0	132.6	138.4	158.5	143.0	143.2
	-	-	36.7	54.7	62.6						
-175	225-275	210-260	150-250	175-200	150-200	200-250	190-240	190-240	200-240	175-225	175-225
.4	761.3	744.5	940.4	987.8	997.7	812.4	888.2	907.7	1015.9	1026.3	1010.8
	4525	4450	5589	5908	5964	8402	9006	9203	10300	10614	10249

ressure Ratio, P/P_c (<.1)	T - Temperature in °R
t Rate in Btu/ft^2/sec (>1.)	F - Force in lb.

FOLDOUT FRAME 3

Posn. (in.)	% AL / Run	X/D = 16 100,000'					100,0			
	% AL	2%		10%			2%			
	Run	12/1	12/2	13/1	13/2	13/3	1/1	1/2	1/3	
(West)		.000253	.000235	.000255						
11		.000295	.000286	.000367	.000492	.000467	.000382	.000348	.000307	.
		.000335	.000296	.000494	.000673	.000626				
10		.000483	.000416	.000755	.000975	.000979	.000583	.000593	.000488	.
9		.001030	.000889	.001329	.001528	.001491	.000960	.000927	.000872	.
8		.001948	.001685	.001847	.001879	.001690	-	.001388	.001397	.
7		.002577	.002548	.001721	.001666	.001214	.001686	.001662	.001805	.
6		.002215	.002801	.000683?	.000644	.000469	.001620	.001715	.002037	.
5		.000633	.000872?	.000411	.000404	.000392	.000996	.001253	.001842	.
4		.000608	.000594	.000460	.000440	.000424	.000539	.000607	.001077	.
3		.000641	.000623	.000520	.000505	.000501	.000443	.000445	.000451	.
2		.000648	.000641	.000474	.000455	.000464	.000416	.000391	.000412	.
1		.000676	.000652	.000533	.000453	.000512	.000416	.000381	.000390	.
℄		.000601	.000567	-	.000302	.000494	.000416	.000383	.000394	.
-1							-	35.0	80.2	[illegible]
-2		0.55#	0.38#	0.67#	-	-	.000421	.000395	.000400	.
-3							-	101.0	98.3	[illegible]
-4		60.9	57.7	203.0	212.0	221.4	-	-	-	
-5		2043°R	2158°R	2000°R	1955°R	1718°R	-	.001237	.001827	.
-6		120.2	127.4	150.9	160.6	-	-	92.6	99.4	
-7							-	-	-	
-8		96.4	78.7	162.4	180.7	201.3	-	78.1	60.3	
-9		12.0	5.0?	42.6	41.1	62.8	-	-	-	
-10							-	17.6	8.5	
-11 (East)							.000387	.000428	.000287	.
time (ms)		200-250	225-250	200-250	175-225	125-175	150	150	150-200	
P_c (psia)		761.1	709.8	859.8	900.5	893.5	816.5	860	773.1	
P_c/P_∞		4524	4219	5110	52[illegible]1	5311	4863	5123	4595	

P - Pressure Ratio, P/P_c (<.1)
Q - Heat Rate in Btu/ft^2/sec(>1.)

T - Temperature in
F - Force in lb.

FOLDOUT FRAME

TED

TABLE 16
RAKE DATA SUMMARY
(Concluded)

	X/D = 16 100,000'			X/D = 20 100,000'							112,000'	
	10%			2%		10%			15%		2%	10%
2/2	13/1	13/2	13/3	1/1	1/2	1/3	2/1	2/2	3/1	3/2	41/1	42/1
235	.000255											
0286	.000367	.000492	.000467	.000382	.000348	.000307	.000508	.000418	.000642	.000419		
0296	.000494	.000673	.000626									
[illegible]16	.000755	.000975	.000979	.000583	.000593	.000488	.000787	.000660	.000890	.000644		
0889	.001329	.001528	.001491	.000960	.000927	.000872	.001208	.001014	.0011[illegible]9	.000941		
.685	.001847	.001879	.001690	-	.001388	.001397	.001552	.001311	.001236	.001215	.000897	.000298
											.000846	.000283
2548	.001721	.001666	.001214	.001586	.001662	.001805	.001791	.001483	.001439	.001611	.000539	.000254
											.000465	.000278
2801	.000683?	.000644	.000469	.001620	.001715	.002037	.002087	.001407	.000593	.001059	.000392	.000273
											.000358	.000244
0872?	.000411	.000404	.000392	.000996	.001253	.001842	.000822	.000442	.000268	.000374	.000370	.000255
											.000361	.000243
0594	.000460	.000440	.000424	.000539	.000607	.001077	.000440	.000348	.000296	.000262	.000378	.000202
											.000395	.000286
0623	.000520	.000505	.000501	.000443	.000445	.000451	.000367	.000311	.000285	.000224	.000385	.000269
											.000397	.000288
0641	.000474	.000455	.000464	.000416	.000391	.000412	.000404	.000339	.000325	.000206	.000425	.000348
0652	.000533	.000453	.000512	.000416	.000381	.000390	.000416	.000356	.000309	.000299	.000440	.000368
0567	-	.000302	.000494	.000416	.000383	.000394	.000412	.000357	.000291	.000244	.000428	.000336
				-	35.0	80.2	323.2	379.8	416.5	408.7		
38#	0.67#	-	-	.000421	.000395	.000400	.000372	.000317	.000298	.000264		
				-	101.0	98.3	204.2	224.5	372.0	357.9	-	5.2#?
.7	203.0	212.0	221.4	-	-	-	-	727°R	741°R	807°R		
58°R	2000°R	1955°R	1718°R	-	.001237	.001827	.000801	.000528	.000278	.000412		
.4	150.9	160.6	-	-	92.6	99.4	184.5	179.8	190.3	212.5	49.3	133.8
				-	-	-	-	-	-	-	-	-
.7	162.4	180.7	201.3	-	78.1	60.3	139.2	149.1	198.8	179.1	78.3	112.1
.0?	42.6	41.1	62.8	-	-	-	-	-	-	-		
				-	17.6	8.5	38.3	47.1	64.6	55.5		
				.000387	.000428	.000287	.000431	.000440	.000481	.000428		
-250	200-250	175-225	125-175	150	150	150-200	150-200	150-200	70-120	100-200	200-250	165-215
.8	859.8	900.5	893.5	816.5	860	773.1	748.8	908.5	955.1	942.0	792.5	948.1
9	5110	5291	5311	4863	5123	4595	4450	5412	5678	5599	8196	9613

Ratio, P/P_C (<.1)
te in Btu/ft^2/sec(>1.)

T - Temperature in °R
F - Force in lb.

FOLDOUT FRAME 2

APPENDIX A

NOZZLE CALIBRATION

The nozzle calibration phase of FA-21 was quite distinct from the primary rocket testing phase. The goal was to provide an acceptance test and to determine the effective expansion ratio. Acceptance was judged by the degree that wall pressures and plume shapes of a specimen nozzle flowing air matched values predicted by accepted methods (Ref. A1). Three of the 30 rocket nozzles were calibrated, by flowing air through the nozzle into a quiescent chamber. Wall pressures acceptably matched predictions. Unfortunately, an accident in photography development destroyed the schlieren plume photographs. Thus, evaluation of the plumes was not accomplished.

This appendix describes the setup, procedures, results, and acquired data of this phase. The nozzle calibration phase was denoted FA-21C by the SSLV Project, and TWT-633 by the MSFC facility.

TEST SETUP AND PROCEDURES

The setup for this test was conventional for this facility (Fig. A1). The facility was the 14 x 14 Inch Trisonic Wind Tunnel at MSFC, fitted with the Special Test Section (Ref. A2). The 3 tested nozzles were selected at random from the 30 items available and described in Section 3.2, Fig. 4, and Table 3 of the main text.

Instrumentation consisted of pressures and schlieren photographs. There were 7 pressures measured: P_c, P_{n1}, P_{n2}, P_{n3}, and P_∞ at 3 places. Table A1 gives characteristics of the pressure transducers:

TABLE A1

PRESSURE TRANSDUCER CHARACTERISTICS

Parameter	(Units)	PA208TC P_c	PM856 or PM131TC P_{n1}	P_{n2}	P_{n3}, $P_{\infty 1-3}$
Rated Pressure	(psid)	1000 psia	30	15	12.5
Max. Pressure	(psia)	2000	60	30	25
Temp. Limits	(°F)	-65 to +250			
Accel. Sensitivity	(%FS/g)	.01	.04	.06	.03
@ Frequency	(Hz)	3800	1125	875	1700
Non-Linearity	(%FS)	.75			
Hysteresis	(%FS)	.75			
Thermal Zero Shift	(%FS/°F)	.01			
Thermal Sensitivity	(%FS/°F)	.01			

The schlieren system was the standard facility equipment. Imagery was recorded as 90 mm negatives and Polaroid positives.

The test plan called for 3 values of P_∞ at each of 3 values of P_c, with P_c/P_∞ = 400 included for each value of P_c. A procedure was developed to maximize run productivity while maintaining adequate control of P_c. The sequence was:

1. Establish P_c while flowing air and note P_c control position.
2. Stop flow and evacuate chamber to desired P_∞.
3. Start flow with P_c control at previously-established position.
4. If P_c correct, take data.
5. Continue flowing; when P_∞ rises to next desired value, take data.
6. Repeat Step 5 for third value of P_∞.

In taking data, a Polaroid schlieren photograph was taken, then (about 5-10 seconds later) the 90 mm schlieren negative and the pressure data were recorded simultaneously. Transducers were calibrated at the start of each day.

RESULTS AND DATA

The data acquired as a result of this calibration permitted an affirmative acceptance test but did not determine the effective expansion ratio.

It was difficult to control P_c during this test. The facility had been modified immediately before this test to provide higher airflows for the planned test of large nozzles, and some control precision had evidently been sacrificed. However, an adequate spectrum of P_c/P_∞ ratios were investigated.

The recorded nozzle wall pressures (Table A2) did not exactly match predicted values. In all cases the measured values of P_c/P_n were lower than predicted. However, the tolerance band associated with the average measured value overlaid the tolerance band associated with the predicted value (Fig. A2) for P_{n_1} and P_{n_3}. Several diagnostic investigations were made seeking instrumentation or hardware dimensional discrepancies to account for this situation. No discrepancies were discovered, and the correct instrumentation operation was verified. It was concluded that these nozzles were acceptable, primarily because of the overlap of tolerance bands in Fig. A2.

The 90 mm schlieren photographs were accidently destroyed. Although several Polaroid photographs were available, the recorded P_c/P_∞ values did not correspond to these photos. Some effort was made to derive P_c/P_∞ appropriate to the Polaroids using dP_∞/dt recorded on one run and the estimated Δt between Polaroid and 90mm negative. Satisfactory results were not obtained, and it was concluded that the schlieren photographs could not be utilized. Thus, the plume acceptability could not be evaluated. As a consequence of the lack of plume evaluation combined with the partly ambiguous wall pressure results, it was concluded that an effective expansion ratio could not be determined. Instead the geometric value would be recommended.

REFERENCES

A1 Tevepaugh, J. A., Penny, M. M., and Smith, S. D., "Two-Phase Verification Test Program Pretest Analysis", Lockheed Missiles and Space Co., Huntsville Research and Engineering Center, TMD390903, August 1975.

A2 Simon, Erwin, "The George C. Marshall Space Flight Center's 14 x 14 Inch Trisonic Wind Tunnel Technical Handbook", Aero-Astrodynamics Laboratory, George C. Marshall Space Flight Center, AL, NASA TM X-64624, Nov. 5, 1971.

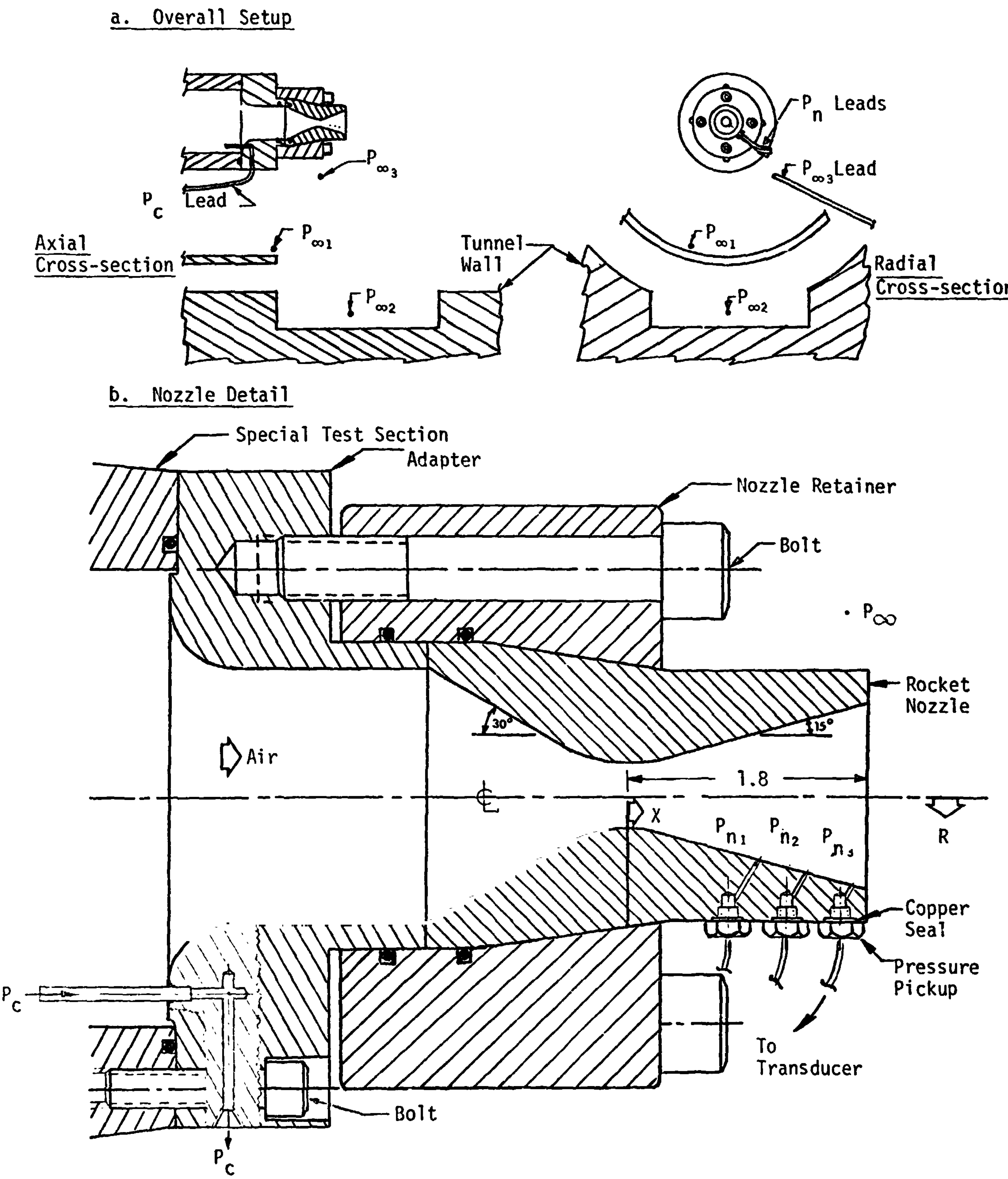


Fig. A-1 Test Setup

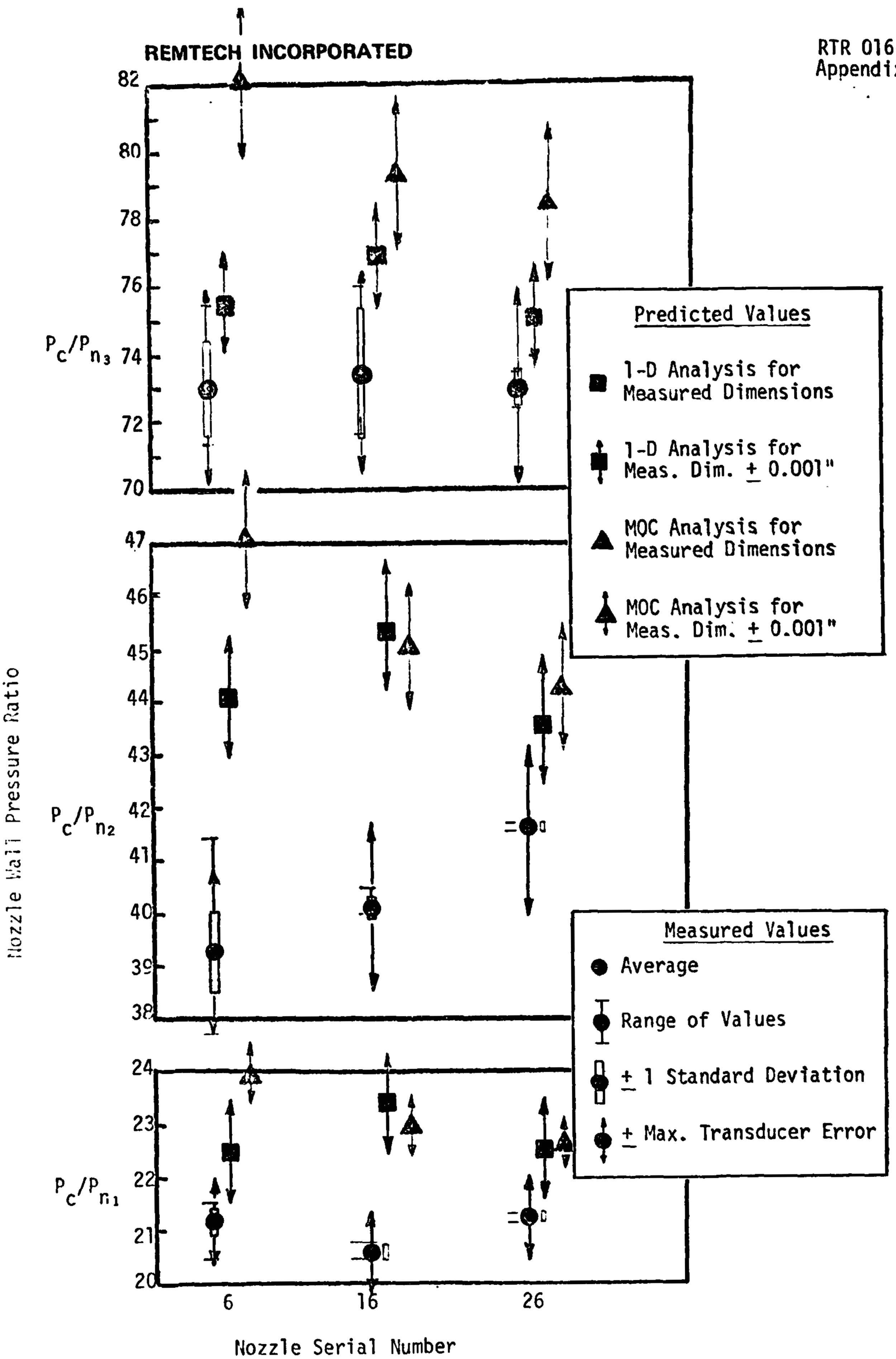


Fig. A-2 Nozzle Wall Pressures

TABLE A2 FA21-C (TWT-633) NOZZLE CALIBRATION DATA

All Pressures in psia

S/N	RUN/R		P-CH	PN1	PN2	PN3	PC/PN1	PC/PN2	PC/PN3	$P1_\infty$	$P2_\infty$	$P3_\infty$	P-STAT	P_c/P_∞
6	1	0	173.2	8.13	4.36	2.29	21.3	39.7	75.6	0.691	0.526	0.593		287
	1	1	201.8	9.56	5.14	2.72	21.1	39.2	74.1	0.792	0.631	0.693		300
	1	2	204.2	9.67	5.20	2.76	21.1	39.2	74.1	1.108	0.950	1.012	0.705	200
	2	0	201.4	9.54	5.14	2.72	21.1	39.2	74.0	1.081	0.926	1.001	0.698	201
	3	0	199.2	9.43	5.07	2.69	21.1	39.3	74.1	1.484	1.329	1.414	1.088	141
	4	0	401.7	18.94	10.35	5.58	21.2	38.8	72.0	1.526	1.371	1.452	1.125	277
	5	0	403.3	19.00	10.39	5.60	21.2	38.8	72.0	0.539	0.373	0.437	0.278	897
	6	0	400.7	18.89	10.22	5.57	21.2	39.2	72.0	1.033	0.878	0.952	0.870	420
	7	0	594.8	27.90	15.18	8.32	21.3	39.0	71.5	1.542	1.387	1.464	1.358	406
	8	0	602.5	29.36	15.99		20.5	37.7		0.840	0.687	0.765	0.773	789
	7	1	619.5	30.01?			20.6?			1.264	1.119	1.191		520
	9	0	606.6		14.64			41.4		0.722	0.561	0.636		946
	7	2	608.1	28.33	15.39	8.43	21.5	39.5	72.1	1.554	1.406	1.487		410
	9	1	605.3	28.21	15.33	8.40	21.5	39.5	72.0	0.589	0.427	0.503		1195
	2	1	201.5	9.48	5.10	2.70	21.2	39.5	74.6	1.056	0.905	0.976		206
16	10	0	603.9	29.11	15.09	8.35	20.7	40.0	72.3	0.630	0.472	0.543		1101
	11	0	597.1	28.79	14.92	8.29	20.7	40.0	72.1	0.826	0.705	0.774		777
	12	0	601.6	29.01	15.04	8.37	20.7	40.0	71.9	1.054	0.934	1.005		603
	10	1	606.6	29.25	15.17	8.44	20.7	40.0	71.9	0.587	0.460	0.532		1153
	10	2	603.8	29.12	15.10	8.38	20.7	40.0	72.0	0.635	0.509	0.580		1051
	13	0	603.6	29.09	15.08	8.34	20.6	40.0	72.4	1.494	1.377	1.458		418
	14	0	195.1	9.54	4.86	2.59	20.4	40.2	75.4	0.556	0.425	0.493		397
	14	1	201.1	9.80	4.98	2.66	20.5	40.3	75.7	0.545	0.413	0.486		418
	15	0	199.1	9.69	4.93	2.62	20.5	40.4	76.0	1.029	0.905	0.976		205
	16	0	198.5	9.65	4.91	2.60	20.6	40.4	76.2	1.507	1.387	1.464		137
26	17	0	199.1	9.37	4.78	2.74	21.2	41.6	72.5	0.554		0.495		380
	18	0	200.1	9.42	4.81	2.76	21.2	41.6	72.5	1.029		0.976		200
	19	0	196.9	9.24	4.72	2.71	21.3	41.7	72.6	1.507		1.464		133
	20	0	614.4	28.91	14.75	8.37	21.3	41.6	73.4	0.921	0.796	0.860		690
	21	0	601.2	28.29	14.42	8.19	21.3	41.7	73.4	1.538	1.422	1.498		405
	22	0	600.4	28.23	14.39	3.17	21.3	41.7	73.5	1.098	0.979	1.049		612
	23	0	605.4	28.47	14.52	8.25	21.3	41.7	73.4	0.574	0.443	0.510		1189

APPENDIX B

The time histories of the measured parameters are presented in run number sequence. The complete sets of recorded data are included without editing. Notes indicate instances where data were not recorded. The drift in the force data (described in Section 6.1 of the main text) was corrected in these plots.

For ease of access, certain illustrations presented in the main text are repeated here. As a guide to the data, Table 1 (Page B1) presents a capsule of the FA-21 test showing design test conditions; Table 10 (Pages B2, B3) is the test run log. Figures 4 (Page B5) and 5 (Pages B6, B7) detail the instrumentation locations.

Nomenclature used on the time histories is defined in Table B1 (Page B4).

TABLE 1

CAPSULE OF FA-21 (HRWT-38) TEST

a. Summary (Showing Altitudes in Feet)
(No. of runs in parentheses)

	X/D = 5	X/D = 12	X/D = 16	X/D = 20	
Plate (ψ = 45°)	50K (6) 100K (6)	100K (6)		100K (26) (+ψ=30°, 60°, 90°)	6 38
Rake	50K (7) 100K (4)	100K (5) 112K (6)	100K (5)	100K (7) 112K (2)	7 21 8
Particle		100K (4)		100K (6)	10
	23	21	5	41	90

b. Details (Showing Run Nos.)

Design P_c = 1000 psia

	X/D=5			X/D=12			X/D=16		X/D=20		
	2%	10%	15%	2%	10%	15%	2%	10%	2%	10%	15%
Plate ψ = 30°									14 ●●●	15 ●●	16 ●●
ψ = 45°	25 ●● 26 ▲▲	21 ●● 23 ▲▲	22 ●● 24 ▲▲	32 ●●	33 ●●	34 ●●			27 ●●	19 ●●	20 ●●
ψ = 60°									28 ●●	39 ●●	40 ●●
ψ = 90°									29 ●●	17 ●●	18 ●●●
Rake	10 ▲▲	4 ●● 11 ▲▲	5 ●● 6 ▲▲▲	44 6 7 ●●	45 66 9 ●	43 666 8 ●●	12 ●●	13 ●●●	41 6 1 ●●●	42 6 2 ●●	3 ●●
Particle				31 ●●	35 ●	36 ●			30 ●●	37 ●●	38 ●●

6 112,000 feet pressure altitude
● 100,000 feet pressure altitude
▲ 50,000 feet pressure altitude

Runs were performed in Run No. Sequence, except:

1. 6/3 occurred after 11/2.
2. 14/2, 14/3 occurred after 27/2.
3. 43/2, 43/3 occurred after 45/2.

TABLE 10

RUN LOG

CHRONOLOGY				NOM. COND.		ROCKET S/N		ACTUAL CONDITION INSTRUMENTATN.								REMARKS
SEQ NO.	RUN NO.	DATE	TIME	ALT. (ft)	% AL	NOZ	CASE ①	P_c ② psia	P_∞ mmHg	θ_m	ψ	X/D	X	θ_o ③	movie	
1	1/1	2/17	1015	100K	2	1	20A=A	-	8.60	R		20	28.73	1A		P_{41} N.G.; P_{11}, P_{17} overscale.
2	1/2	2/20	1545			2	20A=B	860	8.65	A				1B		P_{c1}, P_{N1-N3} not on (Kistlers).
3	1/3	2/23	1400			3	20A=C	773	8.70	K						
4	2/1	2/24	1040		10	4	19A=A	749	8.70	E						Q_{33} deteriorated.
			1500			5	19A=B									No fire.
		2/25	0900				19A=C									No fire.
5	2/2		1050				19A=D	909	8.68							P_{c1} N.G. (Kistler).
6	3/1		1430		15	6	18A=A	955	8.70							P_{c1} N.G. (Kistler).
7	3/2	2/26	1035			7	18A=B	942	8.70							
8	4/1	3/02	1035		10	8	19A=E	904	8.65			5	7.22	2A		P_1, P_2, Q_{32} destroyed; Q_{34} over-scale.
9	4/2	3/03	1130			9	19A=F	935						2B		P_1 damaged.
10	5/1		1520		15	10	18A=C	1043								
11	5/2	3/04	1125			11	18A=D	992						2C		P_2 destroyed.
12	6/1	3/05	0840	50K		12	18A=E	986	97.0					3		P_1 bent; improved T/C instl.
13	6/2		1305			13	18A=F	949								P_{c1} N. G. (Kistler).
14	7/1	3/10	1605	100K	2	14	20A=D	761	8.70			12	17.30	4		Added force gage.
15	7/2	3/11	0950			15	20A=E	745	8.65							
16	8/1		1215		15	16	18A=G	988								
17	8/2		1440			17	18A=H	998								
18	9/1		1645		10	18	19A=G	940	8.70							
19	10/1	3/12	1535	50K	2	19	20A=E	726	96.9			5	7.21	5A		P_1 N.G.
20	10/2	3/15	1135			20	20A=G	749	98.5							
21	11/1		1340		10	21	19A=H	890	97.0							P_1 destroyed; P_2 P_3 P_4 damaged.
22	11/2		1600			22	19A=I	902						5B		
23	6/3	3/16	0920		15	23	18A=I	928								
24	12/1	3/17	1600	100K	2	24	20A=H	761	8.70			16	23.07	6A	x	P_{c2} plugged; added camera.
25	12/2	3/18	0710			25	20A=I	710								P_{c2} plugged.
26	13/1		0925		10	26	19A=J	860							x	P_1 N. G.
27	13/2		1140			27	19A=B	901	8.8					6B		P_1 plugged.
28	13/3		1420			28	19A=C	894	8.7							Force N. G.
29	14/1	3/22	1200		2	29	20A=J	724		P	30°	20	28.86	7.	x	Q_8, Q_{18} N. G.
30	15/1		1515		10	30	19 =A	943		L					x	Plate plating deteriorating.
31	15/2	3/23	0715			1	19 =B	850	8.70	A					x	Q_{12}, Q_{15} N.G.
32	16/1		0935		15	2	18A=J	949		T					x	
33	16/2		1145			3	18 =A	1002		E					x	
34	17/1		1425		10	4	19 =C	950			90°				x	P_{c1} Incorrect sensitivity
35	17/2	3/24	0715			5	19 =D	855							x	P_{c1} N. G. (Kistler)
36	18/1		0920		15	6	18 =B	932							x	
37	18/2		1125			7	18 =C	1001							x	
38	18/3		1355			8	18 =D	973							x	
39	19/1	3/25	0710		10	9	19 =E	875			45°				x	
40	19/2		0920			10	19 =F	890	8.65						x	P_{c2} N.G.(plugged) (Statham).
41	20/1		1120		15	11	18 =E	947	8.70						x	P_{c2} dirty.
42	20/2		1355			12	18 =F	983							x	
43	21/1	3/26	1015		10	13	19 =G	895				5	7.21	8A	x	Q_{18} N.G.
44	21/2		1510			14	19 =H	898						8B	x	Q_{18} N.G., P_{10} plugged.
45	22/1	3/29	0845		15	15	18 =G	936	8.65						x	P_{10} plugged; no RTV on P_{c2} xdcr.
46	22/2		1110			16	18 =H	983	8.70						x	
47	23/1		1310	50K	10	17	19 =I	957	97.0						x	P_{10} eroded; P_{N2} tap loose.
48	23/2		1450			18	19 =J	954							x	P_{10} eroded; P_{11} over scale.
49	24/1		1525		15	19	18 =I	1005							x	
50	24/2		1750			20	18 =J	1024							x	

TABLE 10

(Concluded)

CHRONOLOGY				NOM. COND.		ROCKET S/N		ACTUAL CONDITION		INSTRUMENTATN.						REMARKS
SEQ NO.	RUN NO.	DATE	TIME	ALT. (ft)	% AL	NOZ	CASE ①	P_C ② psia	P_∞ mmHg	Device	ψ	X/D	X	Shield ③	Movie	
51	25/1	4/01	1600	100K	2	21	20 =A	730	8.70	P	45°	5	7.21	3B	x	
52	25/2	4/02	0715			22	20 =B	772		L					x	
53	26/1		1020	50K		23	20 =C	777	97.0	A					x	
54	26/2		1150			24	20 =D	779		T					x	
55	27/1		15[illegible]	100K		25	20 =E	812	8.70	E		20	28.84	7	x	
56	27/2	4/05	0935			26	20 =F	729							x	
57	14/2		1155			27	20 =G	771			30°				x	P_{C1} N.G. (Kistler).
58	14/3		1410			28	20 =H	774							x	
59	28/1	4/06	0715			14	20 =I	792			60°				x	Added smoothing to Q data.
60	28/2		0930			30	20 =J	760							x	
61	29/1		1145			1	20 =K	774			90°				x	P_{C2} N.G. (plugged)
62	29/2		1420			2	20 =L	810							x	P_{16} N.G.
63	30/1	4/07	1025			3	20 =M	-							x	Ⓟ; all channels off.
64	30/2		1425			4	20 =N	815							x	Ⓟ; ign. plug hit wax.
65	31/1	4/08	0715			5	20 =O	765				12	17.31		x	Ⓟ N.G., disk did not rotate
66	31/2		1005			6	20 =P	750							x	Ⓟ
67	32/1		1425			7	20 =Q	796			45°				x	
68	32/2	4/09	0900			8	20 =R	749							x	P_{17} N.G.
69	33/1	4/12	0850		10	9	19 =A	844							x	
70	33/2		1055			10	19 =B	886							x	
71	34/1		1350		15	11	18 =A	1002							x	
72	34/2	4/13	0710			12	18 =B	940							x	
73	35/1		1010		10	13	19 =C	846	8.65		90°				x	Ⓟ
74	36/1		1225		15	29	18 =C	967	8.70						x	Ⓟ; alignment jig in nozzle
75	37/1		1520		10	15	19 =D	950				20	28.85			Ⓟ
76	37/2	4/14	0720			16	19 =E	845								Ⓟ
77	38/1		0920		15	17	18 =D	987								Ⓟ; alignment not verified.
78	38/2		1120			18	18 =E	996								Ⓟ; used red wax.
79	39/1		1430		10	19	19 =F	935			60°					P_1 N.G.
80	39/2	4/15	0850			20	19 =G	888							x	
81	40/1		0940		15	21	18 =F	880							x	P_{C2} Appears too low
82	40/2		1230			22	18 =G	1013							x	
83	41/1	4/19	1015	112K	2	23	20 =S	793	5.00	R				9A	x	T_{45} N.G., F not corrected
84	42/1		1330		10	24	19 =H	948	5.1	A					x	T_{45} N.G., F N.G.
85	43/1	4/20	0905		15	25	18 =H	1016	5.1	K		12	28.84		x	P_9 N.G. ④
86	44/1		1215		2	26	20 =T	812	5.05	E					x	P_1 P_3 damaged
87	45/1		1600		10	27	19 =I	888	5.1					9B	x	P_1 N.G.
88	45/2	4/21	0850			28	19 =J	908	5.1						x	
89	43/2		1155		15	1	18 =I	1025	5.0					9C	x	P_{13} N.G.
90	43/3		1450			30	18 =J	1011	5.1						x	

Notes: ① Full S/N = given S/N preceded by "12", i.e., for Run No. 1/1, "1220A = A".
② Average P_{c_1} per Eqn. 5 and Tables 14-16.
③ Configuration per Fig. 5 and Table 6.
④ T_{45} did not reach steady state condition.

Ⓟ Particle sampling run.

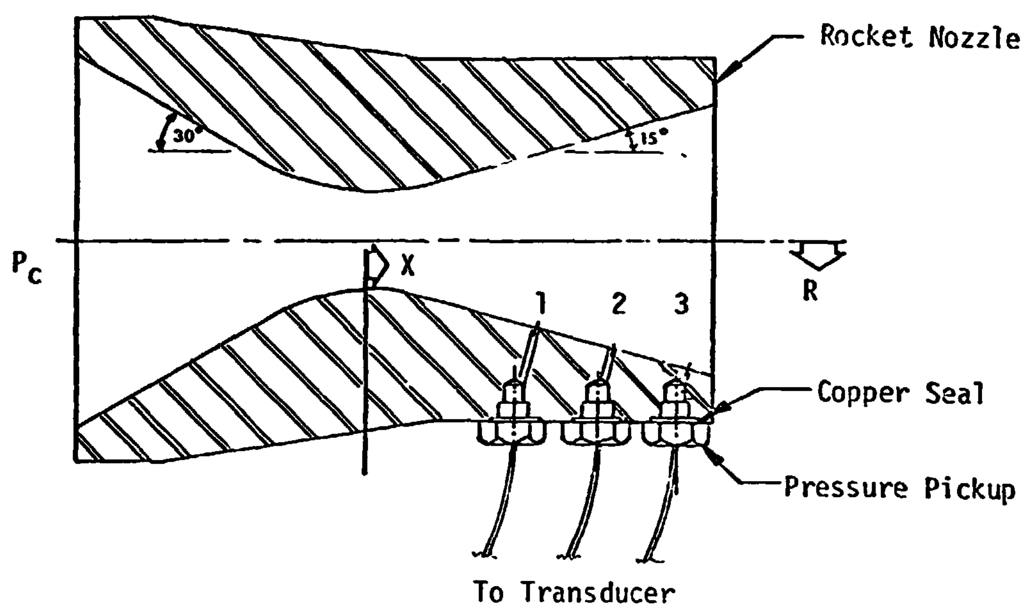
P_{xx} = Pressure at position xx
Q_{xx} = Heat rate at position xx
T_{xx} = Temperature at position xx

} Position per Fig. 5 and Table 6.

TABLE B1

NOMENCLATURE

Symbol	Definition	See Fig. No.
F_{xx}	Rake Force xx inches East of ℄	5c
P_{c1}	Chamber Pressure measured by Kistler transducer	
P_{c2}	Chamber Pressure measured by Statham transducer	
P_{n1}	Nozzle Wall Pressure at Position No. 1	4
P_{n2}	Nozzle Wall Pressure at Position No. 2	4
P_{n3}	Nozzle Wall Pressure at Position No. 3	4
P_{xx}	Rake Pressure xx inches west of ℄	5c
P_{xxE}	Rake Pressure xx inches east of ℄	5c
P_{xxF}	Plate Pressure xx inches from ℄ on "far" side	5e
P_{xxN}	Plate Pressure xx inches from ℄ on "near" side	5e
$P_{2.5}$	Plate Pressure 2.5 inches south of ℄	5f
Q_{xx}	Rake Heat Rate xx inches east of ℄	5c
Q_{xxF}	Plate Heat Rate xx inches from ℄ on "far" side	5e
Q_{xxN}	Plate Heat Rate xx inches from ℄ on "near" side	5e
$Q_{2.5}$	Plate Heat Rate 2.5 inches north of ℄	5c
T_{xx}	Rake temperature xx inches east of ℄	5c

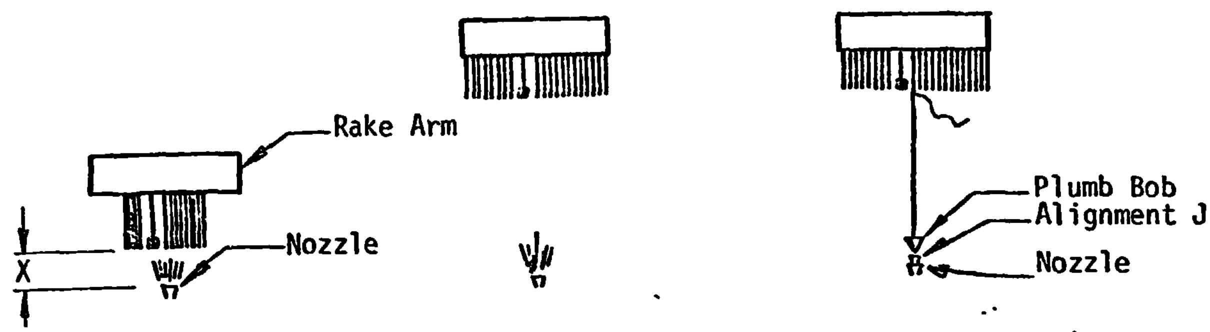


Design Values (See Table 3 for measured values)

Nozzle Pressure No.	X (in.)	R (in.)	A/A*
P_{n_1}	.888	.463	3.170
P_{n_2}	1.288	.570	4.808
P_{n_3}	1.688	.677	6.786

Fig. 4 Nozzle Instrumentation

b. Rake Positions



X/D = 5 X/D = 20 Alignment

c. Rake Probe Combinations

		East													West
Radial Position, inches		-12	-10	-8	-6	-4	-2	0	2	4	6	8	10	12	
Position No.		55	51	47	43	39	35	1	5	9	13	17	21	25	

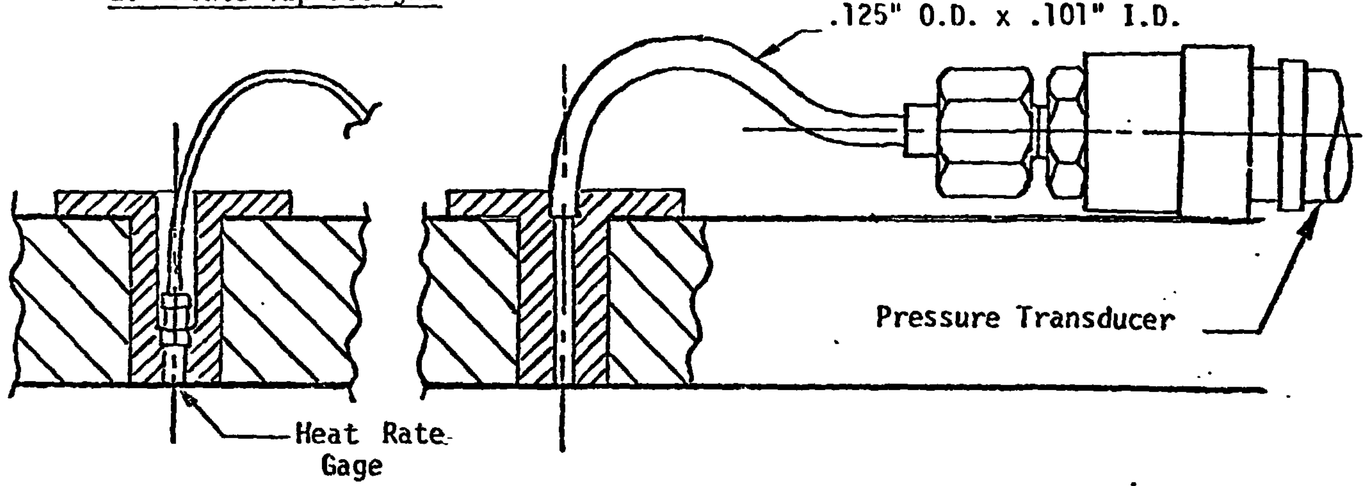
Config. No.	X/D	Probes
1	20	P Q T Q T Q P T Q P Q P P P P P P P P P P P P
6A	16	Q Q Q T Q F P P P P P P P P P P PPPP
6B	↓	Q Q Q T Q F P P P P P P P P P P PPP
4	12	Q Q Q T Q F P P P P P P P P P PPPPPP
9	12,20	Q T Q F P P PPPPPPPPPPPPP
2A	5	PQ Q QPTQPQPPPPPPPPPPPP
2B	↓	PQ Q QPT P PPPP PP PPPP
2C	↓	P Q Q QPTQP PPPP PP PPP P
3	↓	P P P PPPP PPPP
5A	↓	PQQTQQ F PPPPPPPPPPPPPP
5B	↓	QQTQQ F PPPPPPPPPPP

℄

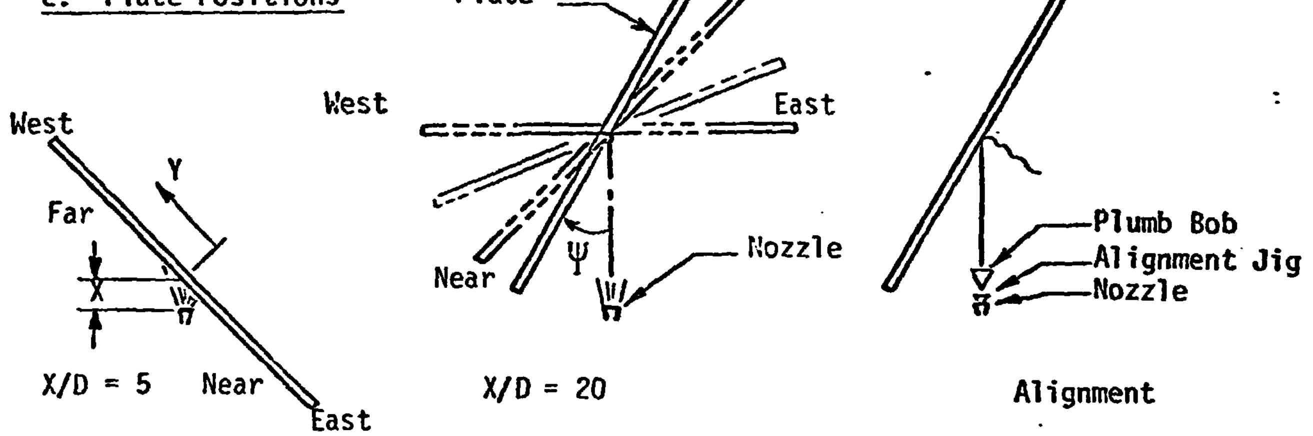
F - Force
P - Pitot Pressure
Q - Heat Rate Gage
T - Thermocouple

Fig. 5 Plume Instrumentation

d. Plate Tap Designs



e. Plate Positions



f. Plate Tap Combination (P = Pressure, Q = Heat Rate Gage)

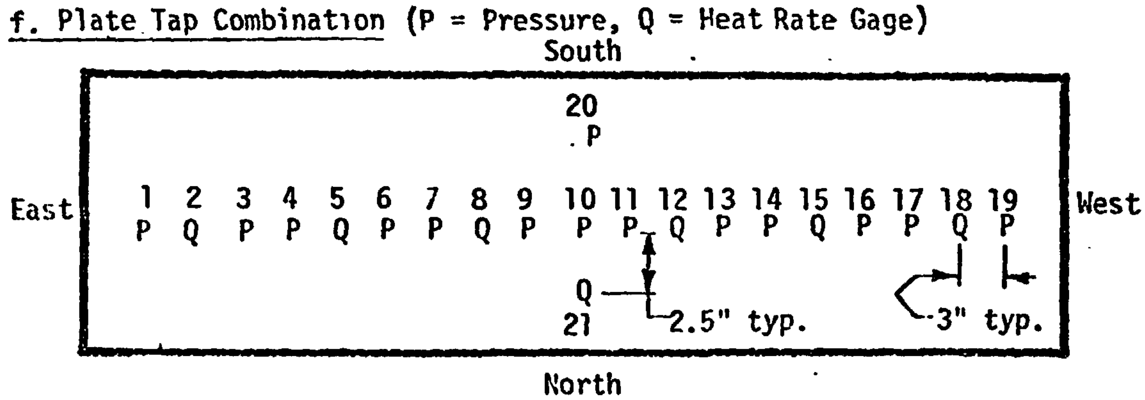
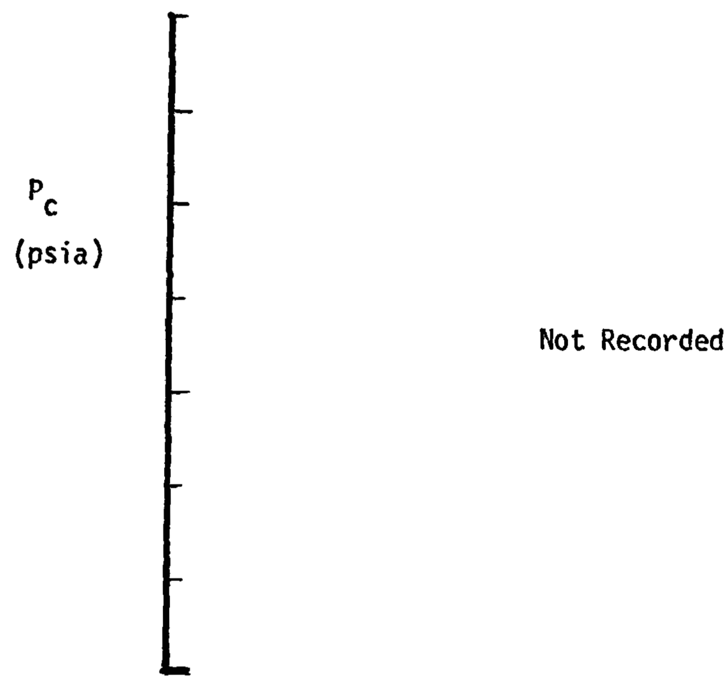
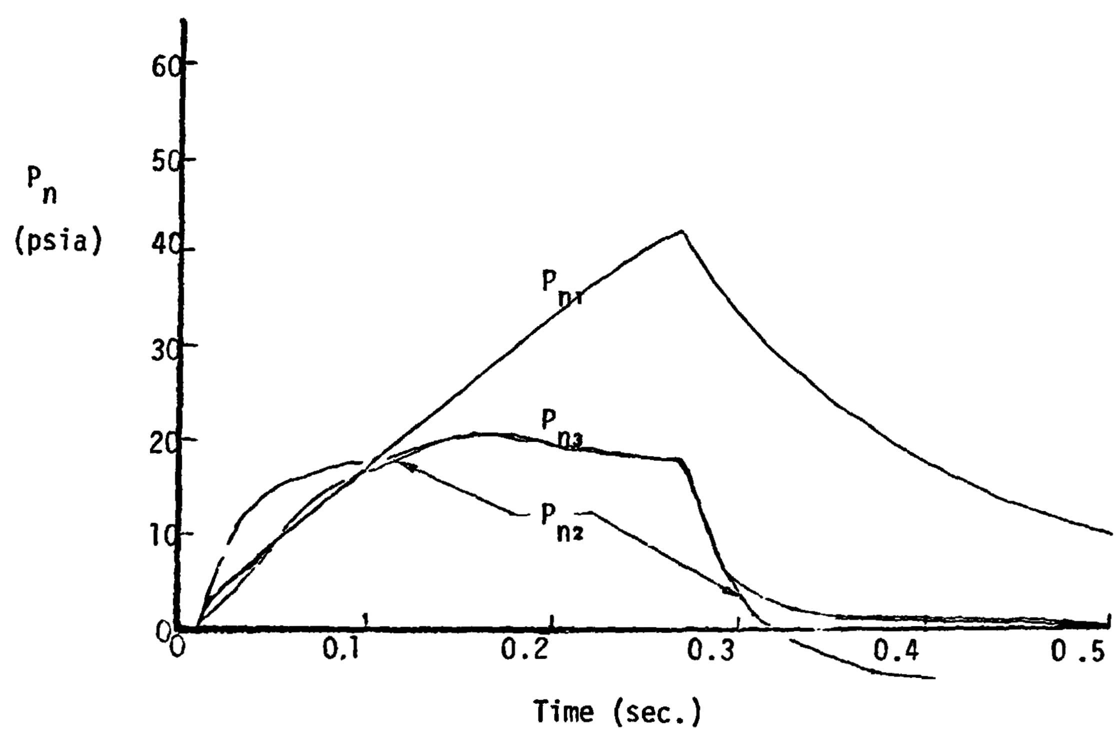


Fig. 5 (Continued)

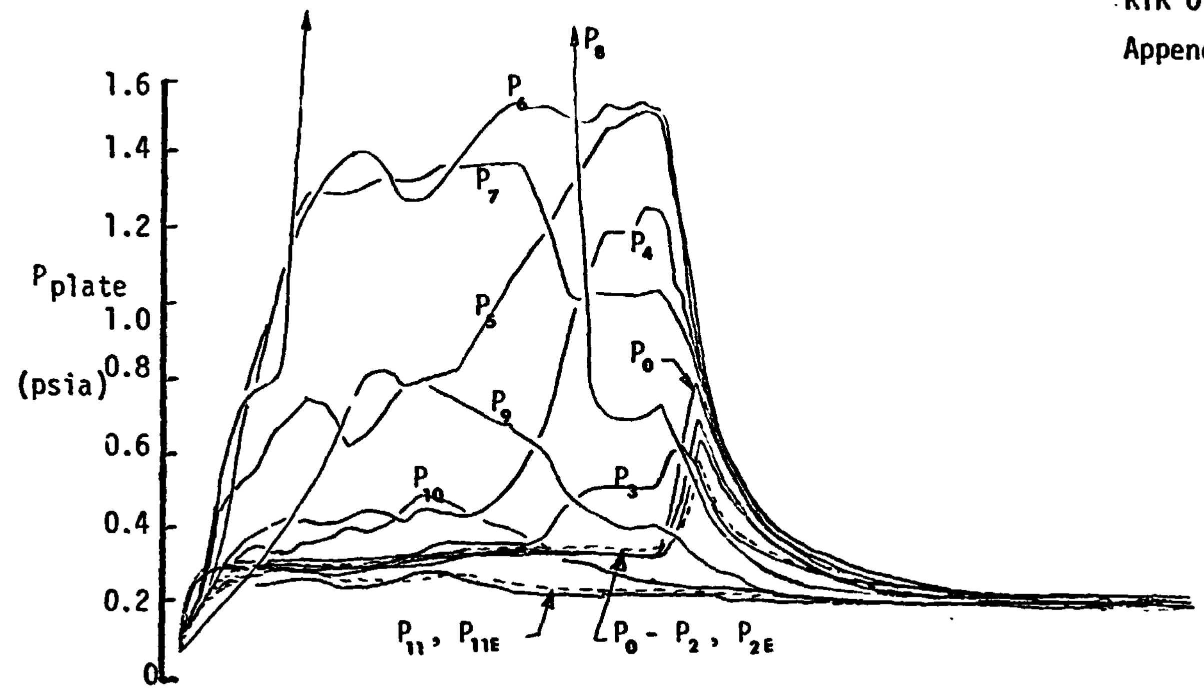


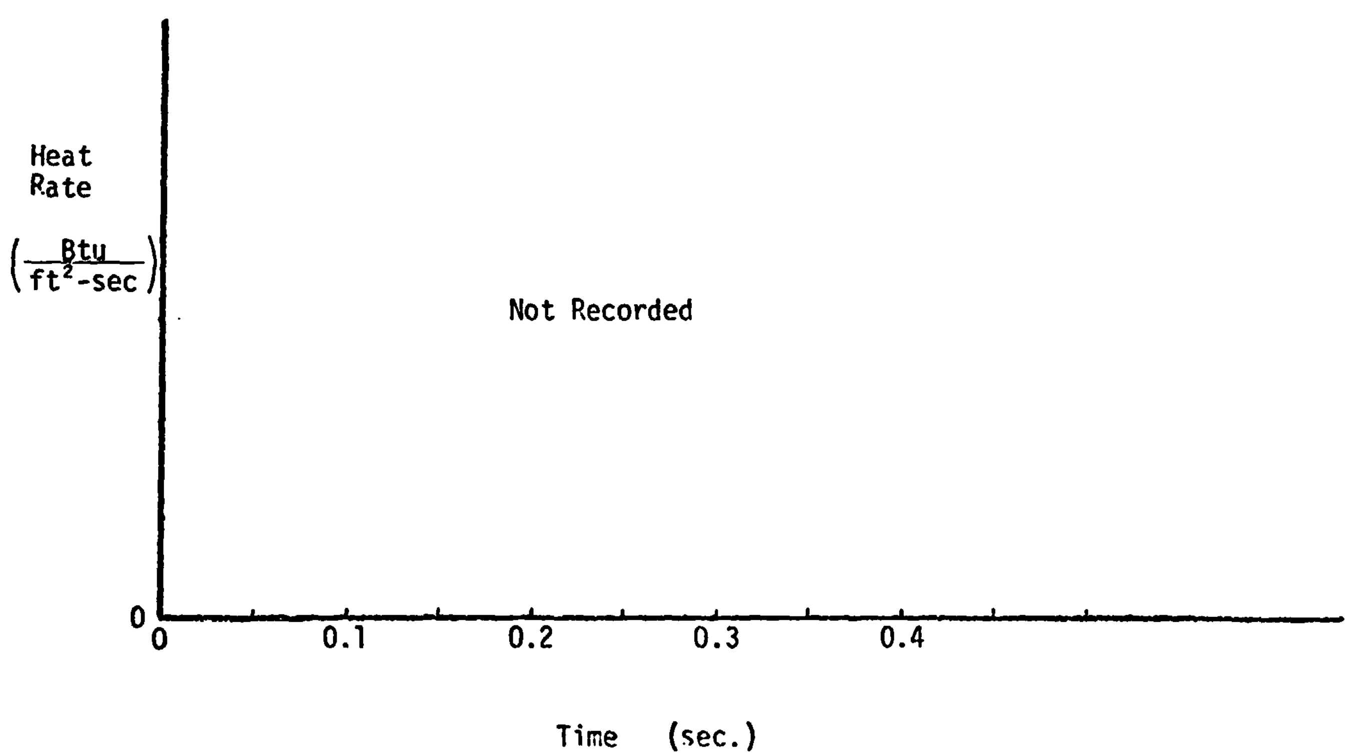


Run No. 1/1

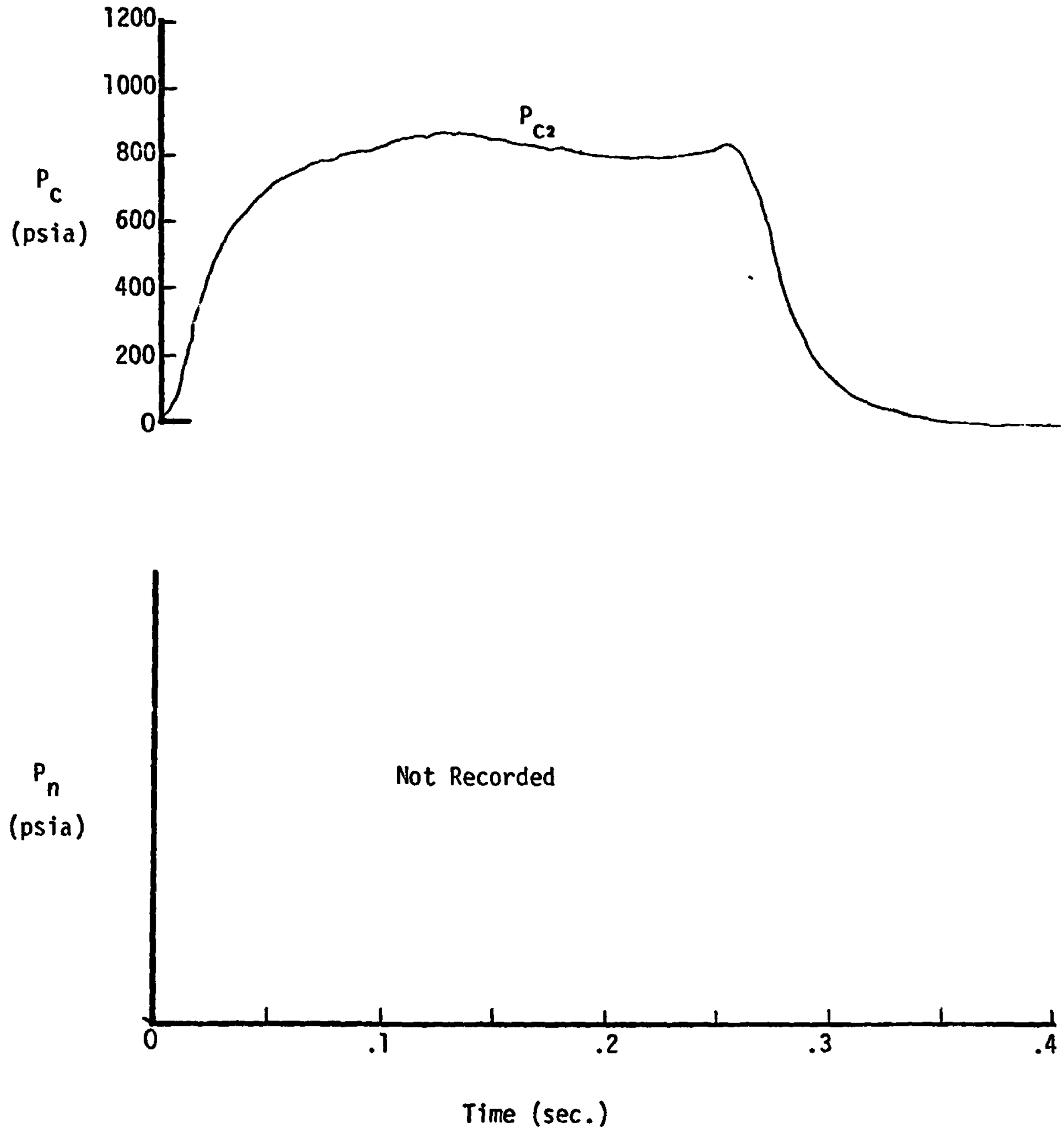
Rake @ X/D=20

Alt.=100,000'
%Aℓ = 2





Run No. 1/1 (Concluded)



Run No. 1/2

Rake @ X/D=20

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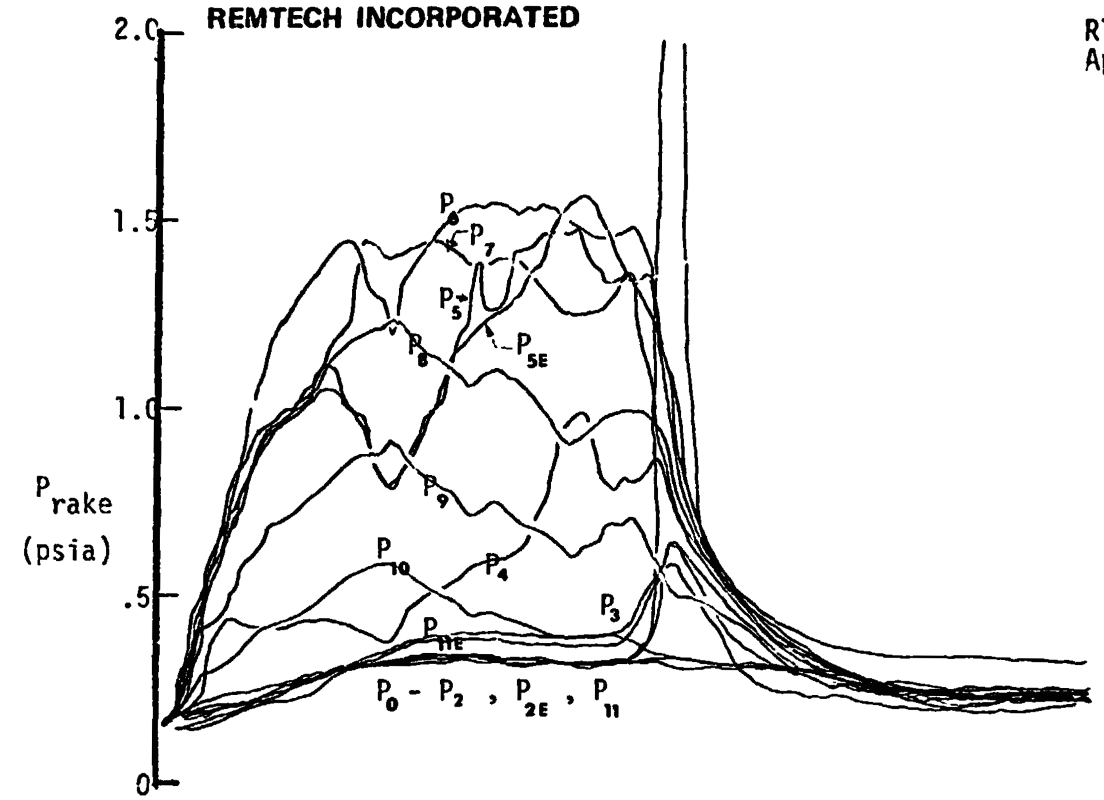
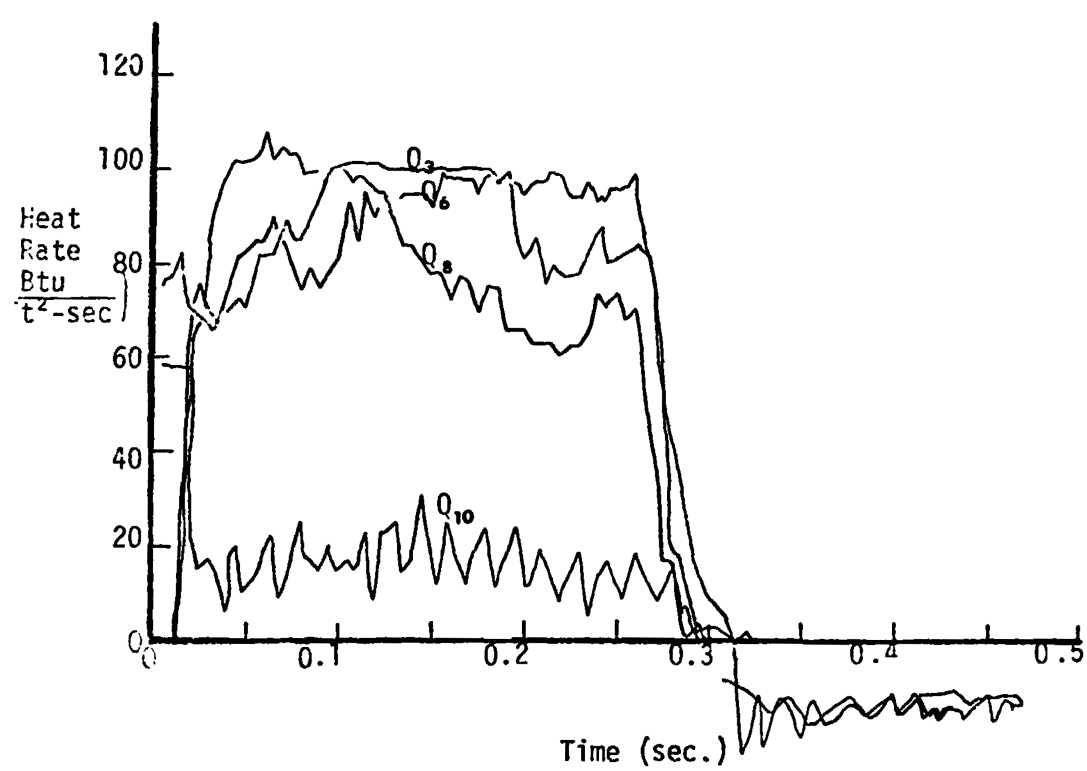
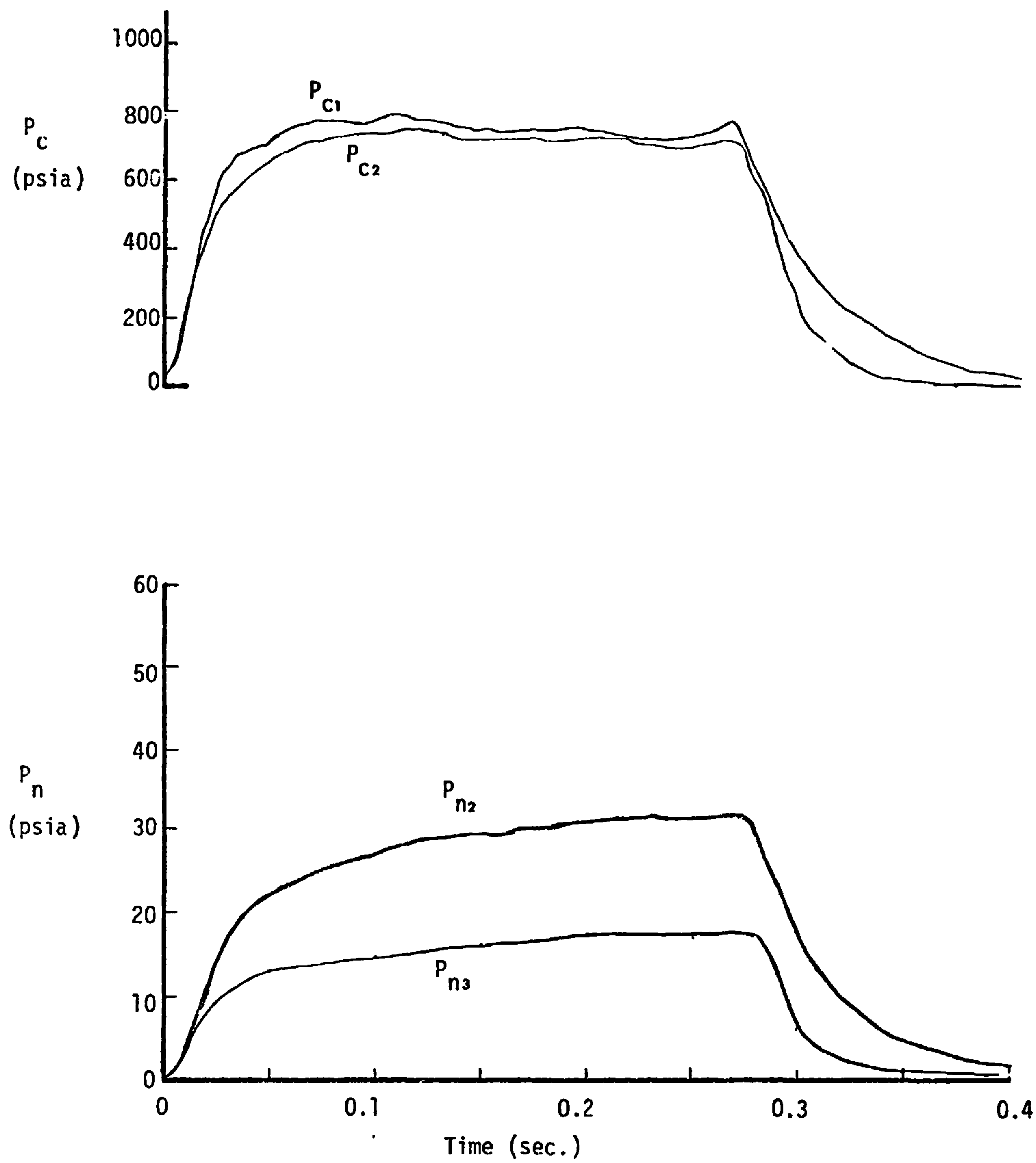




Run No. 1/2 (Concluded)



Run No. 1/3

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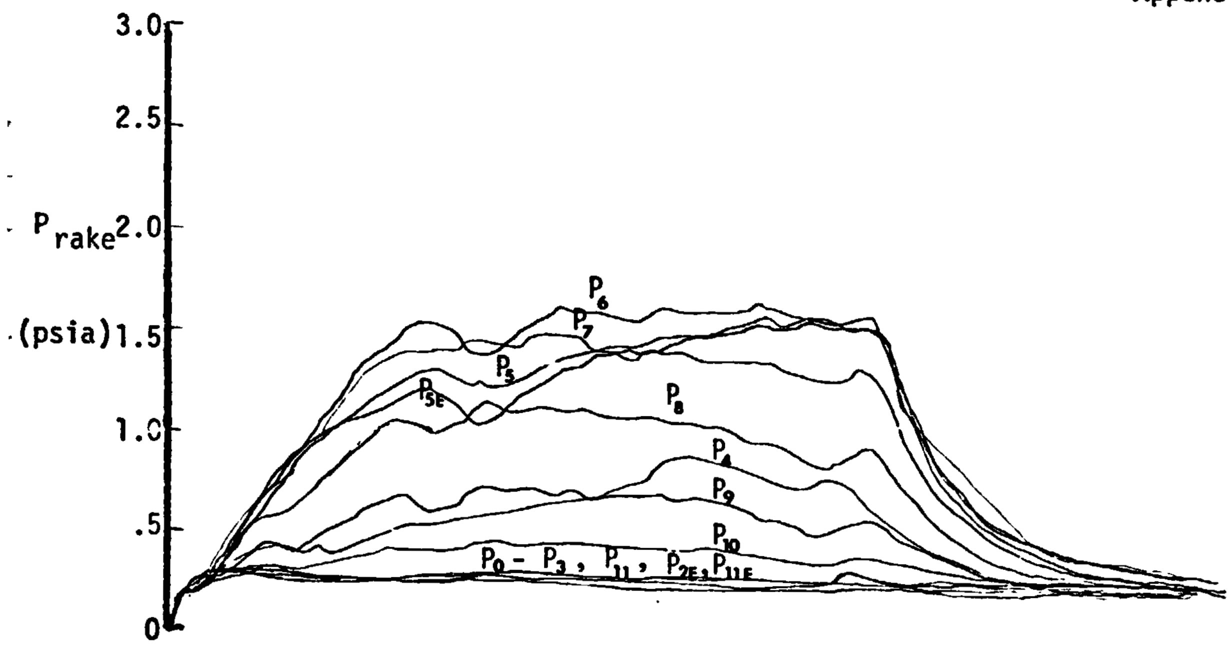

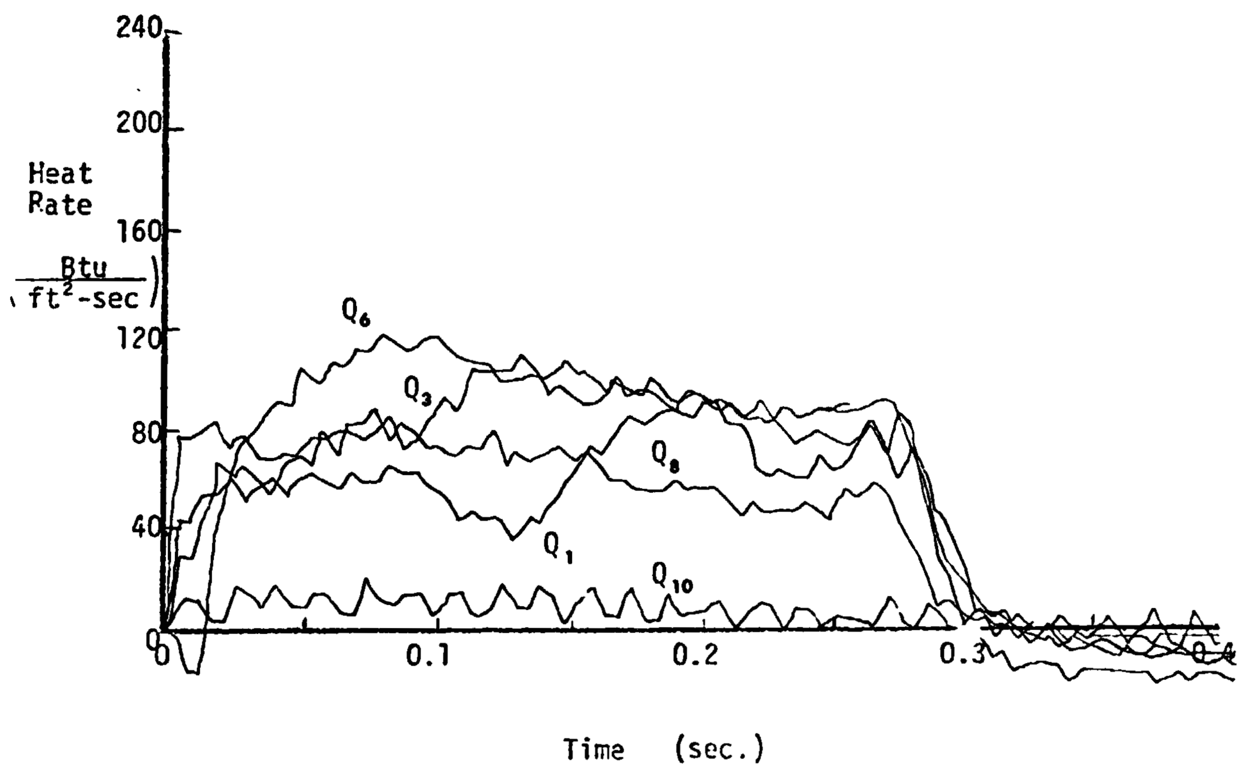

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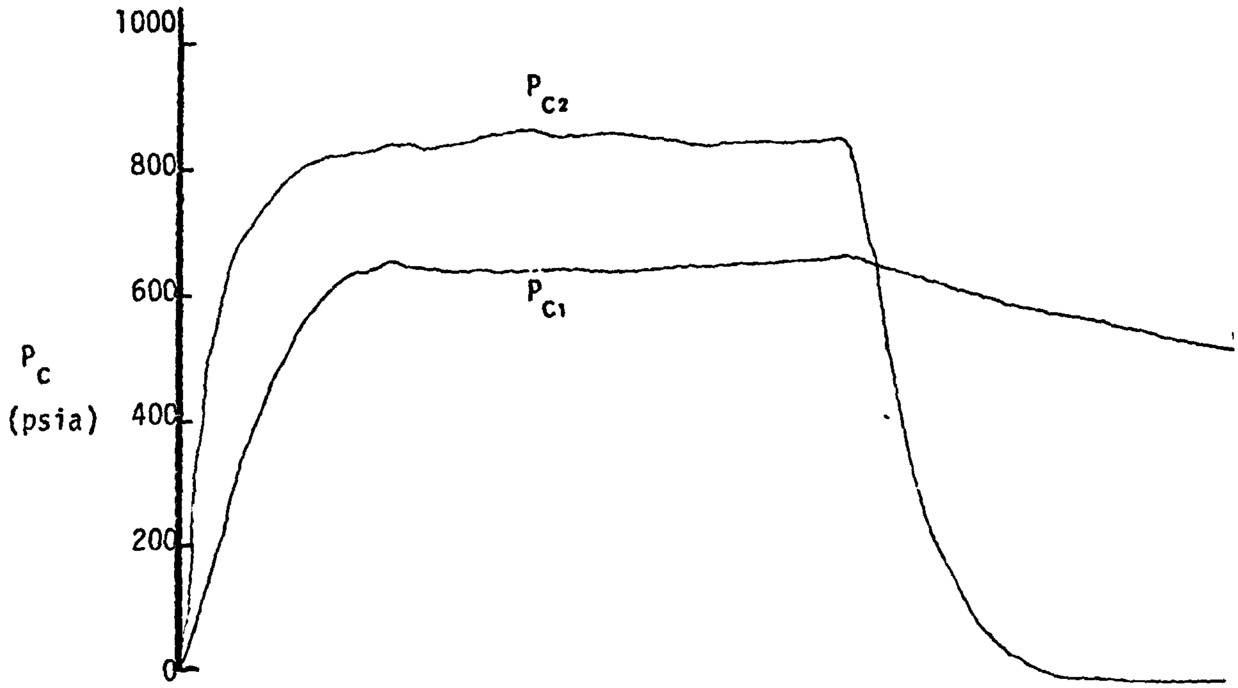

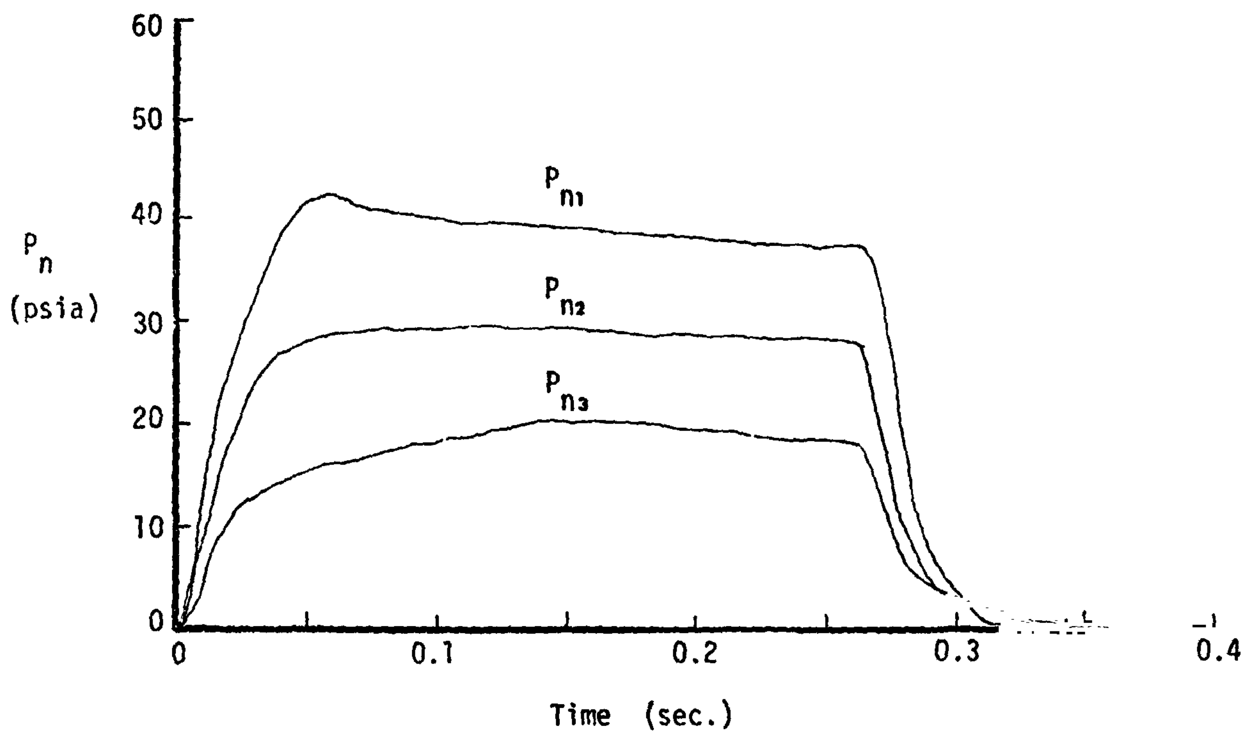

Run No. 2/1

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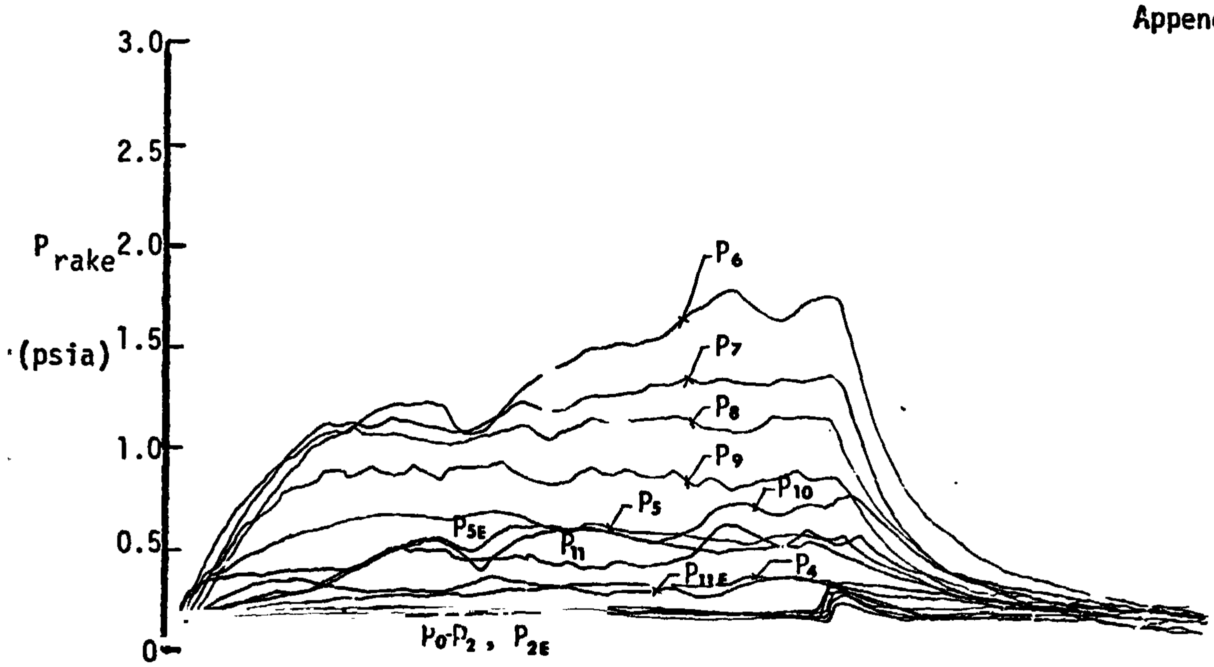

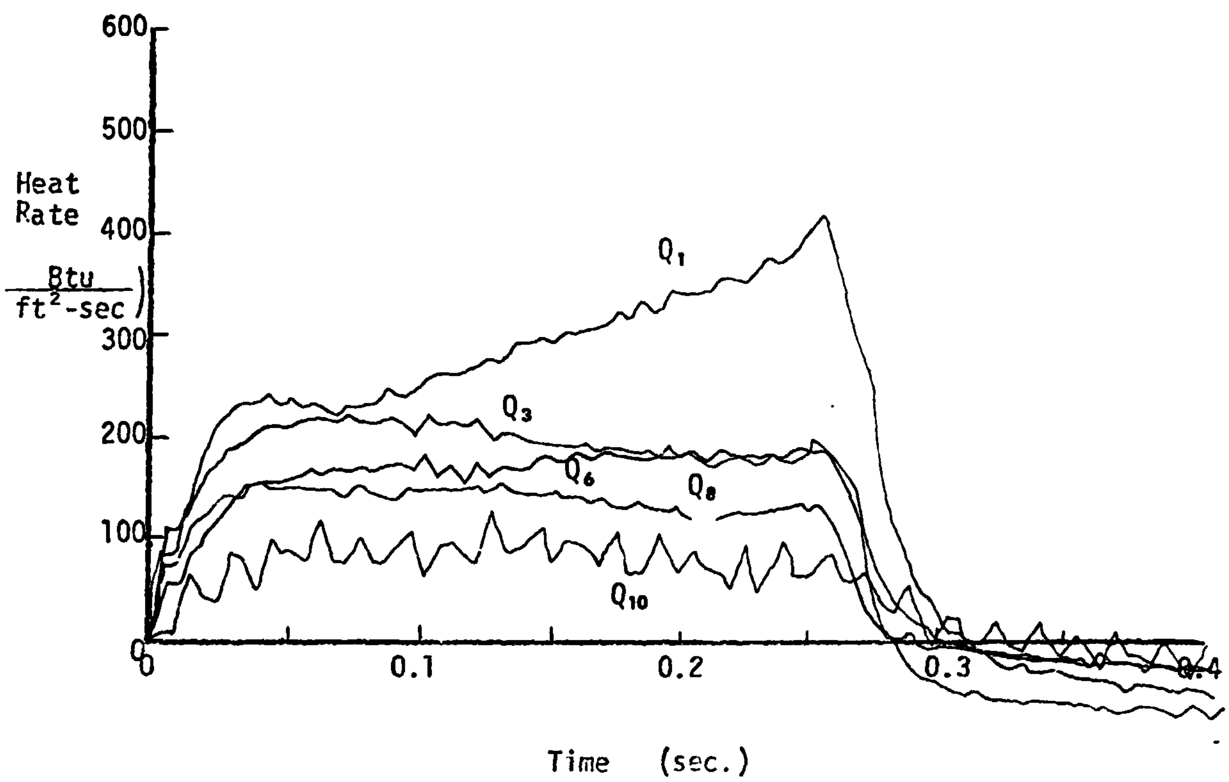

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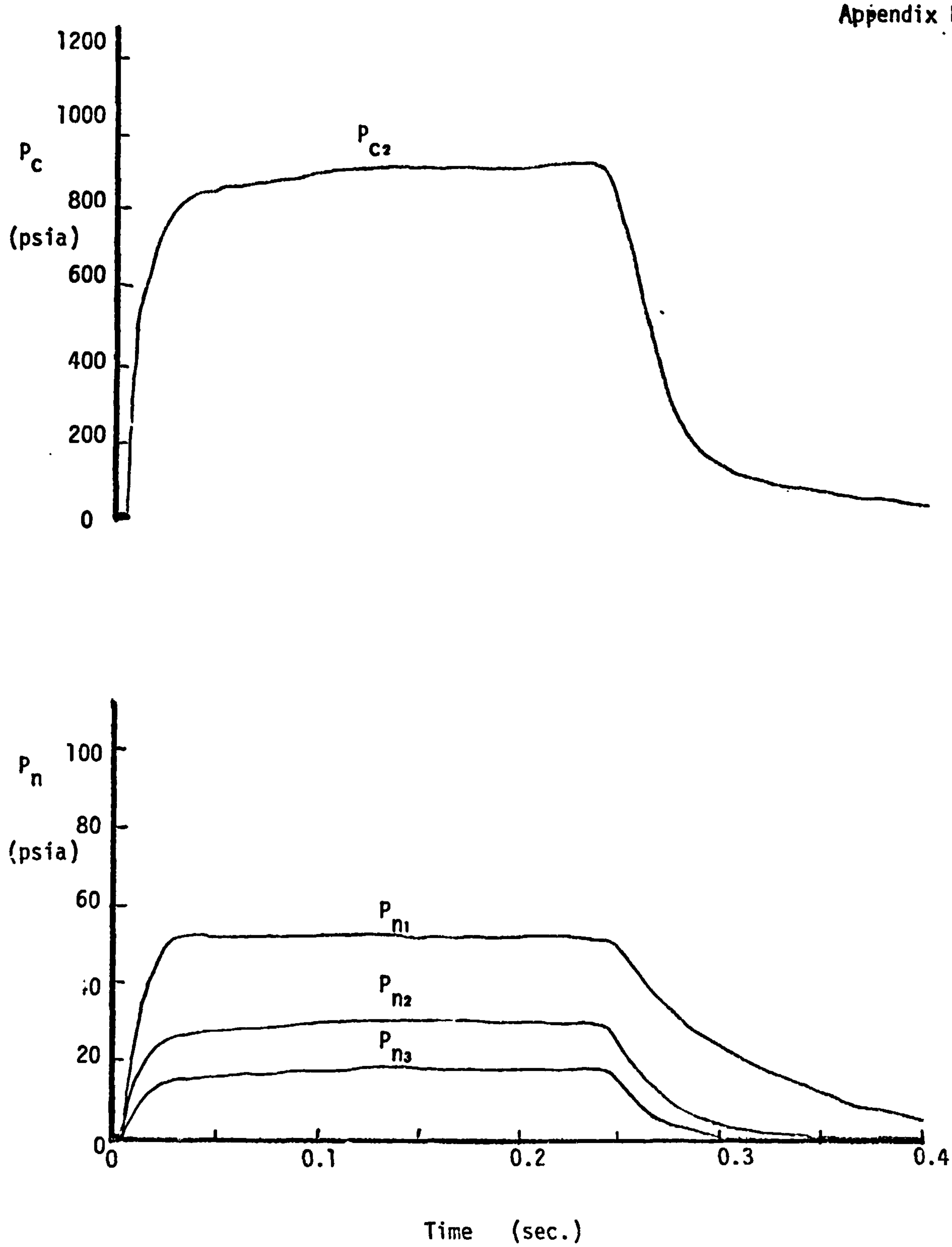

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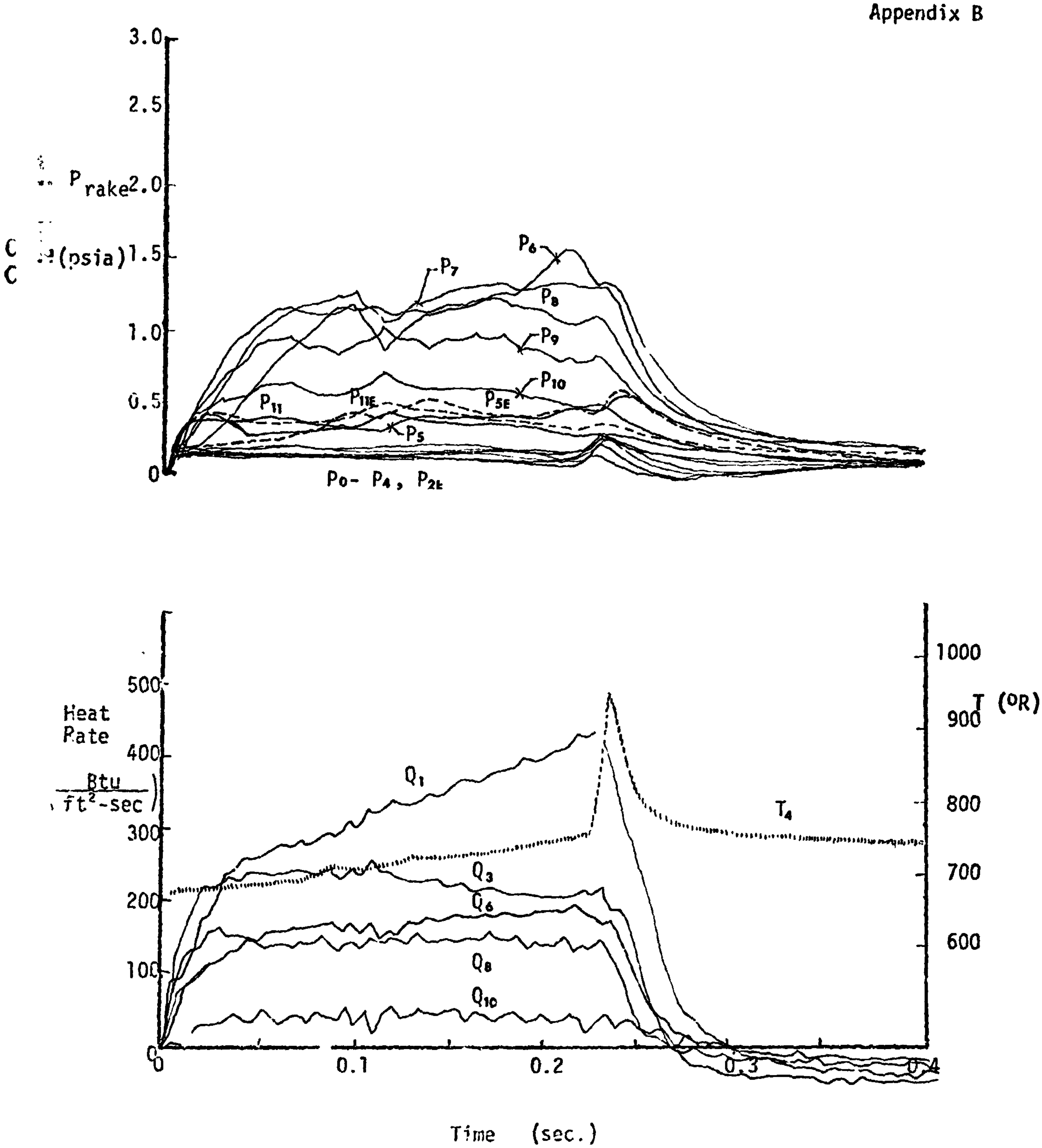

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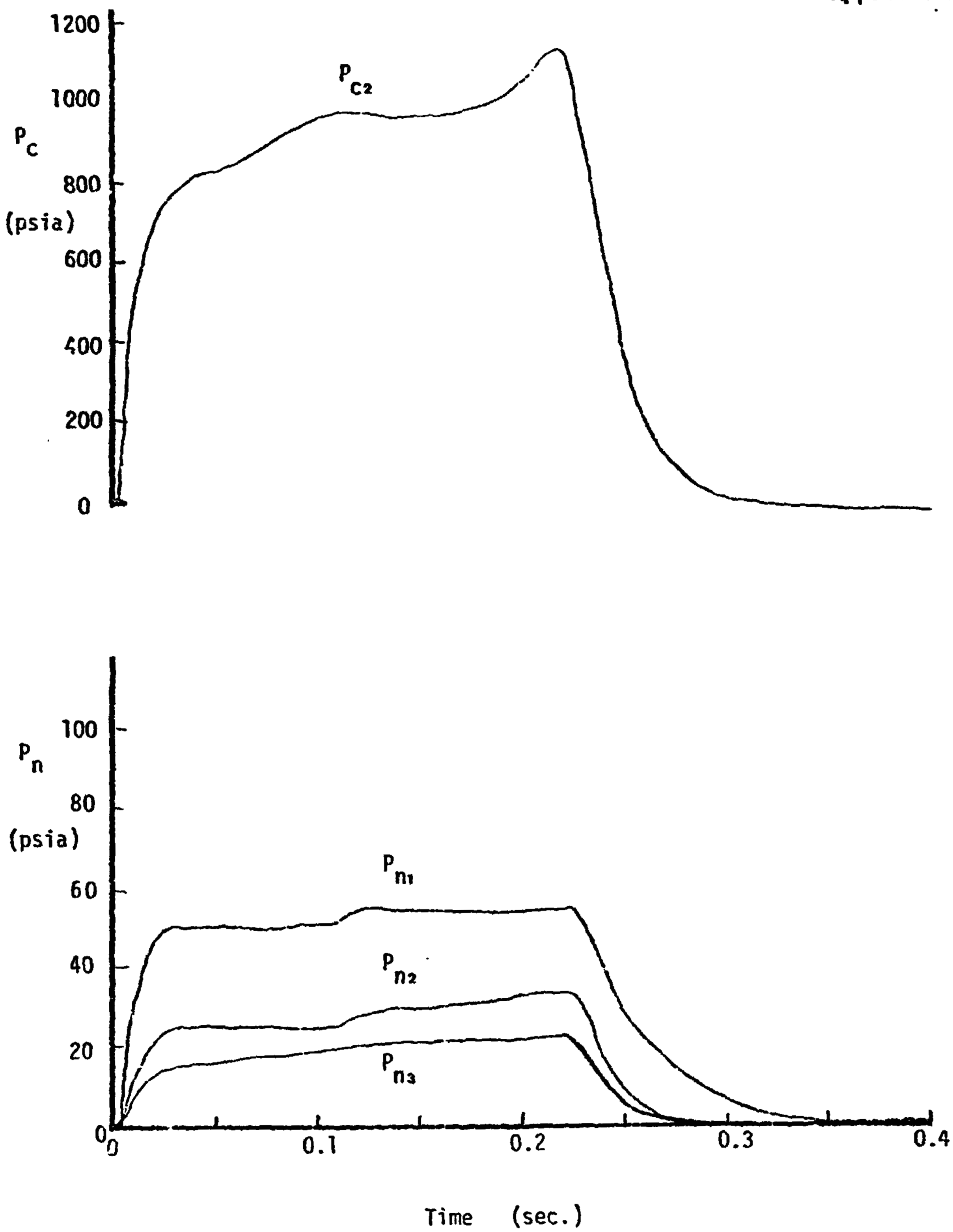

Run No. 3/1

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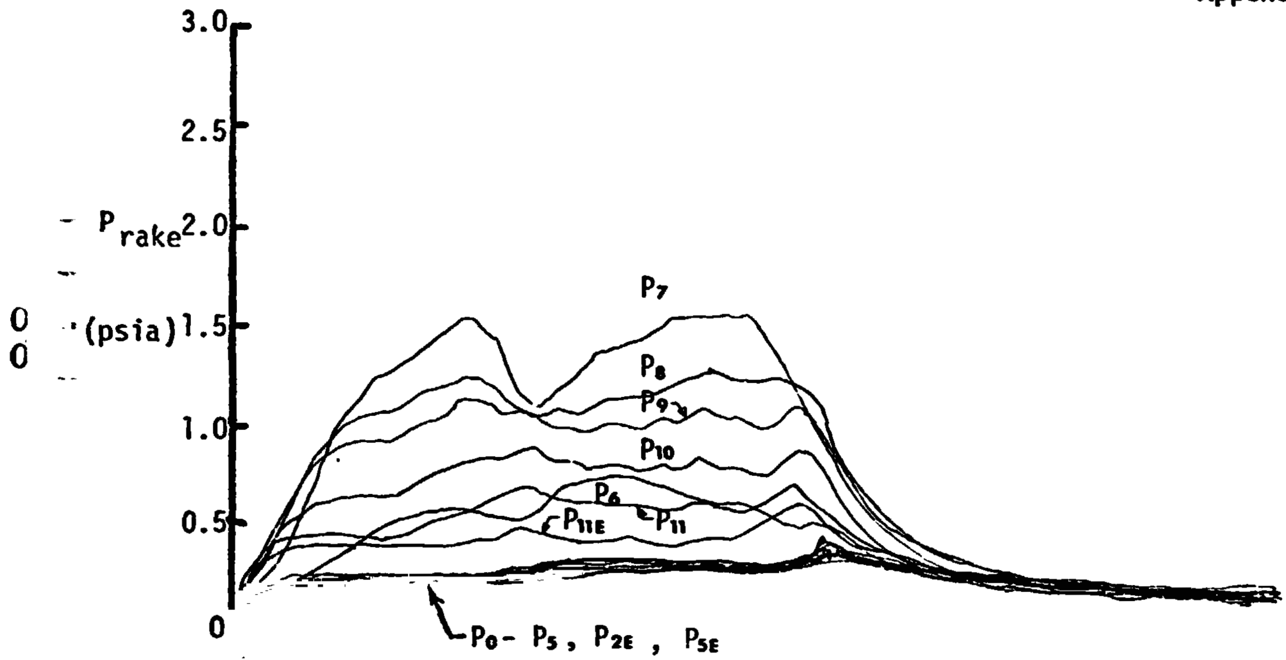

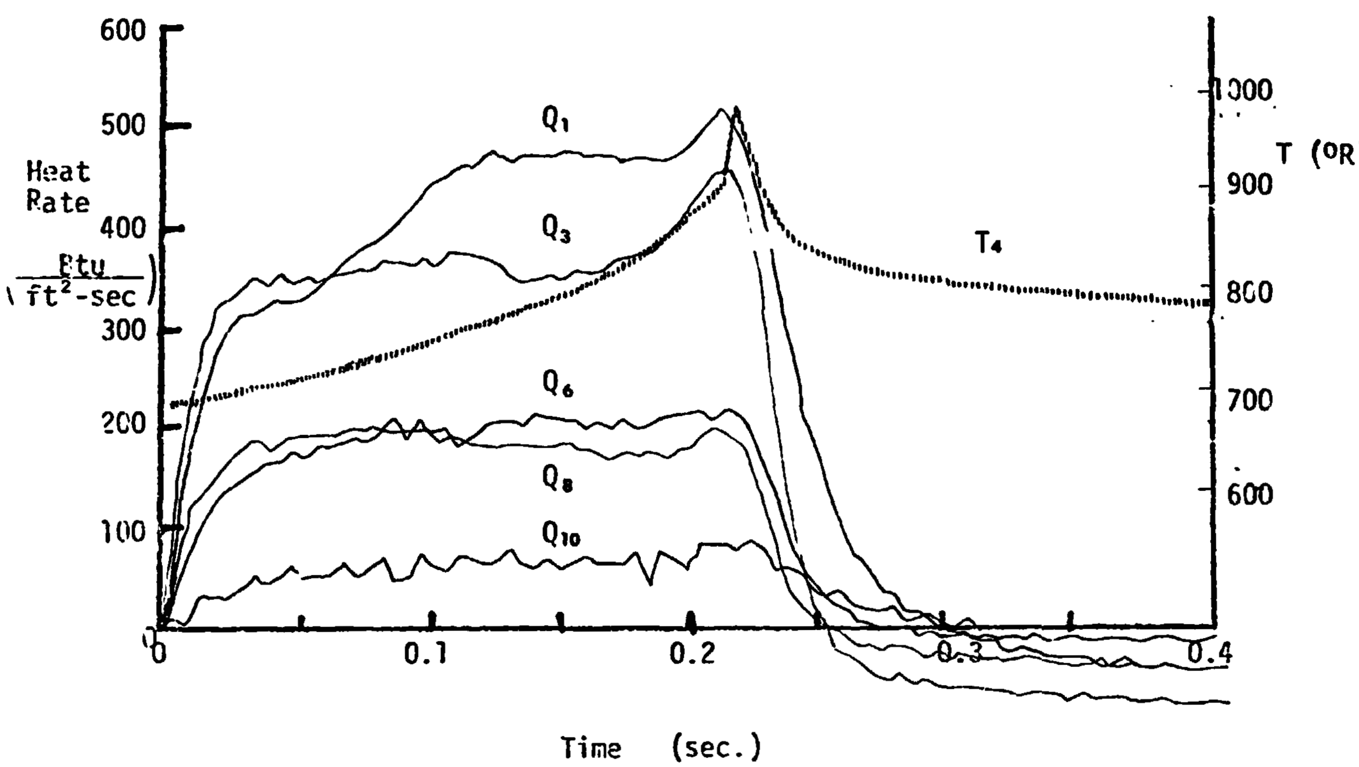

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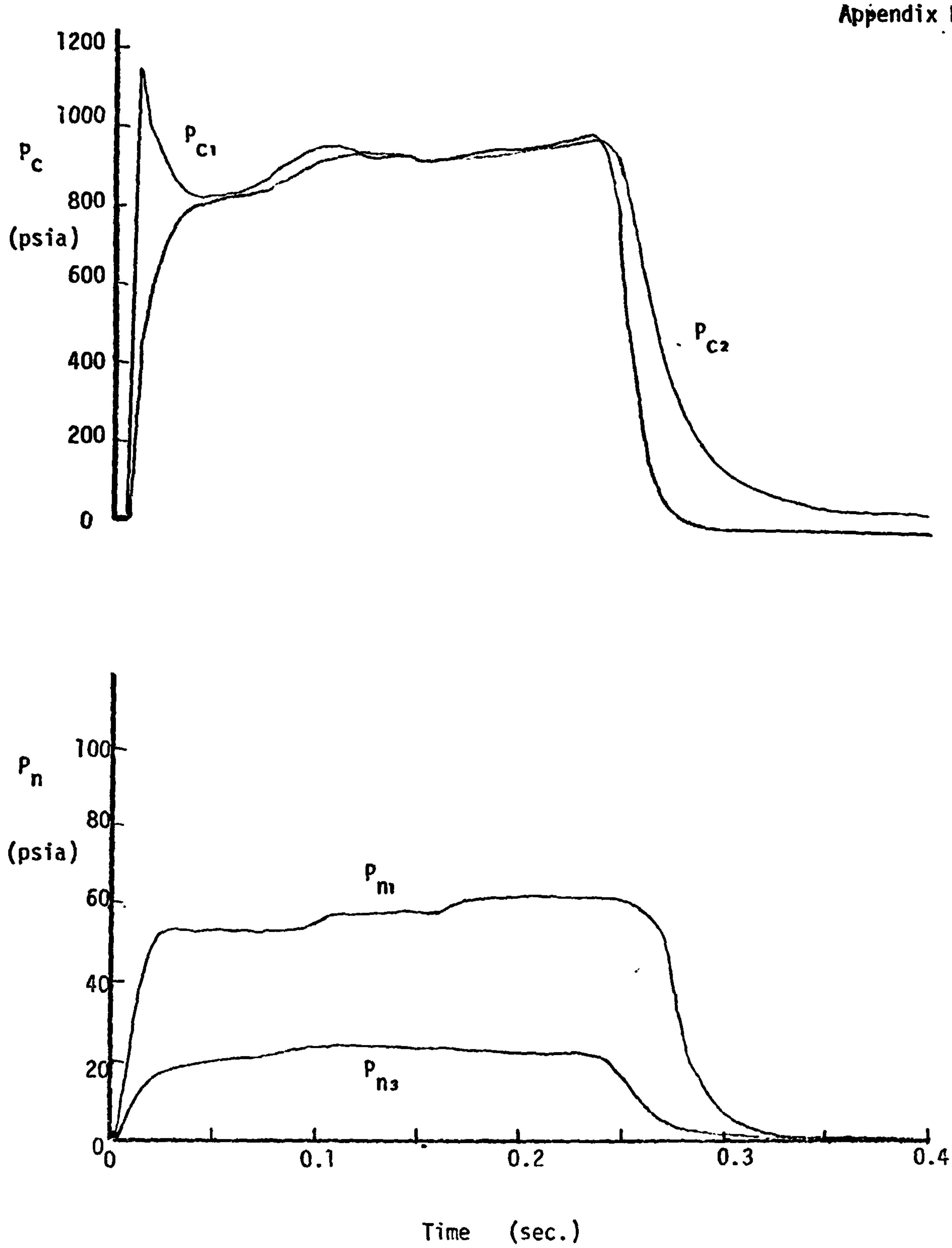

Run No. 3/2
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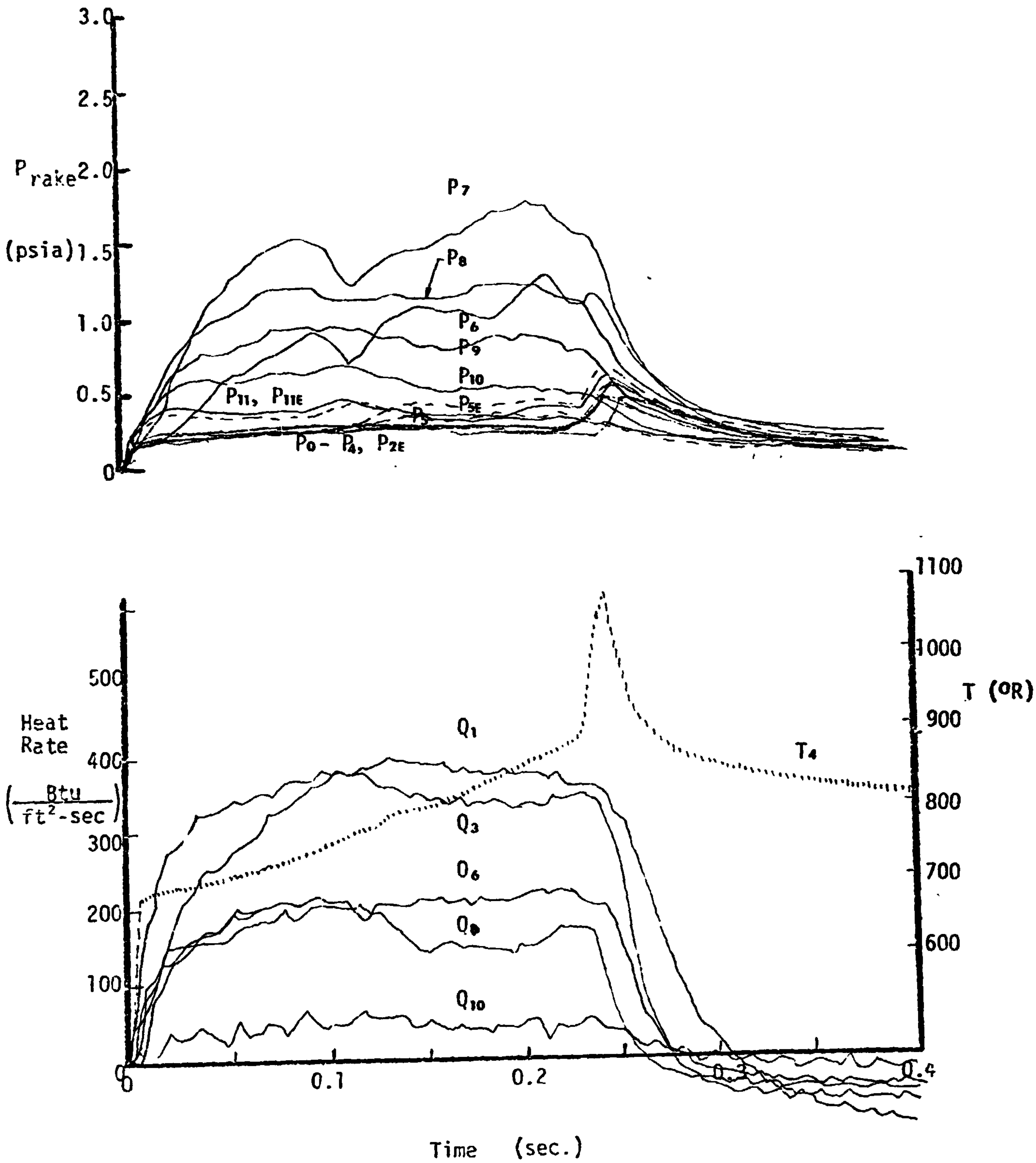

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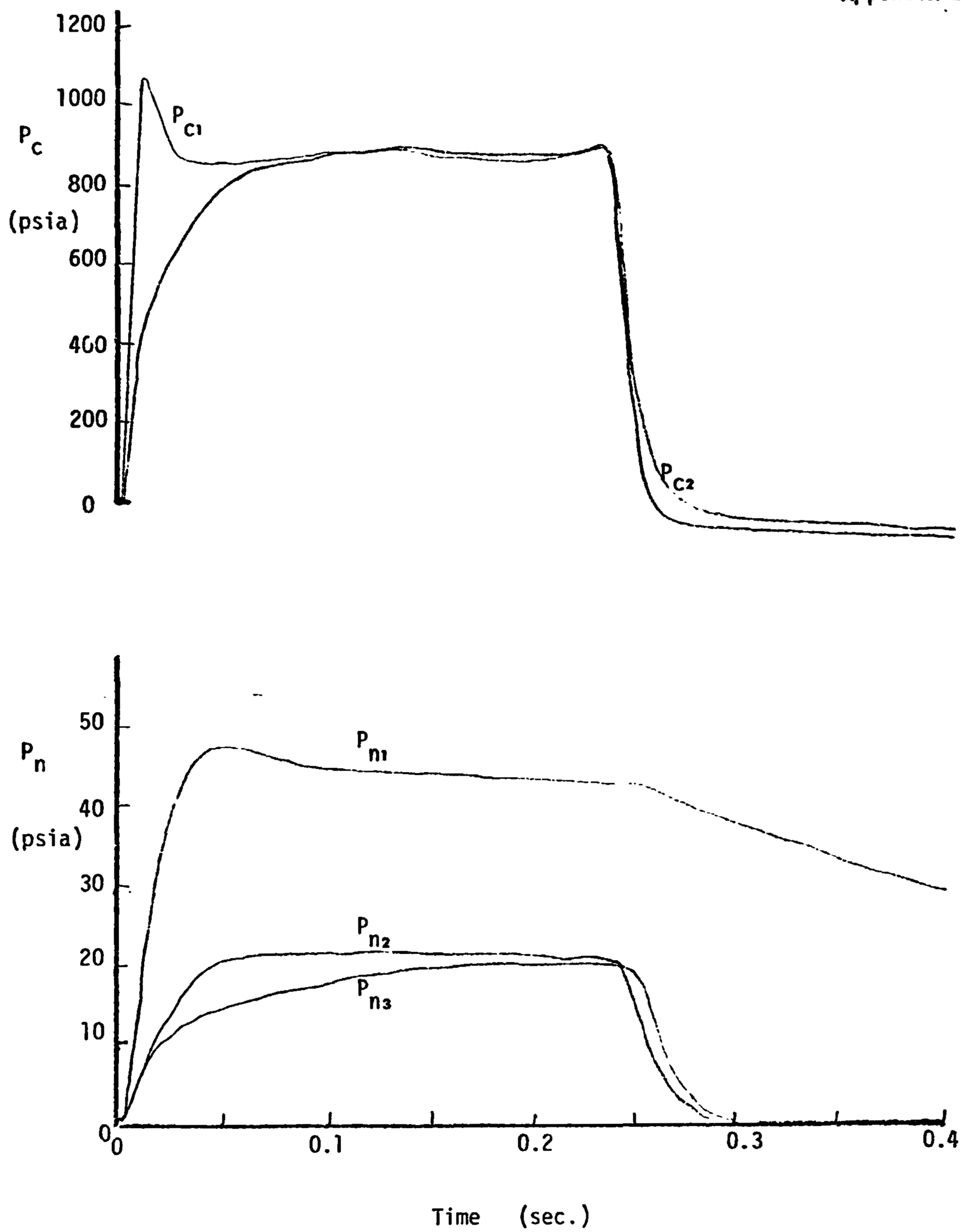

Run No. 4/1

Rake @ X/D=5

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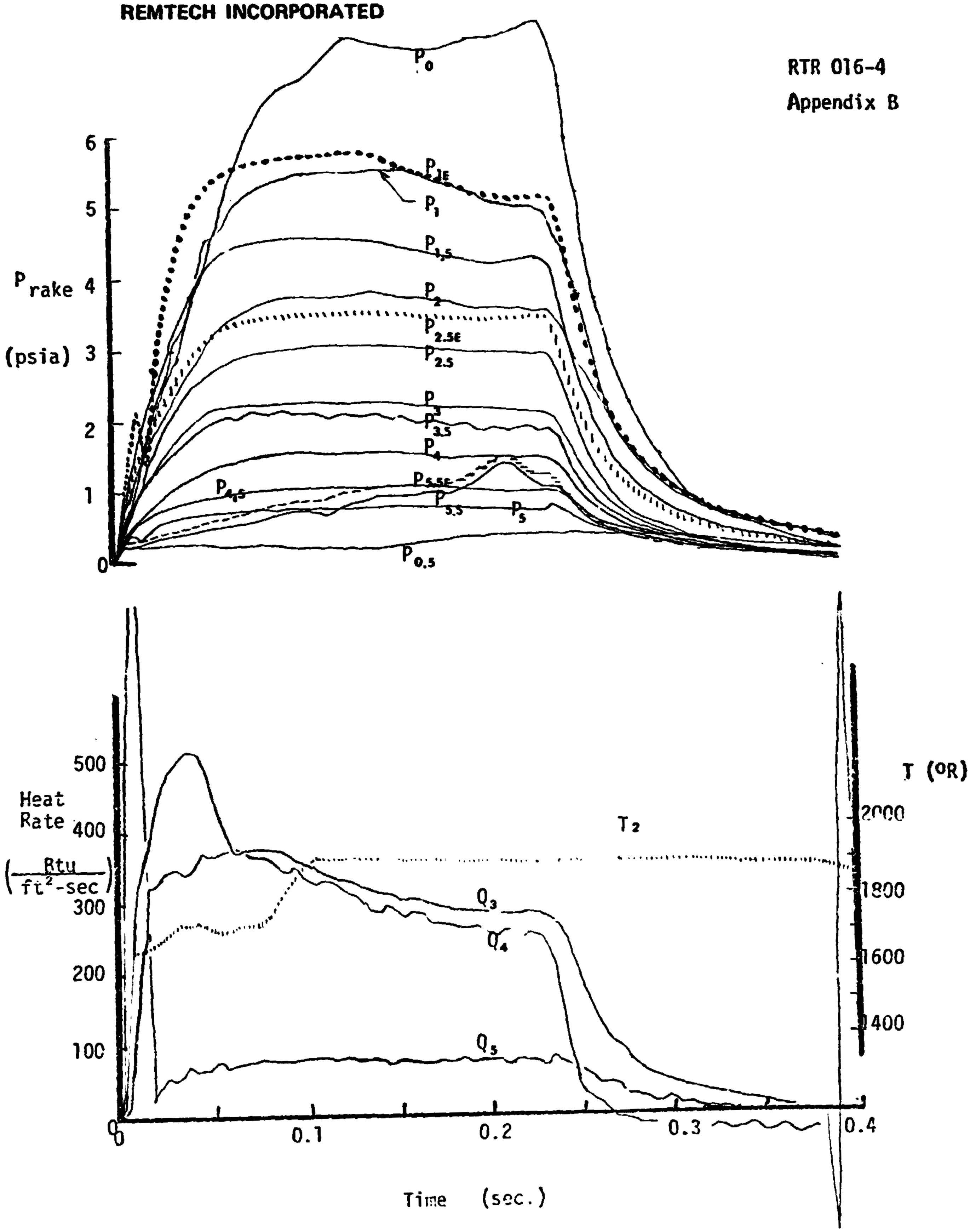

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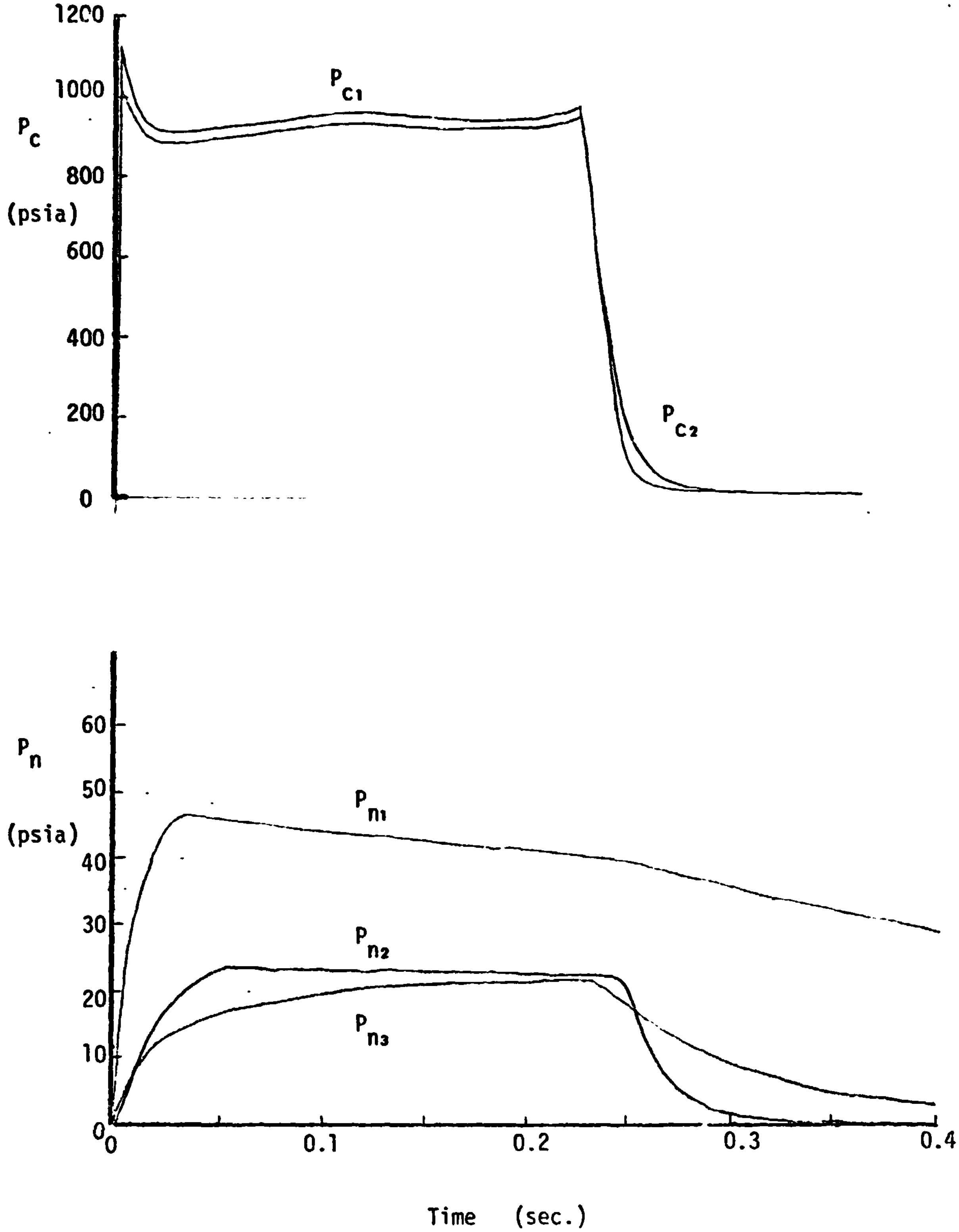

Run No. 4/2

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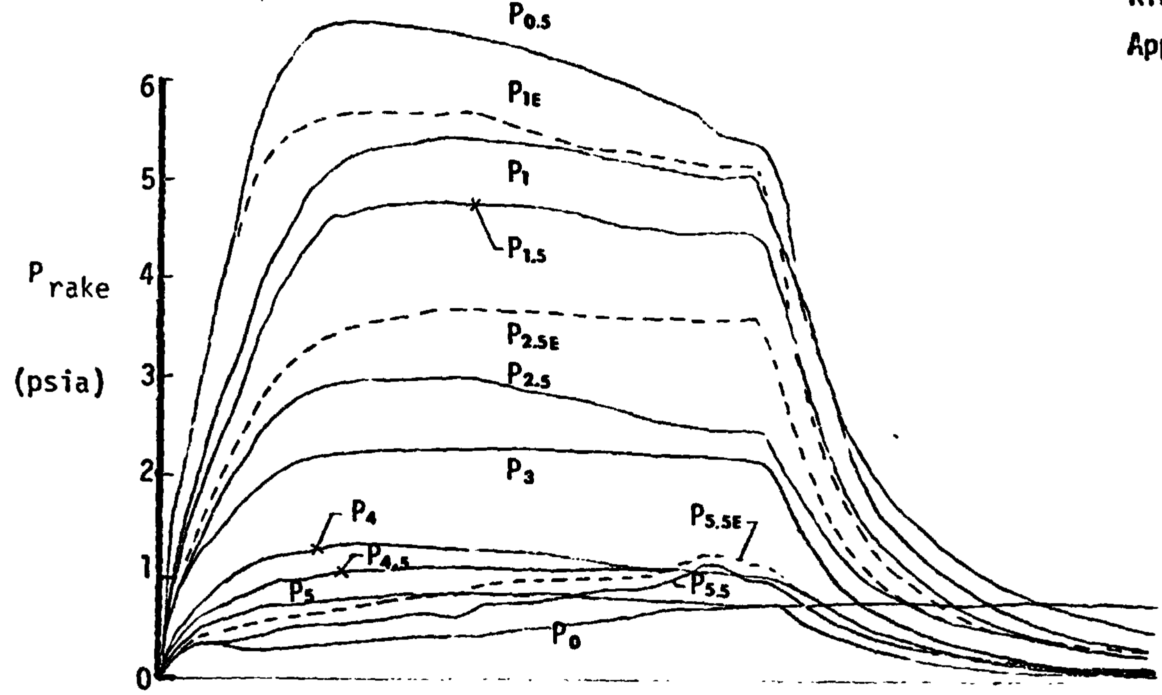

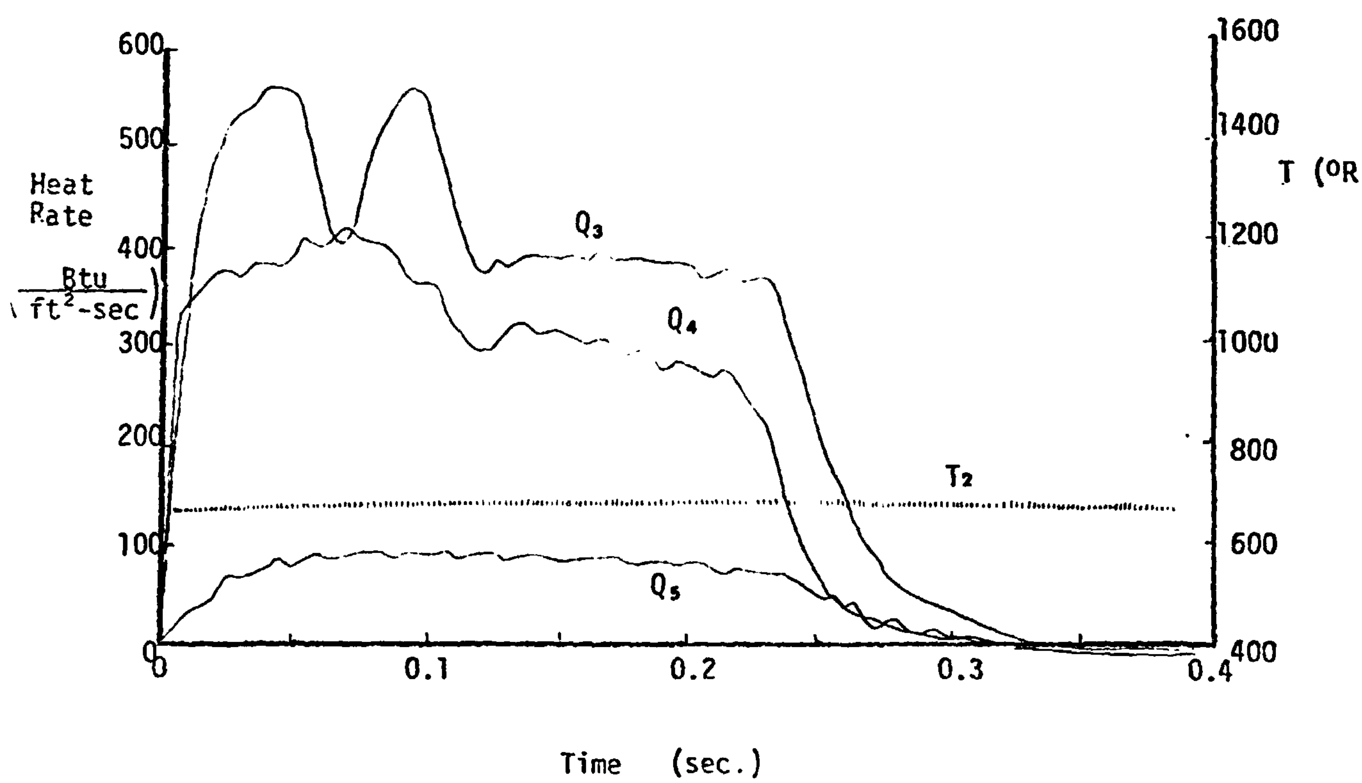

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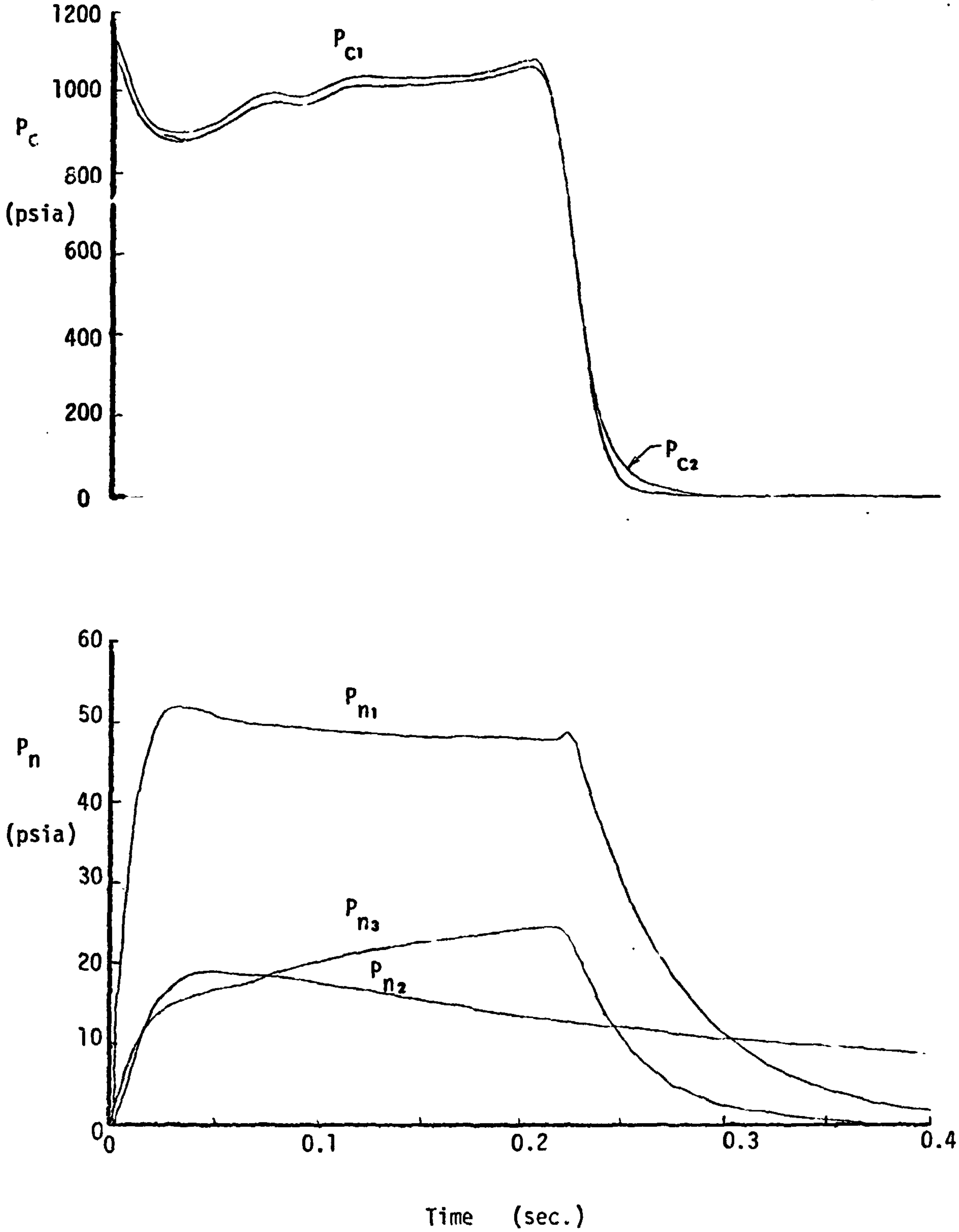

Run No. 5/1

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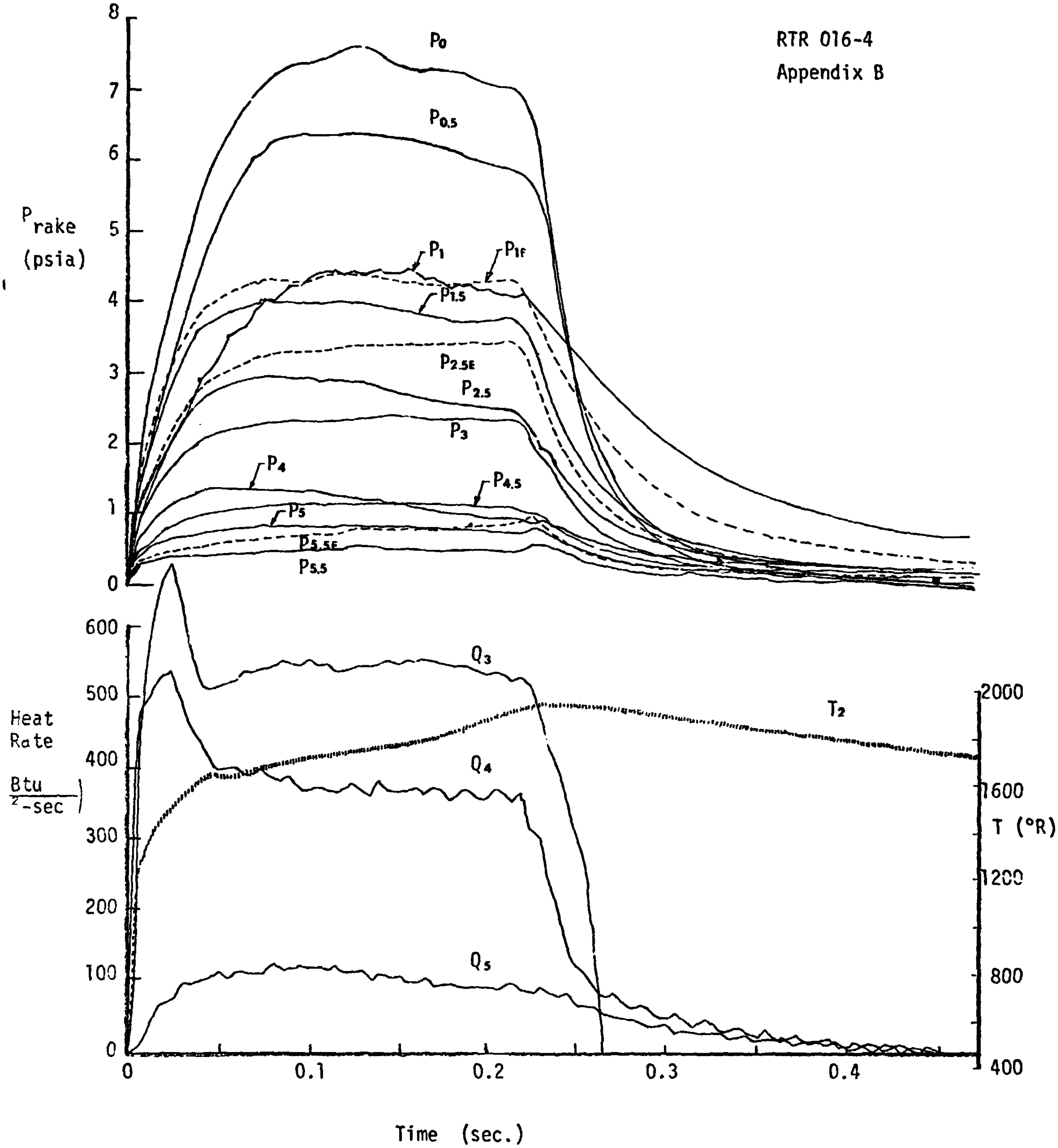

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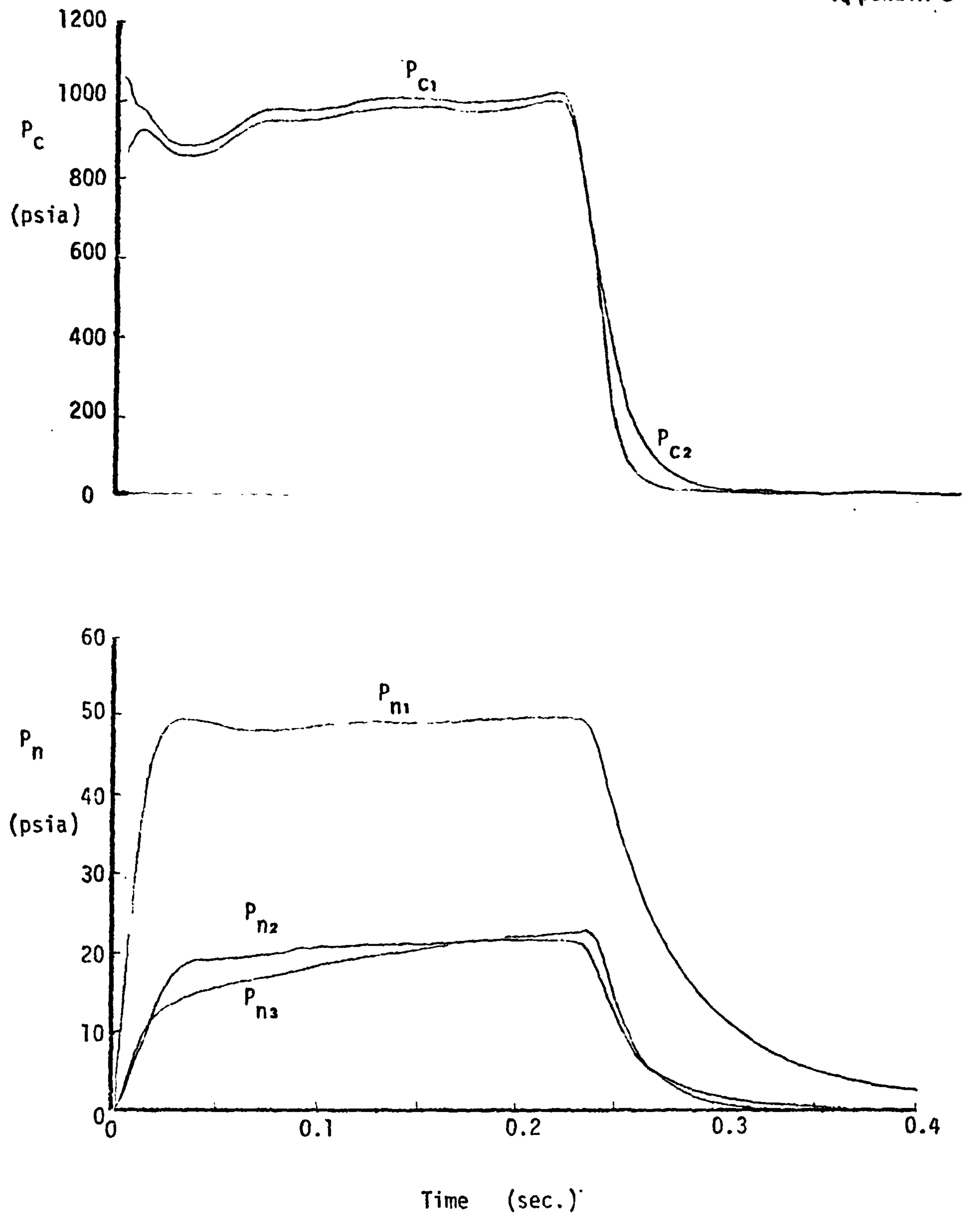

Run No. 5/2
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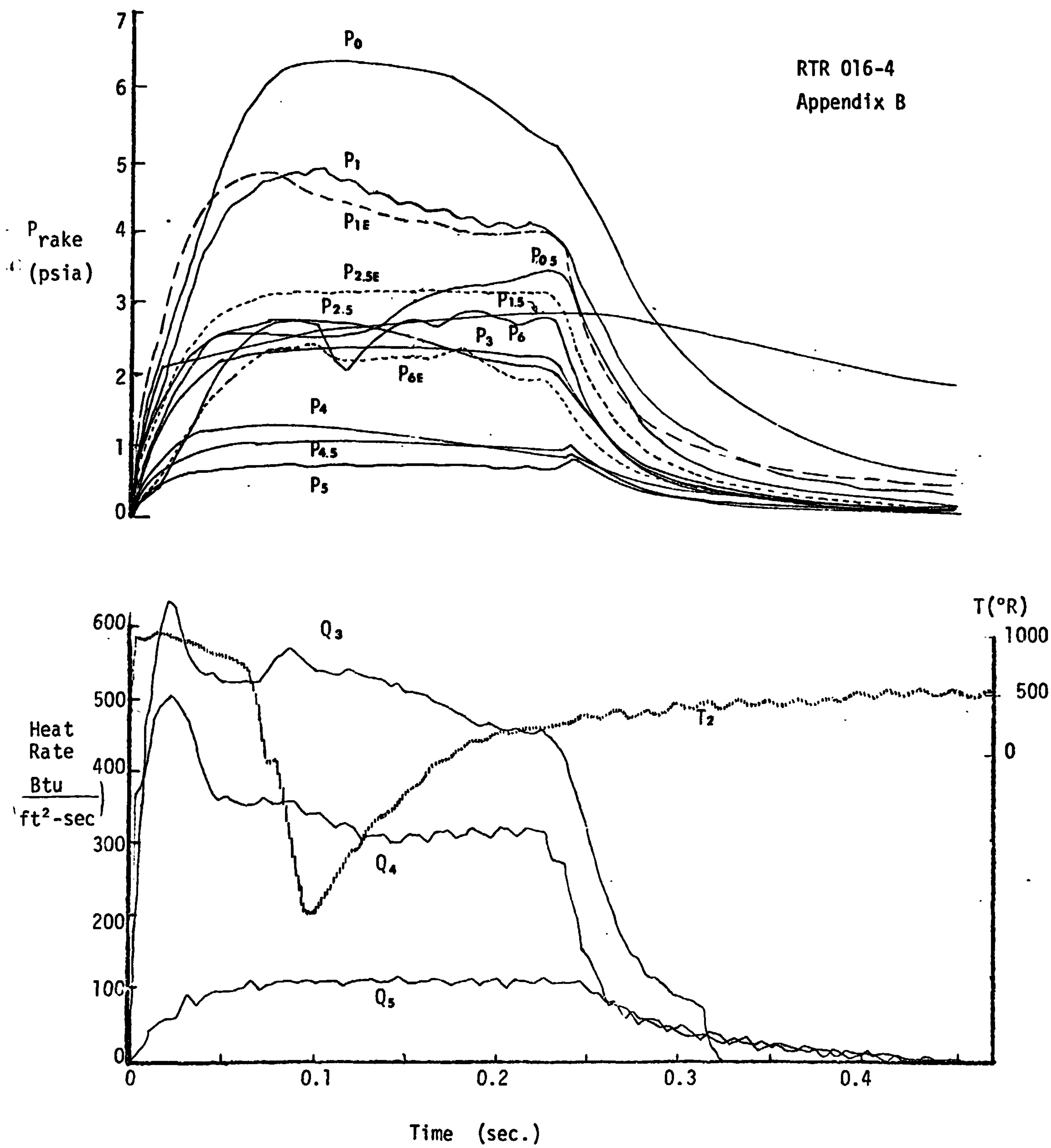
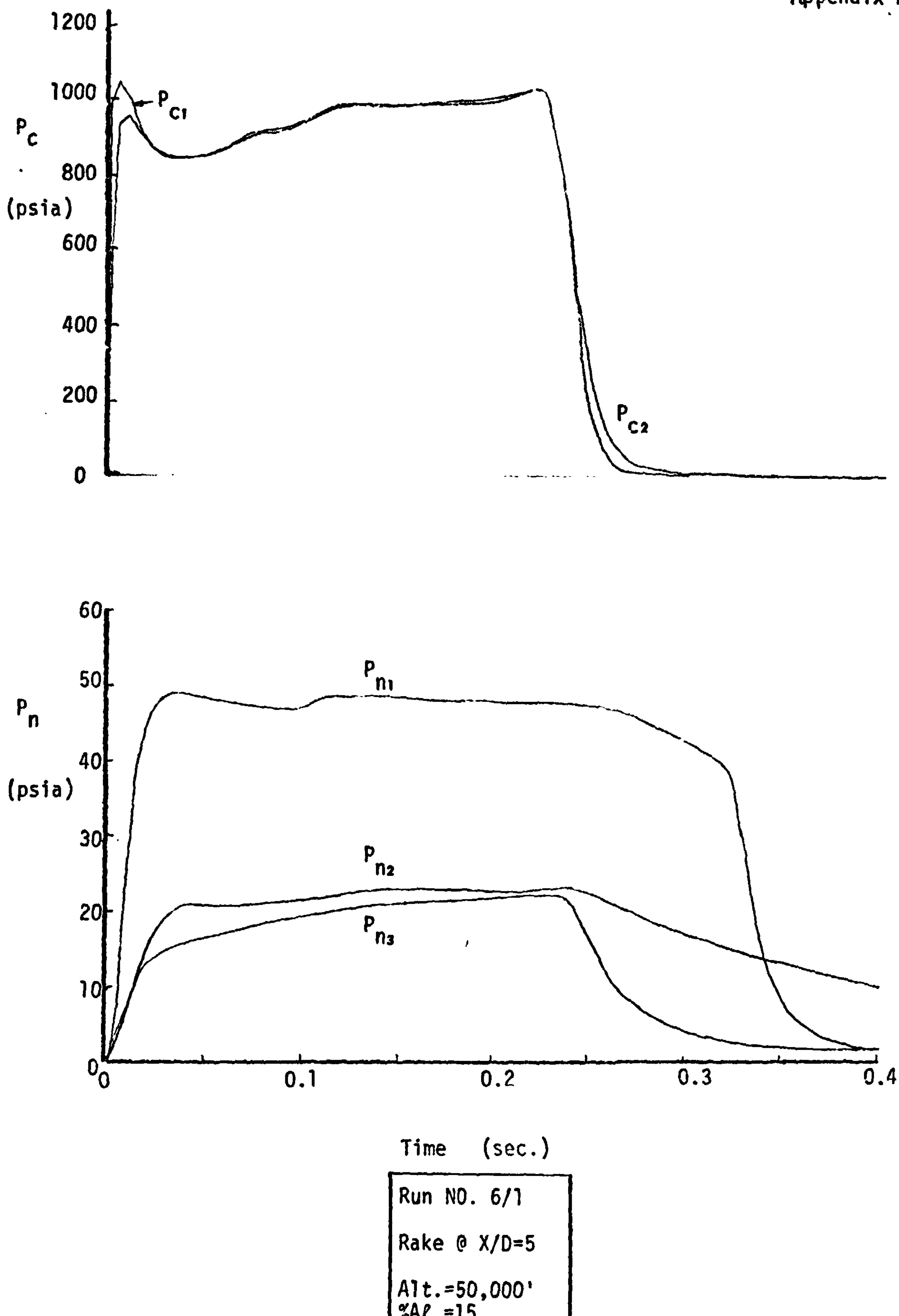


Run No. 5/2 (Concluded)


1200
1000
800
600
400
200
0
Pc
(psia)
Pc1
Pc2
60
50
40
30
20
10
0
Pn
(psia)
Pn1
Pn2
Pn3
0
0.1
0.2
0.3
0.4
Time (sec.)
Run NO. 6/1
Rake @ X/D=5
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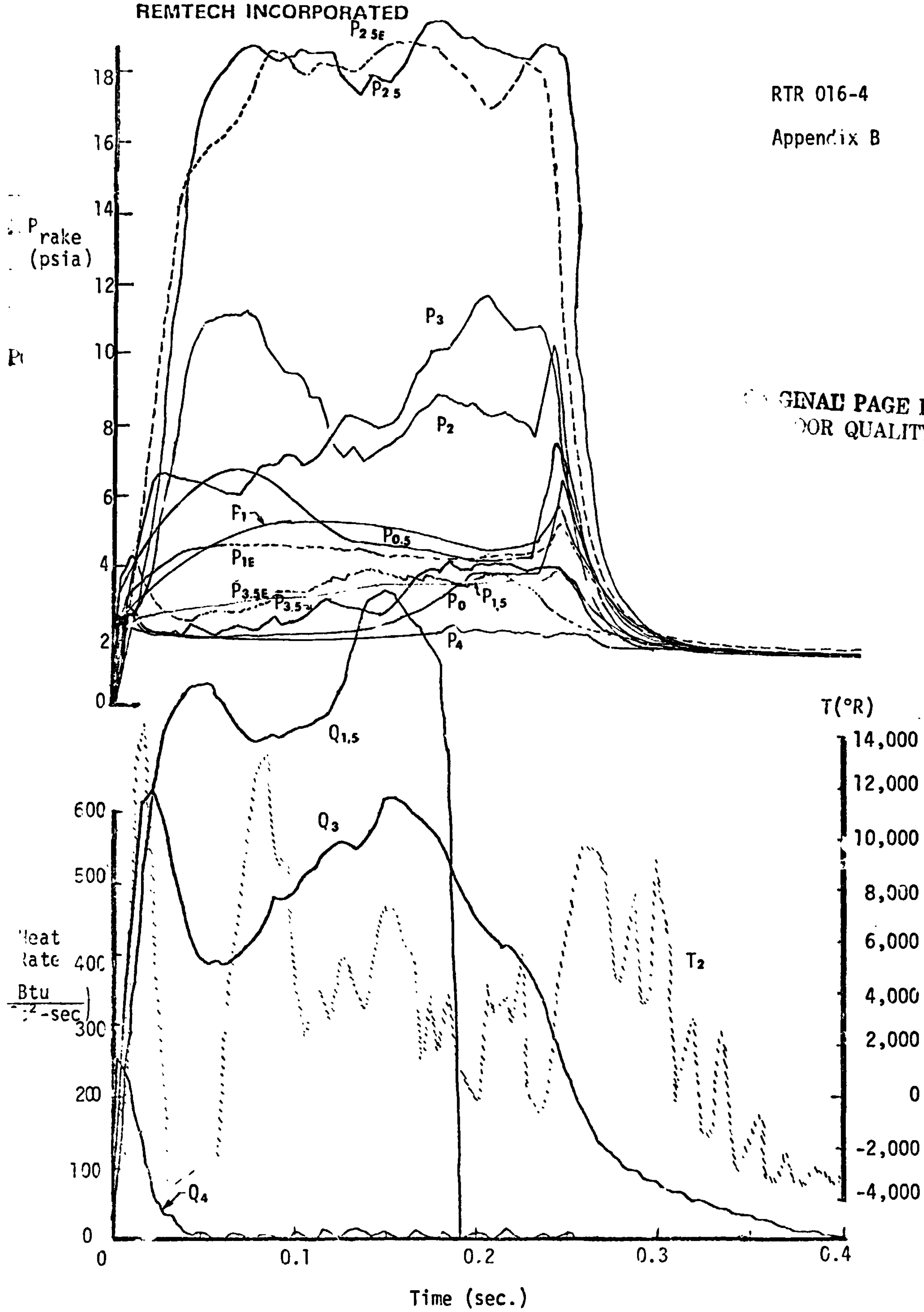

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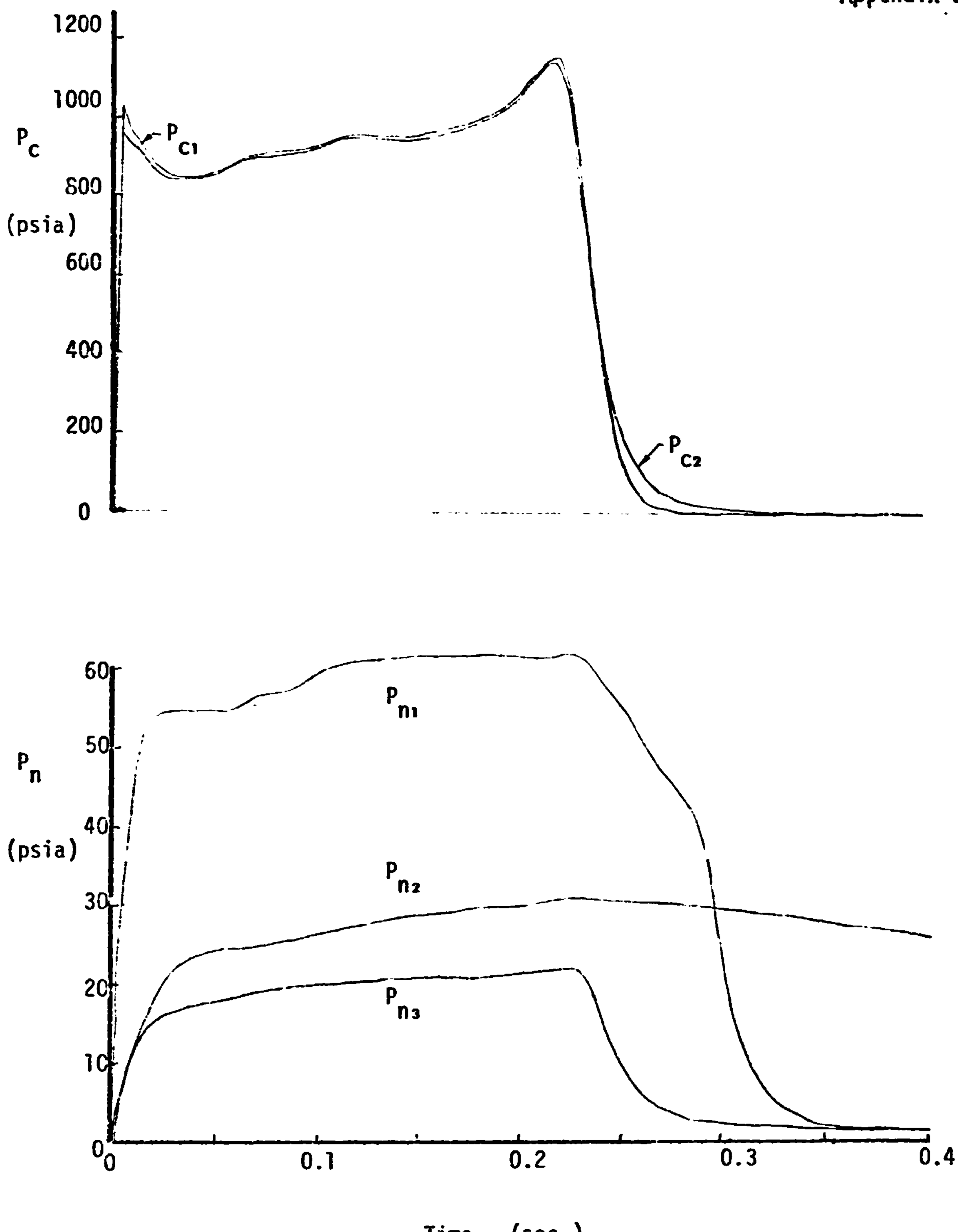

Run No. 6/2

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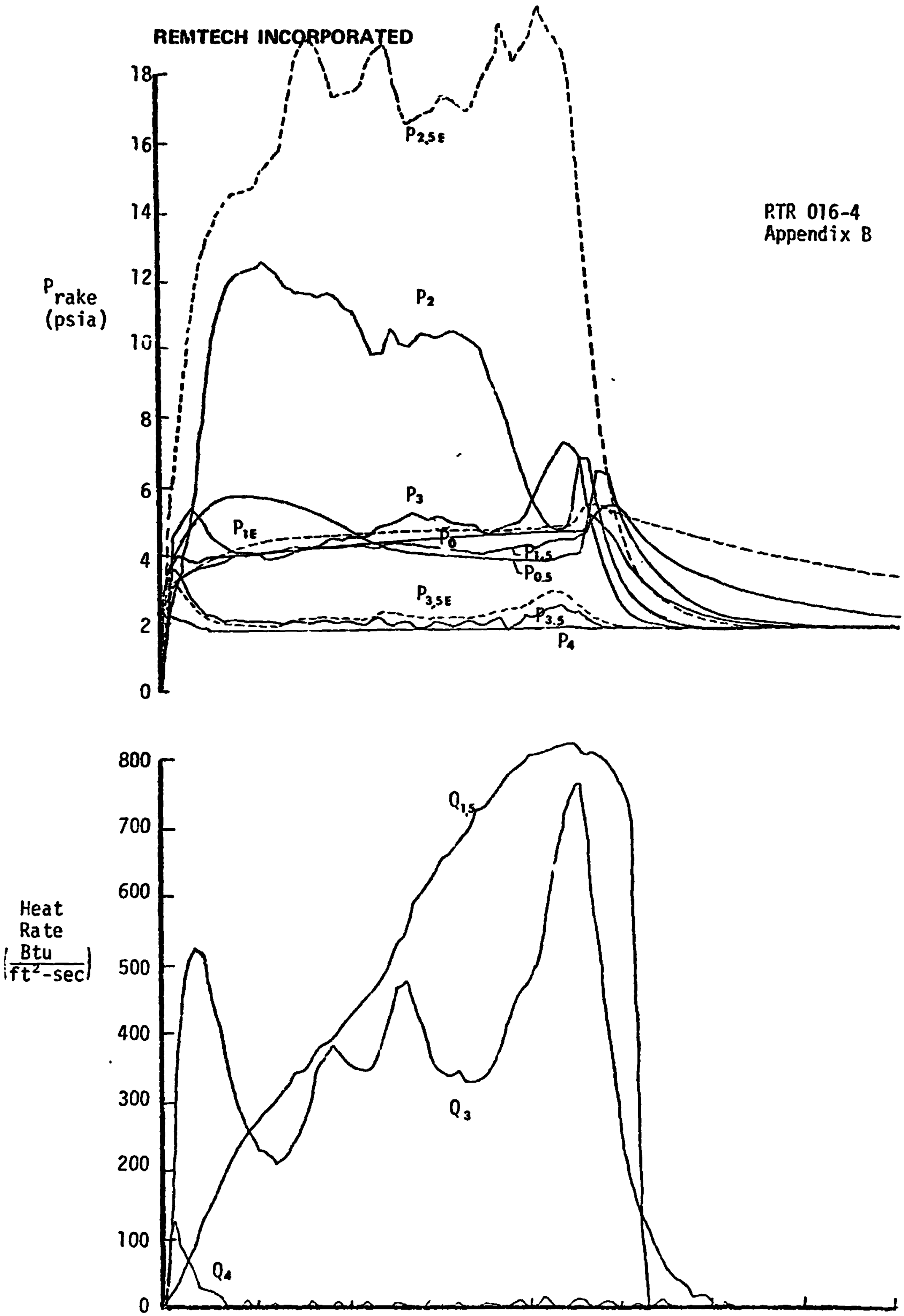

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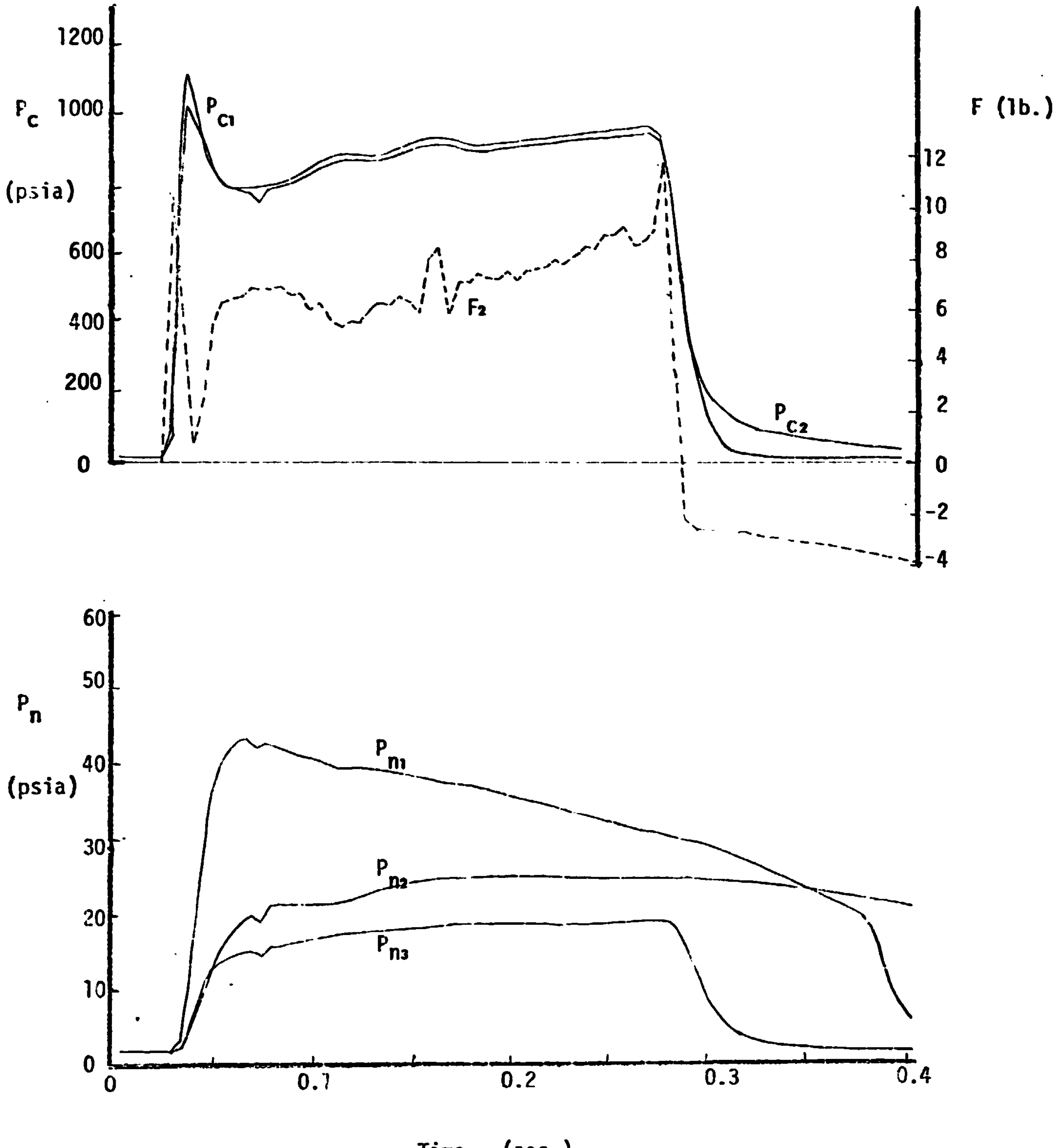

Run No. 6/3

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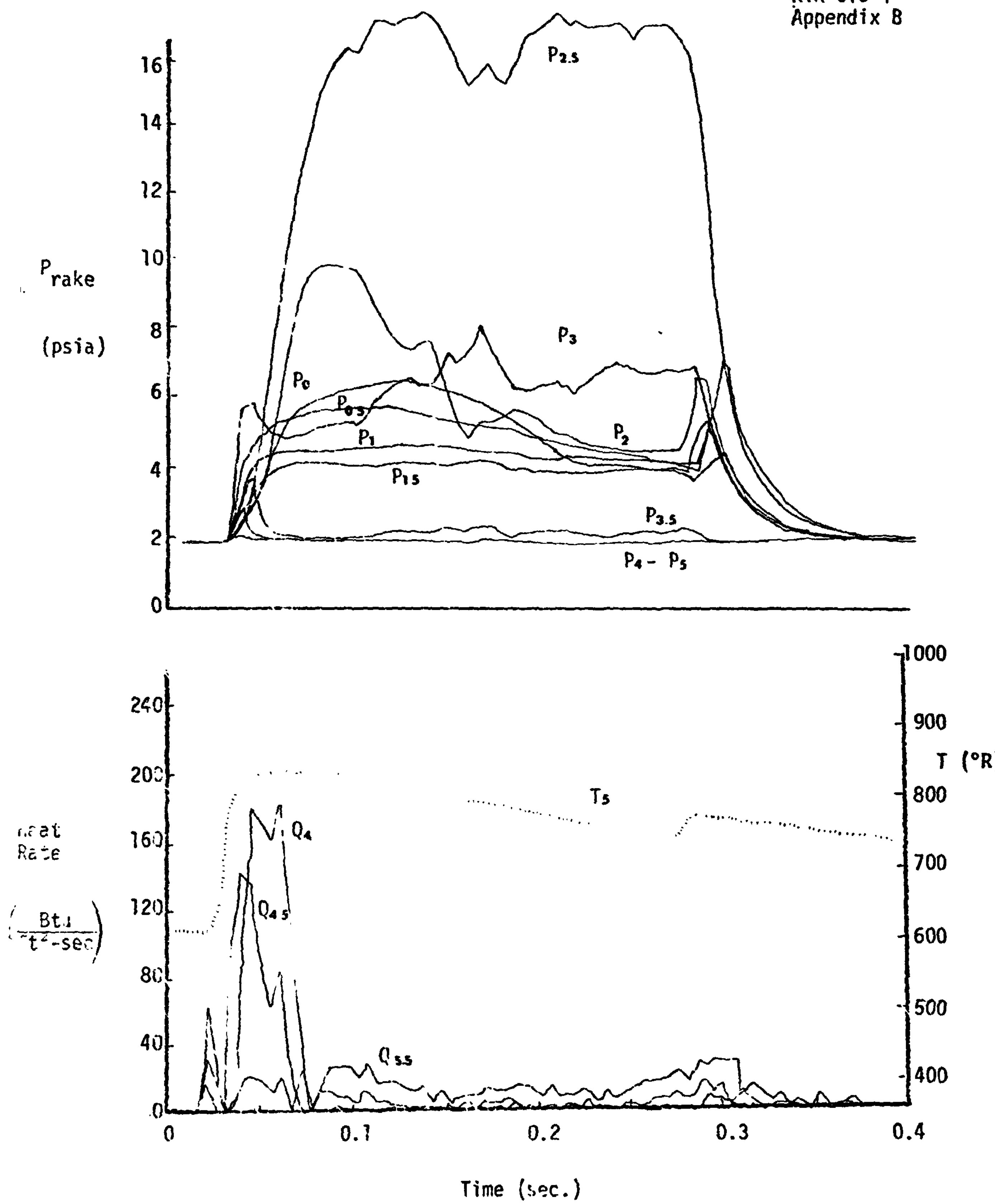

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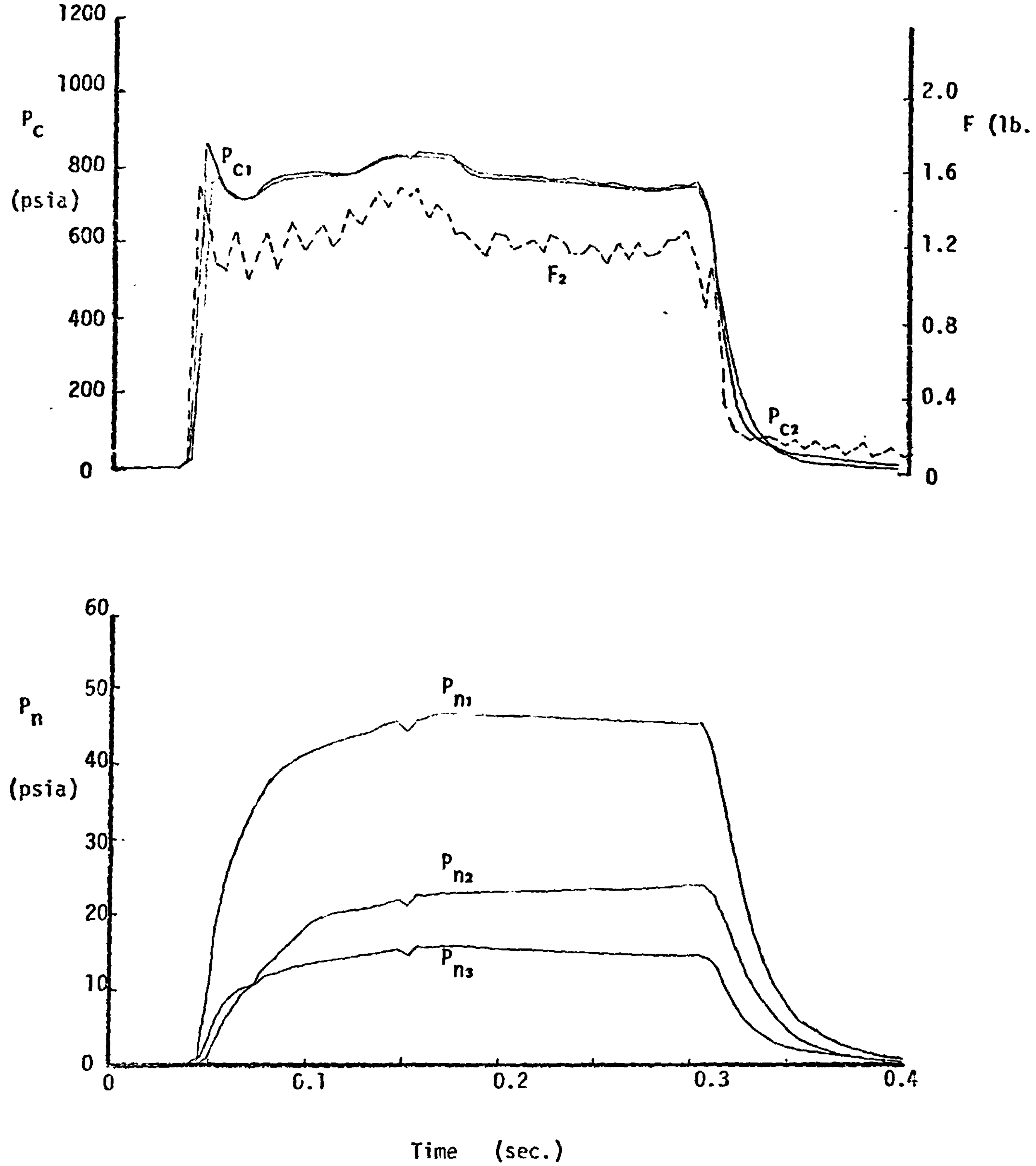

Run No. 7/1

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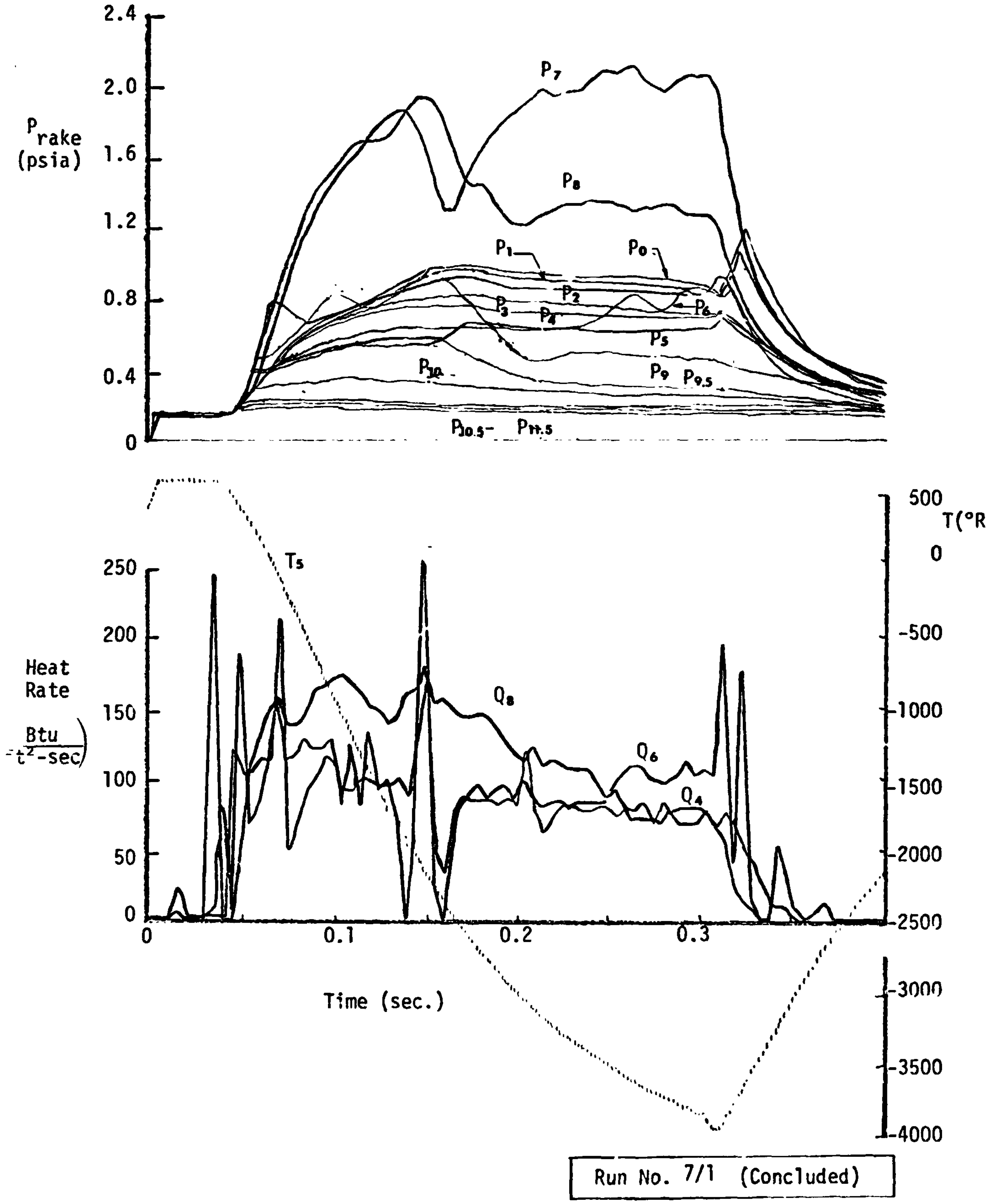

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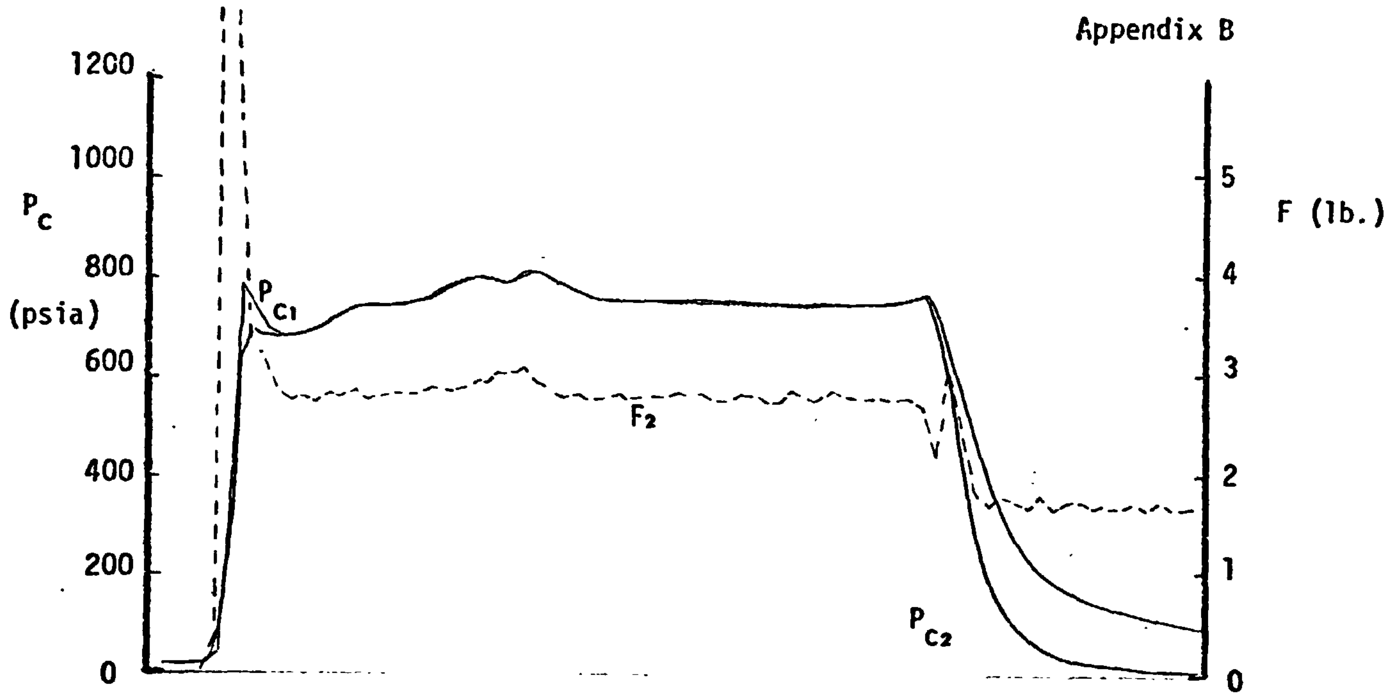

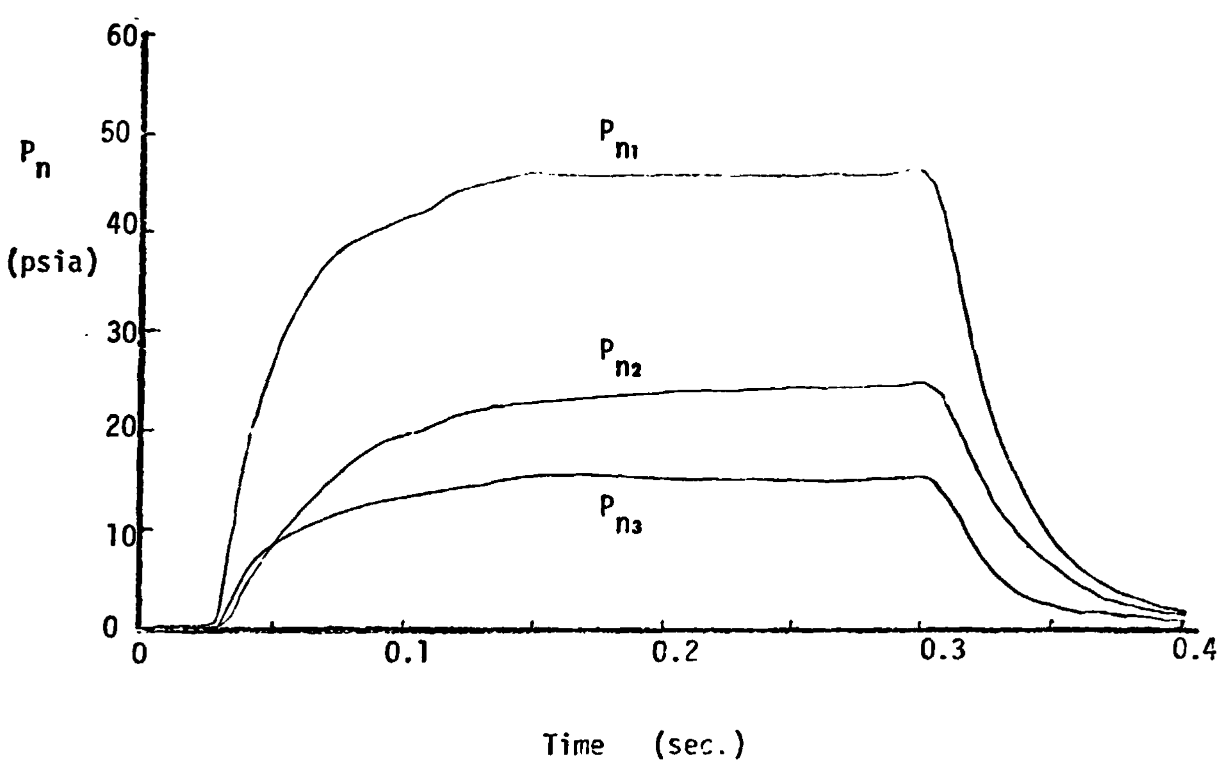

Run No. 7/2

Rake @ X/D=12

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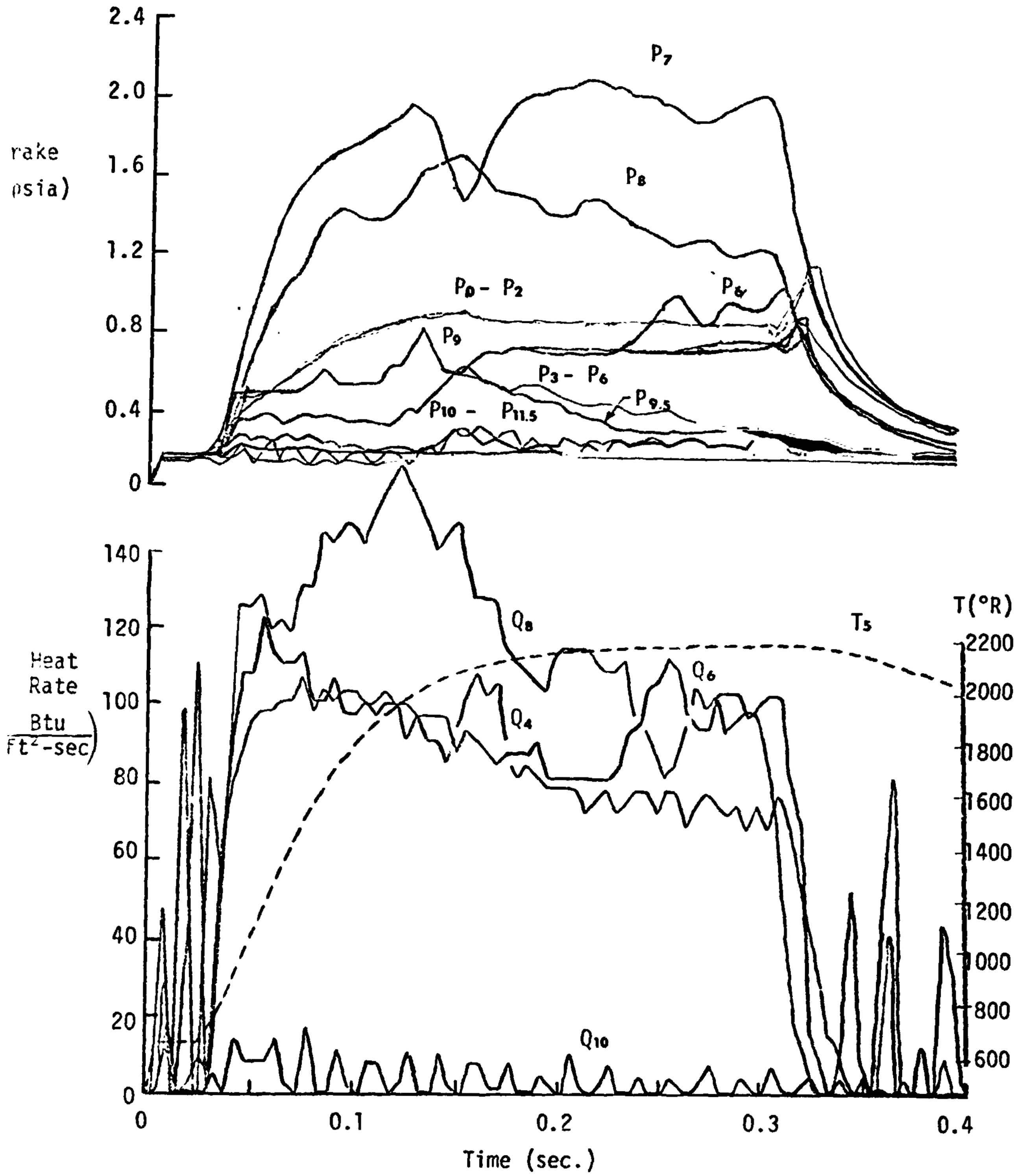

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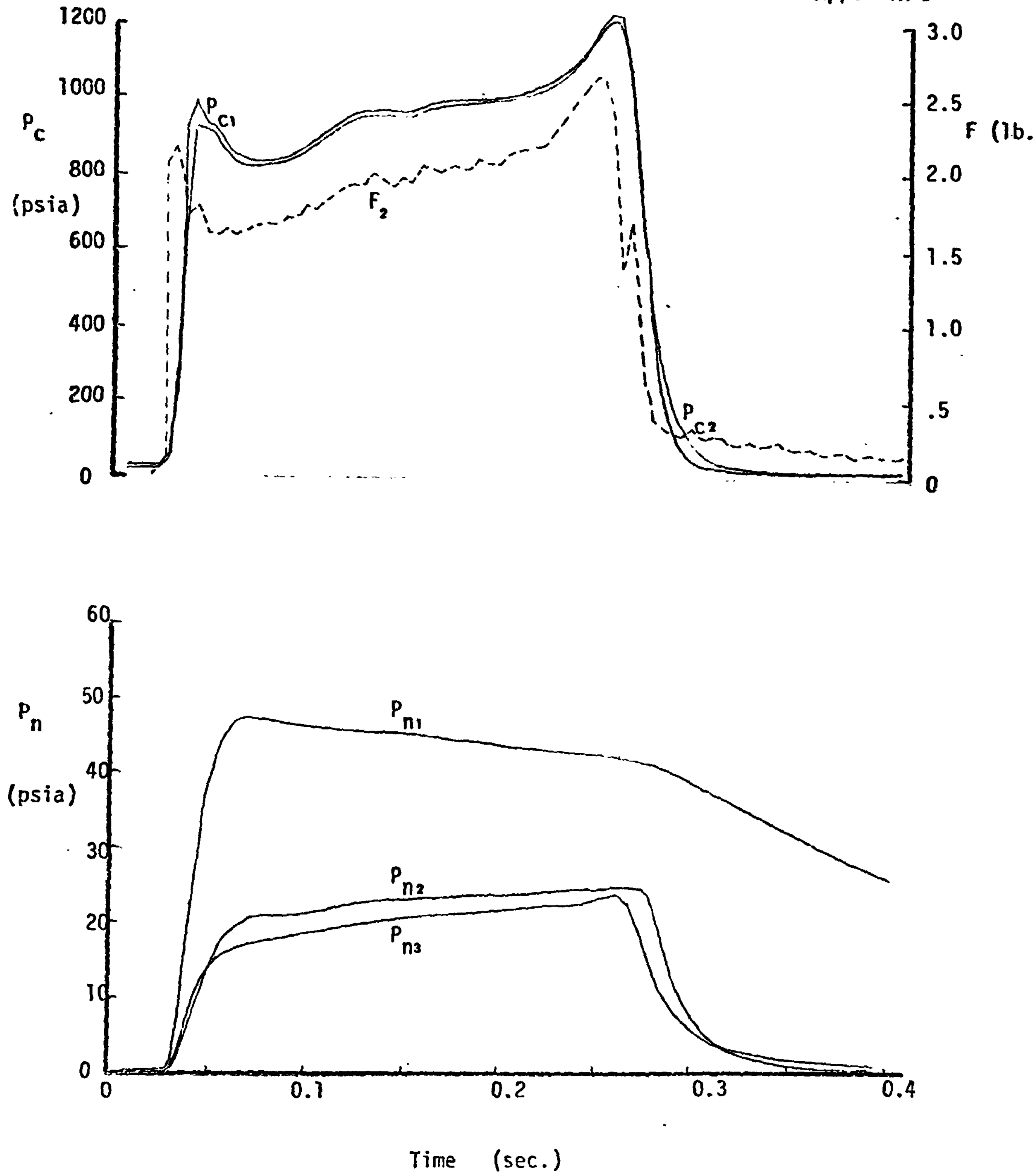

Run No. 8/1

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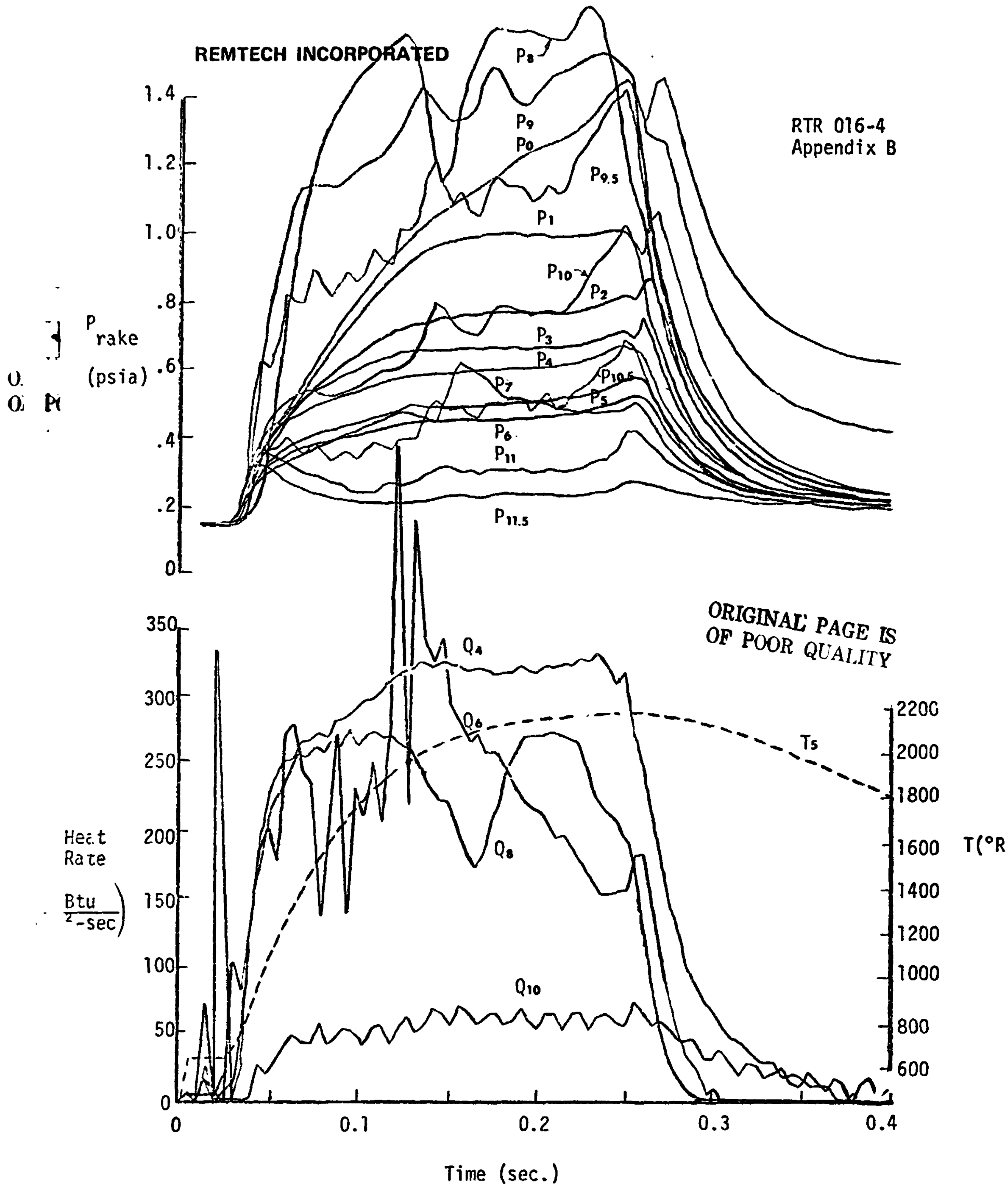
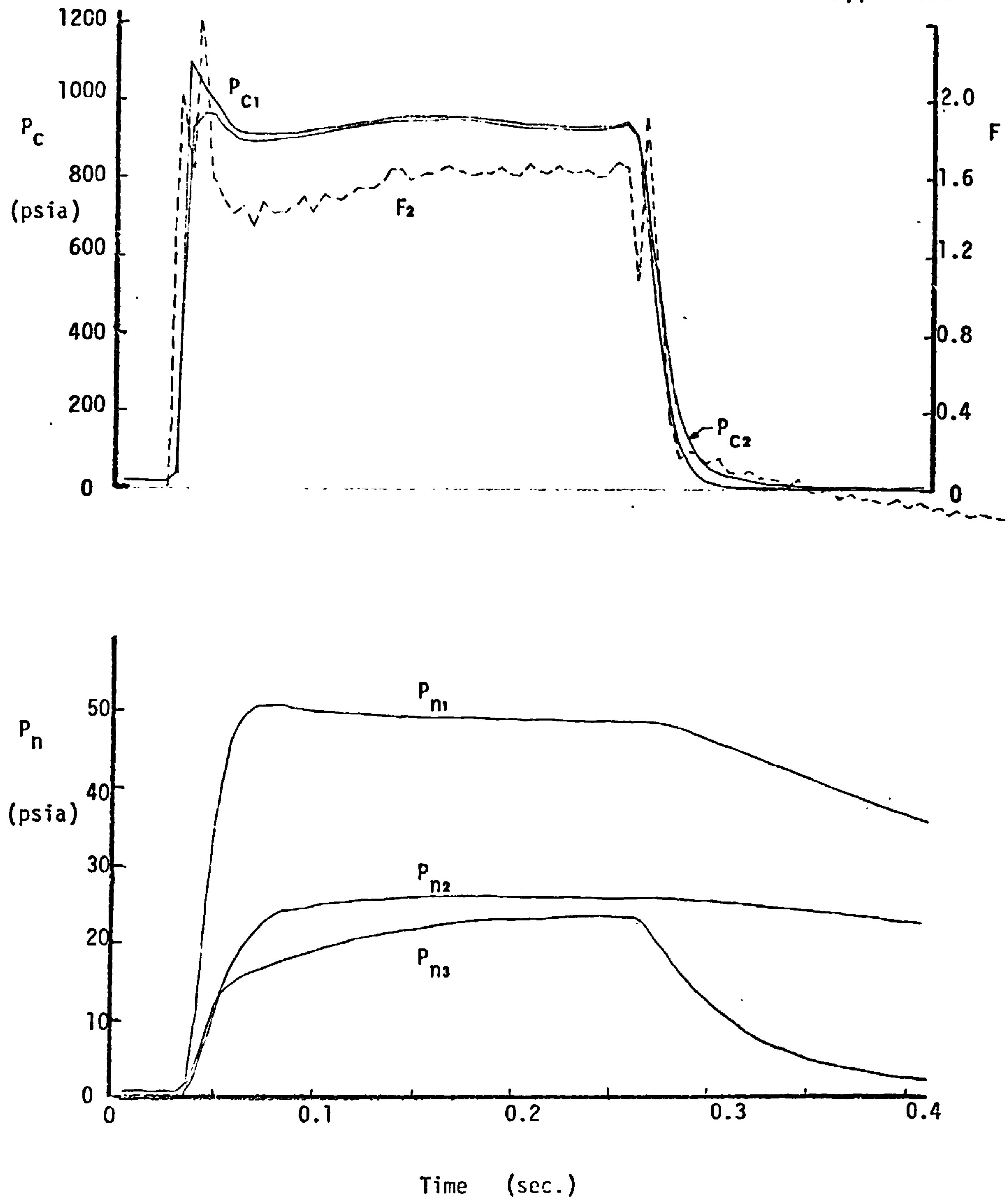


Run No. 8/2 (Concluded)



Run No. 9/1

Rake @ X/D=12

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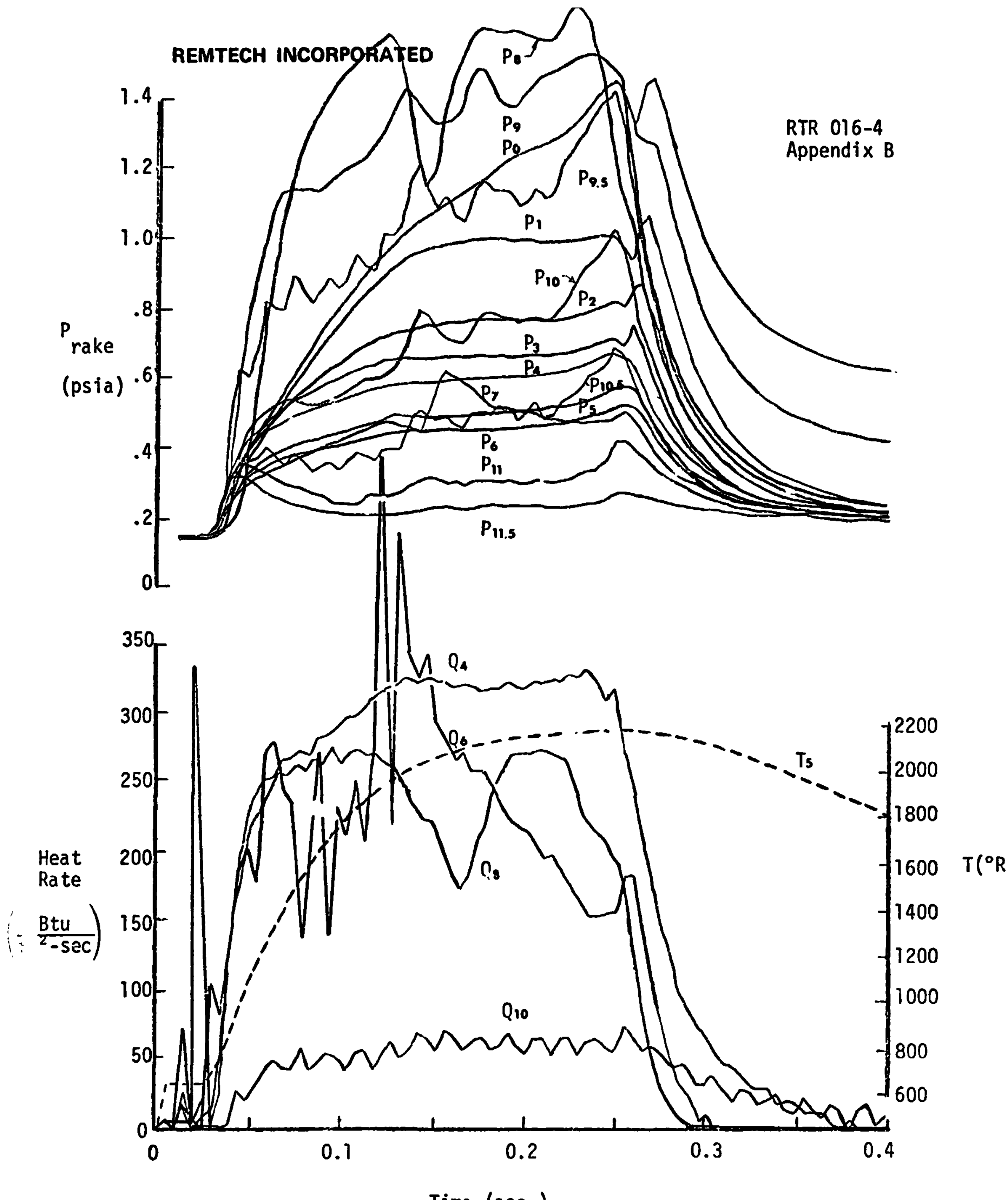

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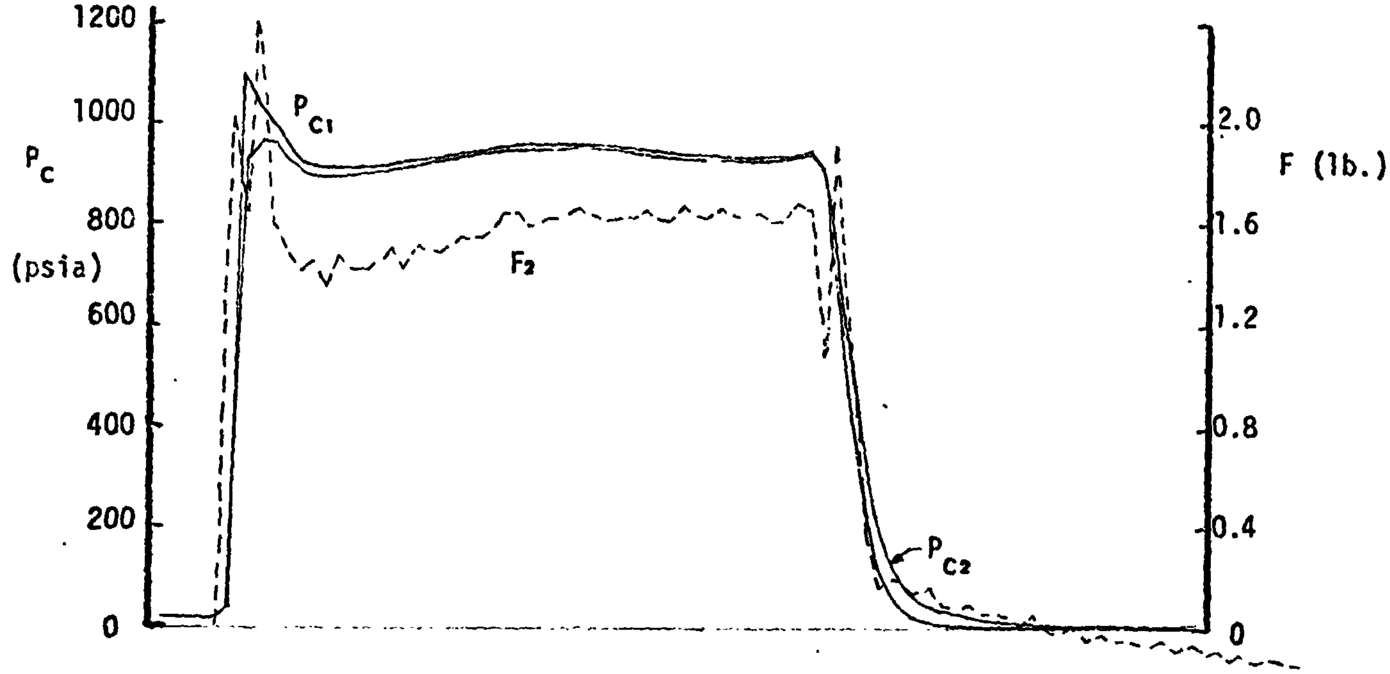

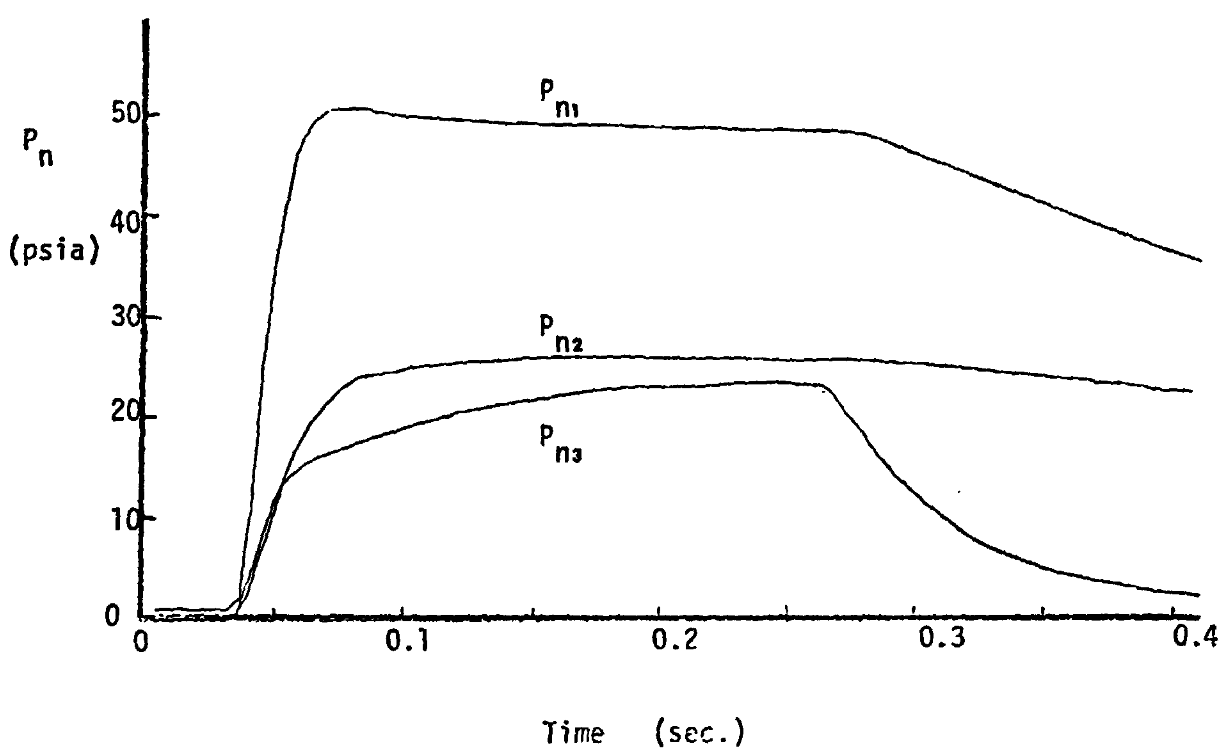

Run No. 9/1

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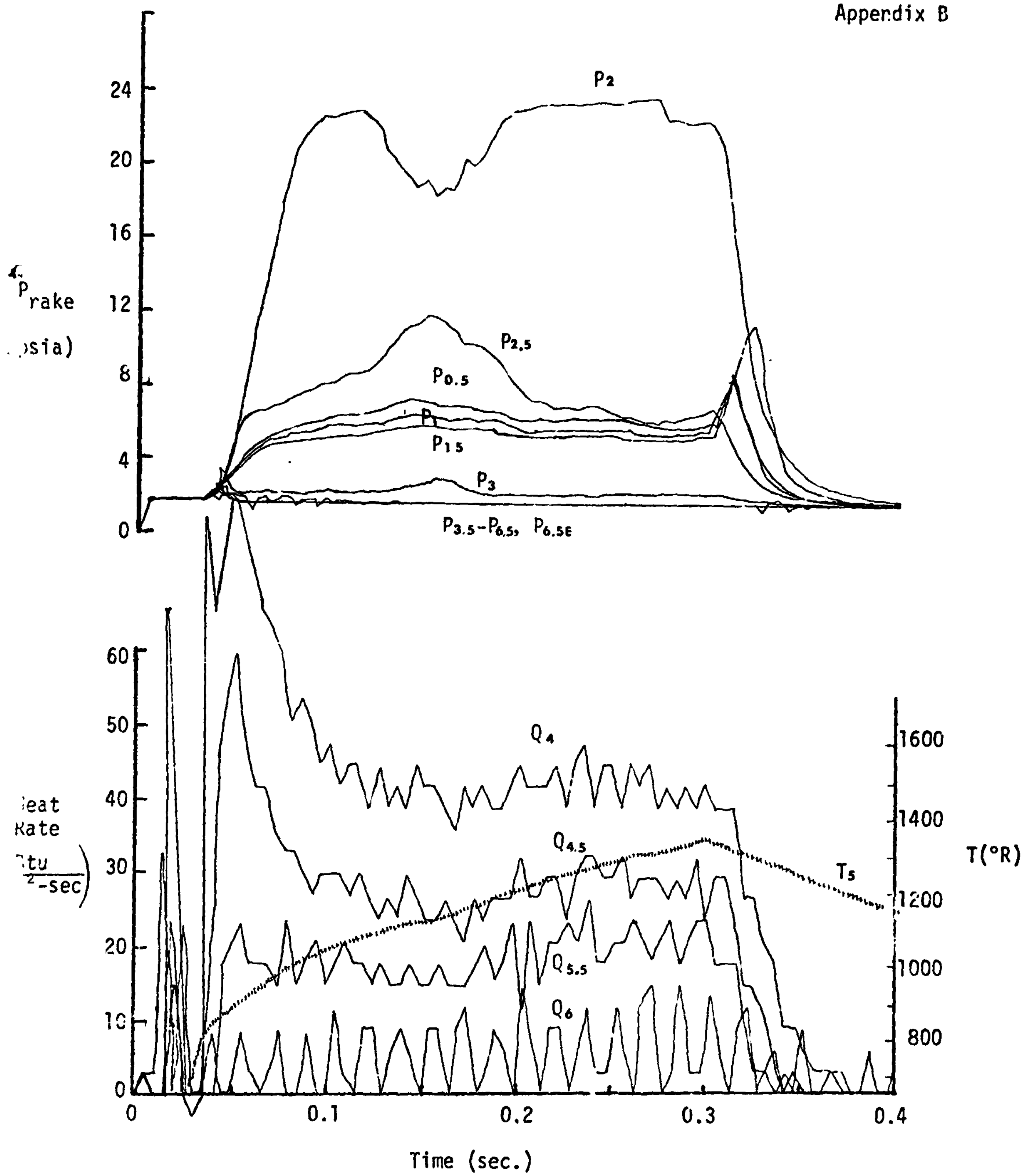

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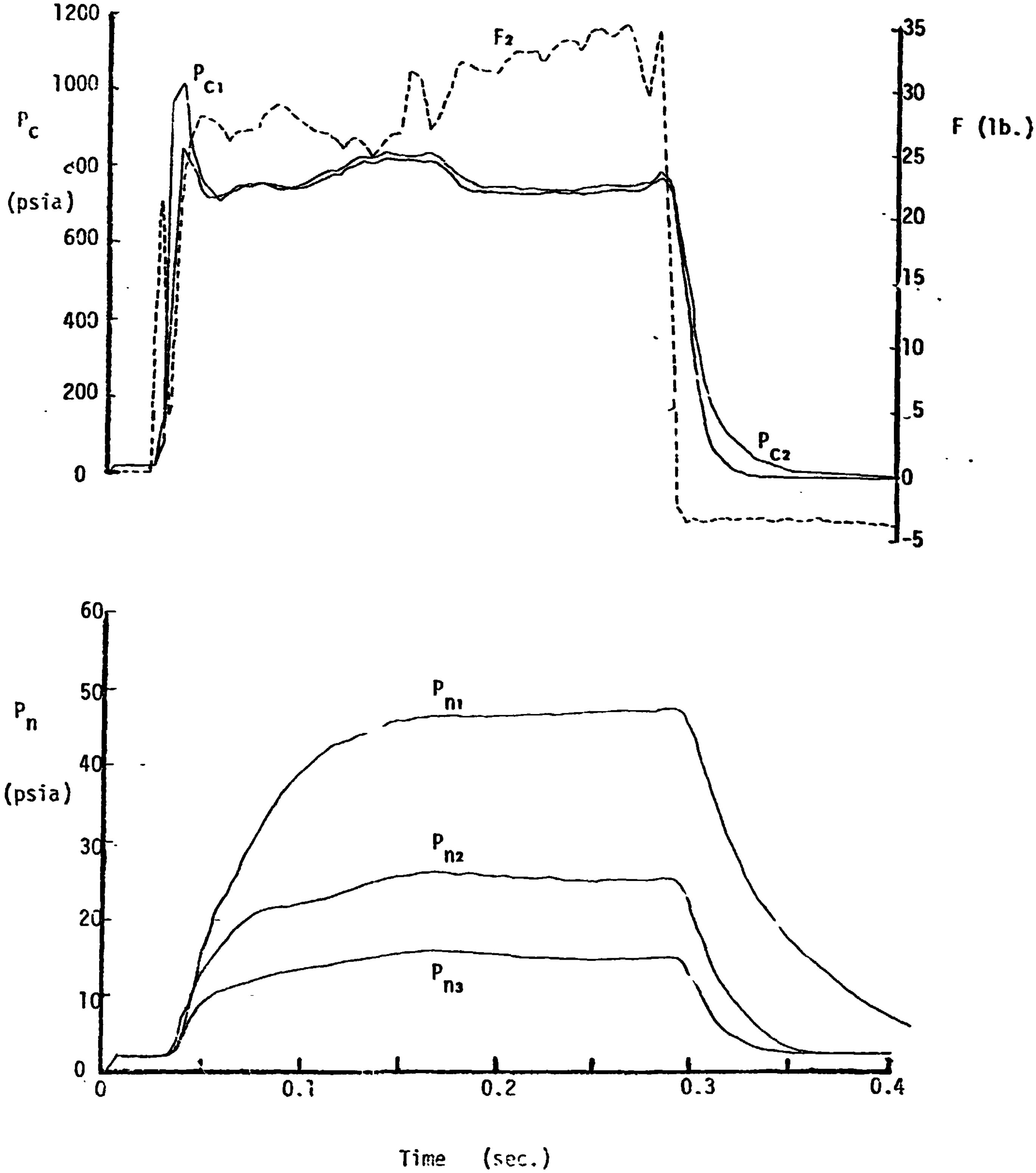

Run No. 10/2

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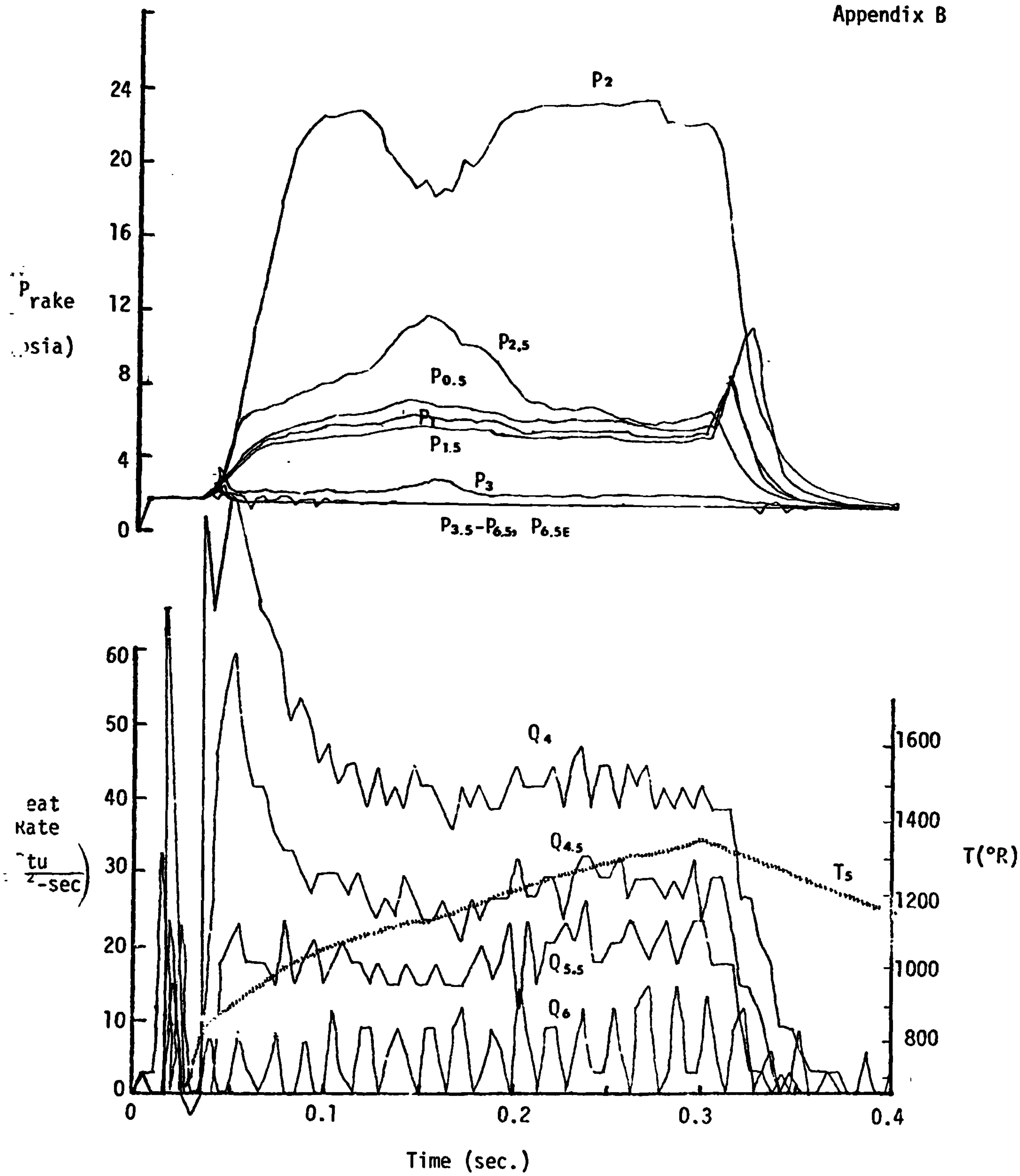

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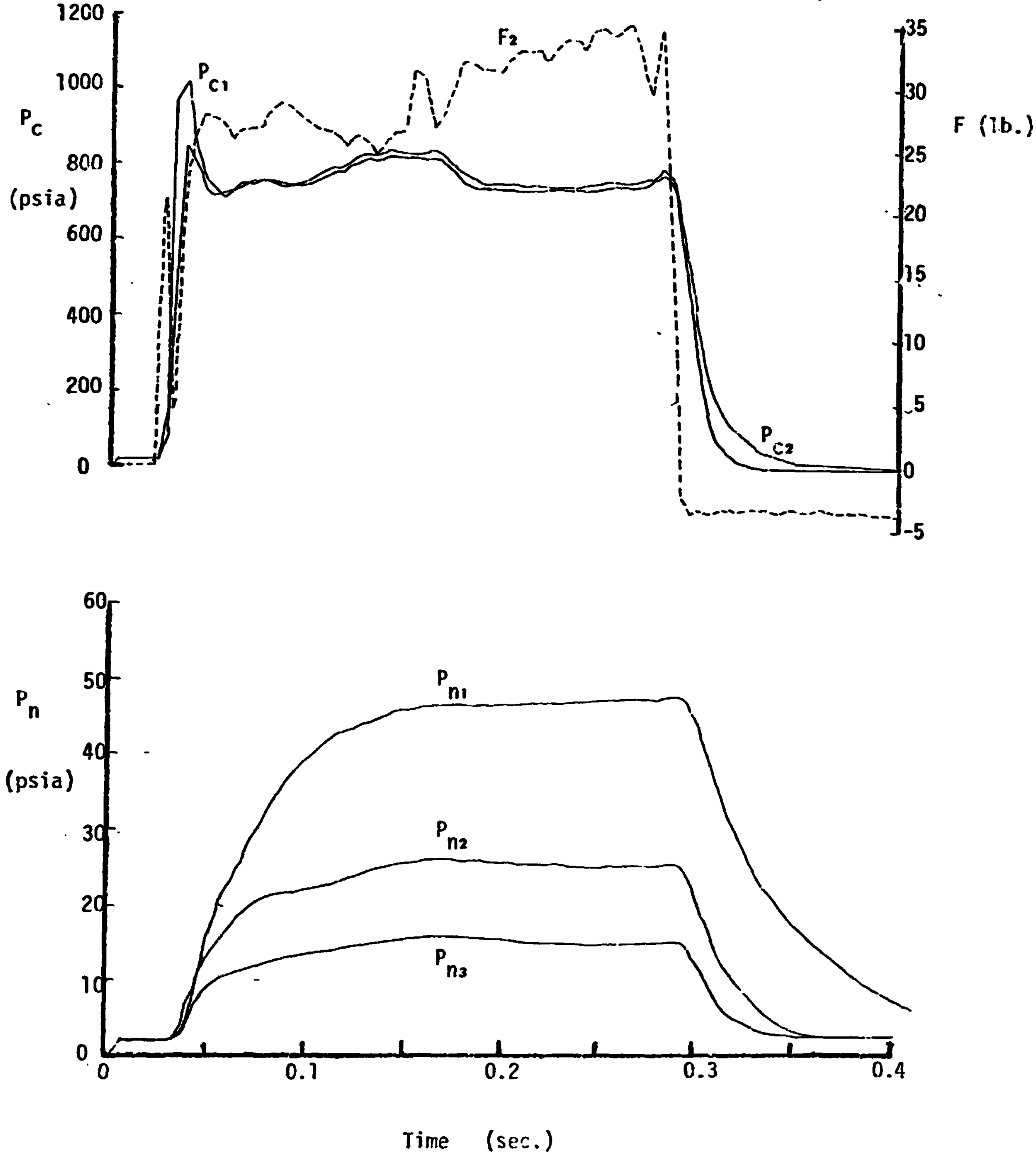

Run No. 10/2

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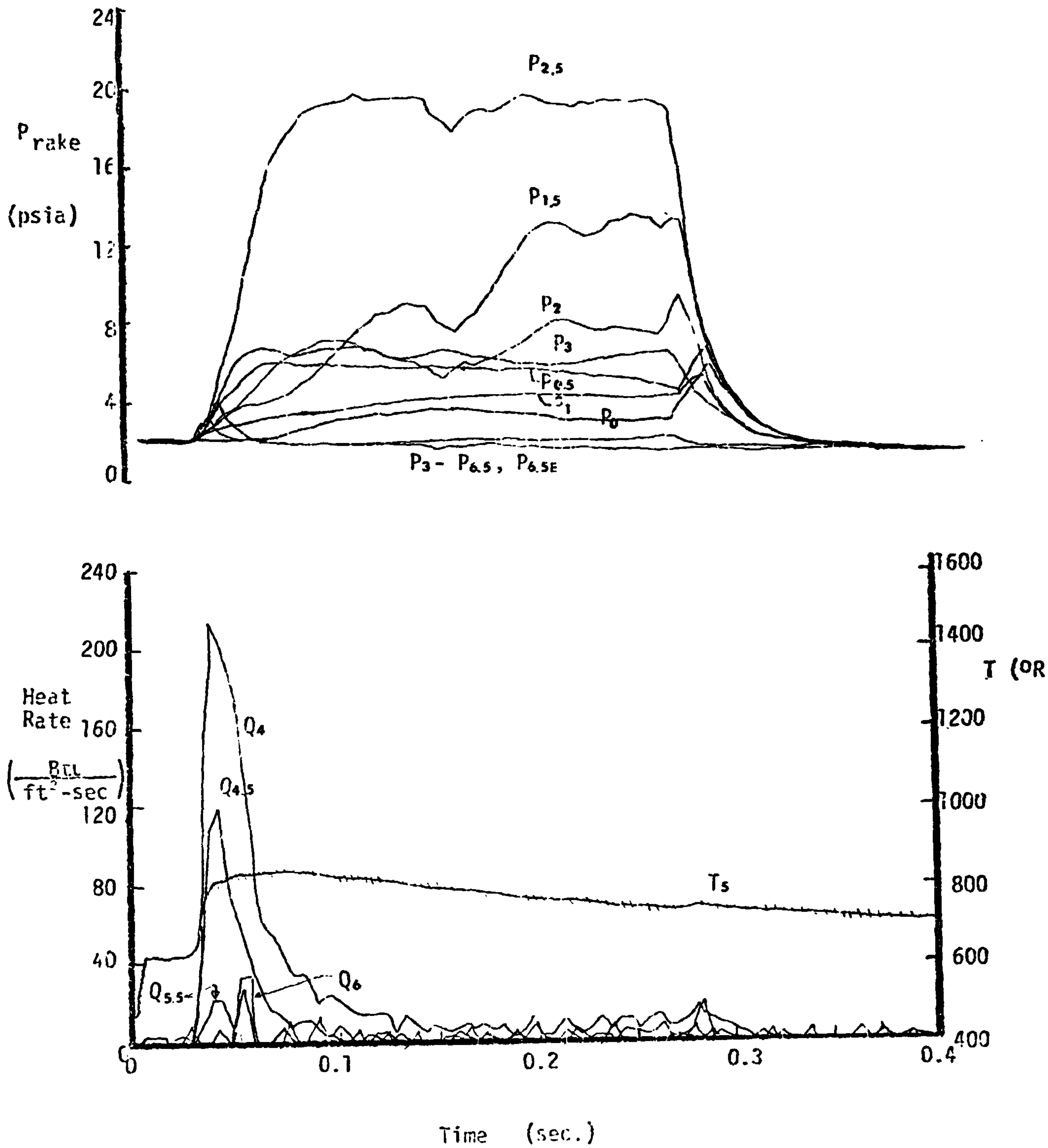

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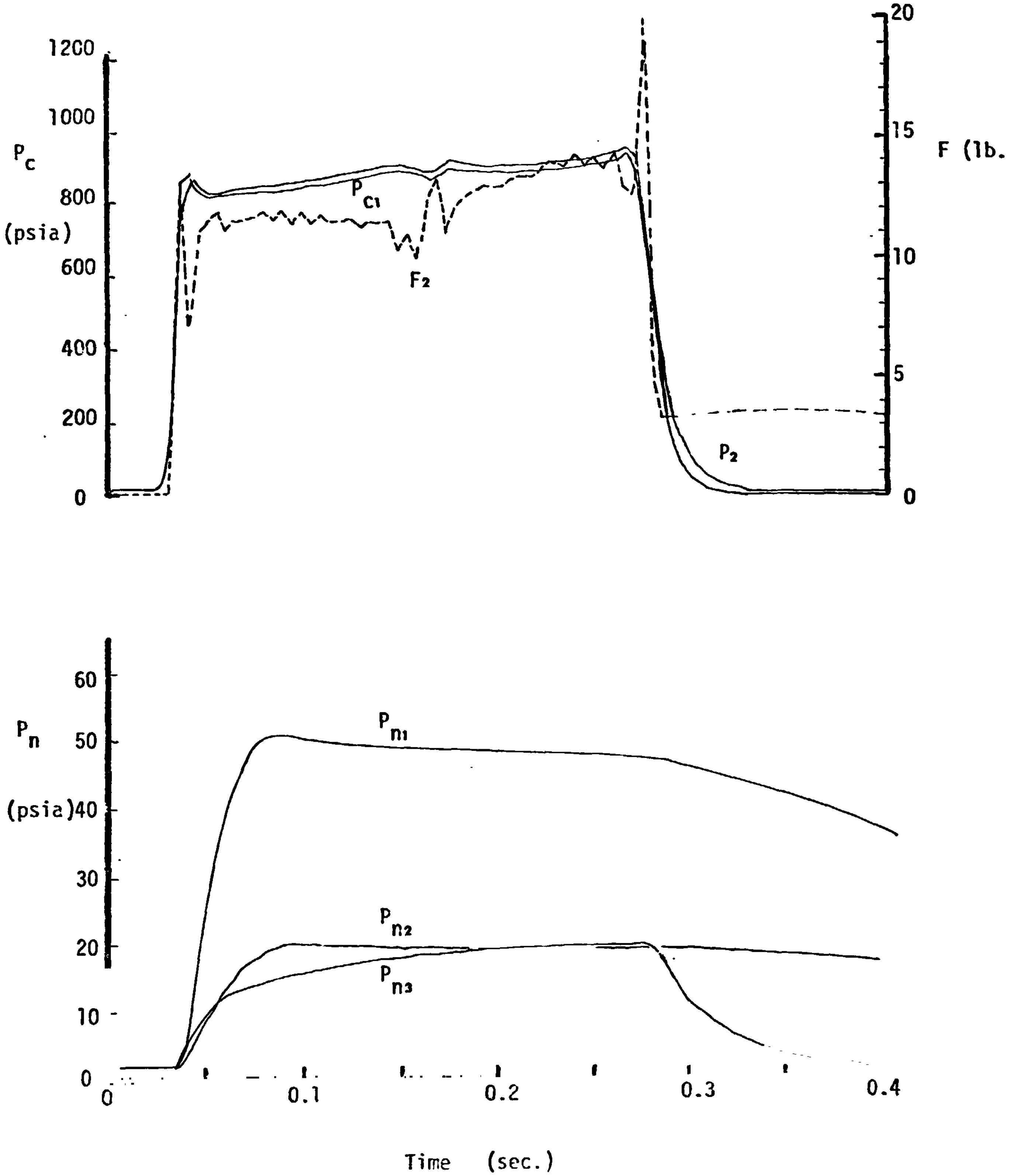

Run No. 11/2

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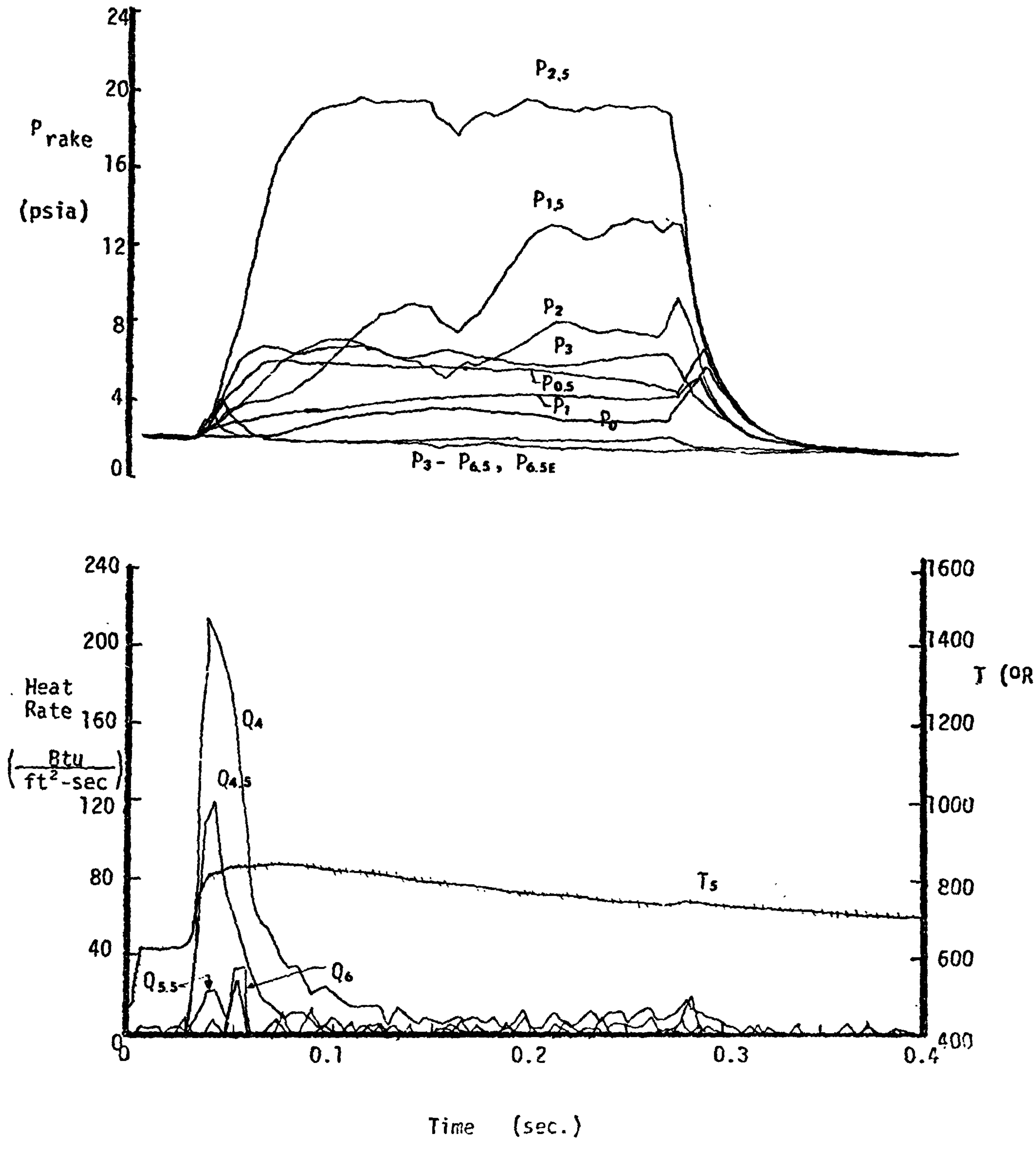

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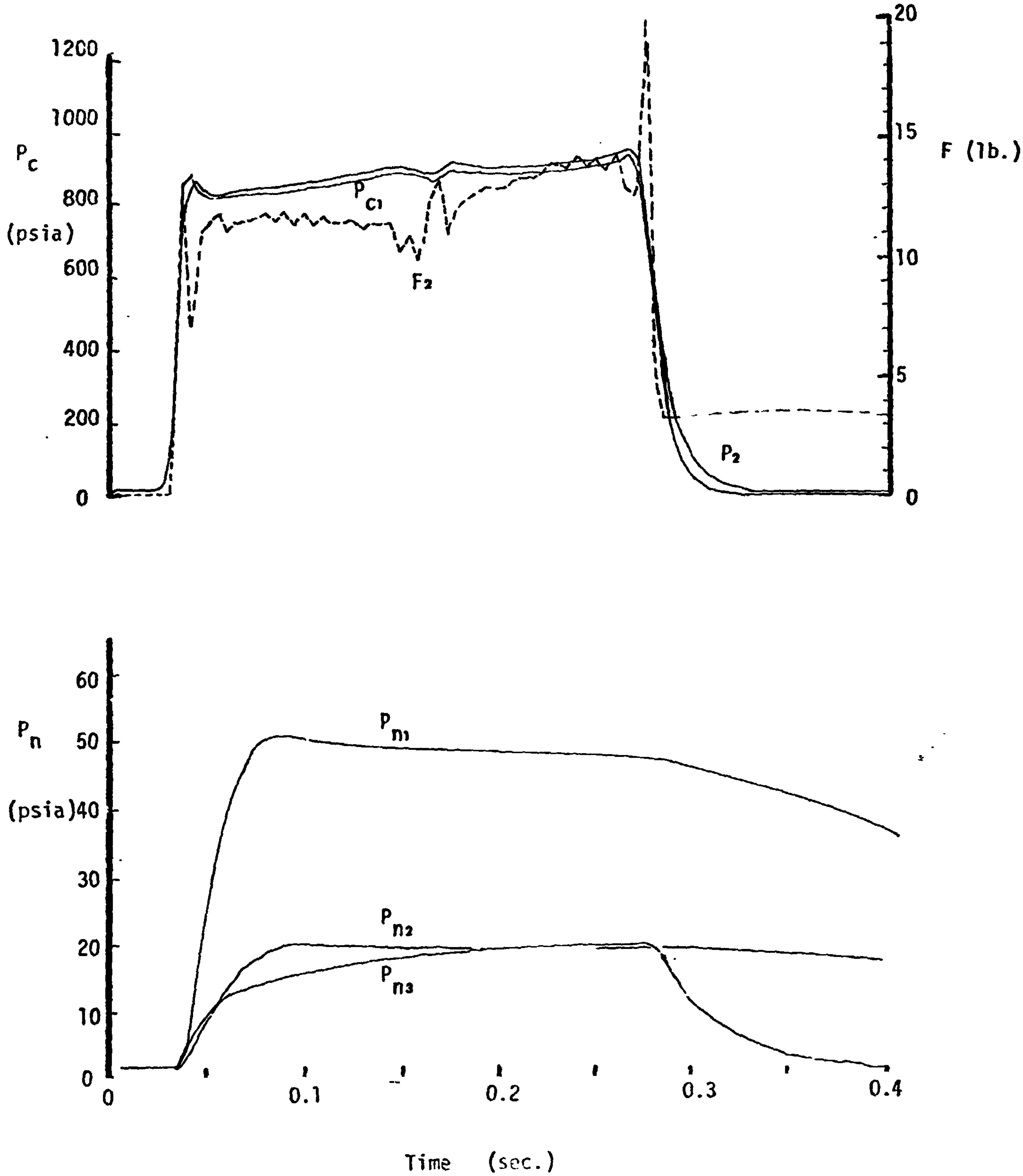

Run No. 11/2

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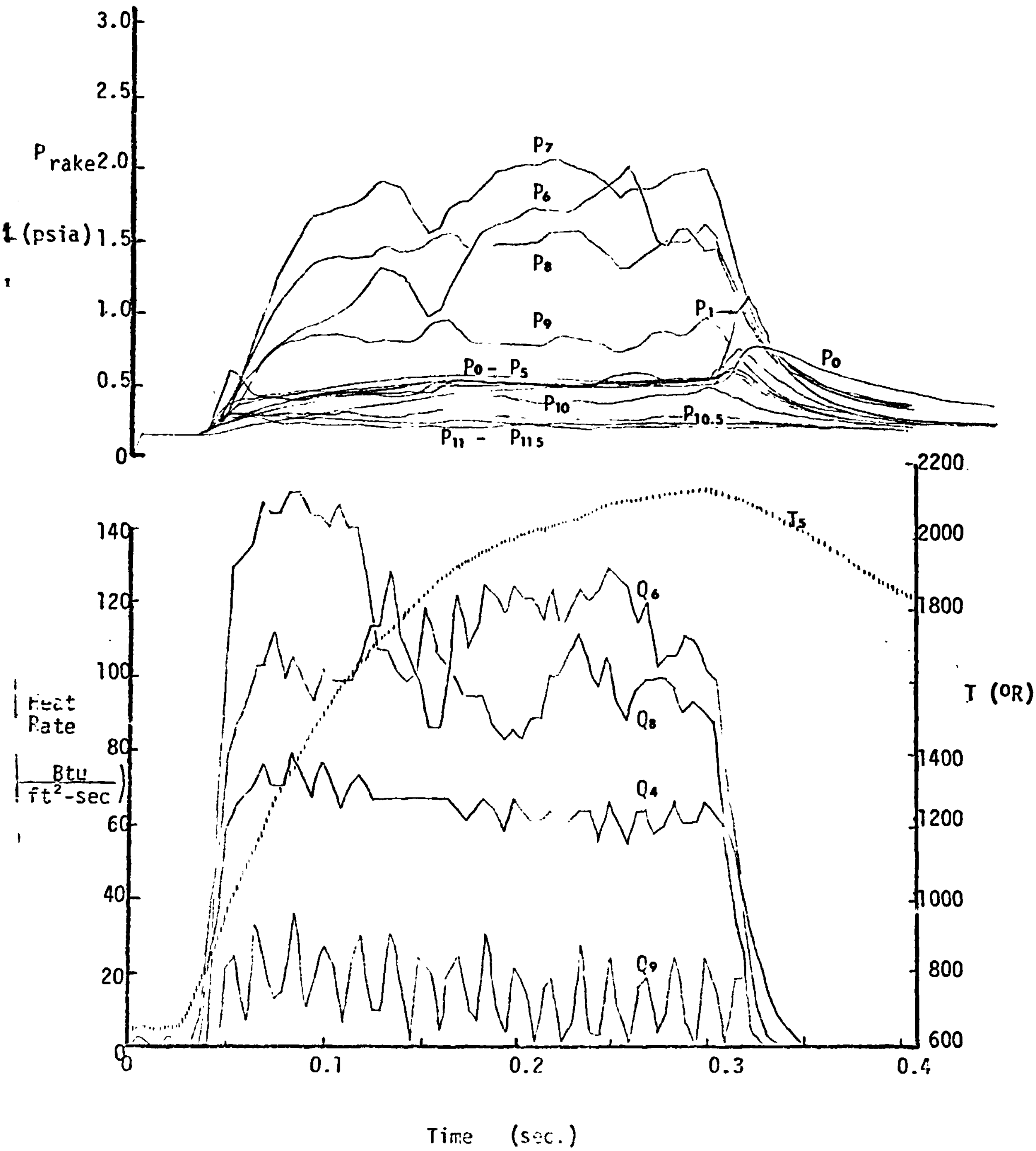

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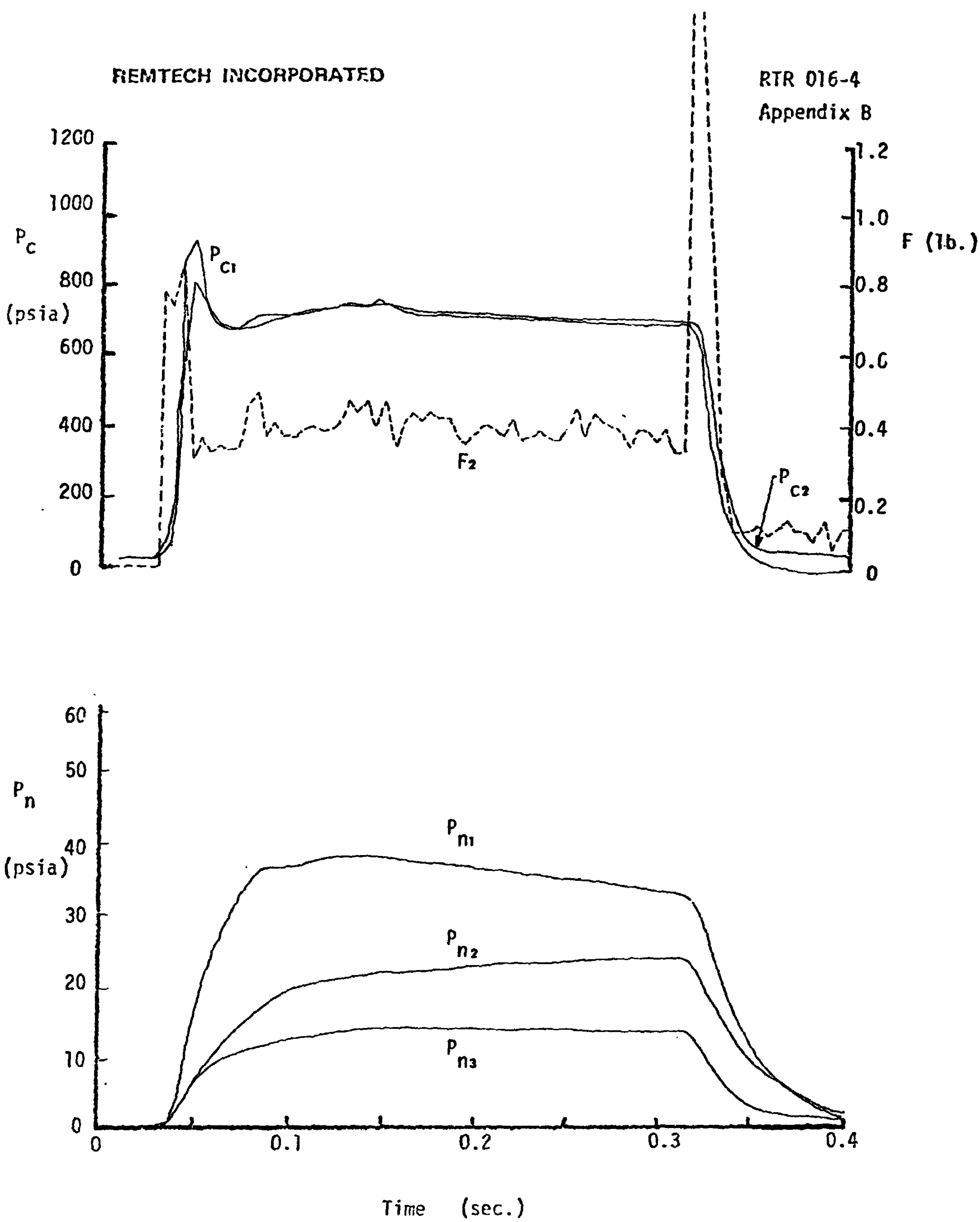

Run No. 12/2

Rake @ X/D=16

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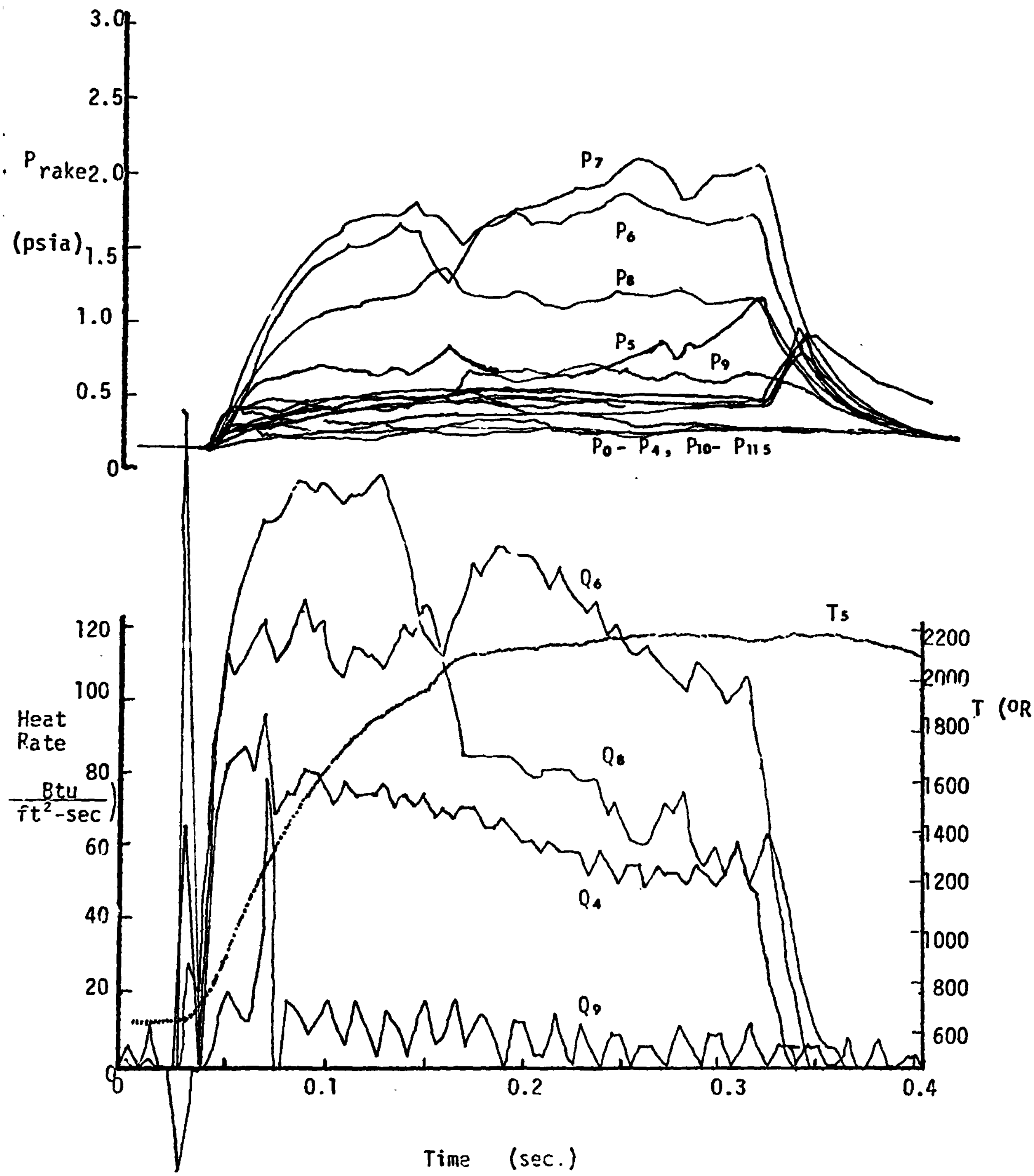

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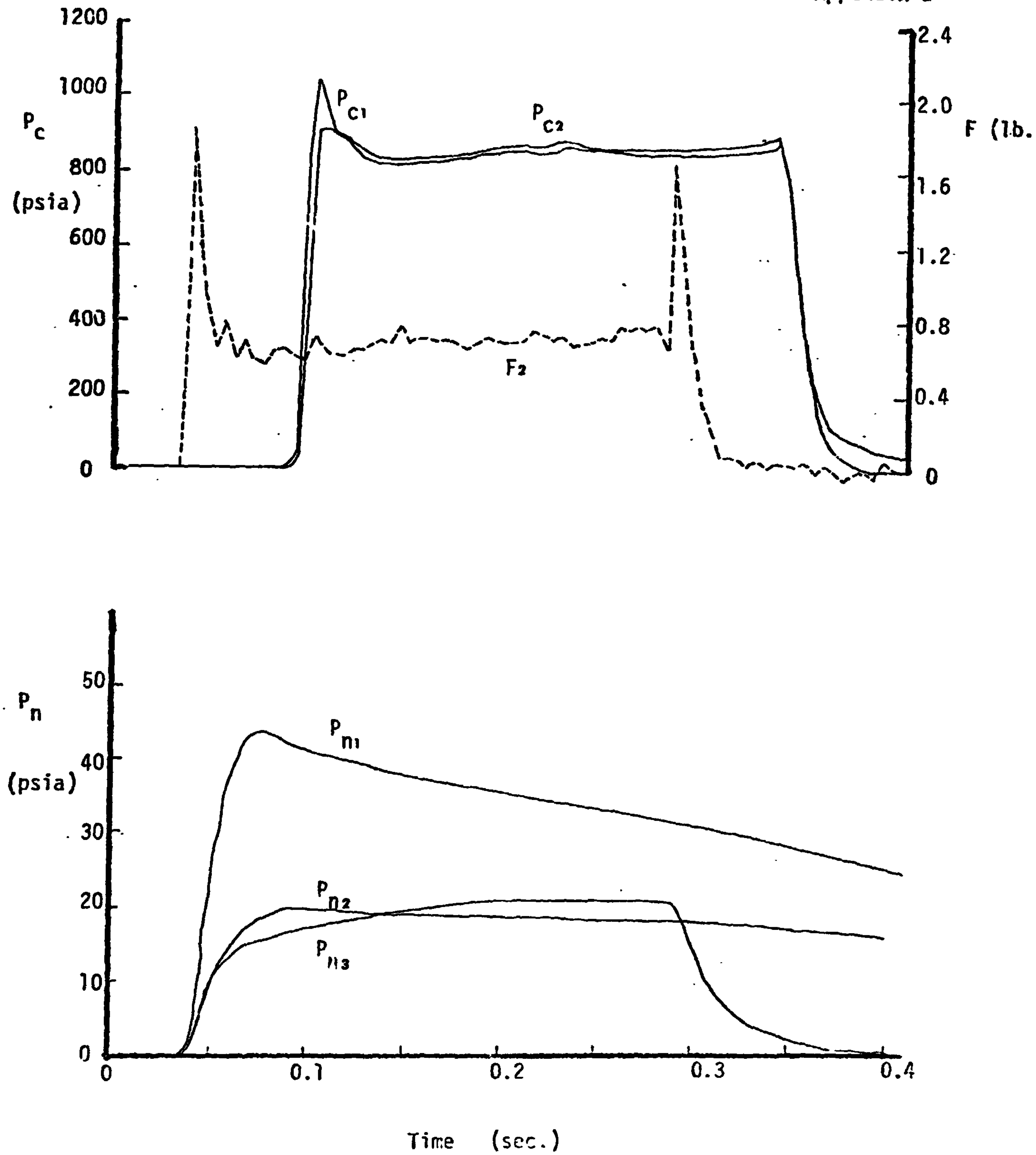

Run No. 13/1

Rake @ X/D=16

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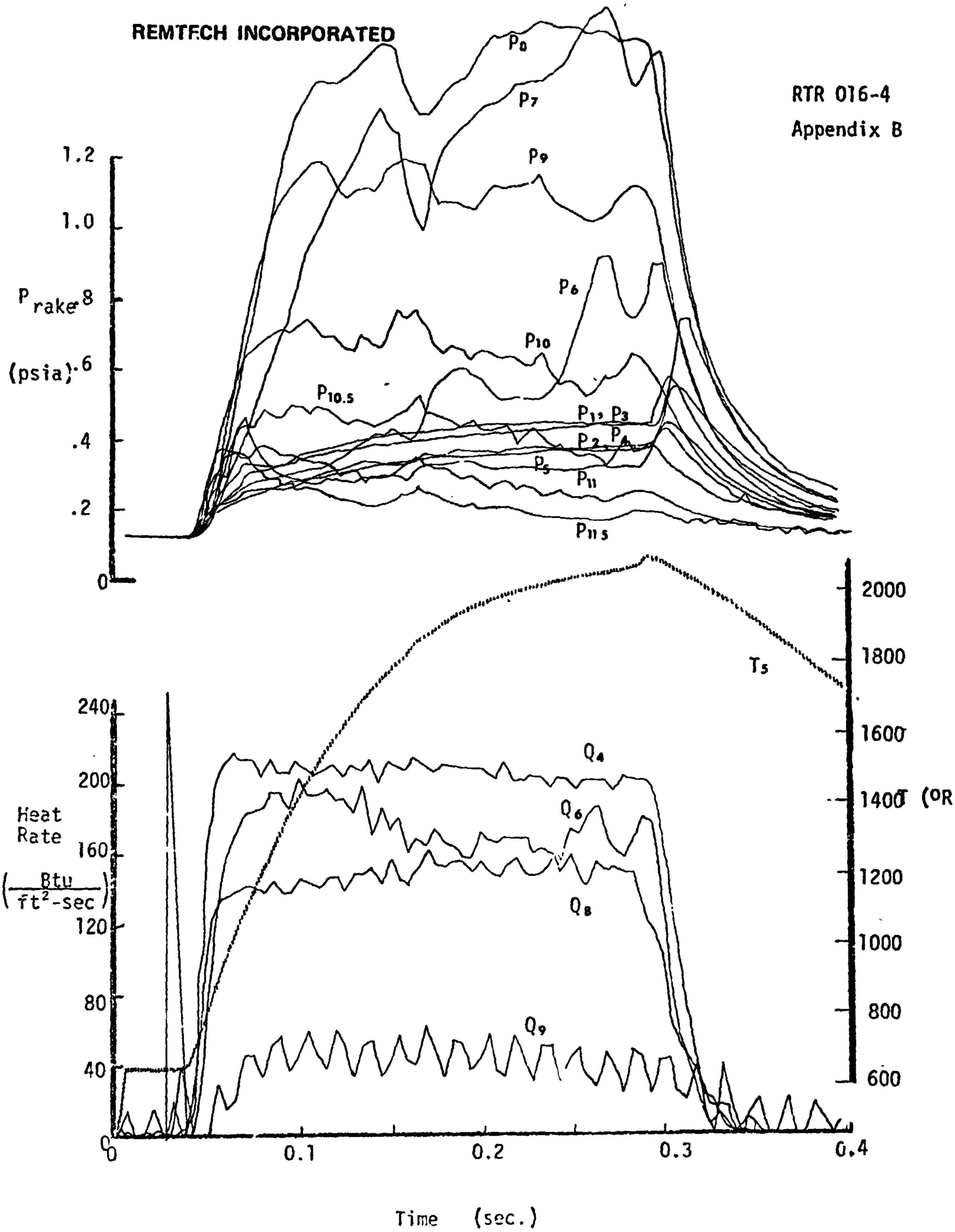

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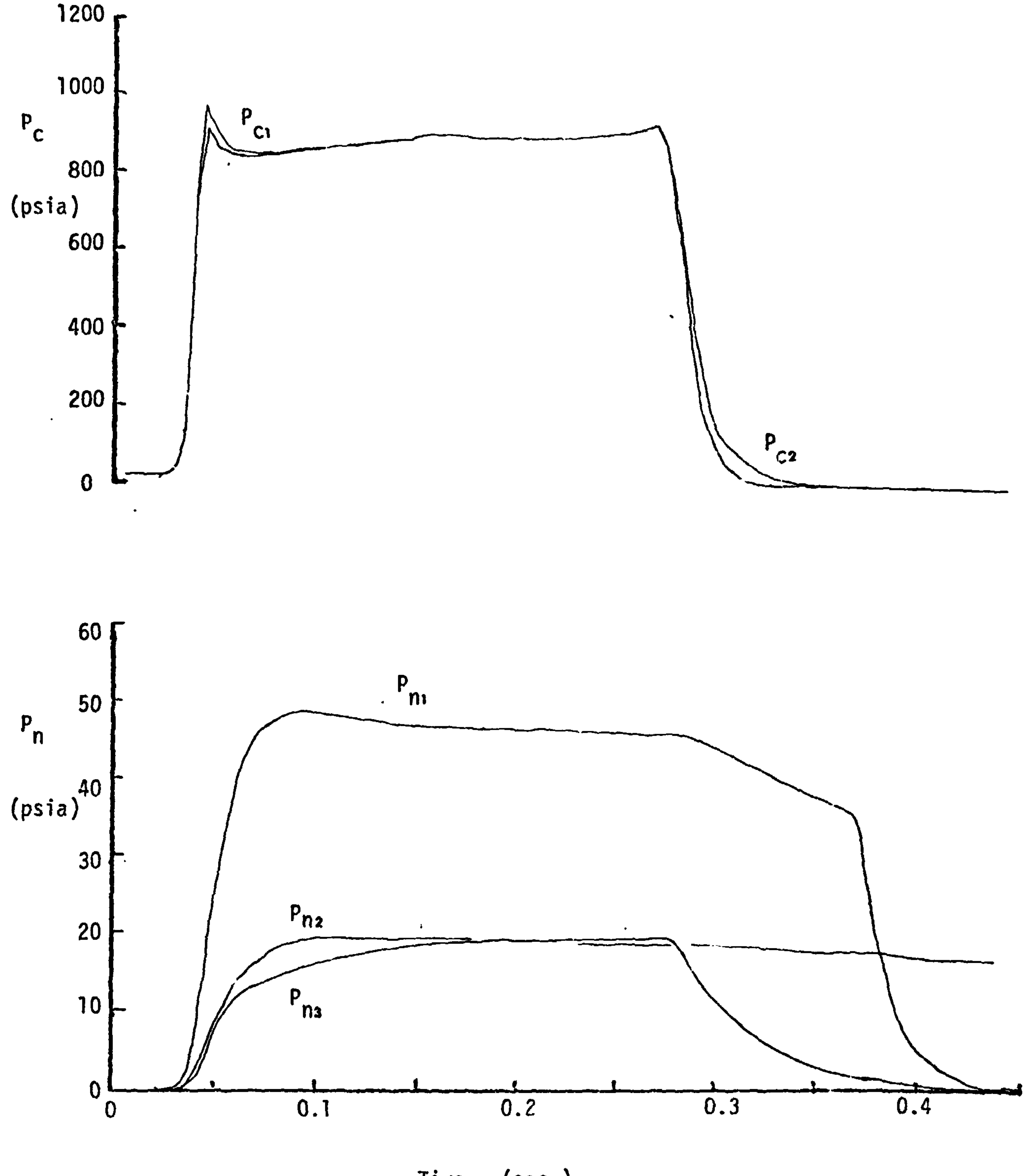

Run No. 13/2

Rake @ X/D=16

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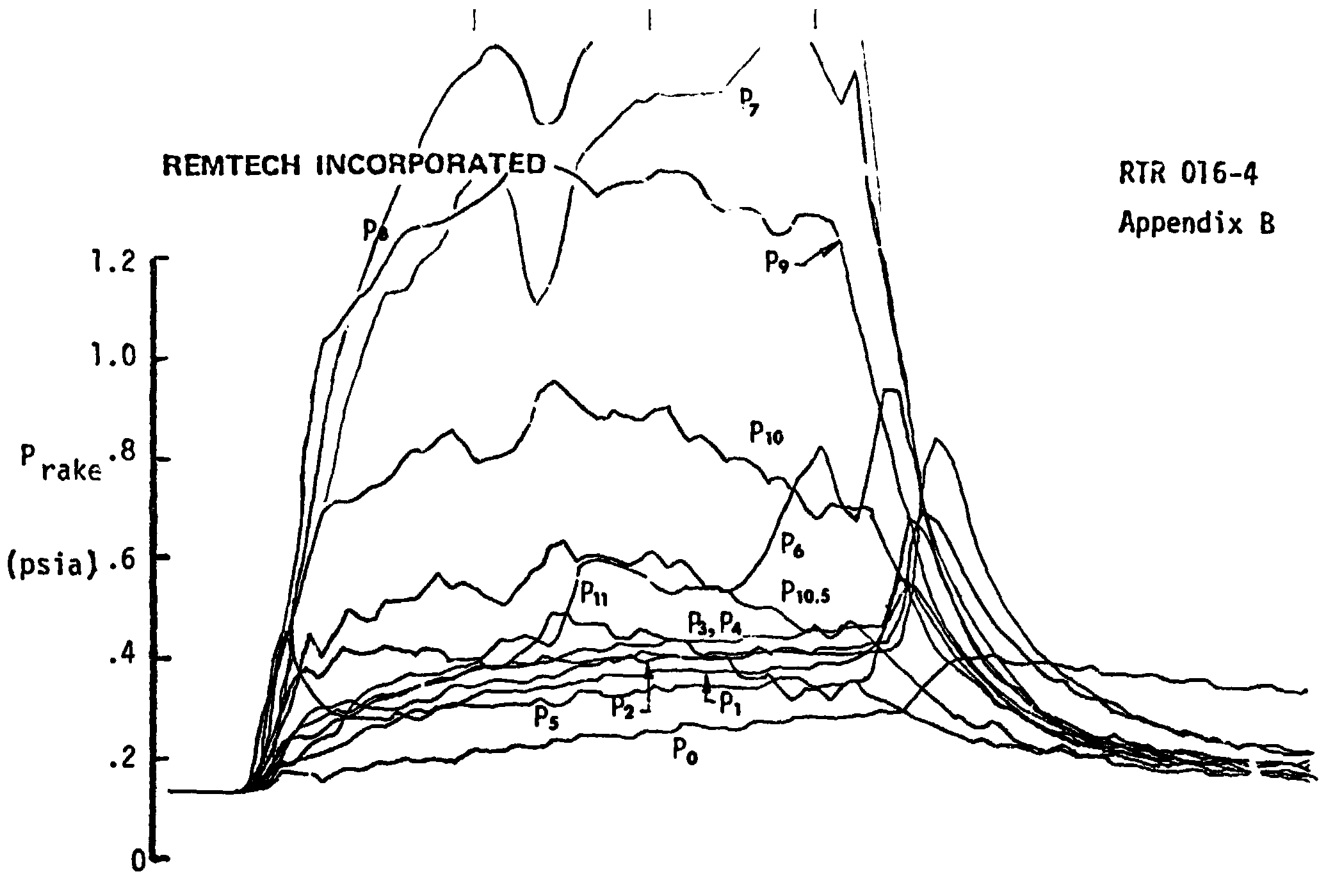

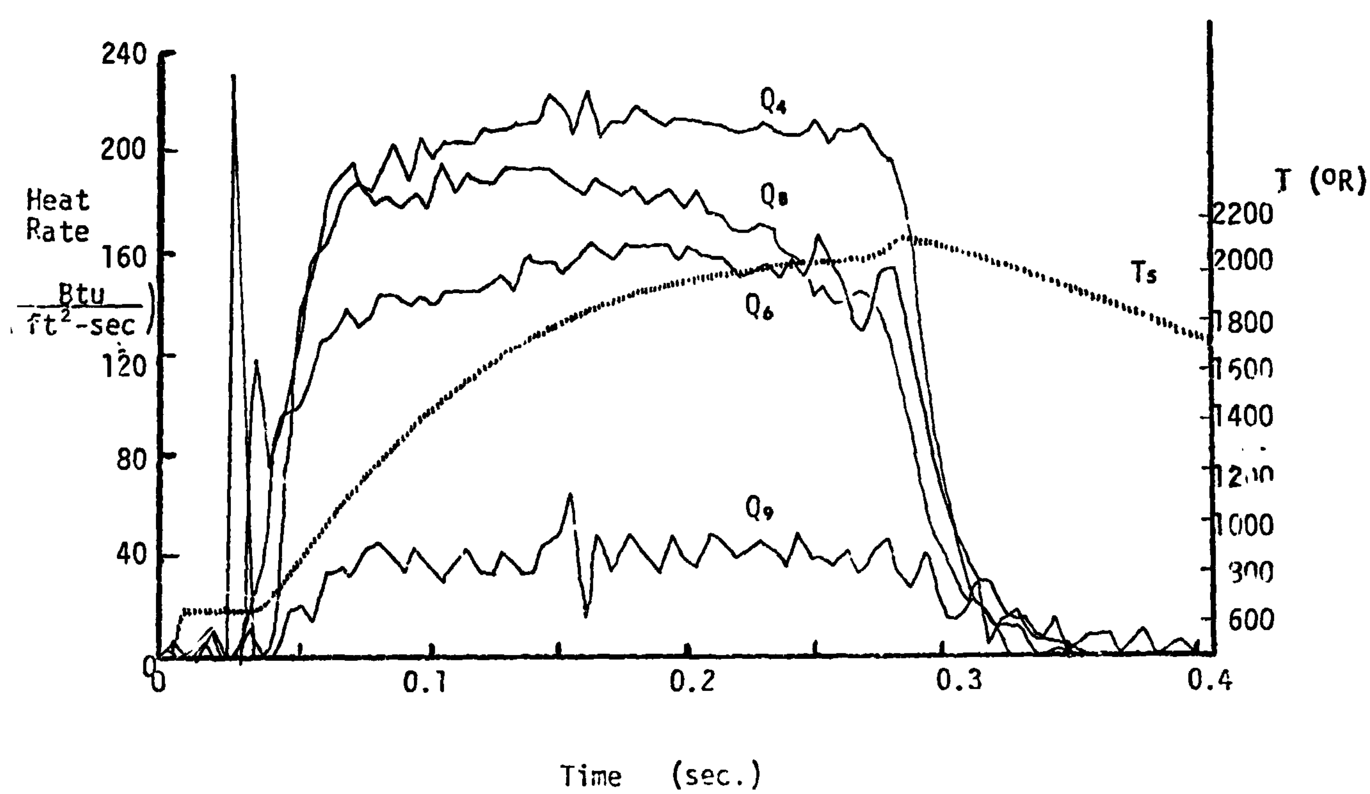

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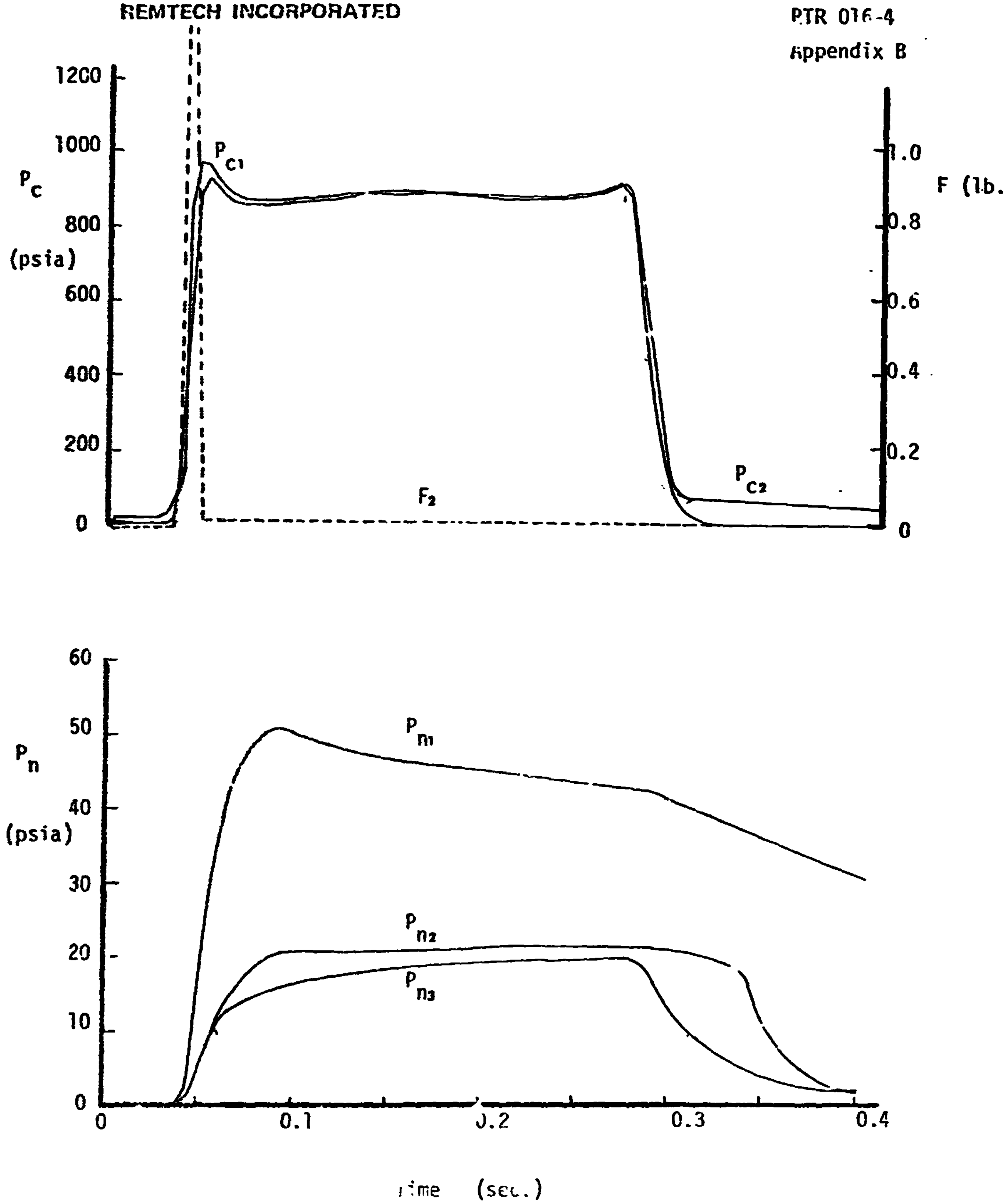

Run No. 13'3

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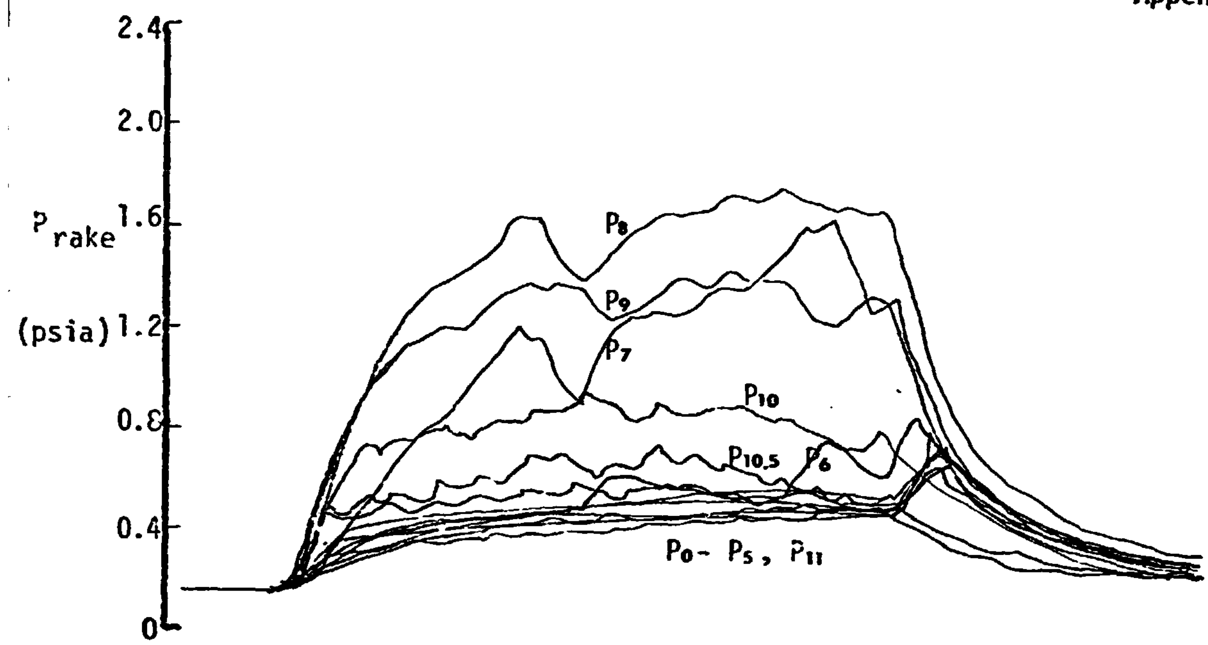

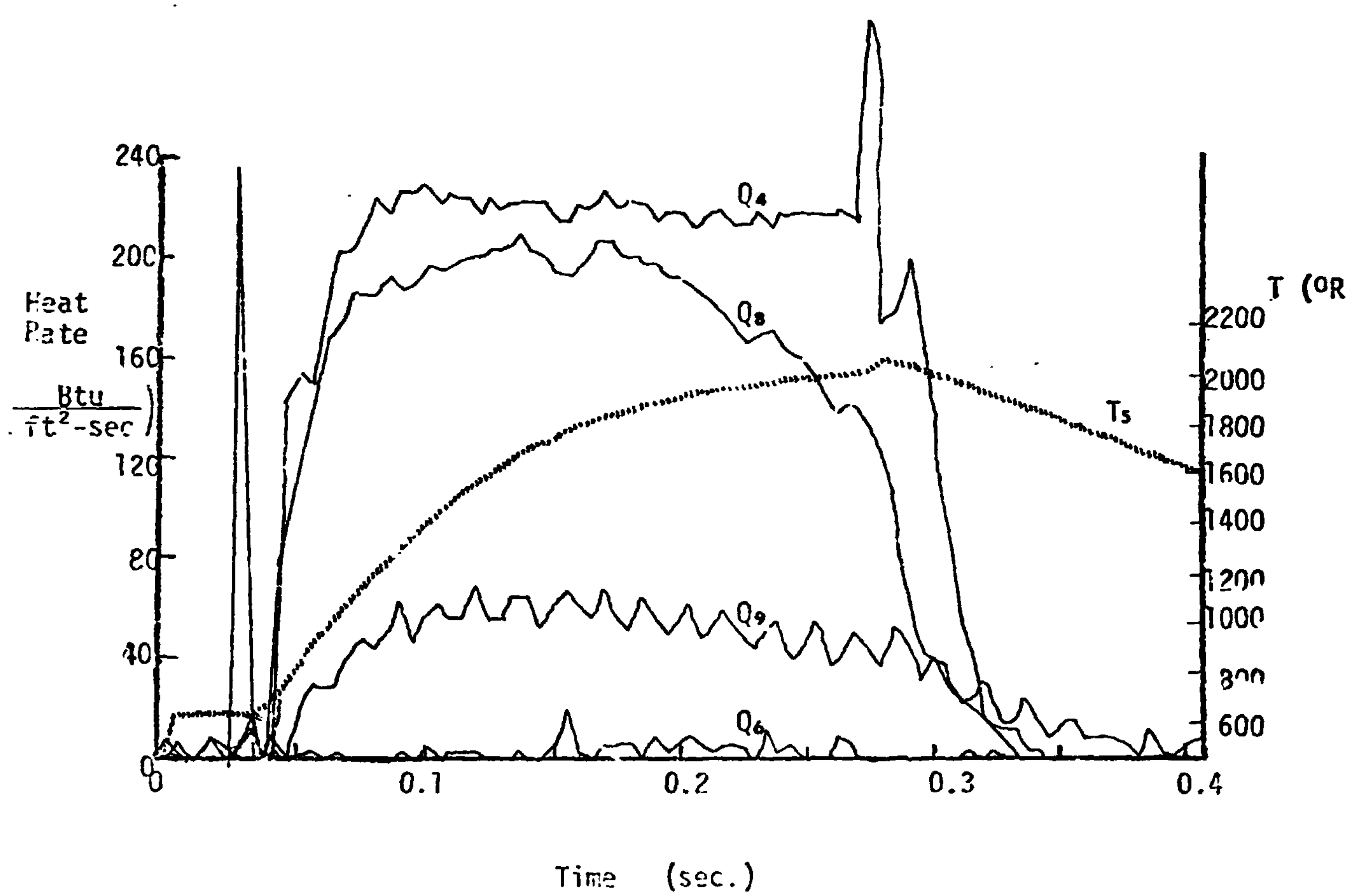

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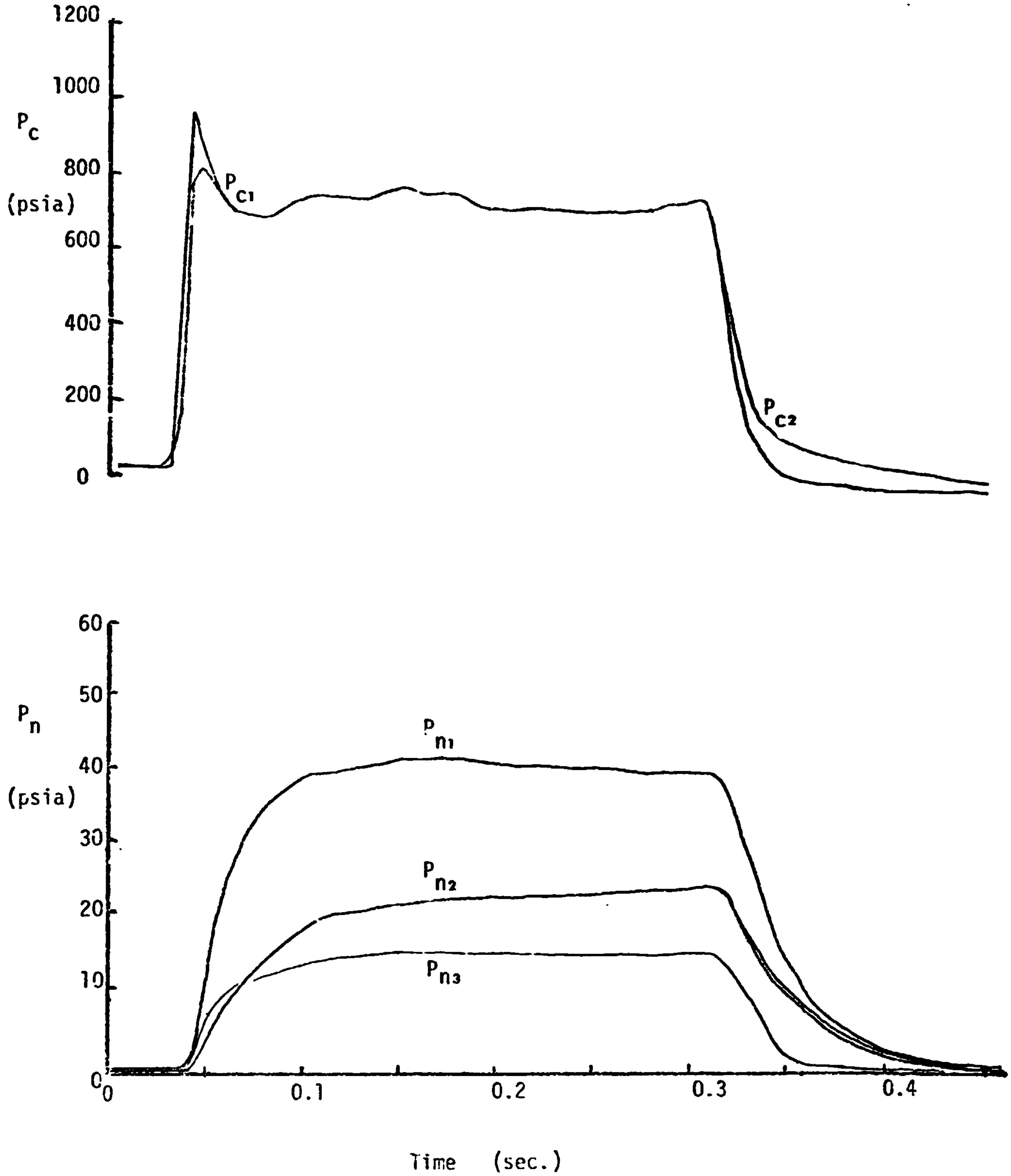
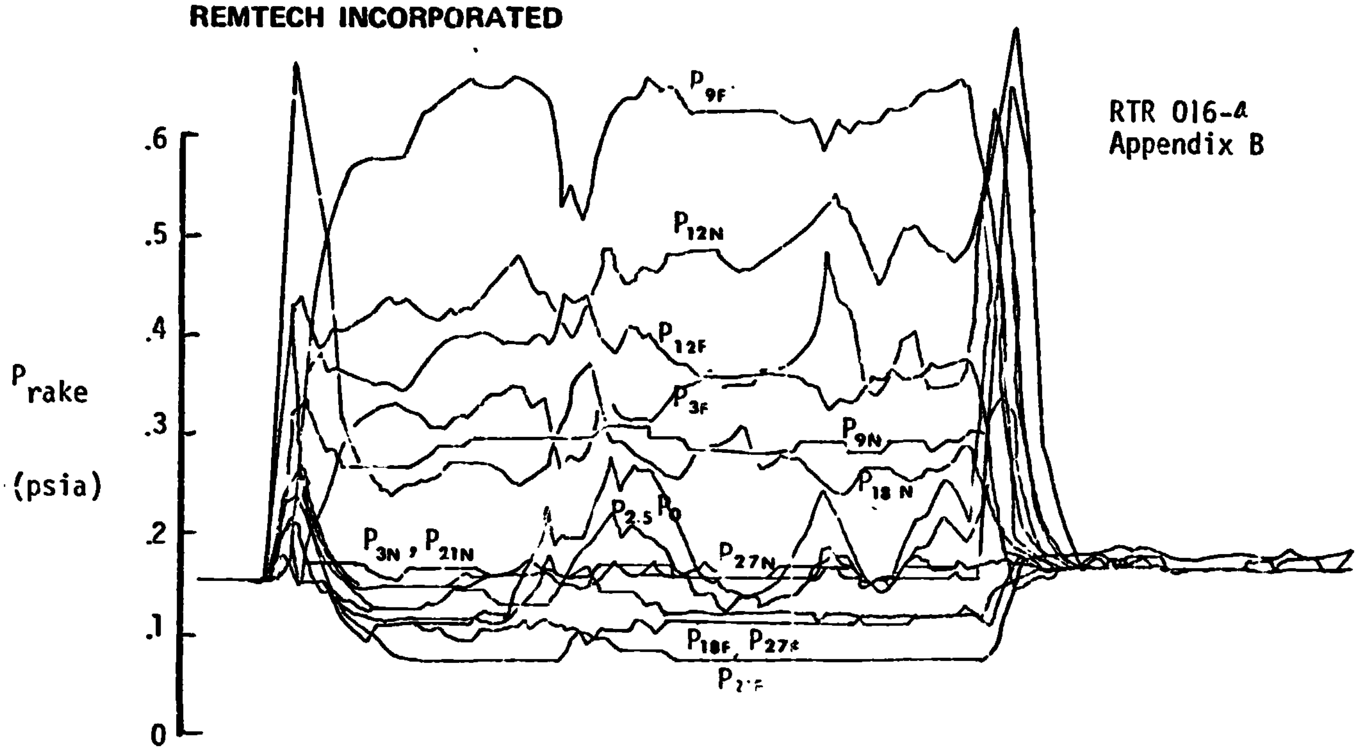
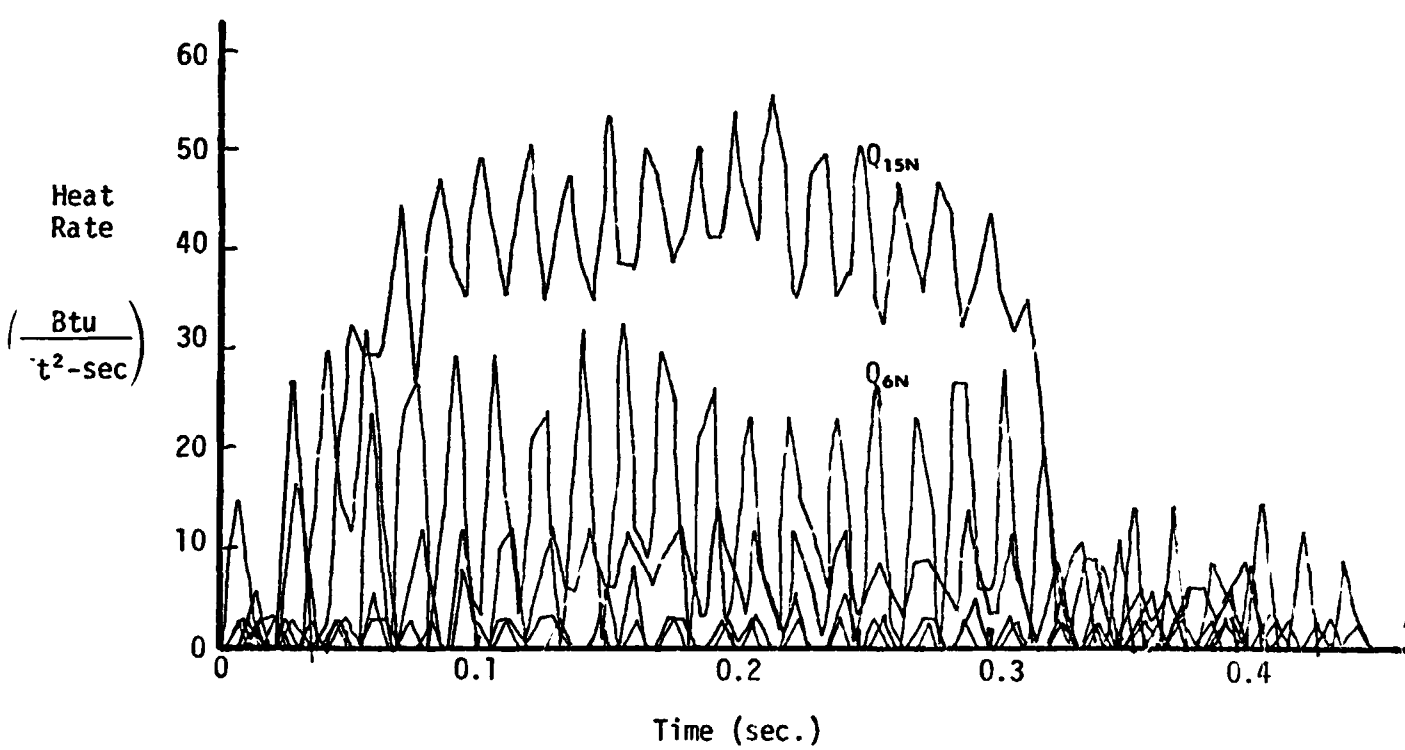


Run No. 14/1

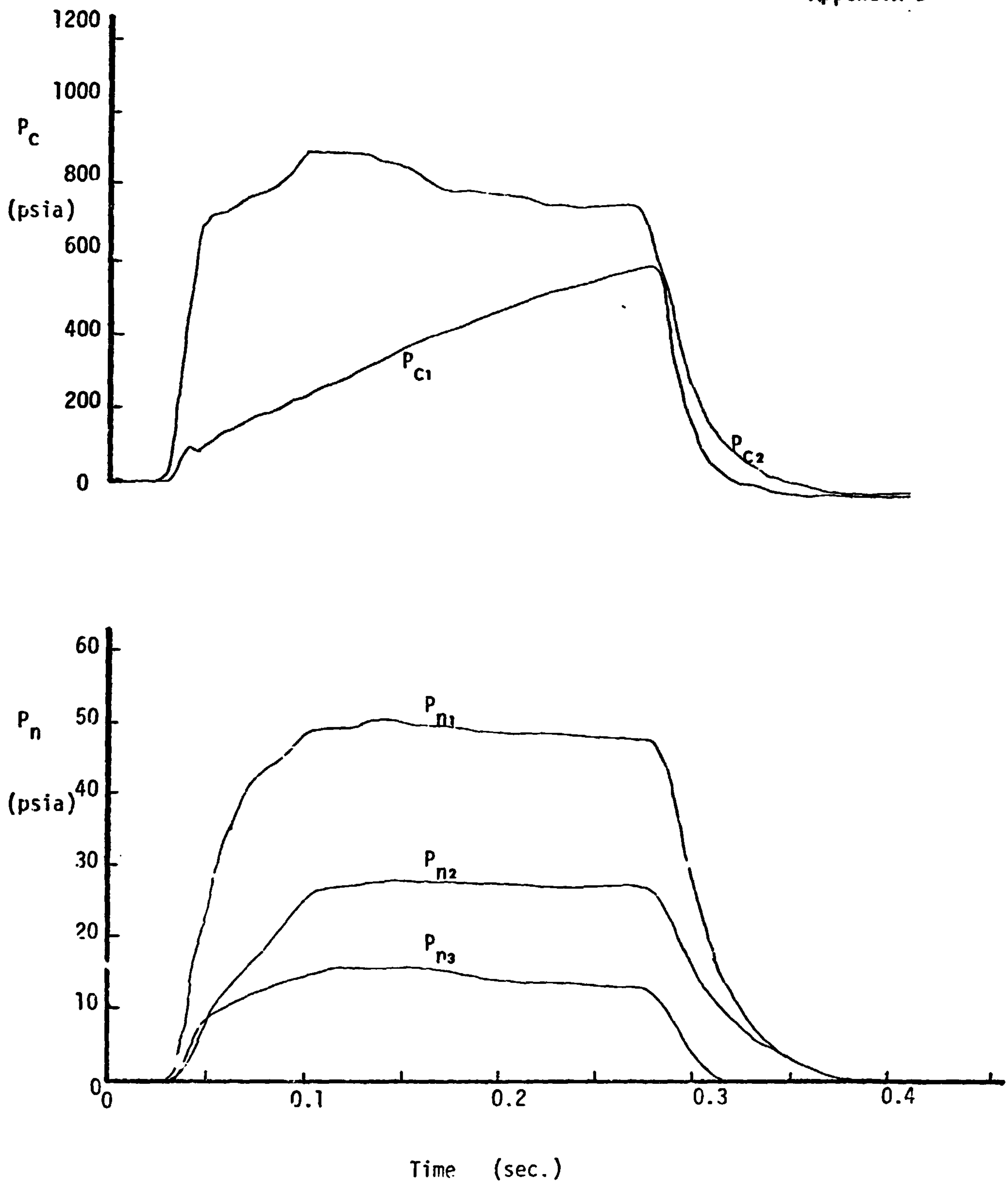
Plate @ X/D=20
ψ = 30°

Alt.=100,000'
%Al = 2





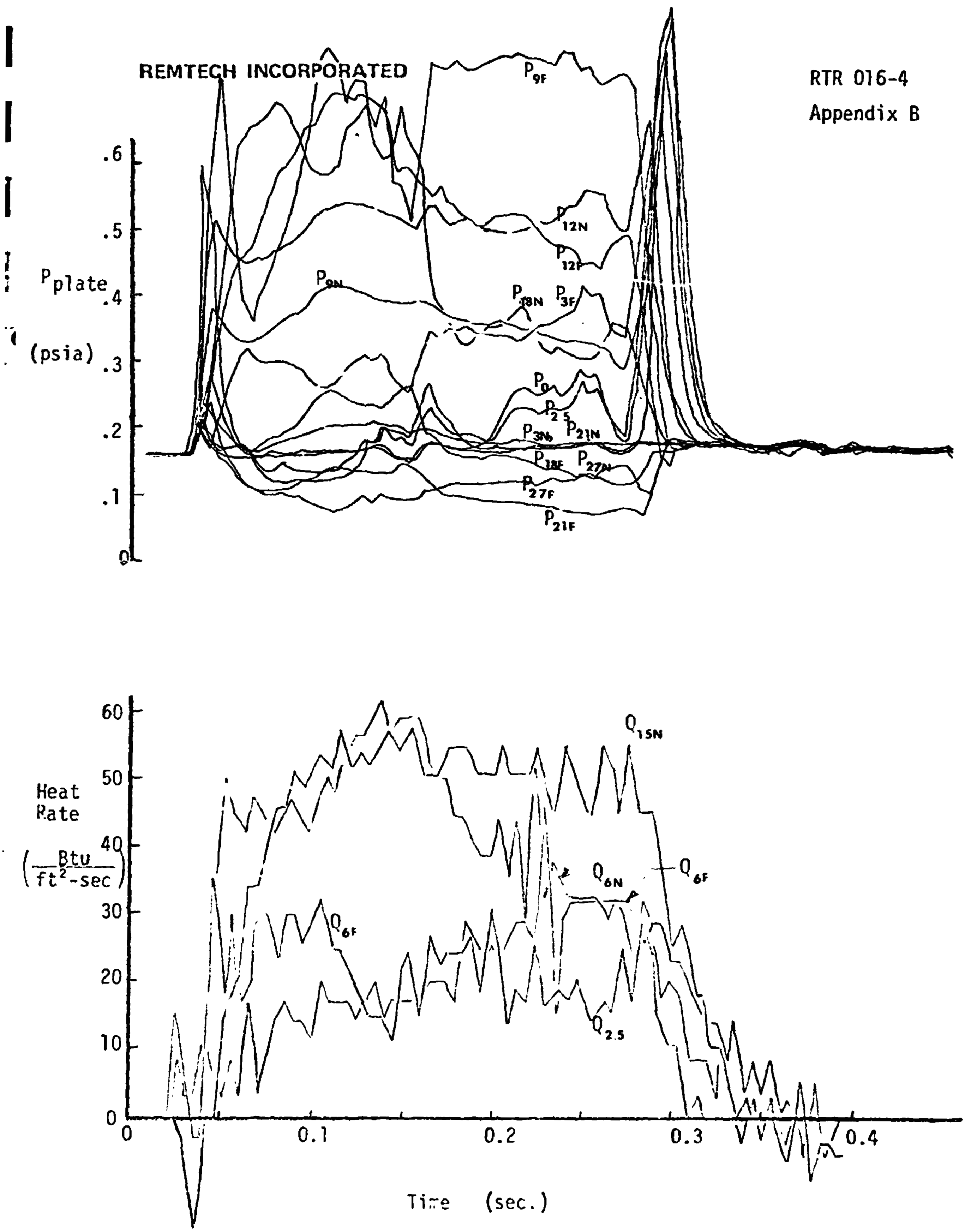
Run No. 14/1 (Concluded)



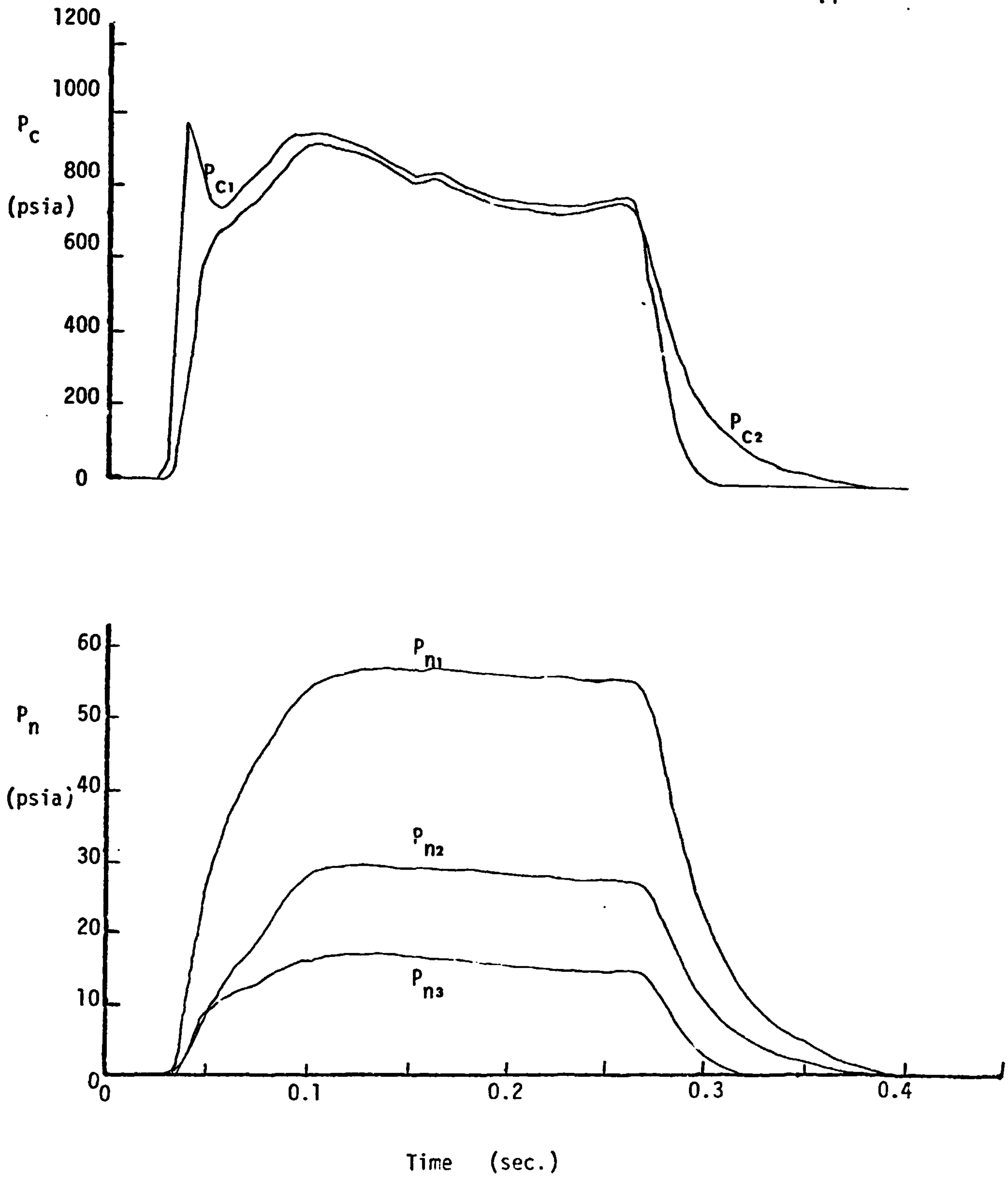
Run No. 14/2

Plate @ X/D=20
ψ = 30°

Alt.=100,000'
%Aℓ = 2



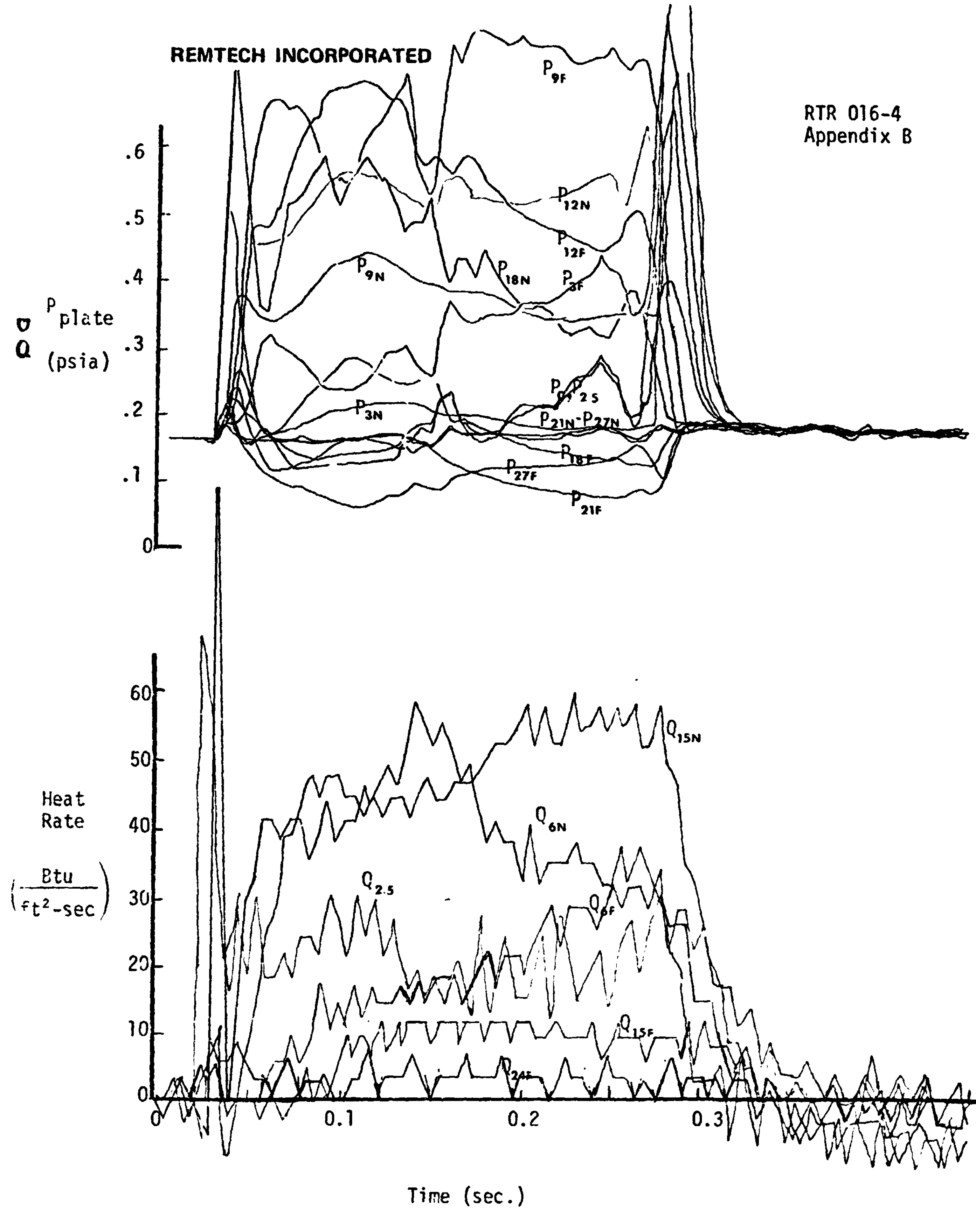
Run No. 14/2 (Concluded)



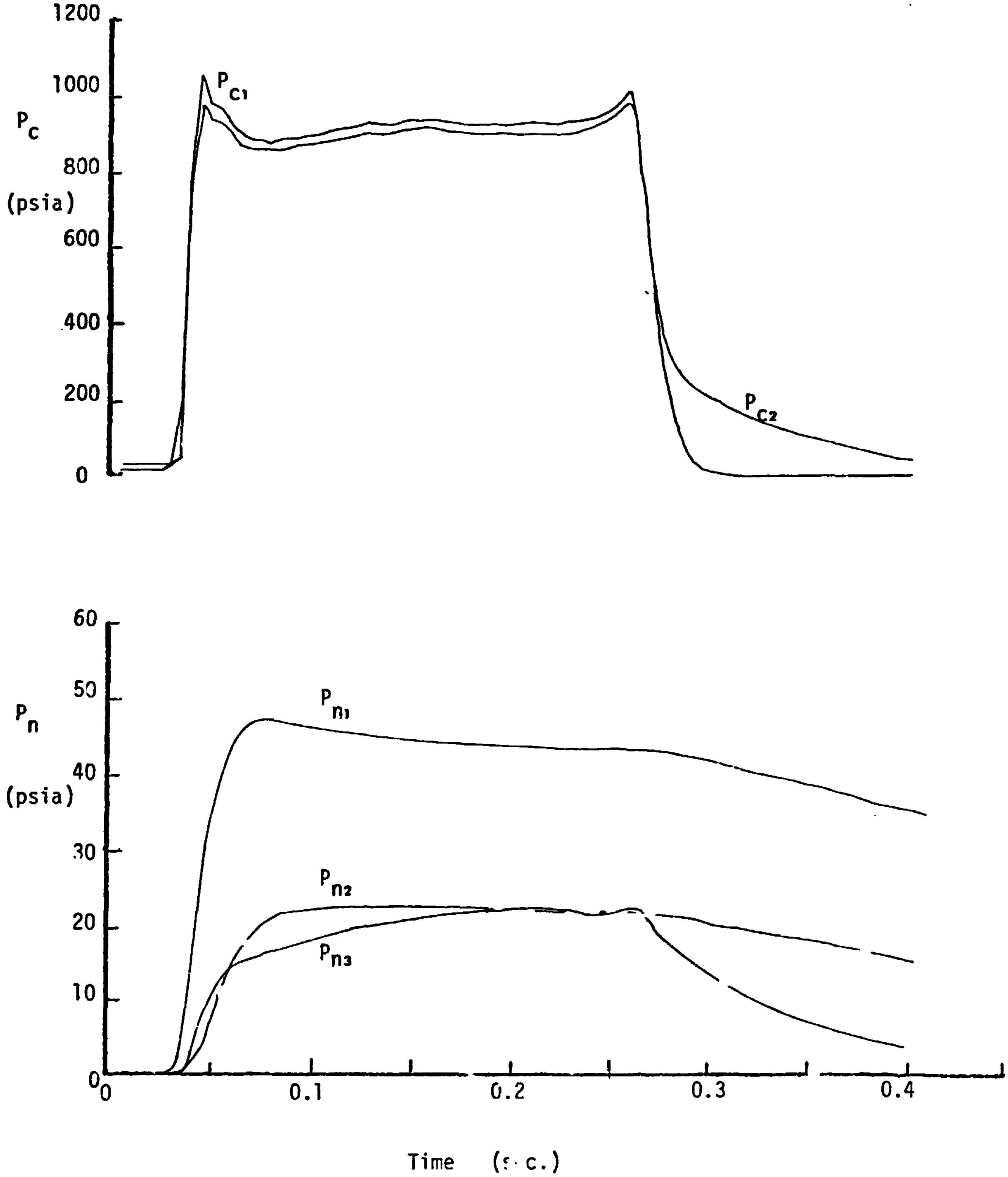
Run No. 14/3

Plate @ X/D=20
ψ = 30°

Alt.=100,000'
%Aℓ = 2



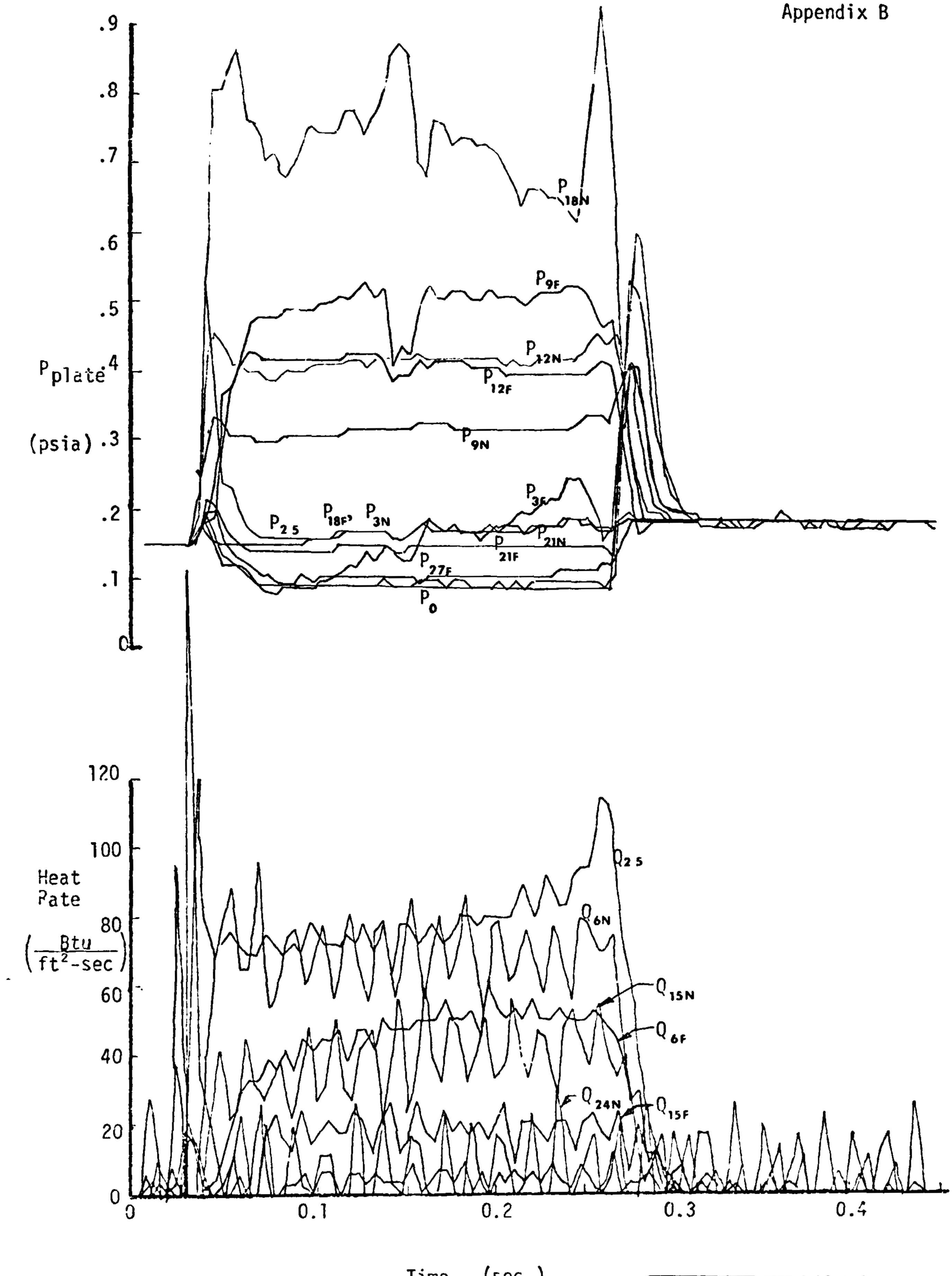
Run No. 14/3 (Concluded)



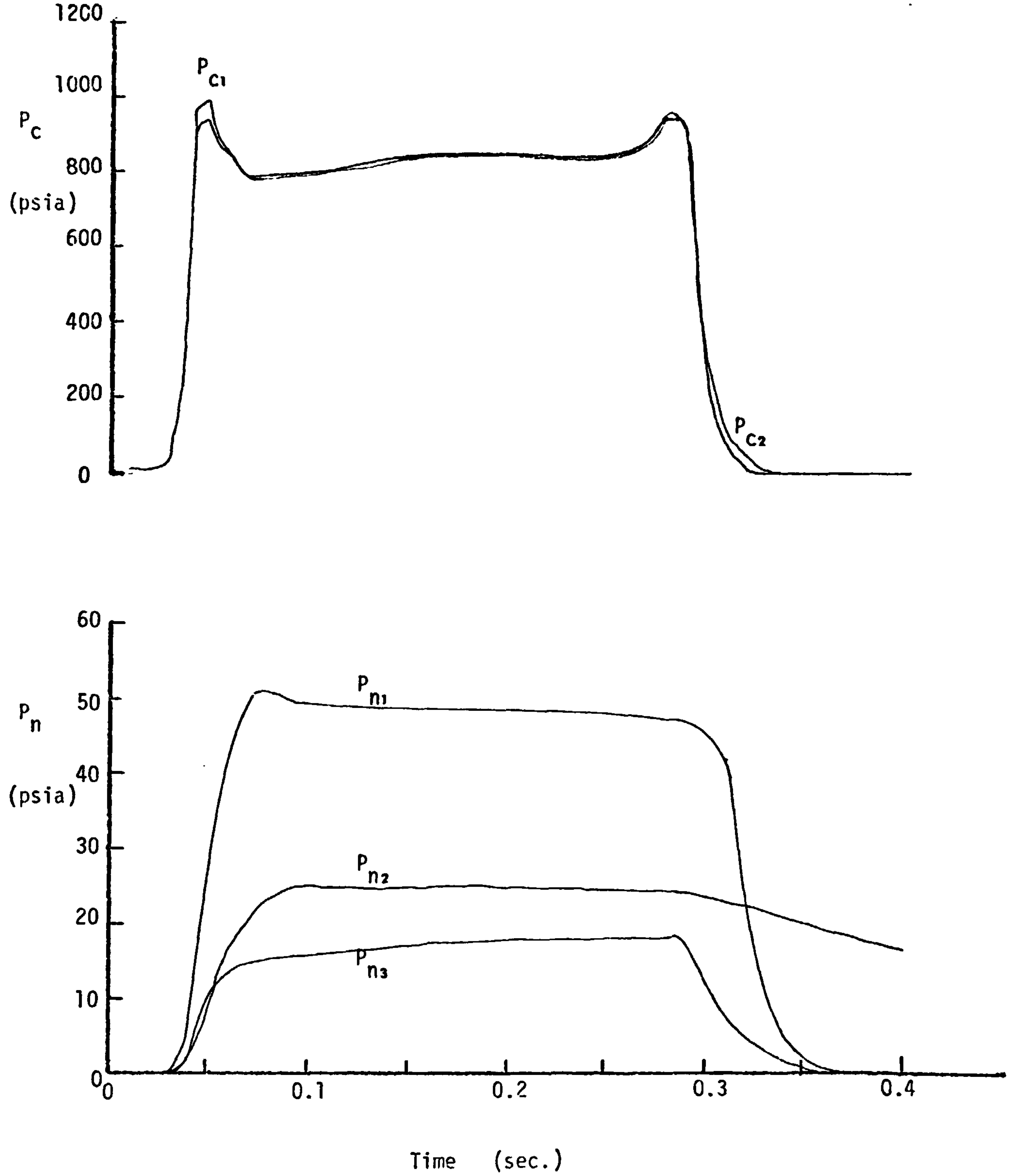
Run No. 15/1

Plate @ X/D=20
ψ = 30°

Alt.=100,000'
%Al = 10



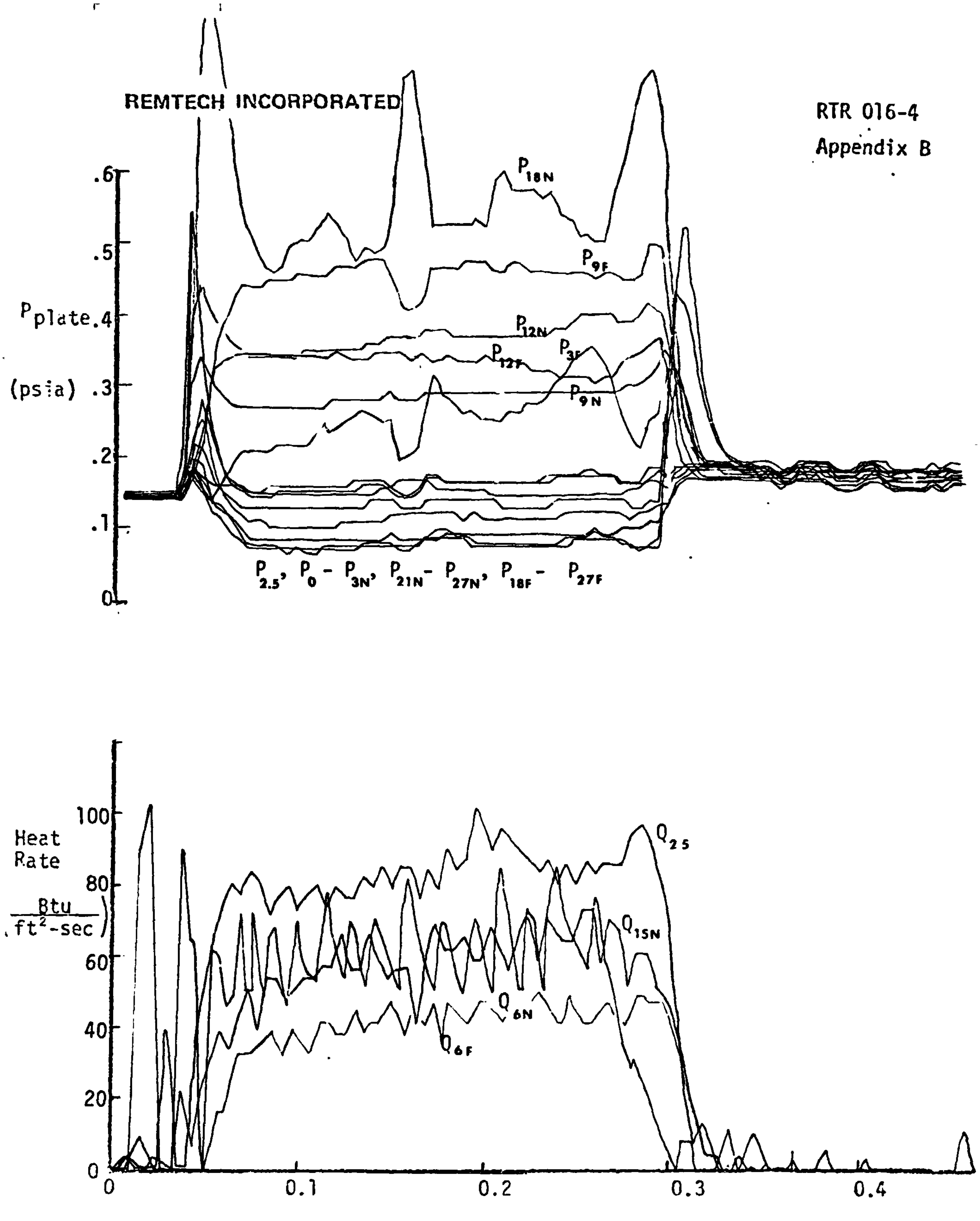
Run No. 15/1 (Concluded)



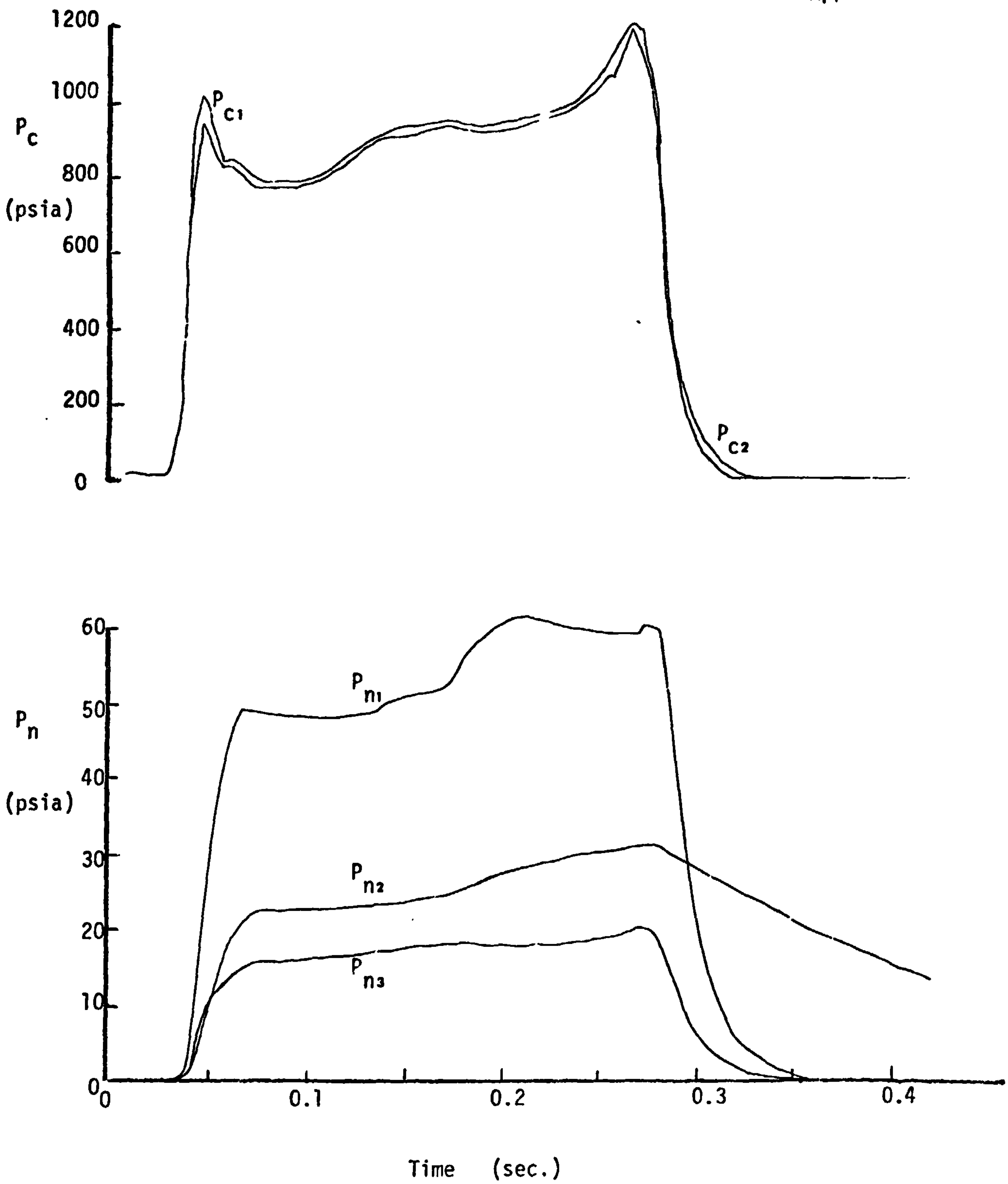
Run No. 15/2

Plate @ X/D=20
ψ = 30°

Alt.=100,000'
%Aℓ = 10



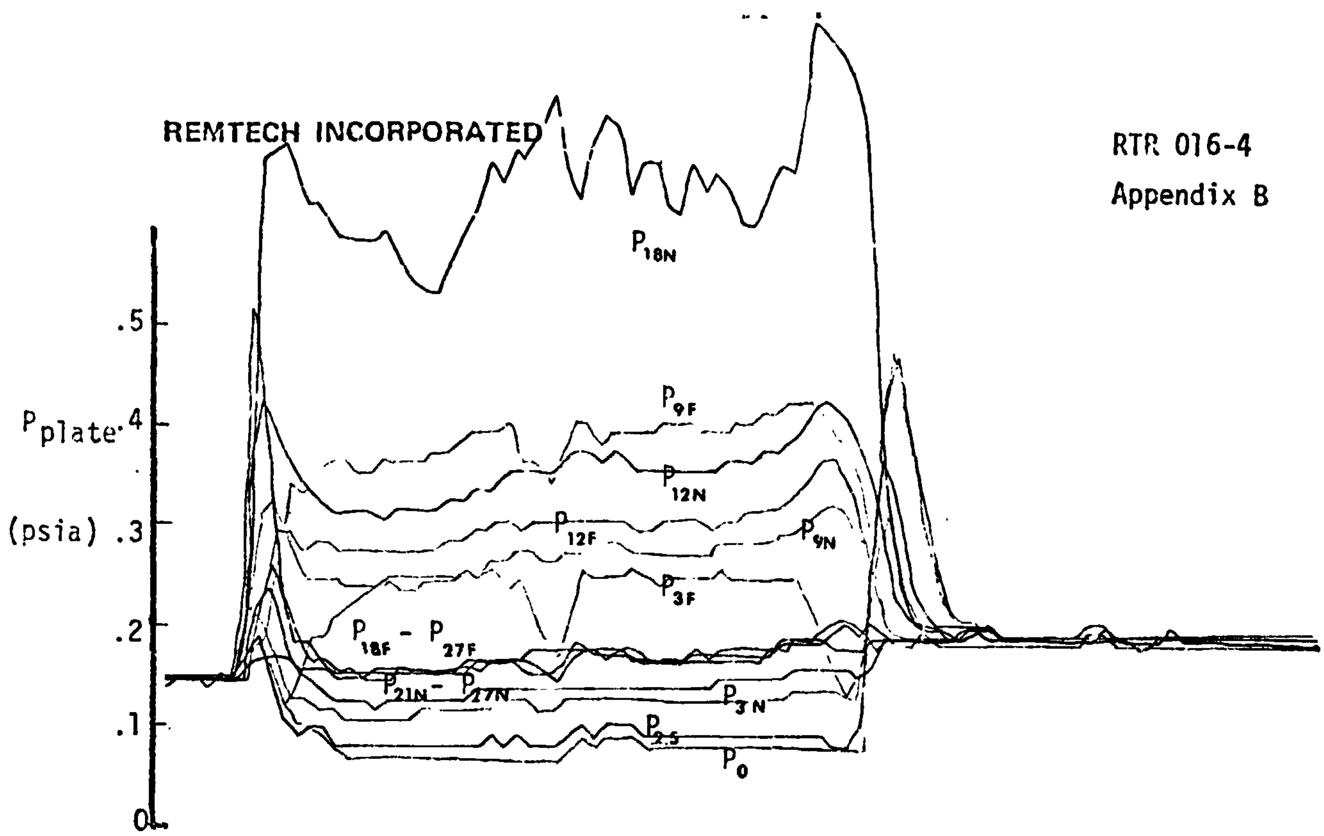
Run No. 15/2 (Concluded)

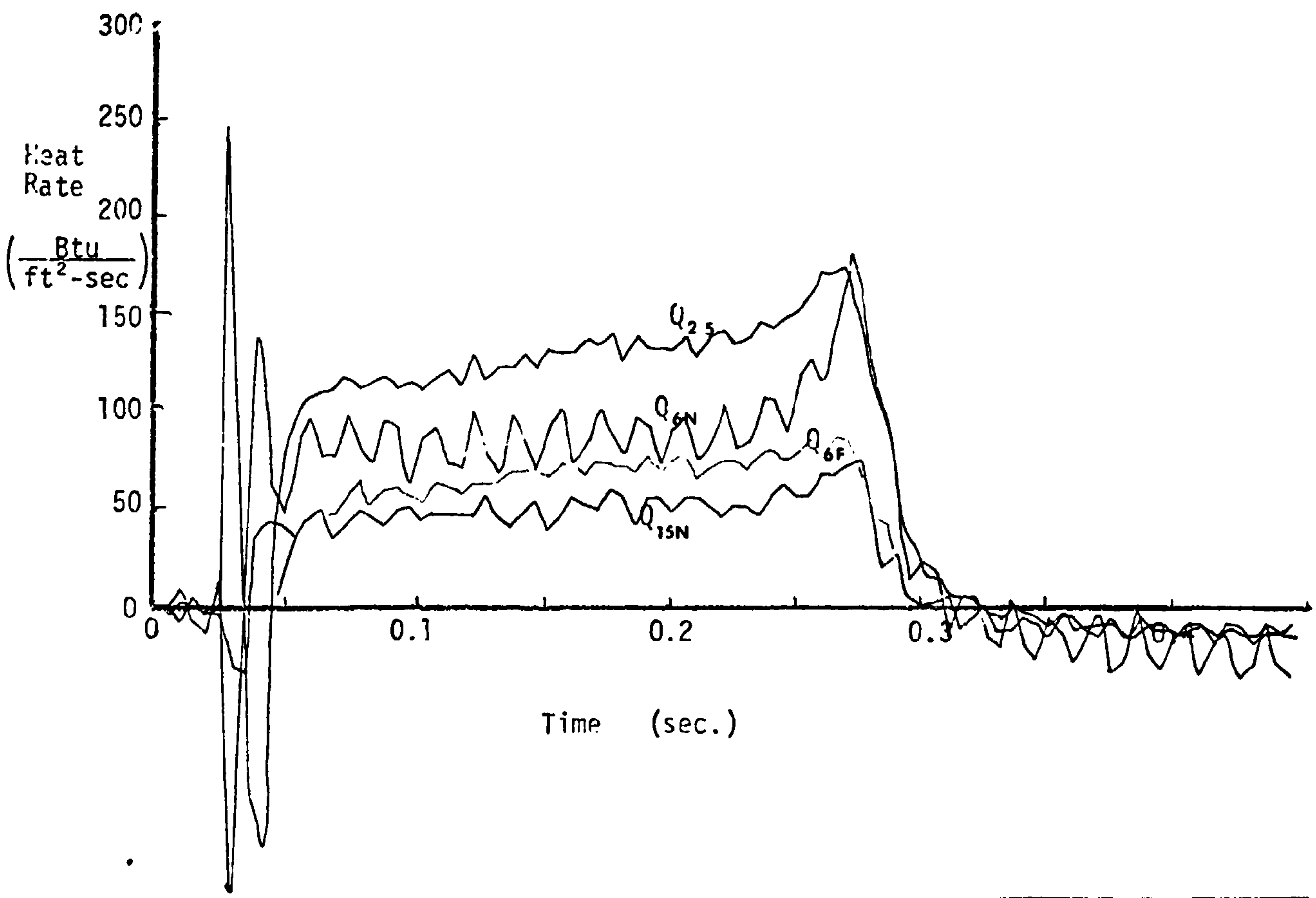


Run No. 16/1

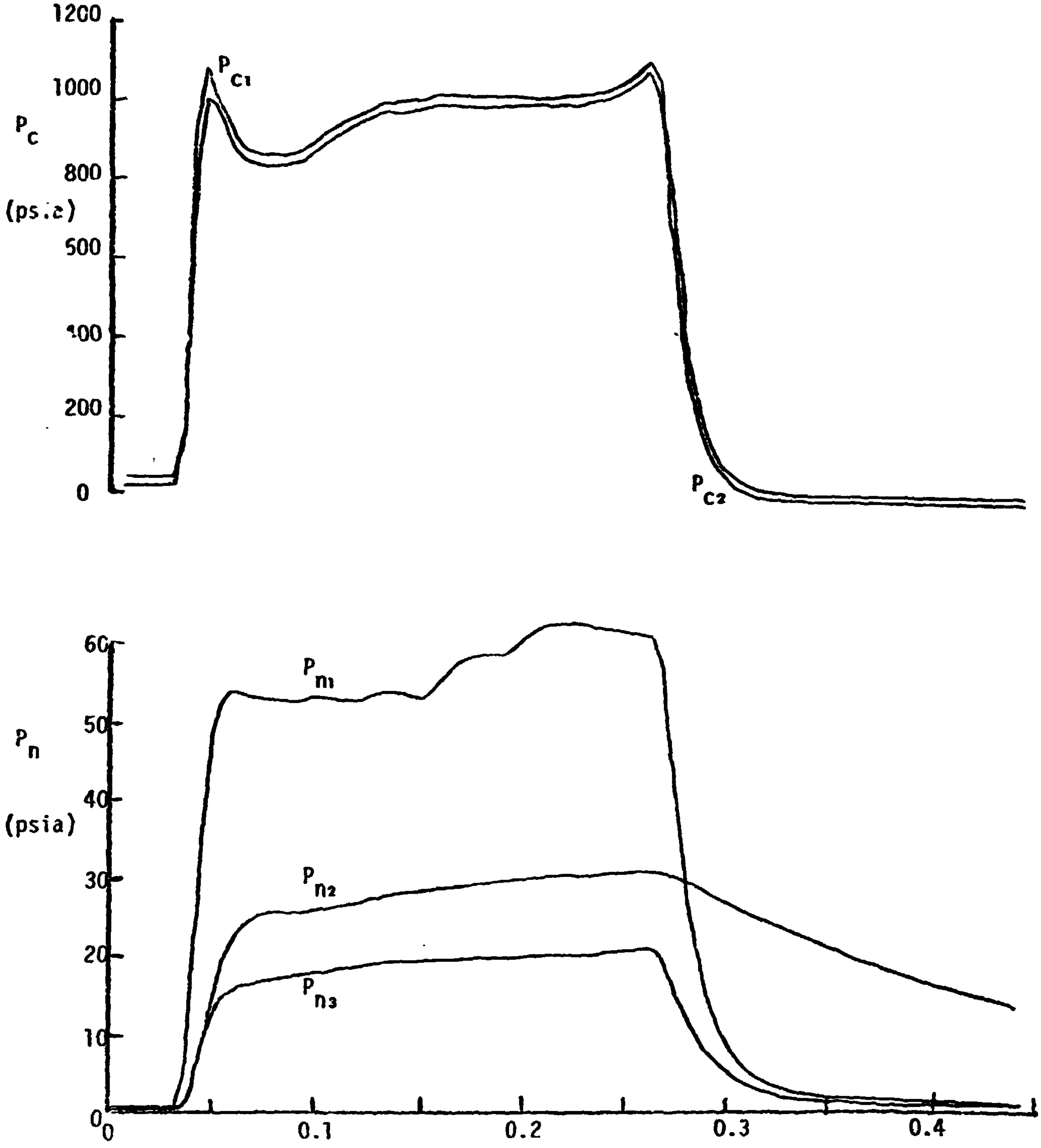
Plate @ X/D=20
ψ = 30°

Alt.=100,000'
%Aℓ = 15





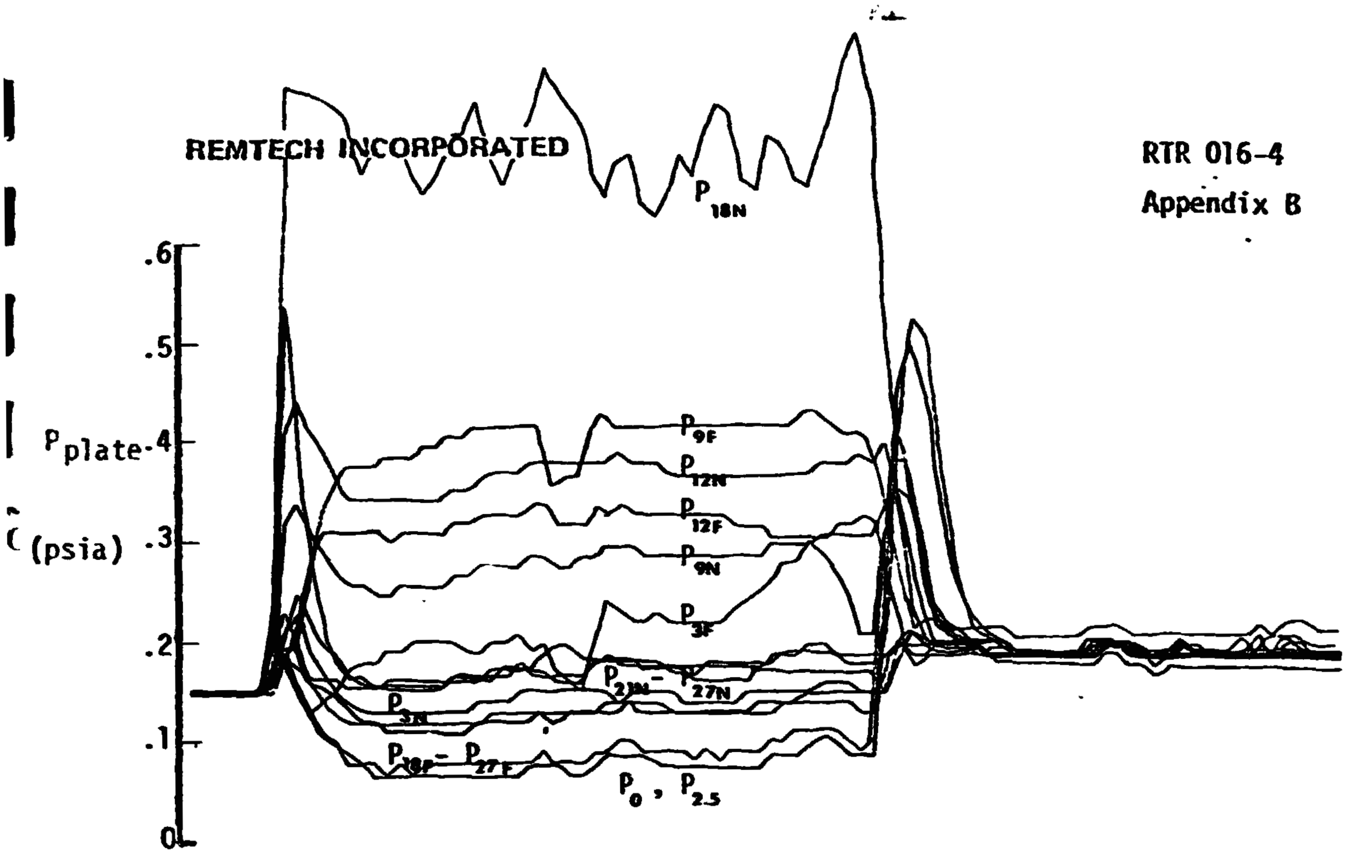
Run No. 16/1 (Concluded)

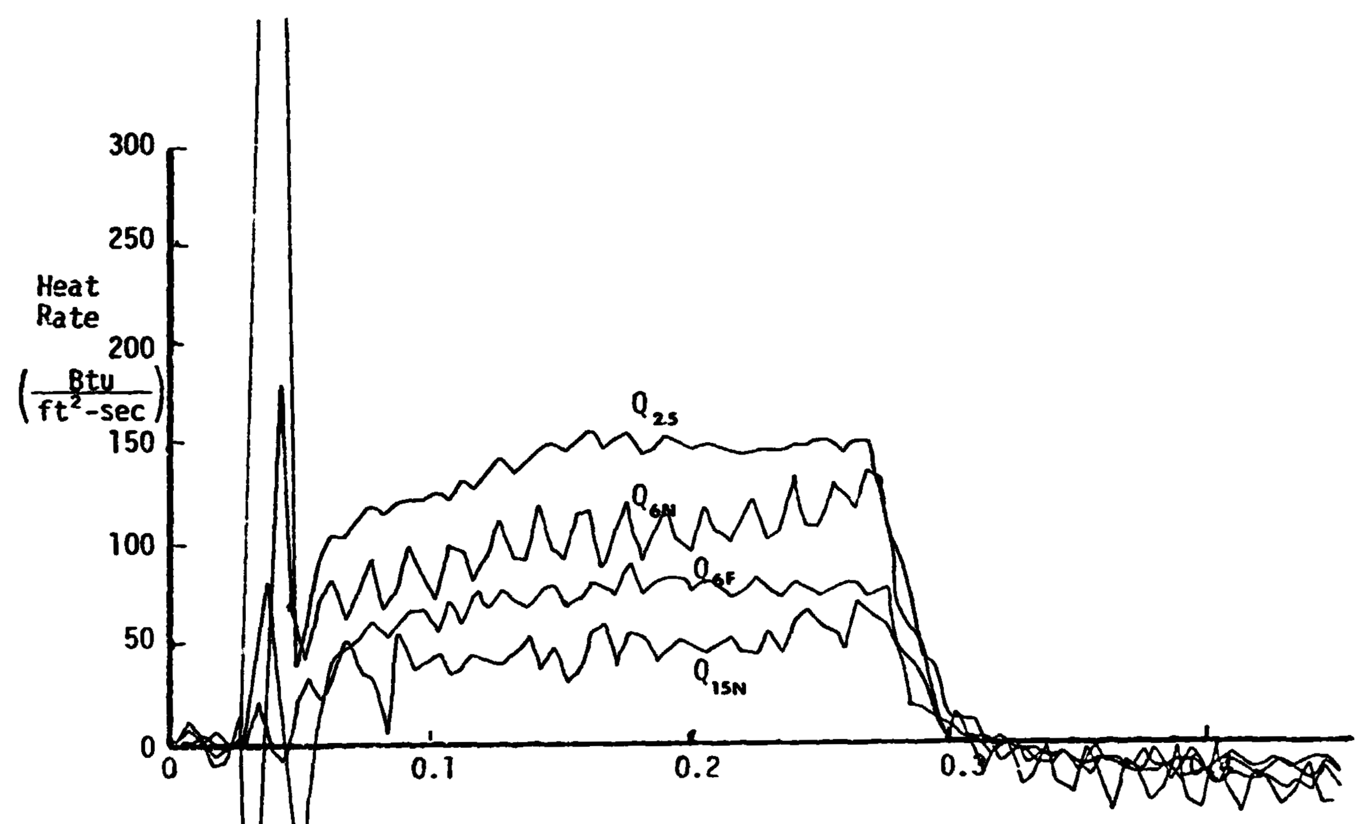


Run No. 16/2

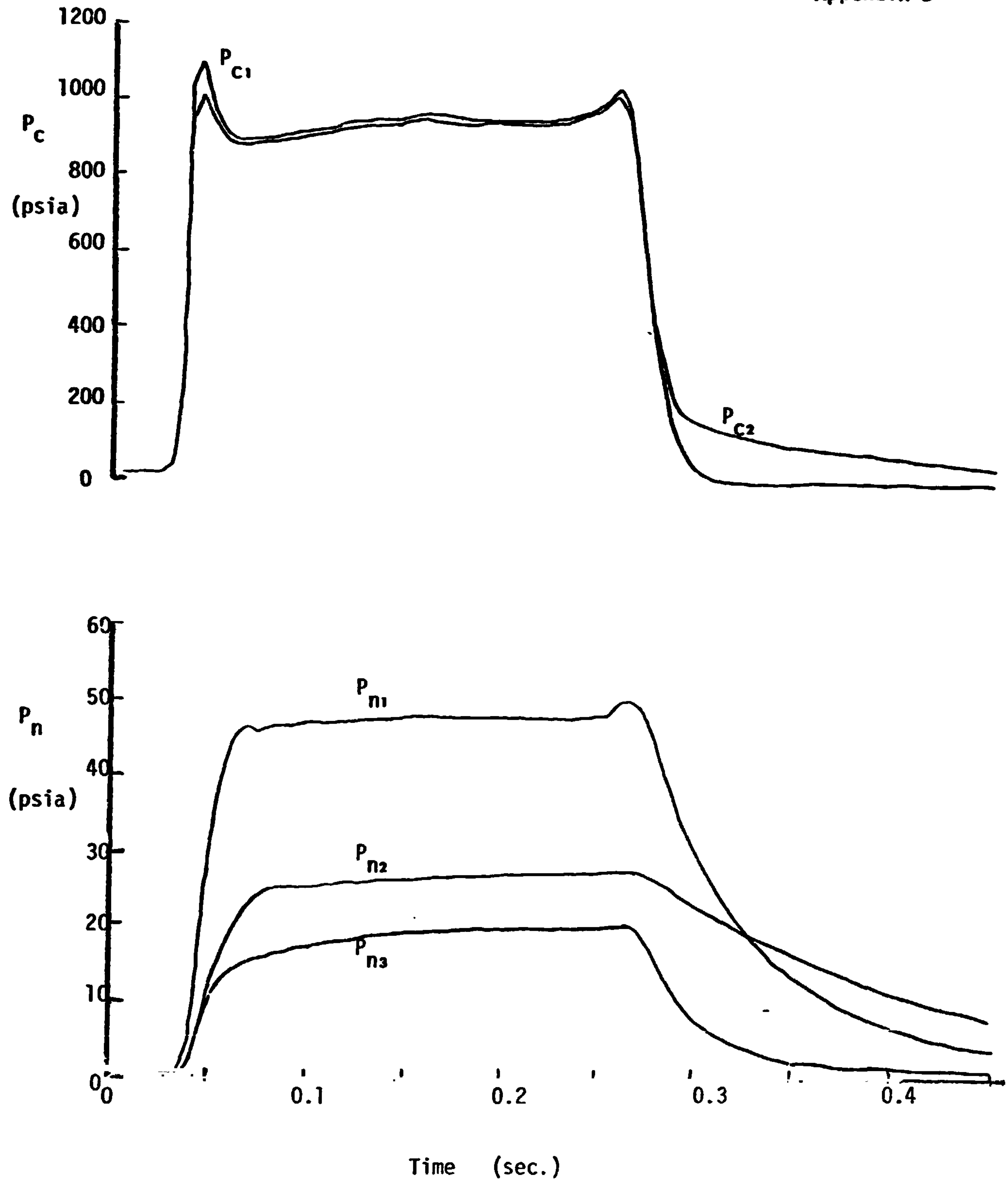
Plate @ X/D=20
ψ = 30°

Alt.=100,000'
%Aℓ = 15





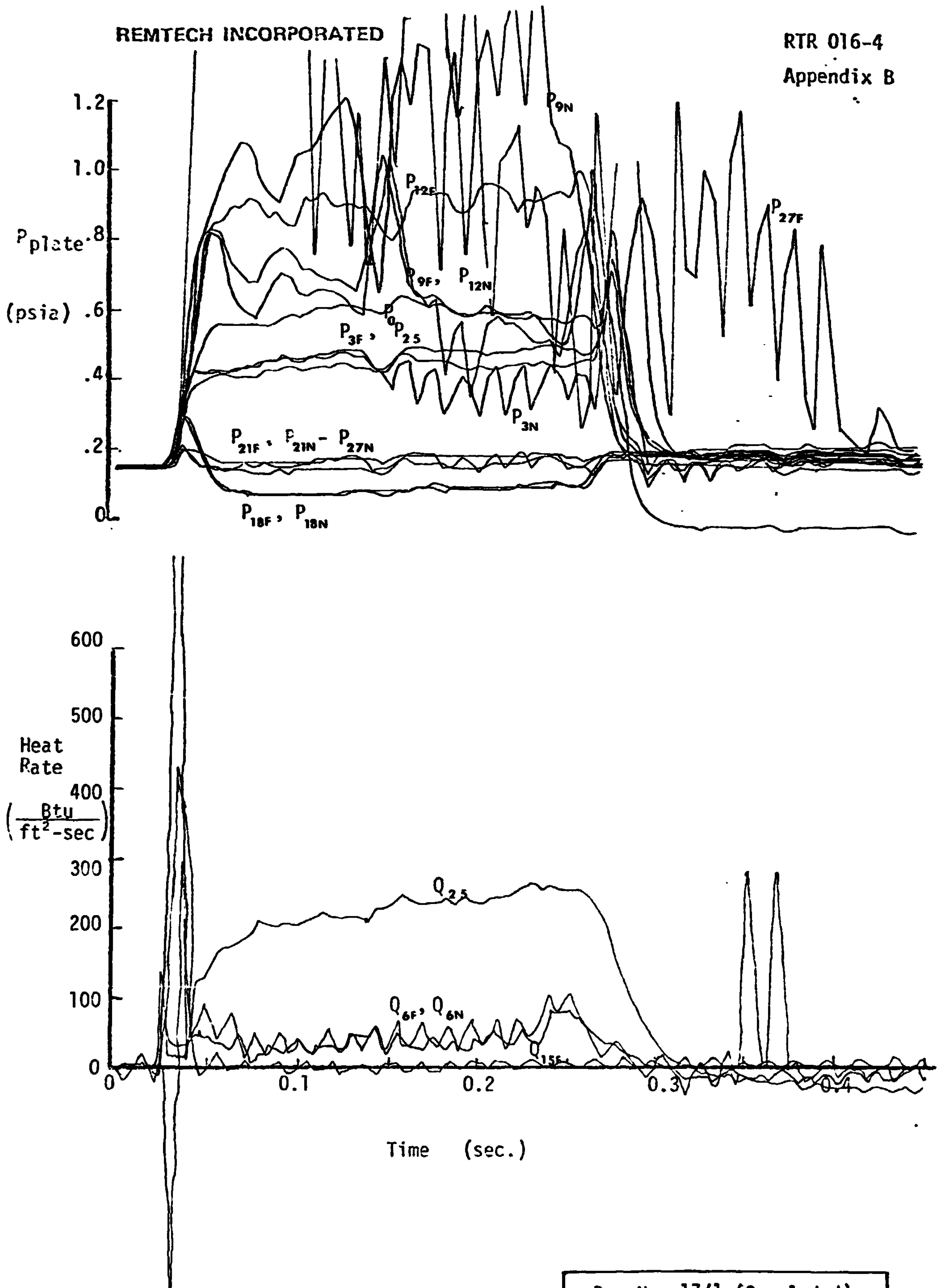
Run No. 16/2 (Concluded)



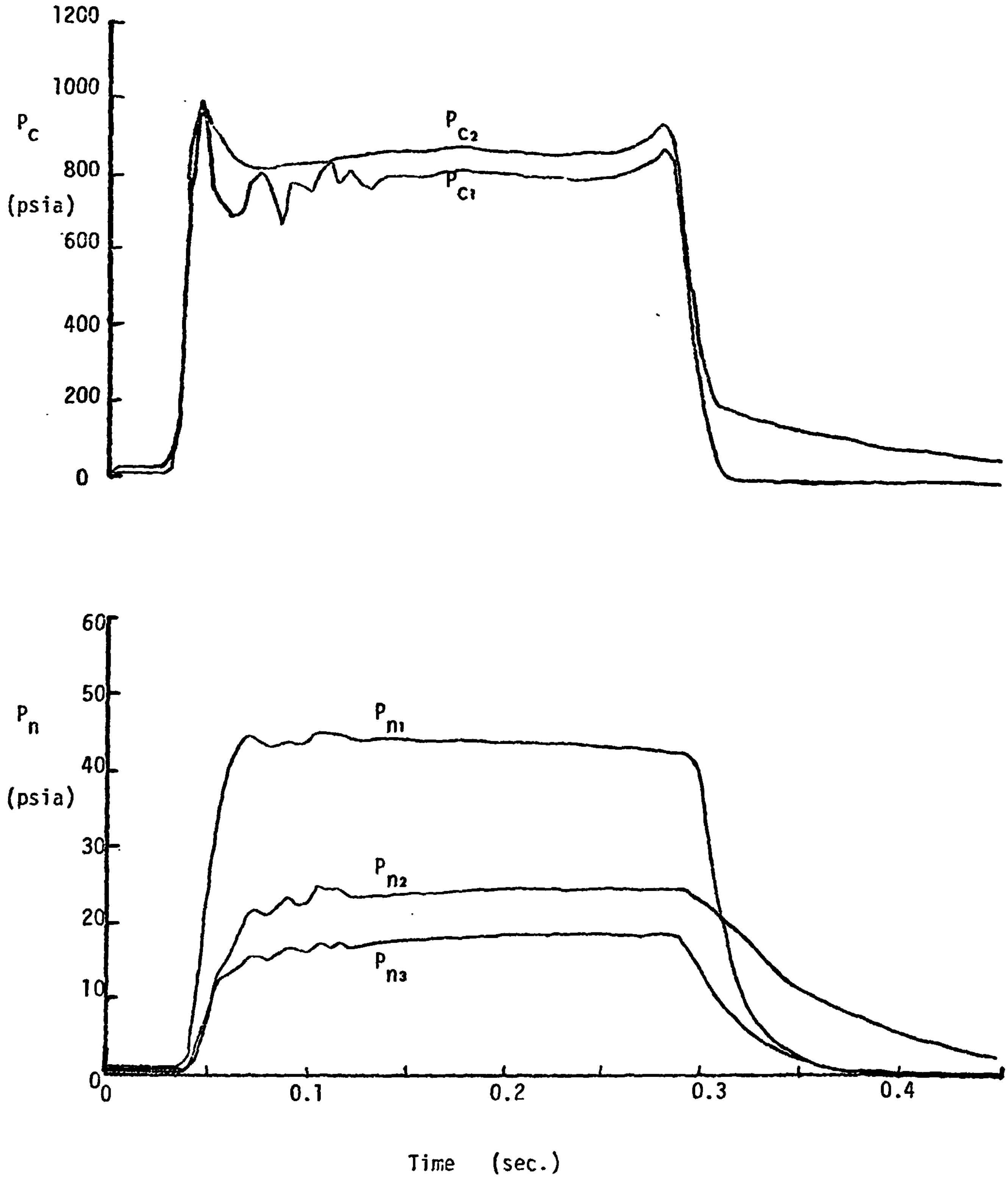
Run No. 17/1

Plate @ X/D=20
ψ = 90°

Alt.=100,000'
%Aℓ = 10



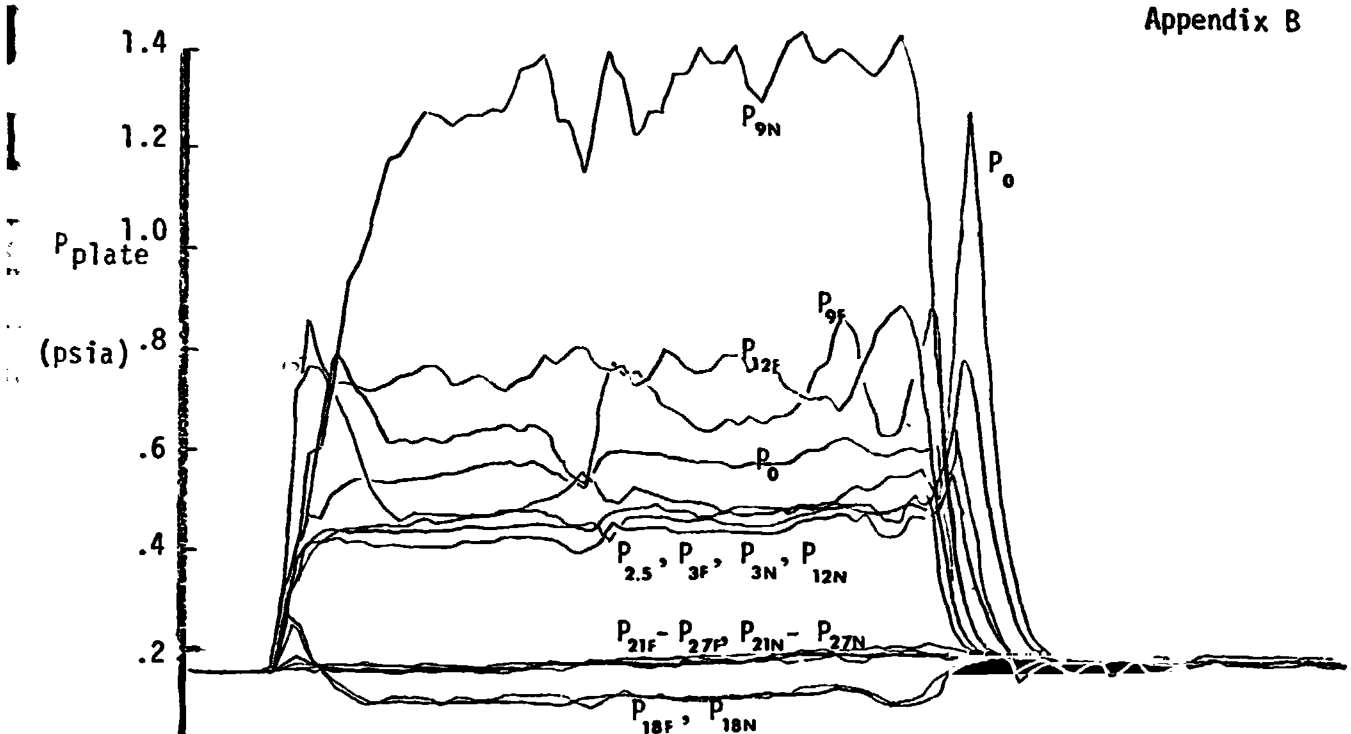
Run No. 17/1 (Concluded)

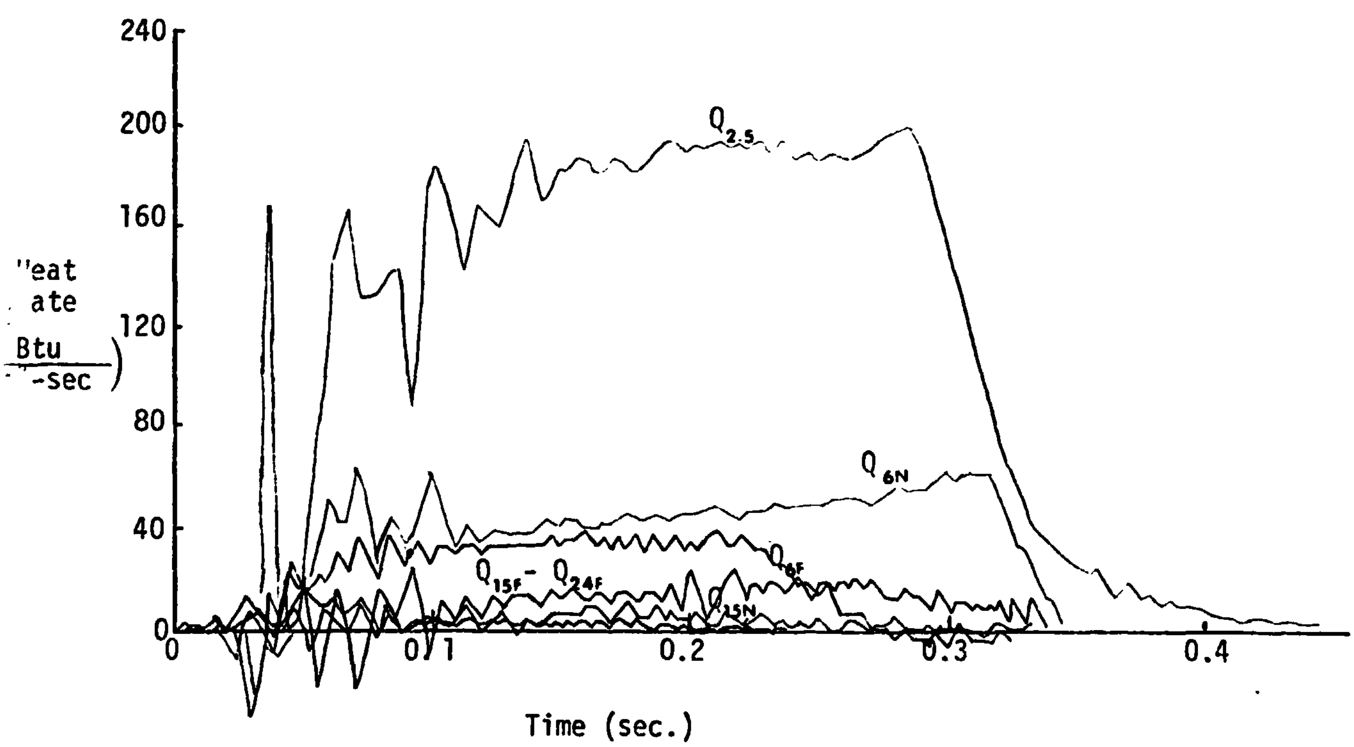


Run No. 17/2

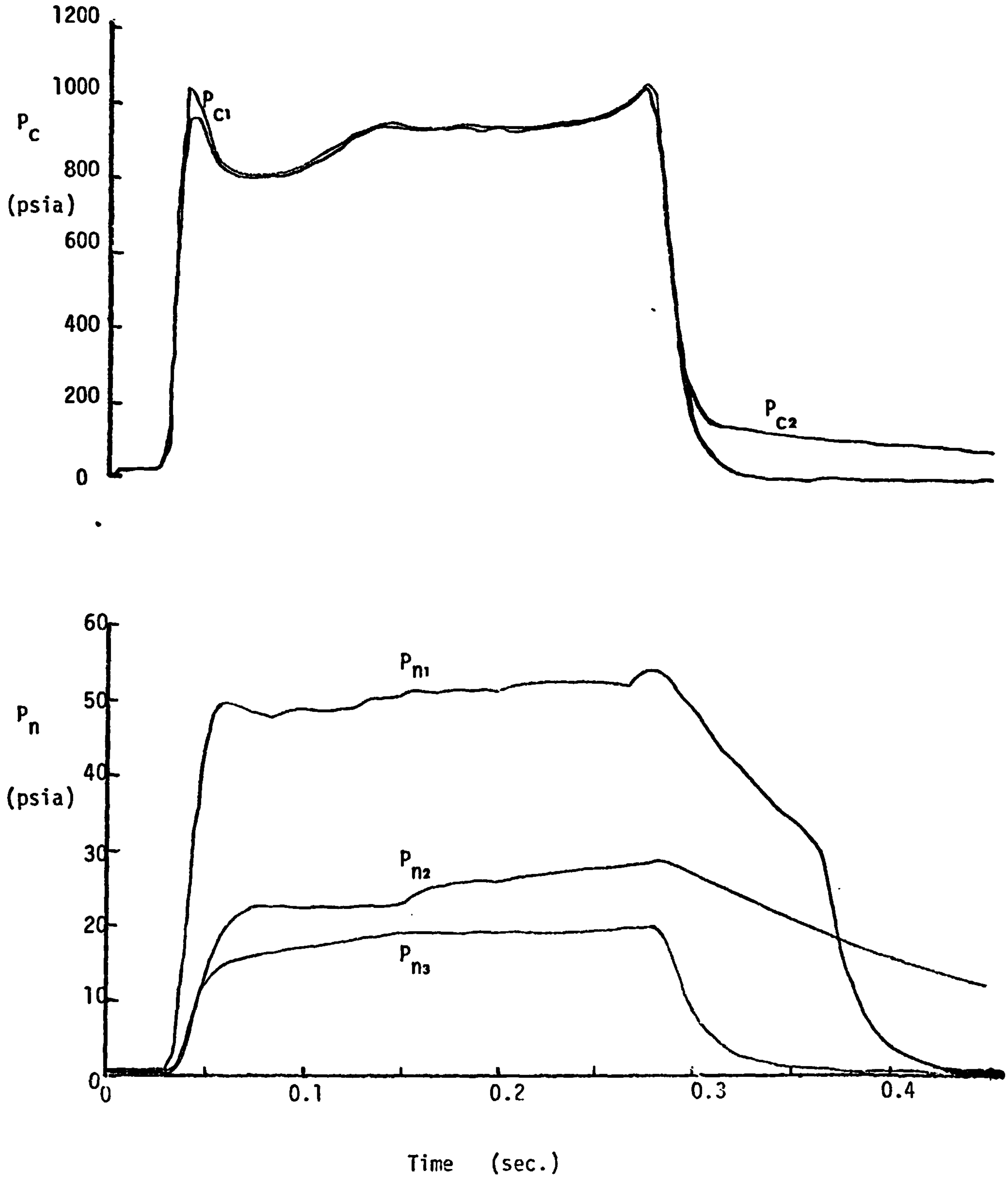
Plate @ X/D=20
ψ = 90°

Alt.=100,000'
%Aℓ = 10





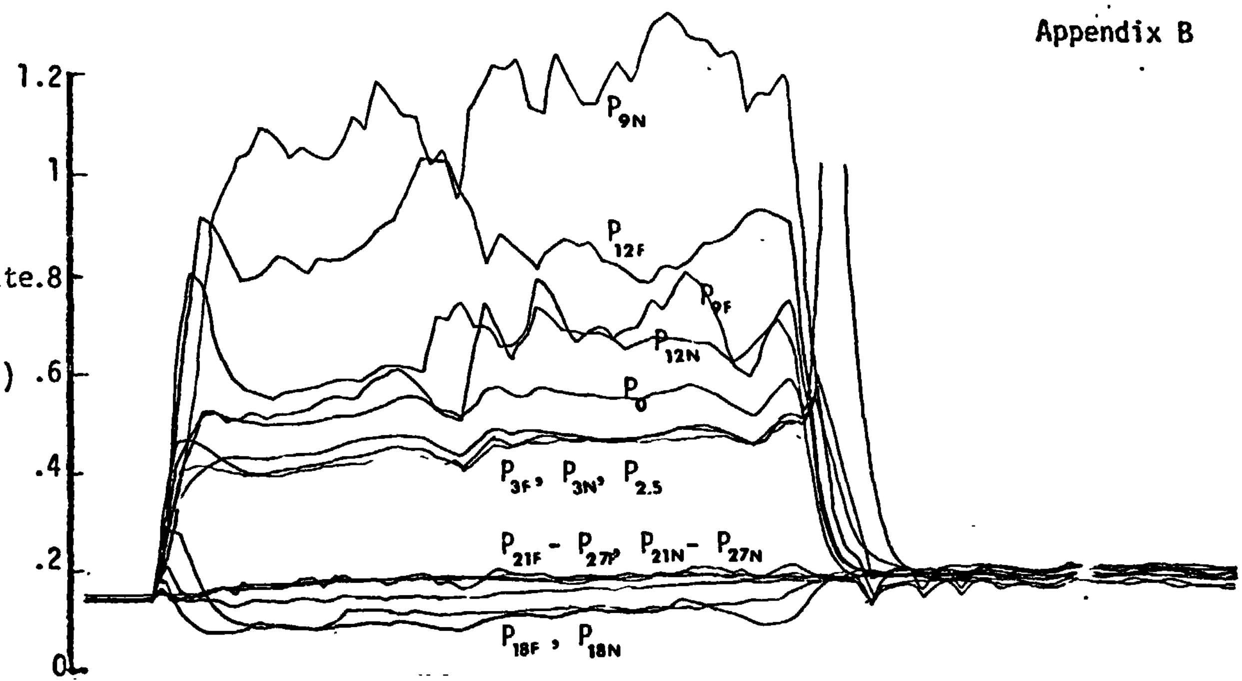
Run No. 17/2 (Concluded)

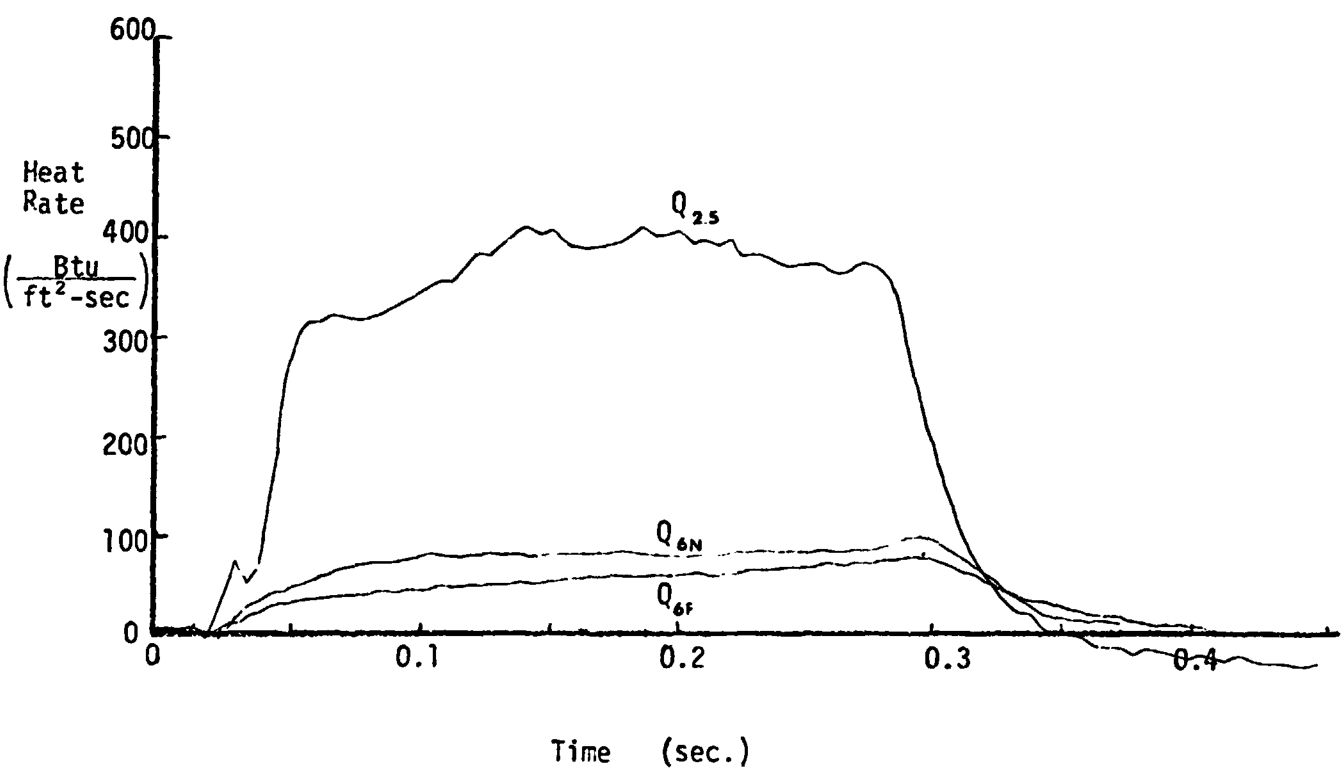


Run No. 18/1

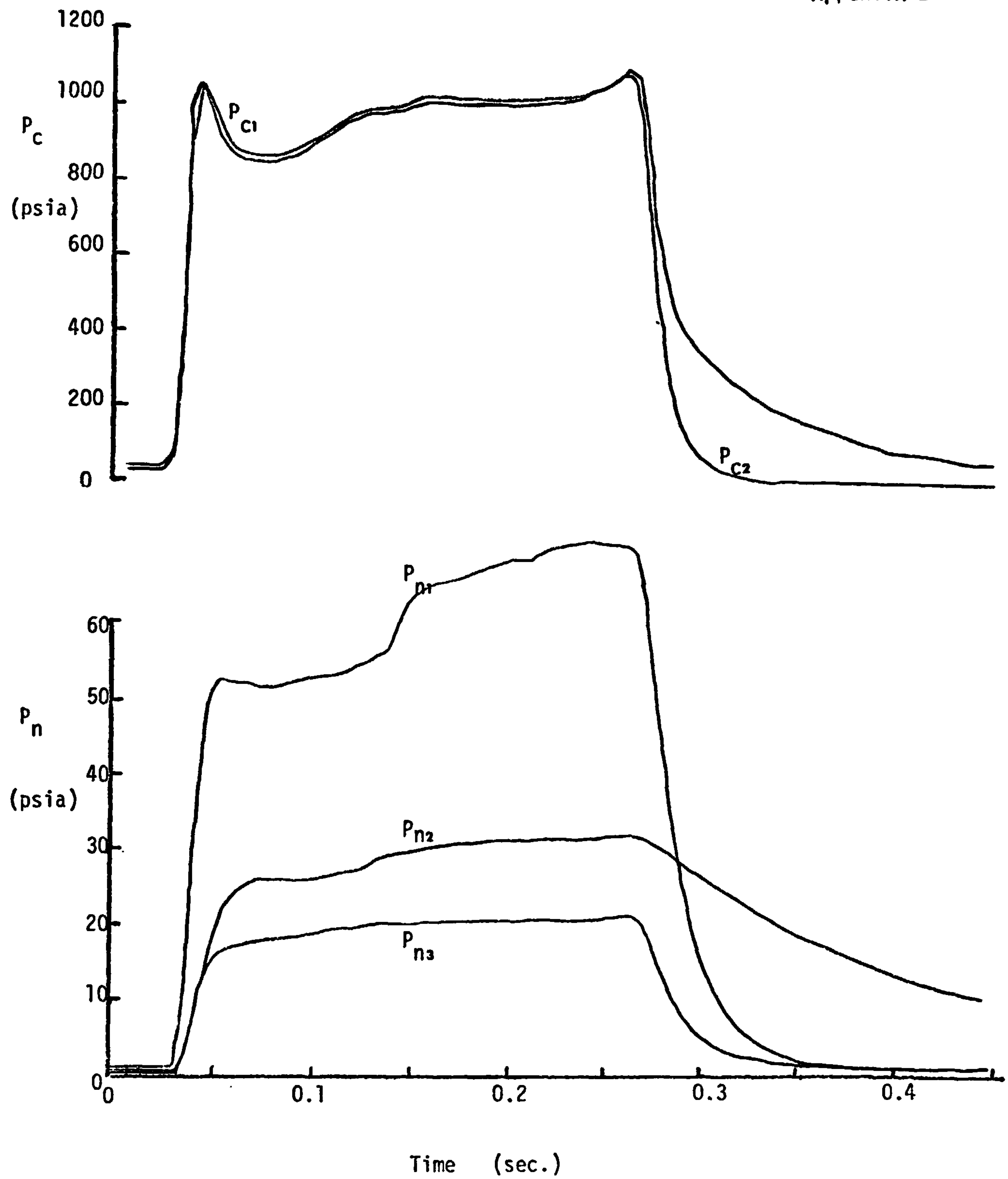
Plate @ X/D=20
ψ = 90°

Alt.=100,000'
%Aℓ = 15





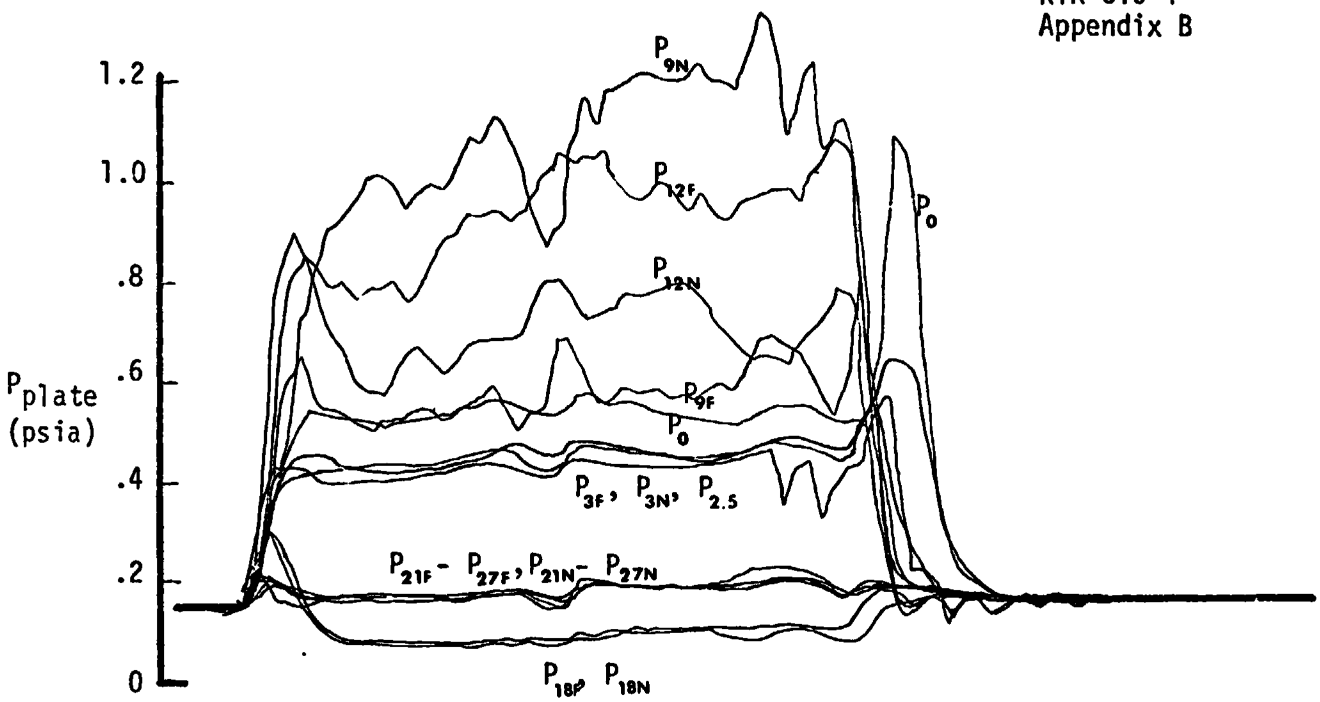
Run No. 18/1 (Concluded)



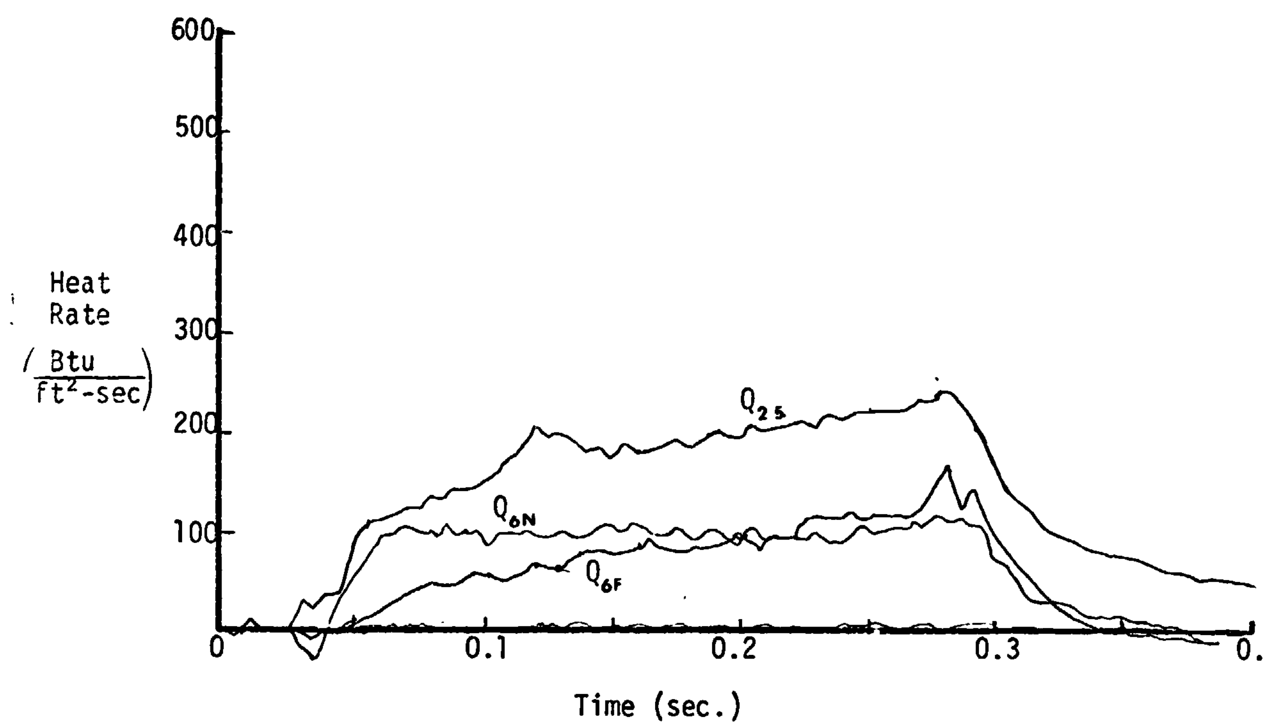
Run No. 18/2

Plate @ X/D=20
ψ = 90°

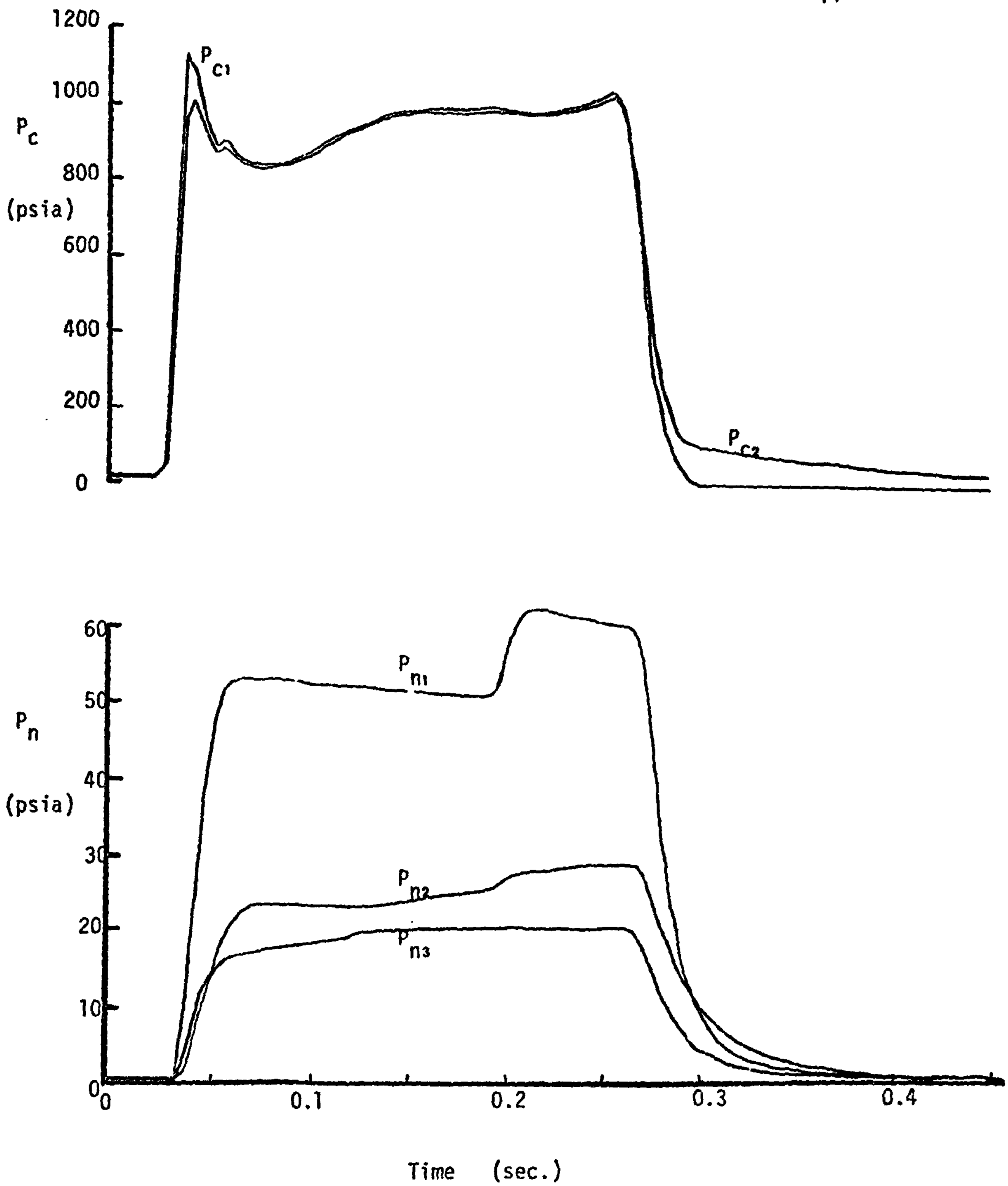
Alt.=100,000'
%Aℓ = 15



1.2
1.0
.8
.6
.4
.2
0
P plate (psia)
P9N
P12F
P0
P12N
P9F
P0
P3F, P3N, P2.5
P21F - P27F, P21N - P27N
P18F, P18N



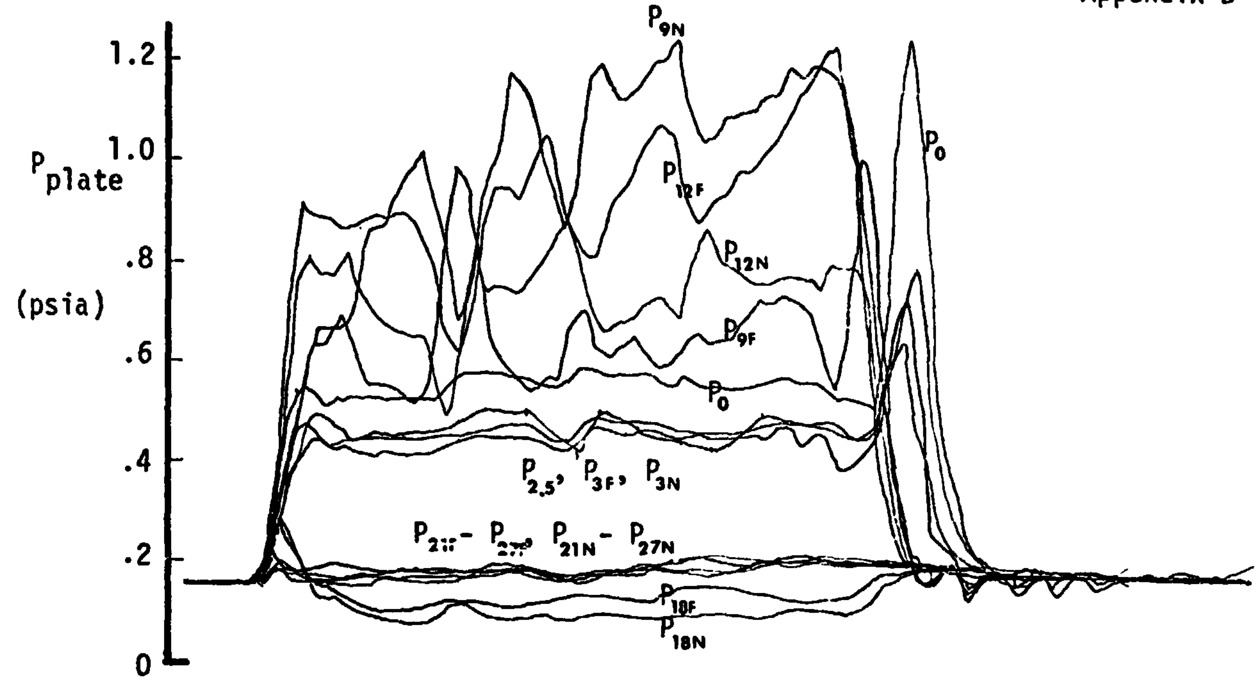
600
500
400
300
200
100
0
0.1
0.2
0.3
0.4
Heat Rate (Btu / ft2-sec)
Q25
Q6N
Q6F
Time (sec.)

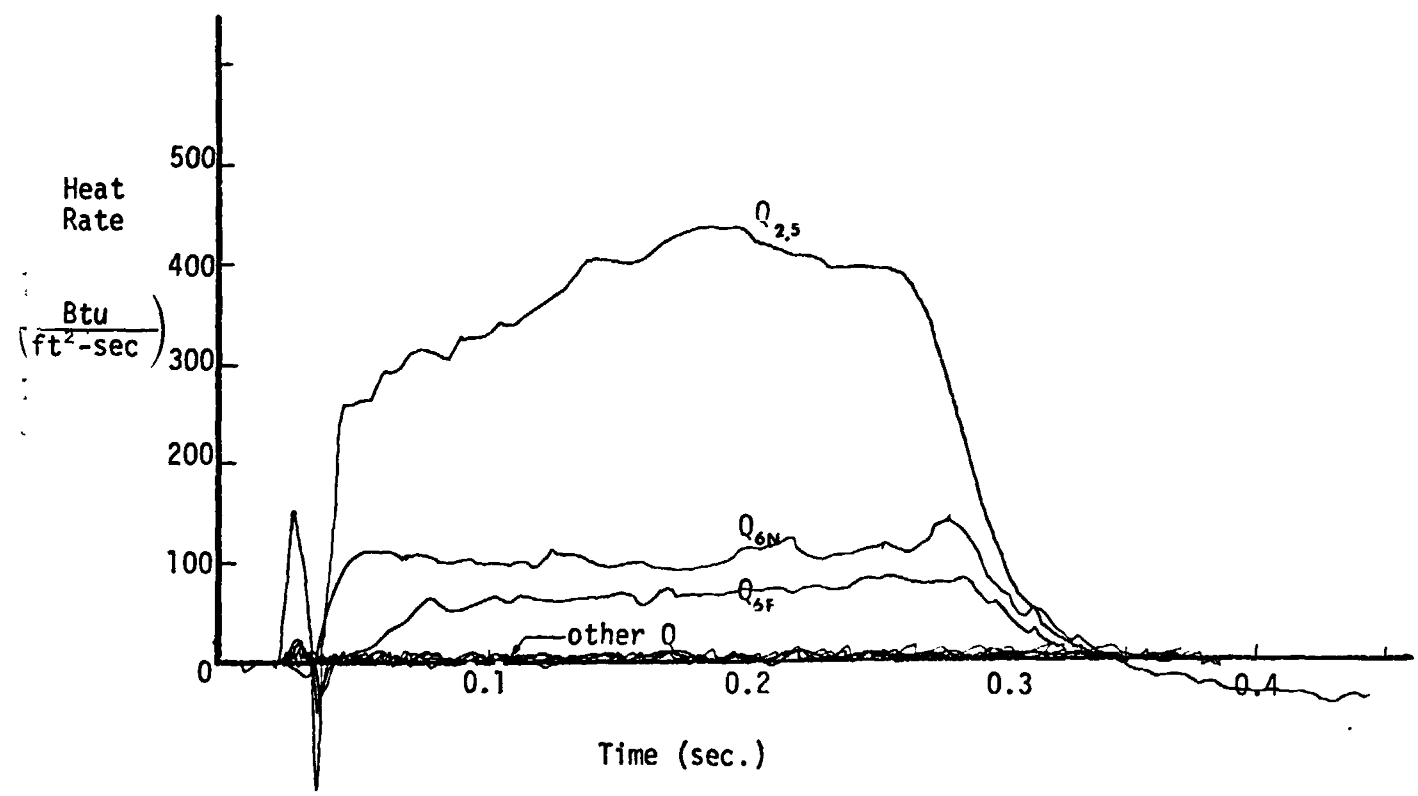


Run No. 18/3

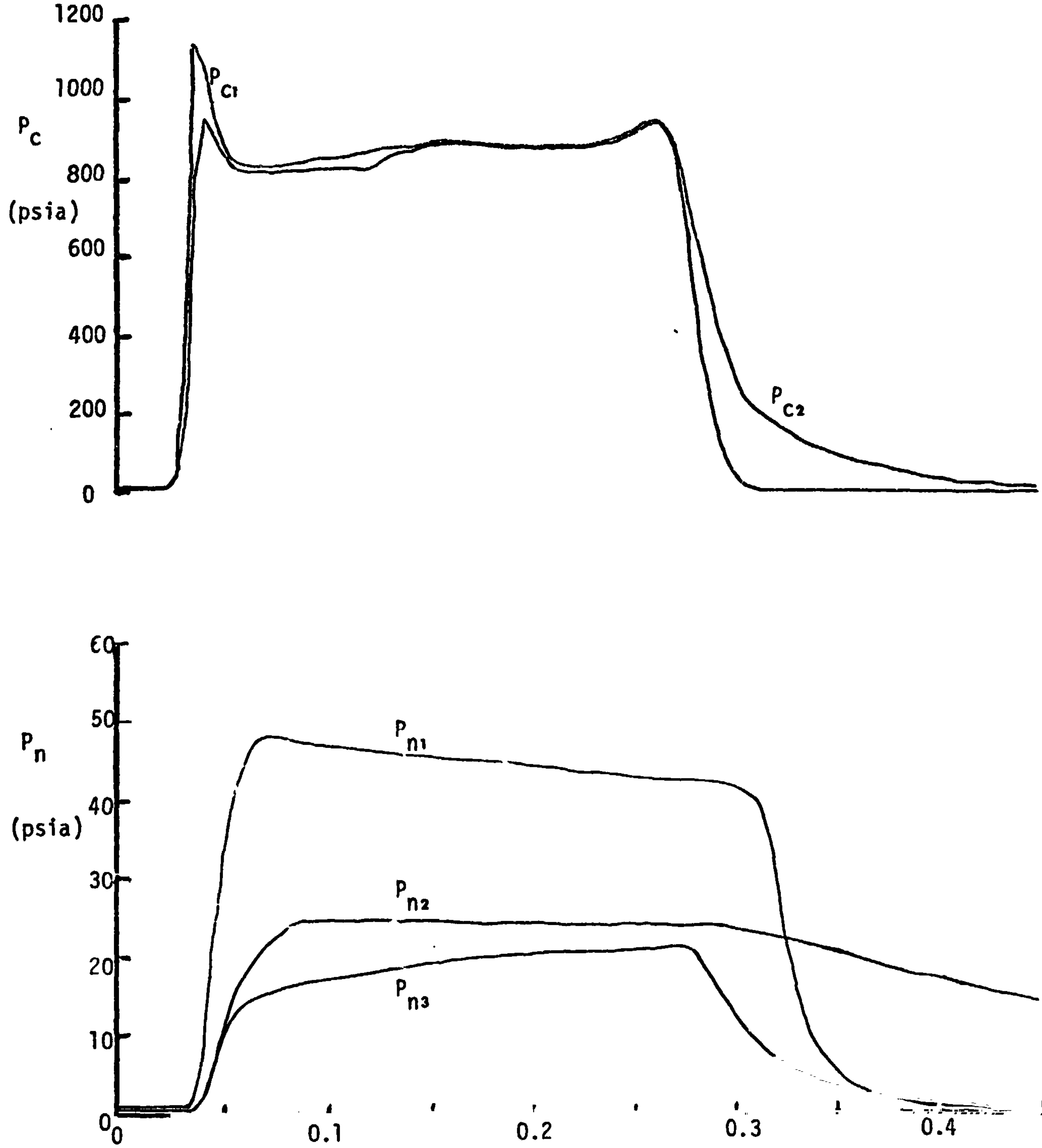
Plate @ X/D=20
ψ = 90°

Alt.=100,000'
%Aℓ = 15





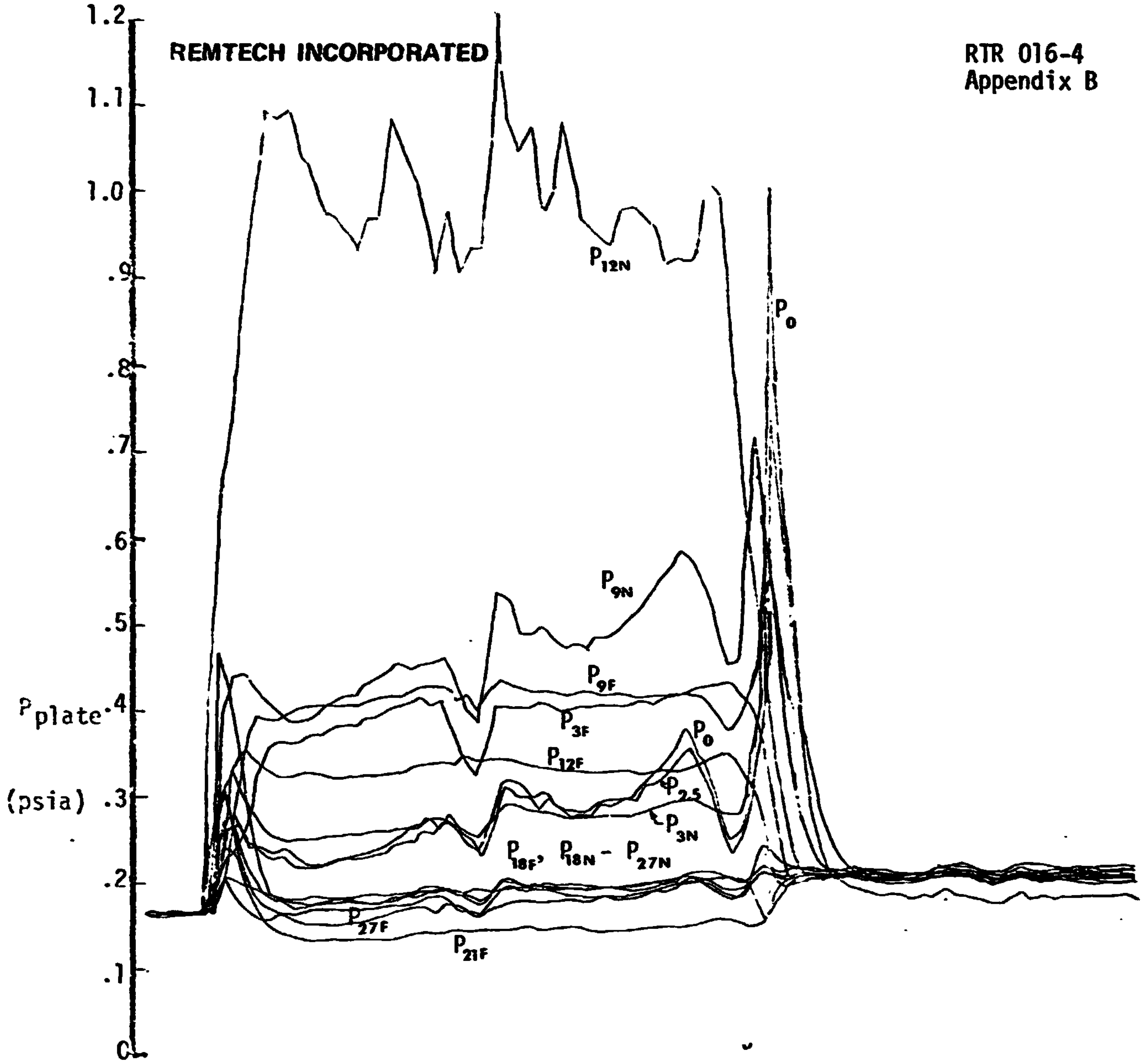
Run No. 18/3 (Concluded)

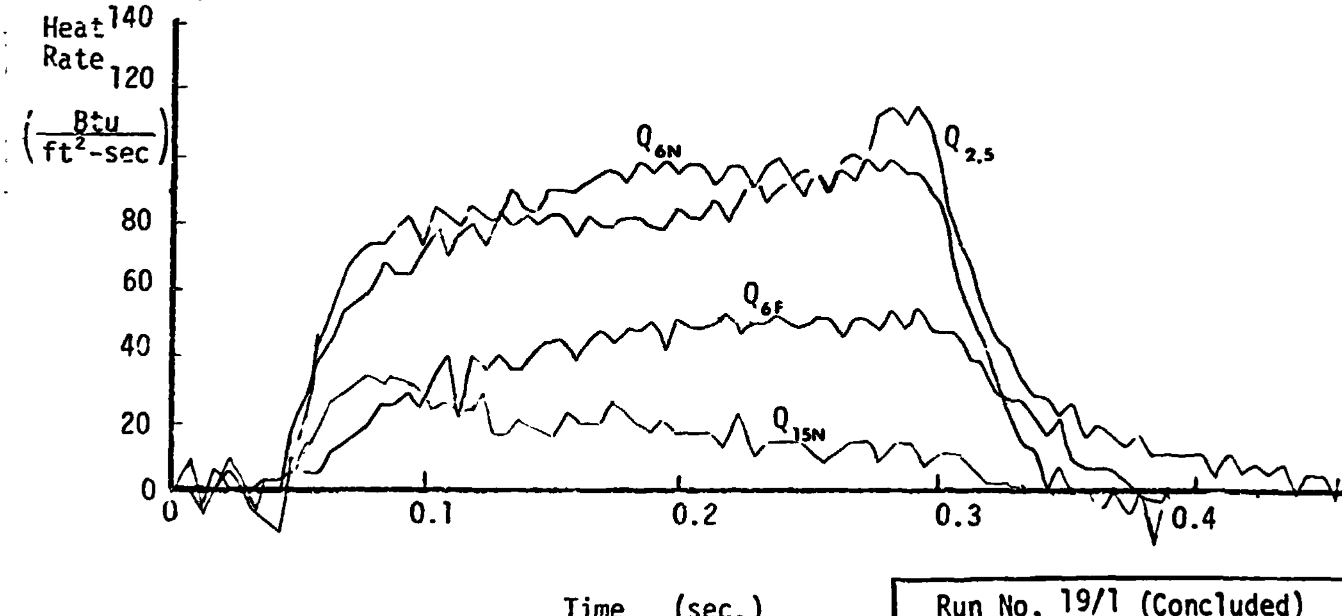


Run No. 19/1

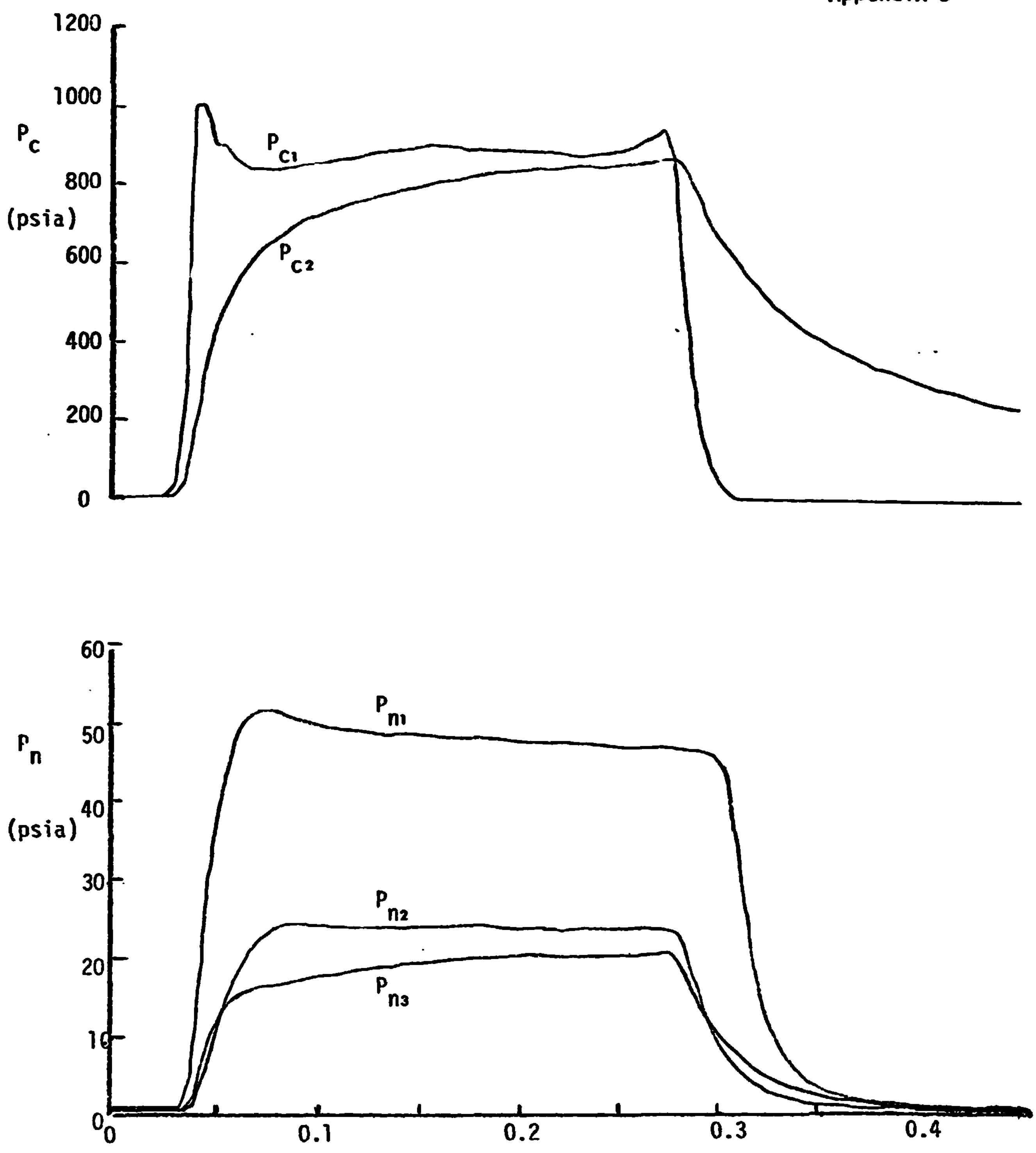
Plate @ X/D=20
ψ = 45°

Alt.=100,000'
%Aℓ = 10





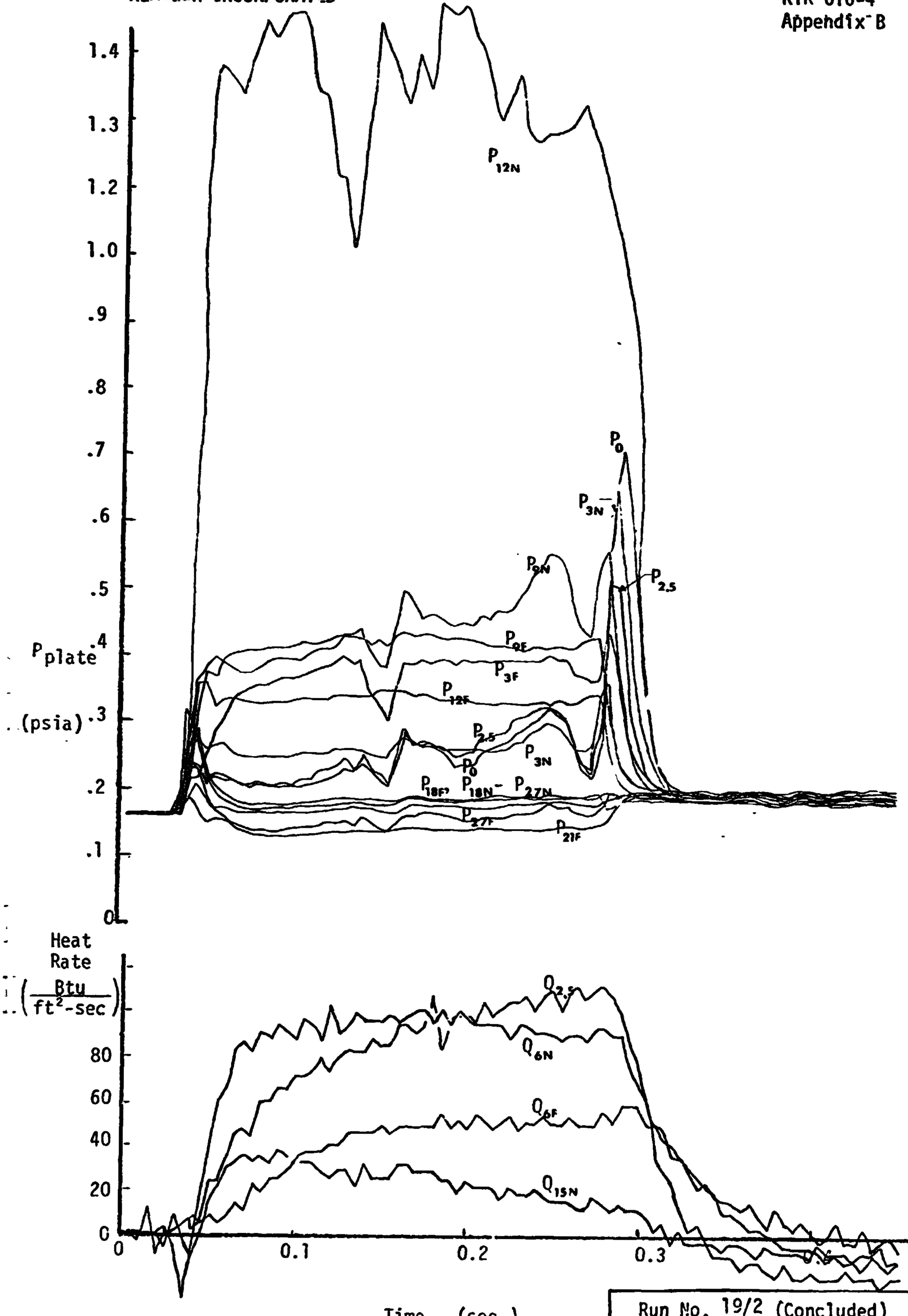
Run No. 19/1 (Concluded)



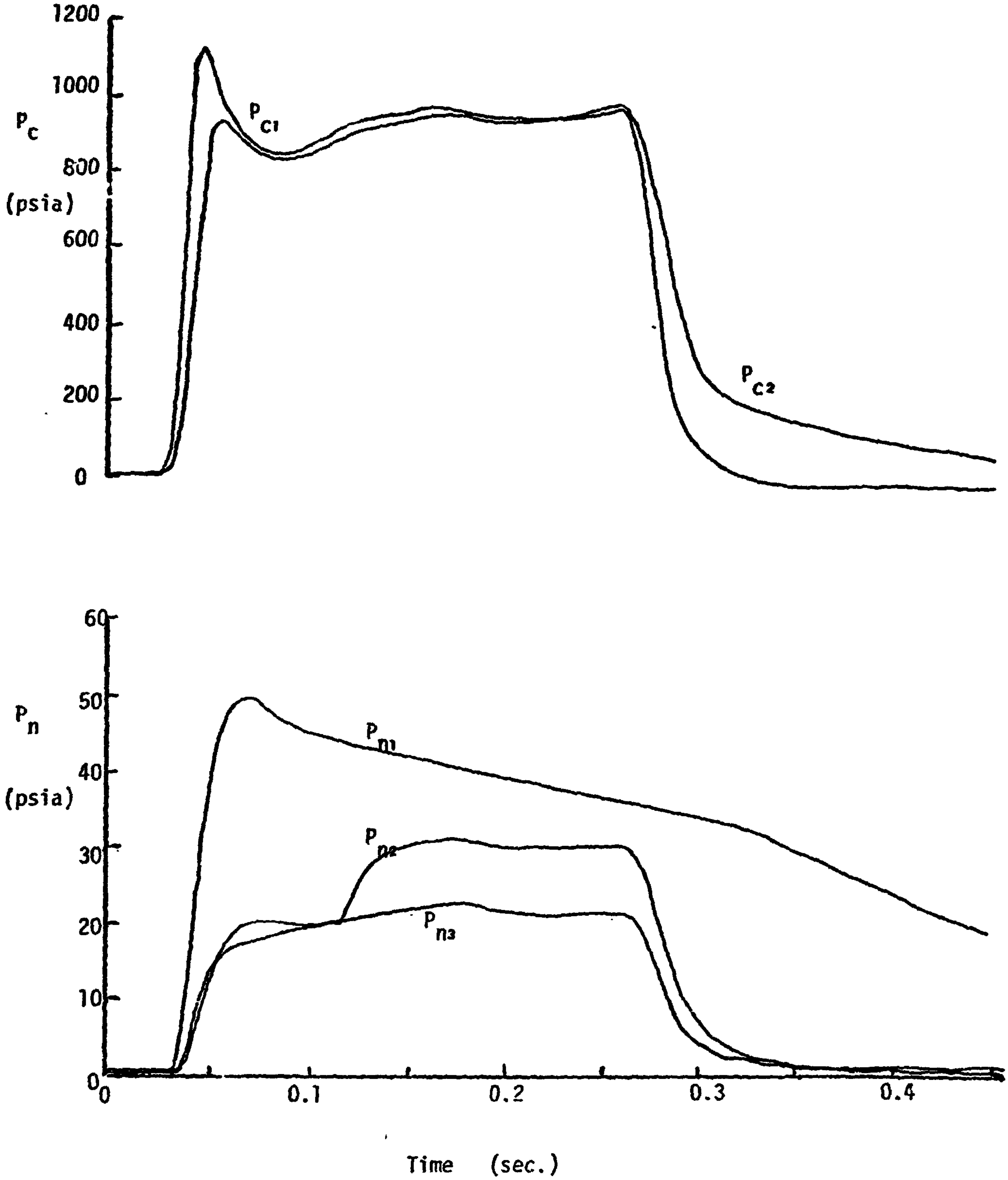
Run No. 19/2

Plate @ X/D=20
ψ = 45°

Alt.=100,000'
%Aℓ = 10



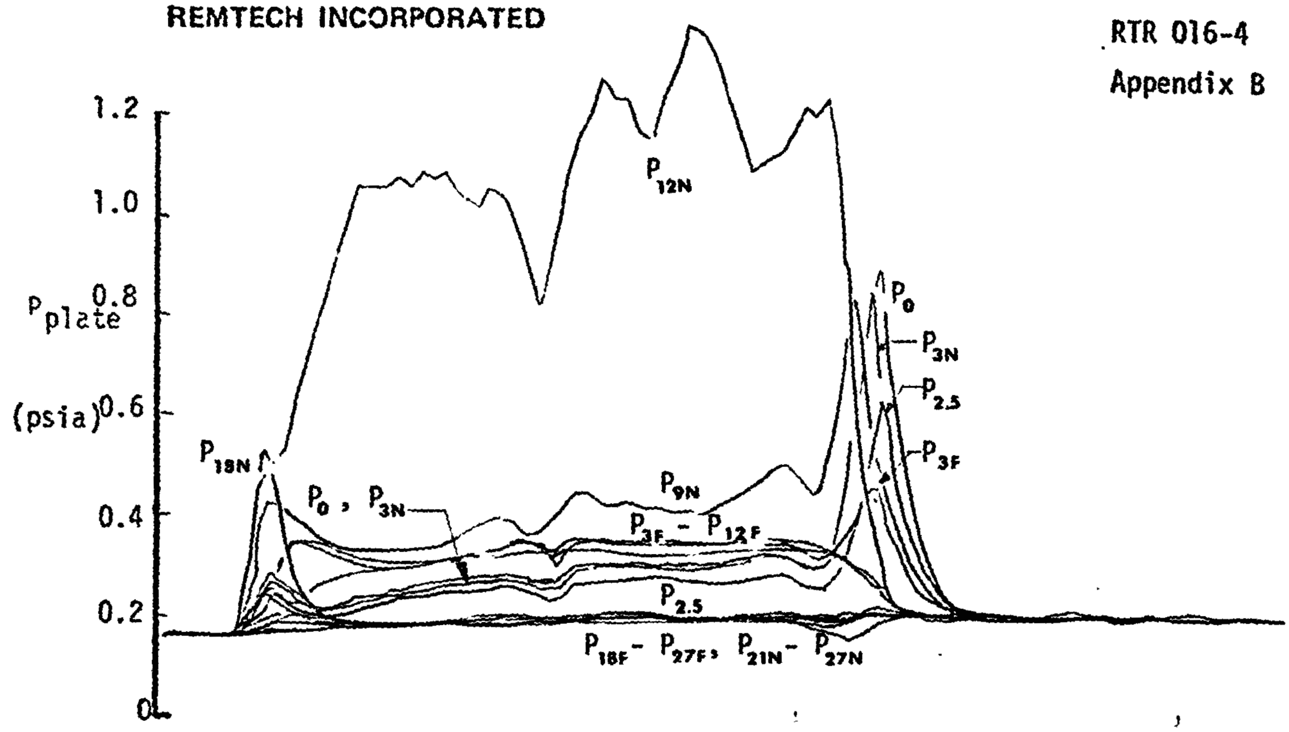
Run No. 19/2 (Concluded)

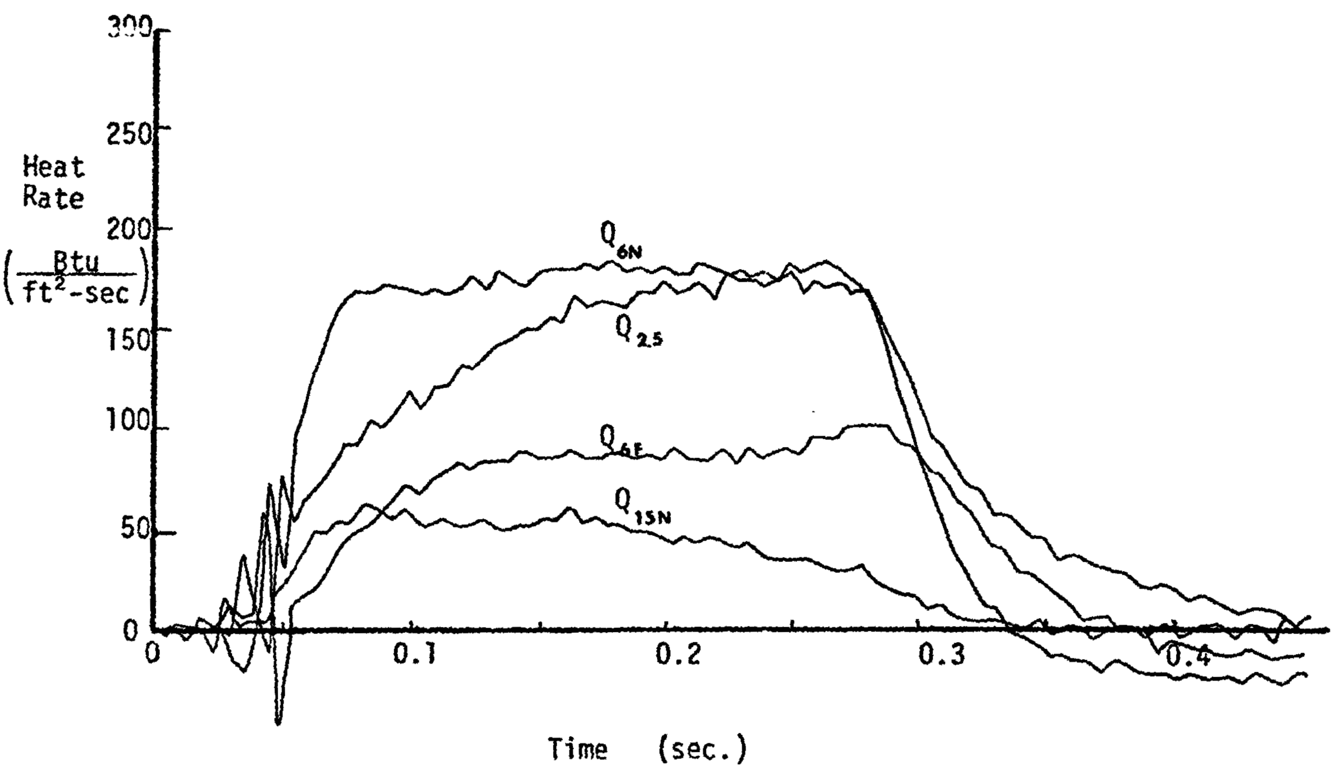


Run No. 20/1

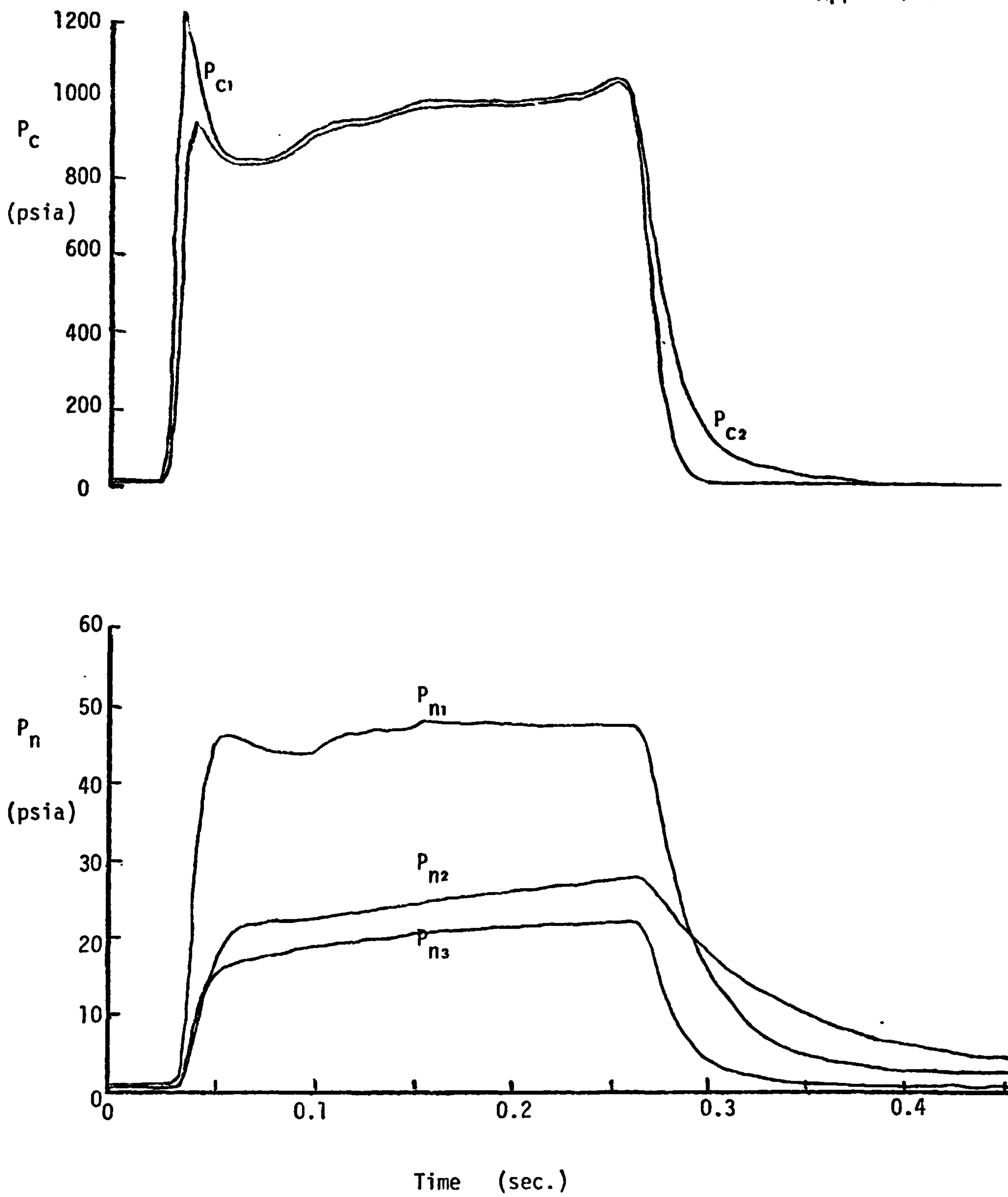
Plate @ X/D=20
ψ = 45°

Alt.=100,000'
%Aℓ = 15





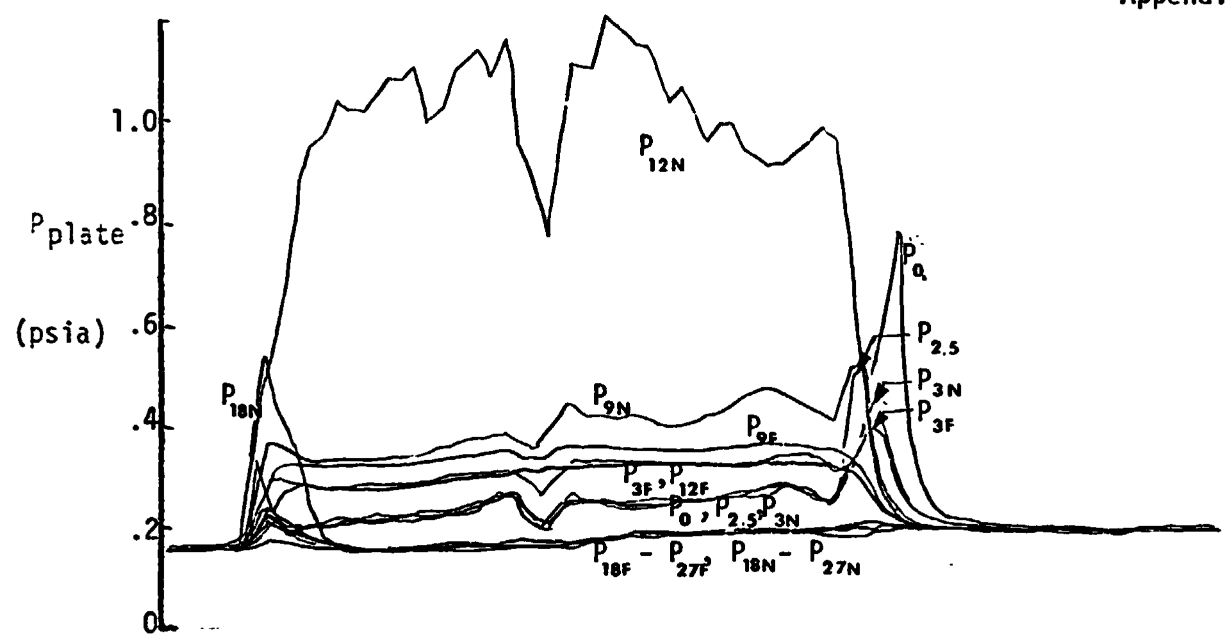
Run No. 20/1 (Concluded)

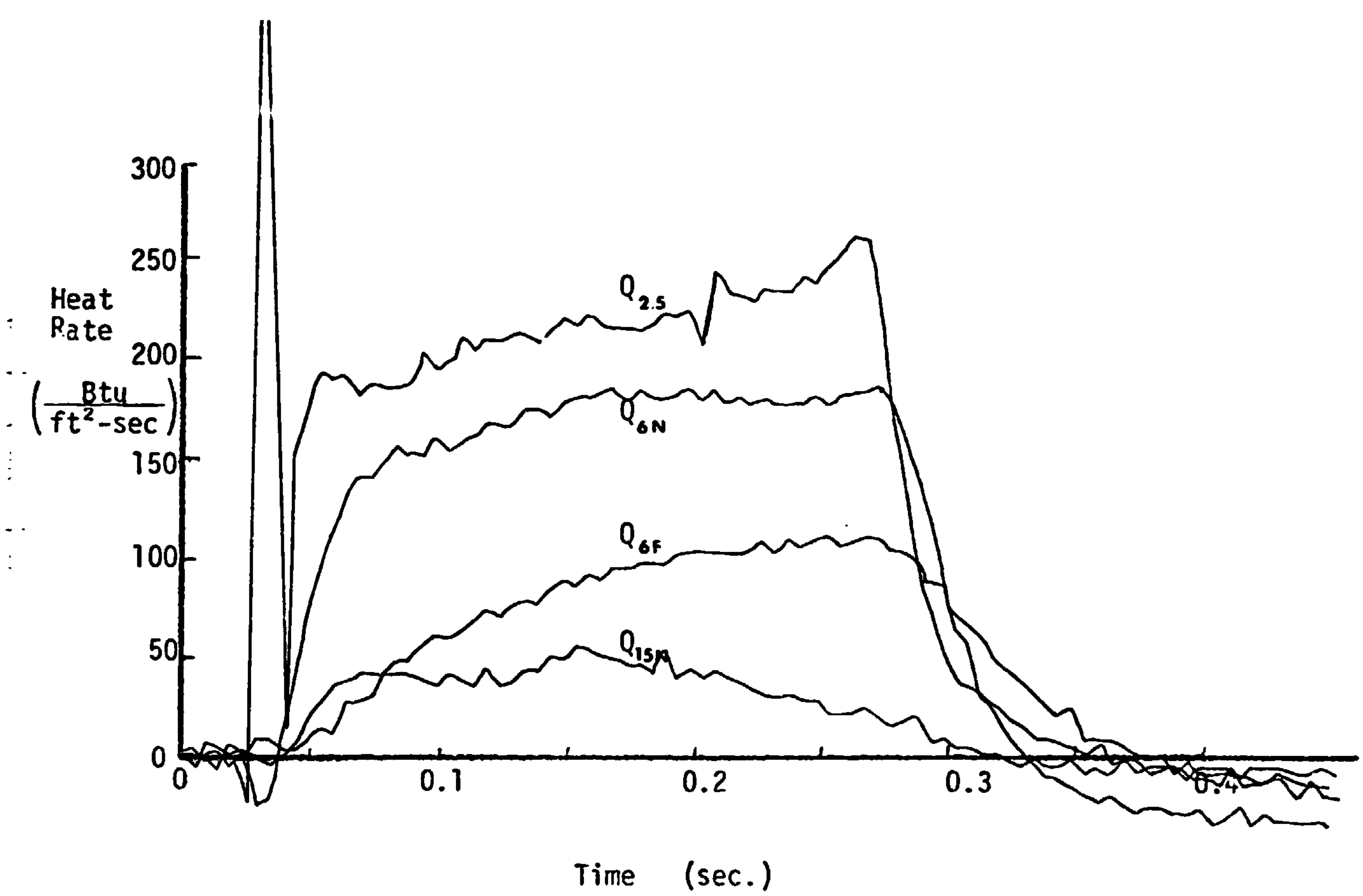


Run No. 20/2

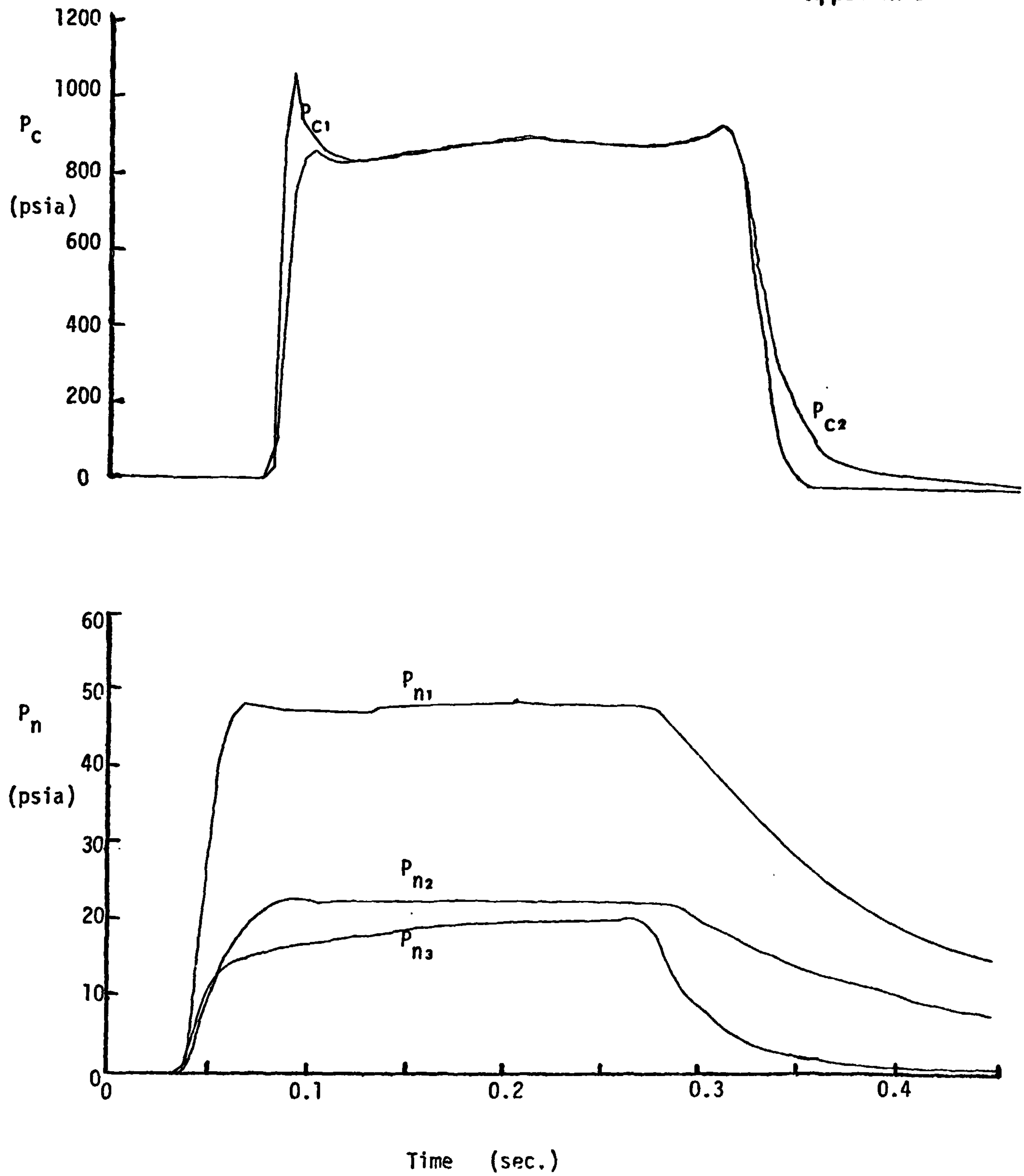
Plate @ X/D=20
ψ = 45°

Alt.=100,000'
%Aℓ = 15





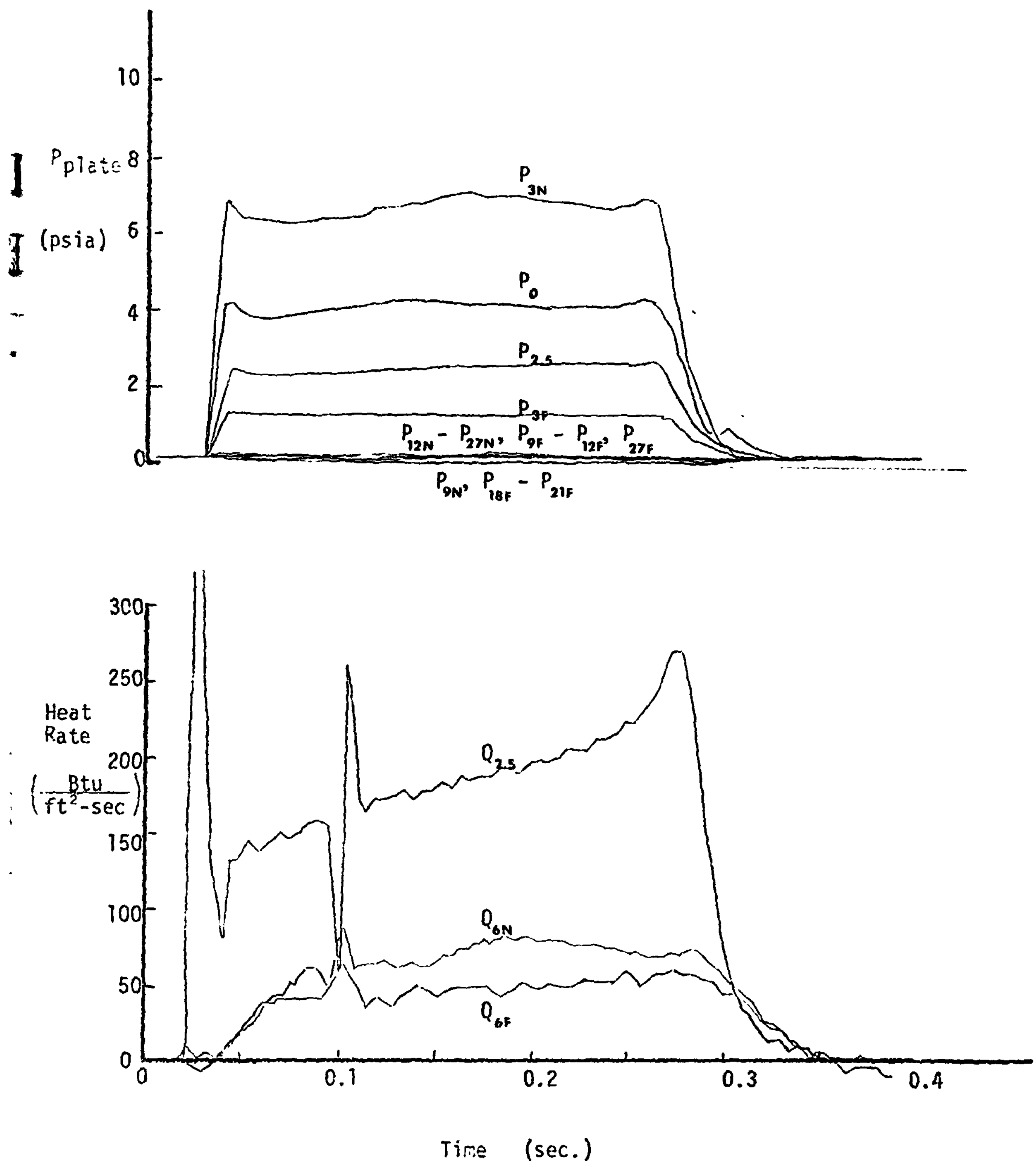
Run No. 20/2 (Concluded)



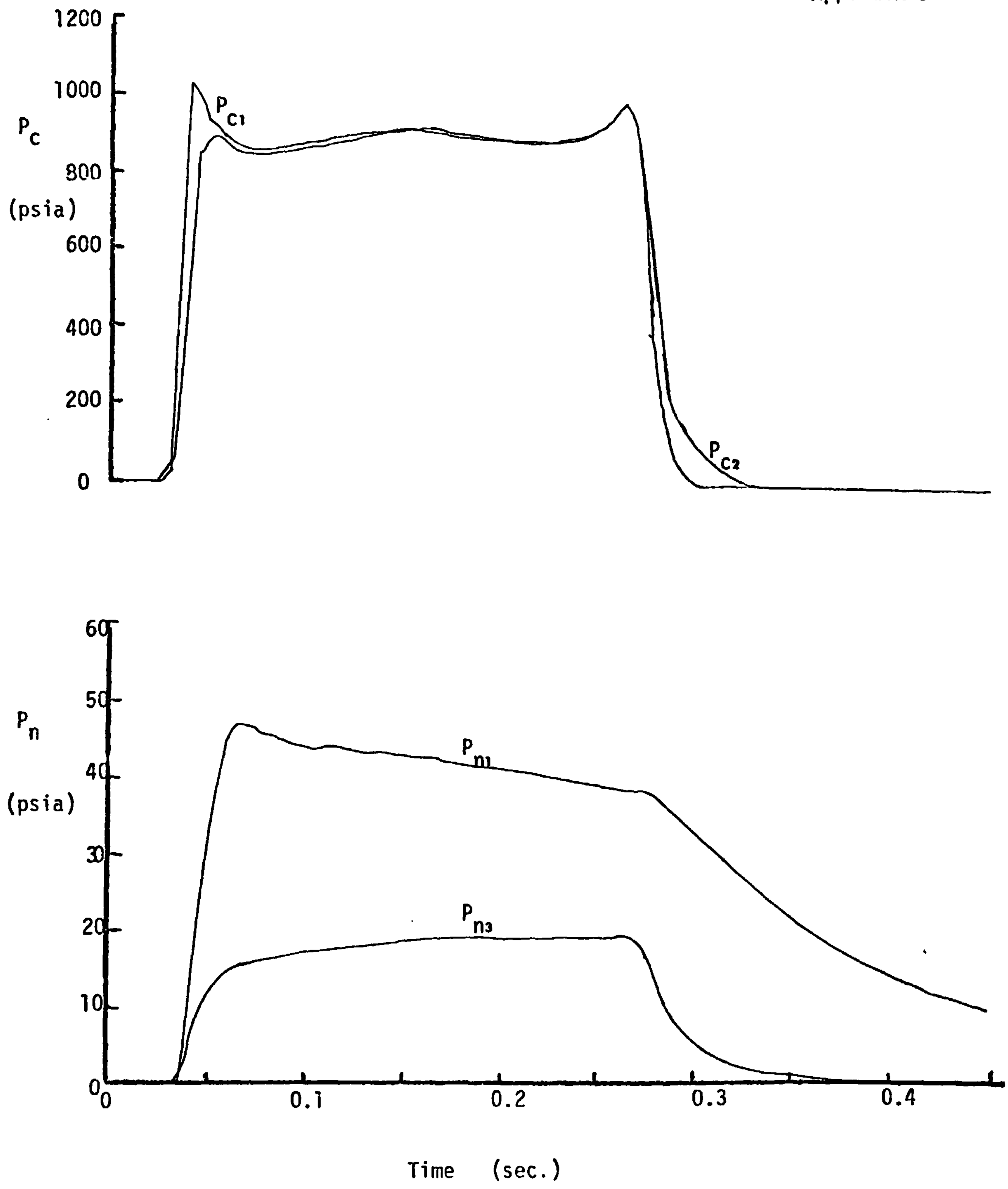
Run No. 21/1

Plate @ X/D=5
ψ = 45°

Alt.=100,000'
%Aℓ = 10



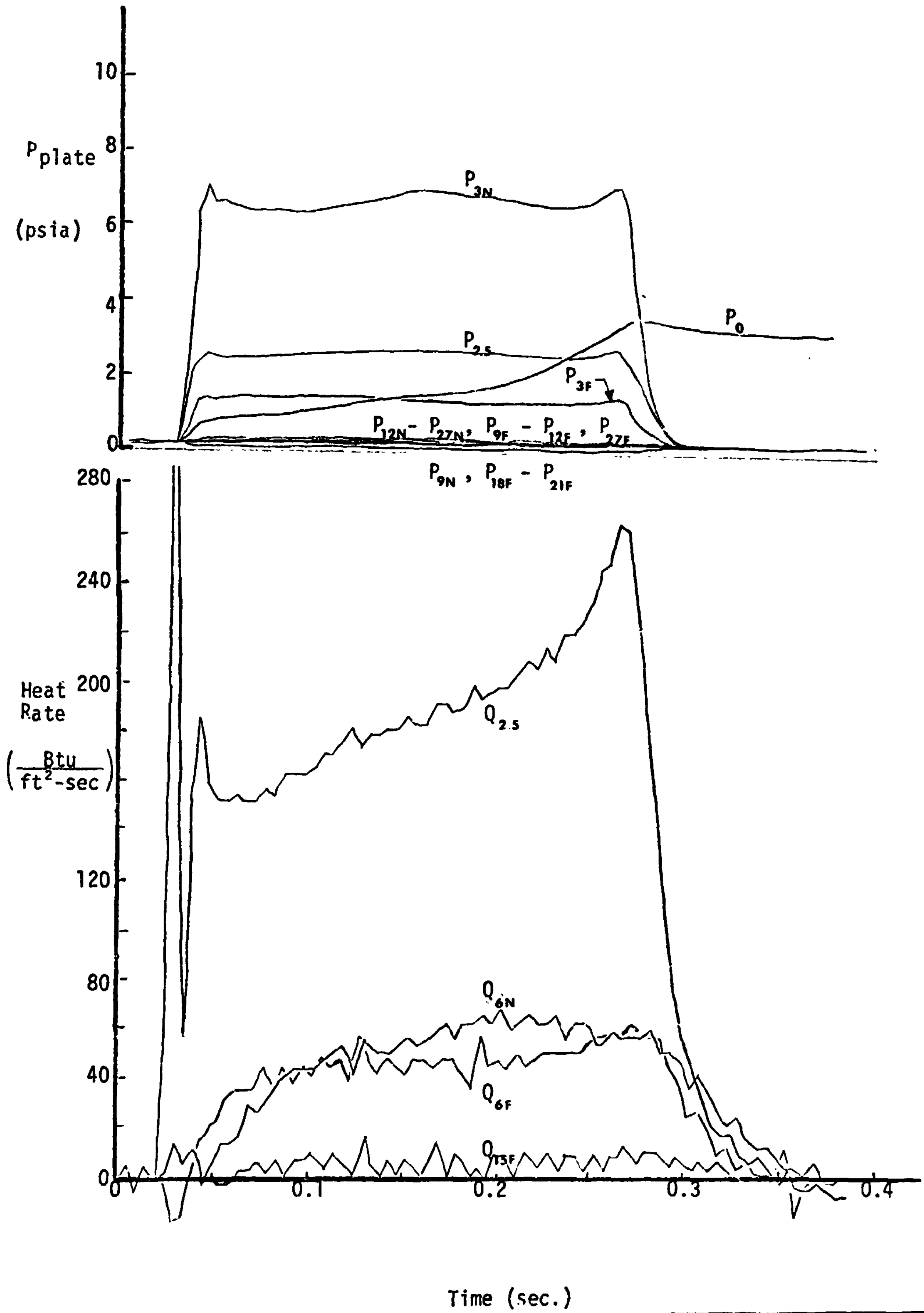
Run No. 21/1 (Concluded)



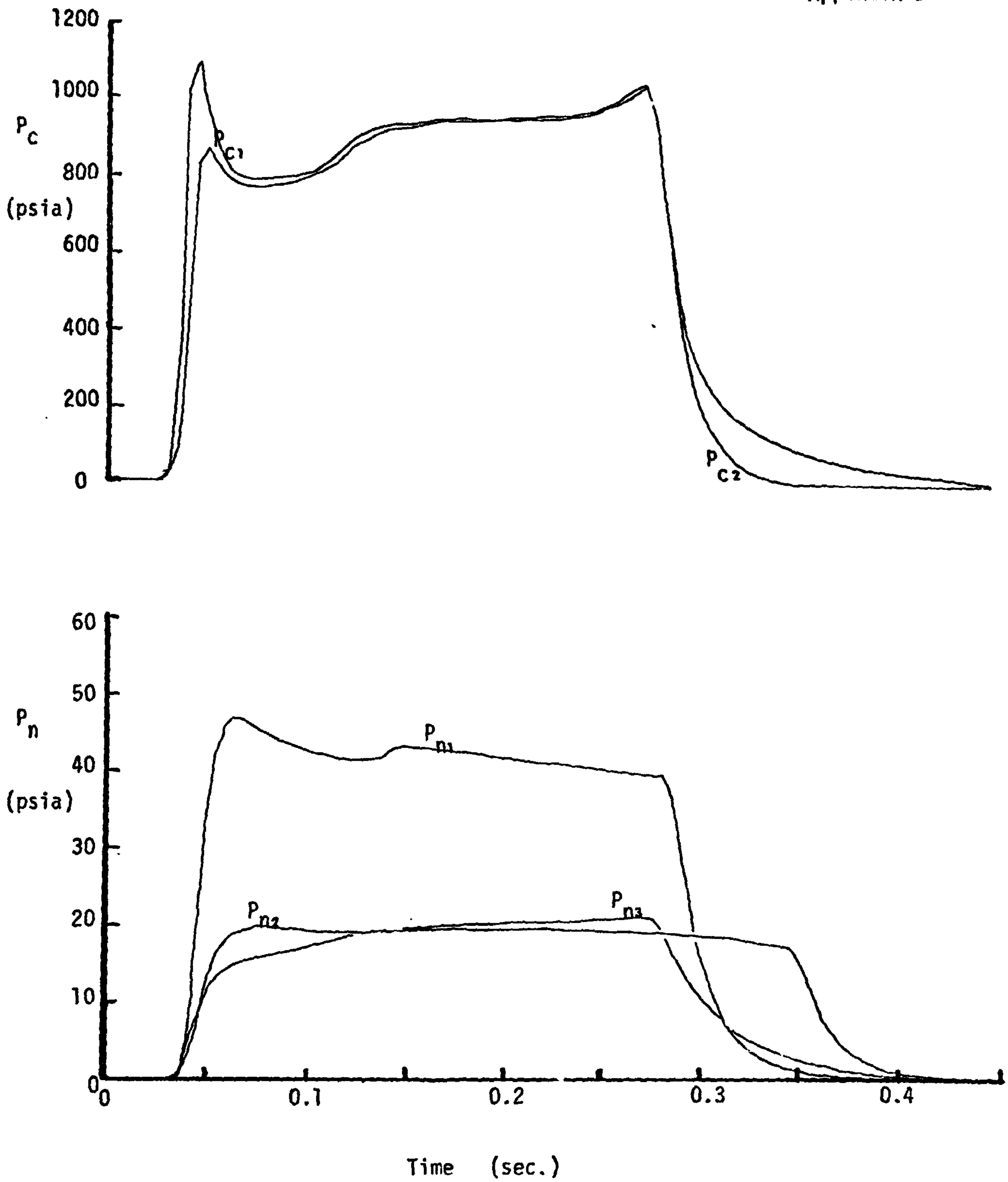
Run No. 21/2

Plate @ X/D=5
ψ = 45°

Alt.=100,000'
%Aℓ = 10



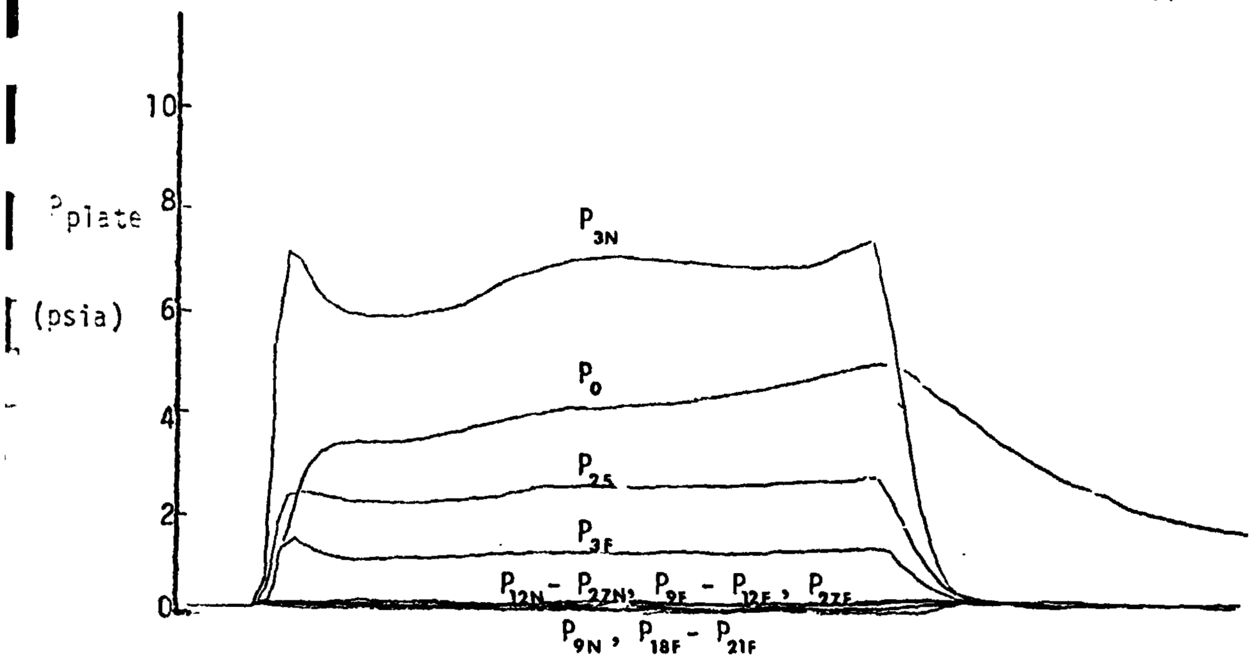
Run No. 21/2 (Concluded)

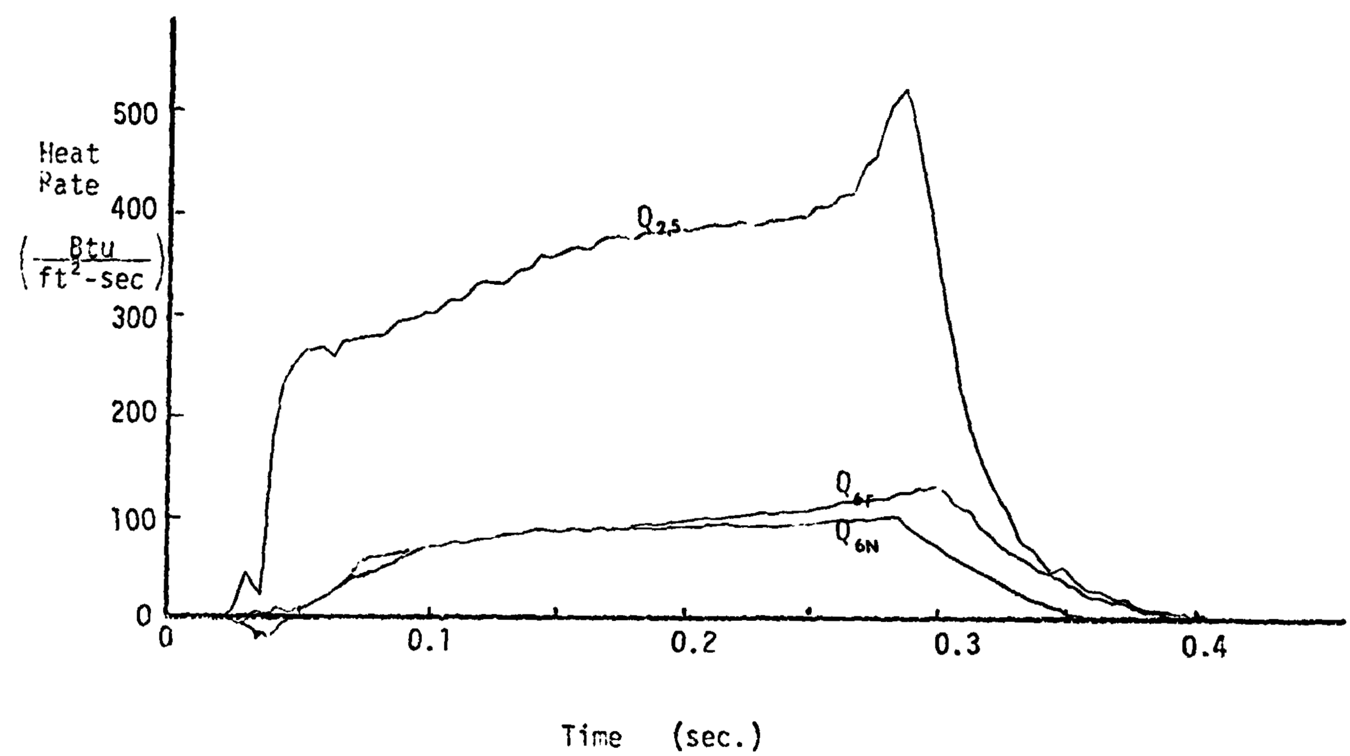


Run No. 22/1

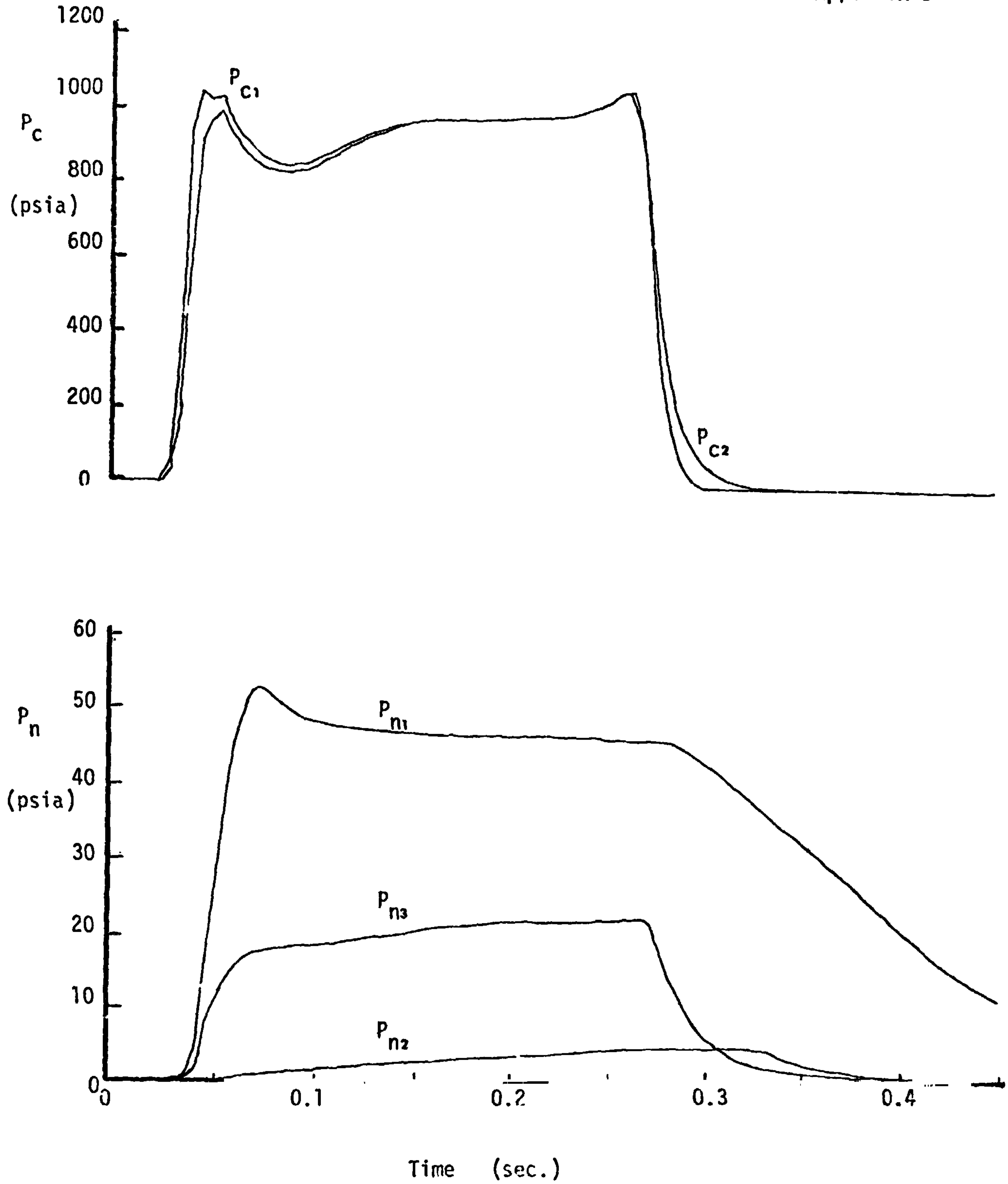
Plate @ X/D=5
ψ = 45°

Alt.=100,000'
%Aℓ = 15





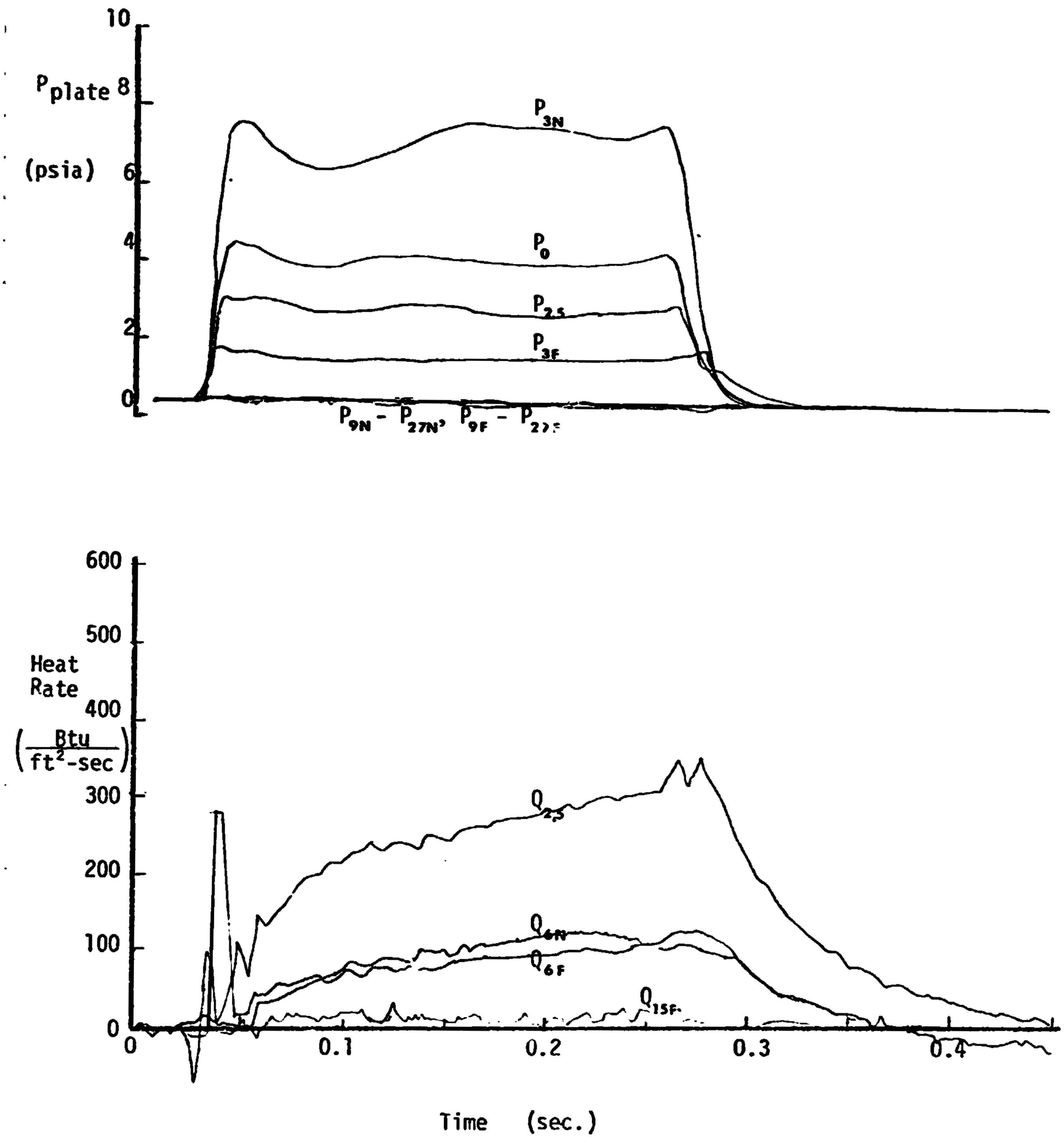
Rur No. 22/1 (Concluded)



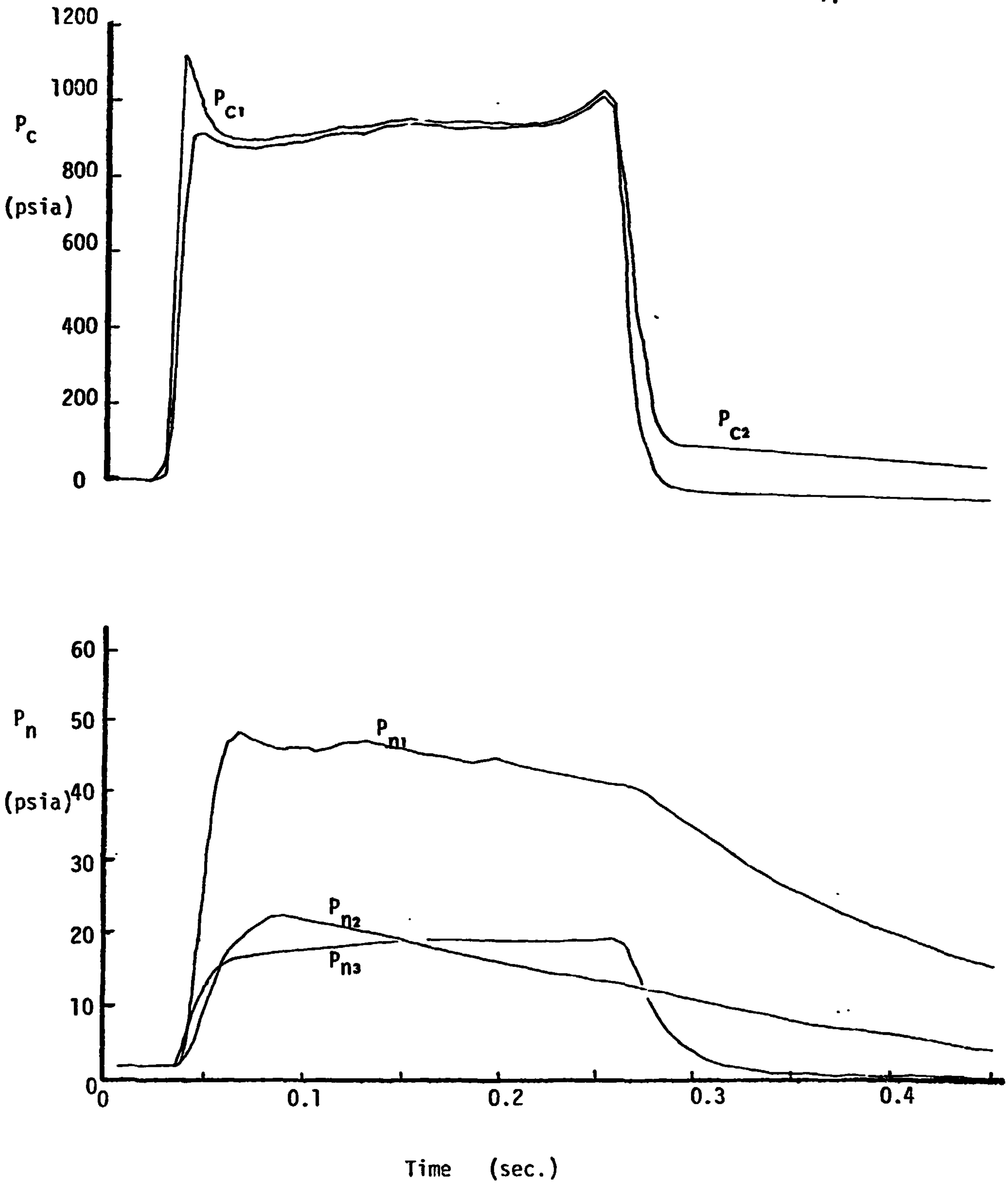
Run No. 22/2

Plate @ X/D=5
ψ = 45°

Alt.=100,000'
%Aℓ = 15



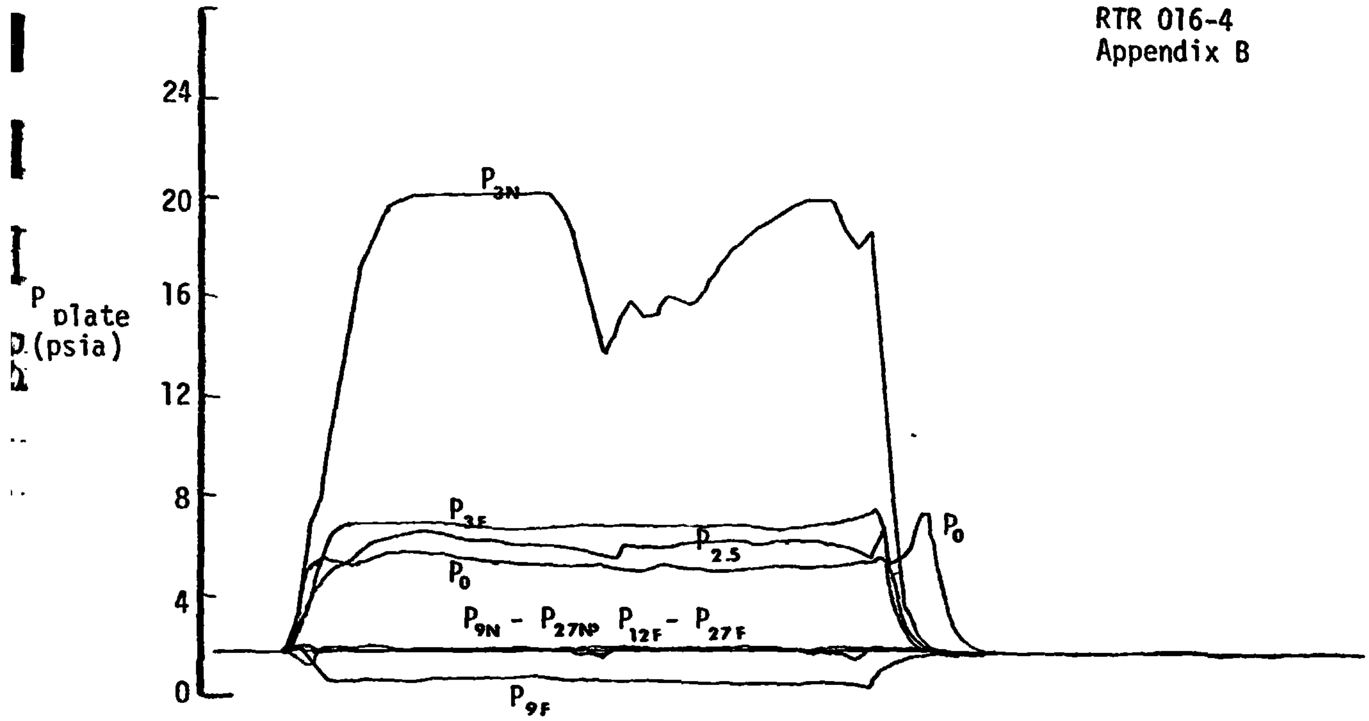
Run No. 22/2 (Concluded)

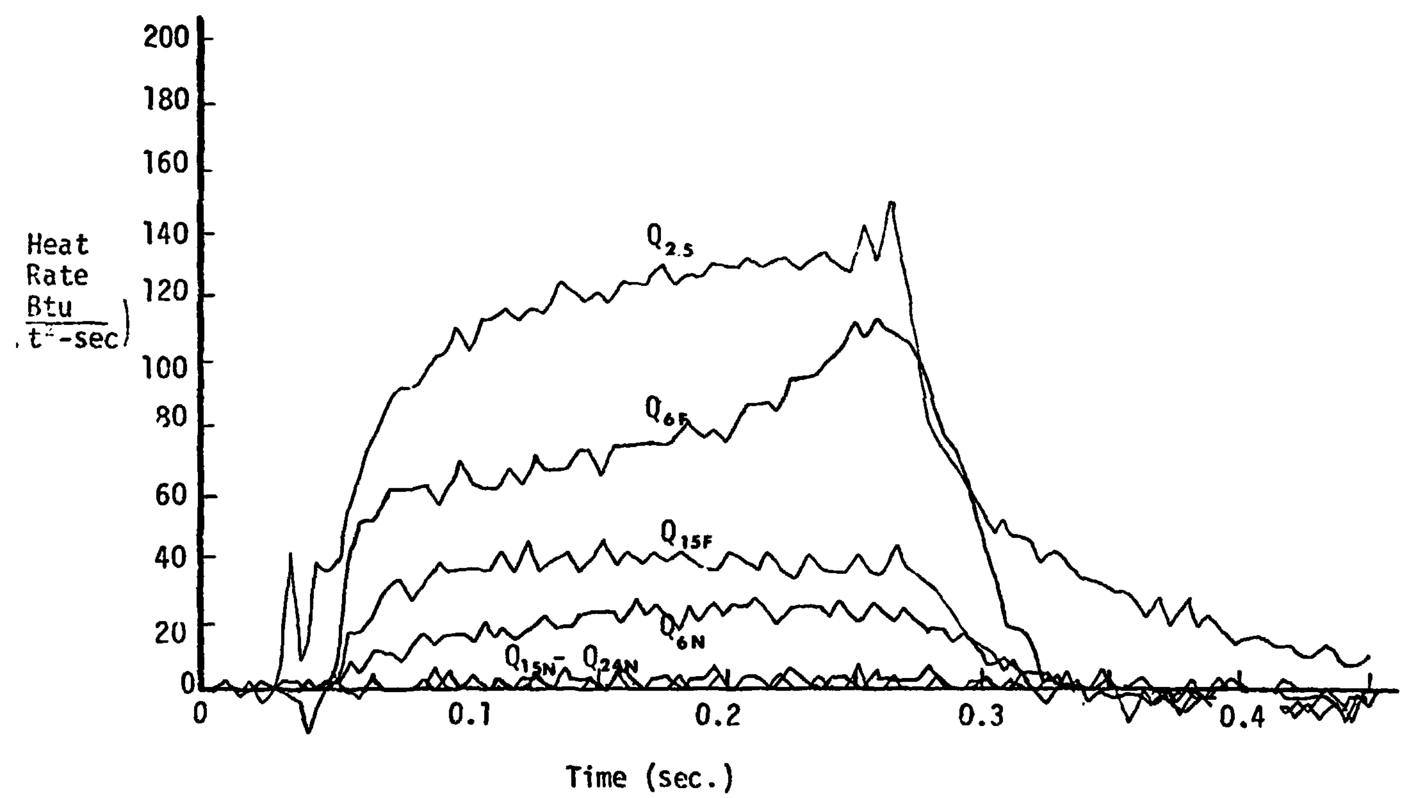


Run No. 23/1

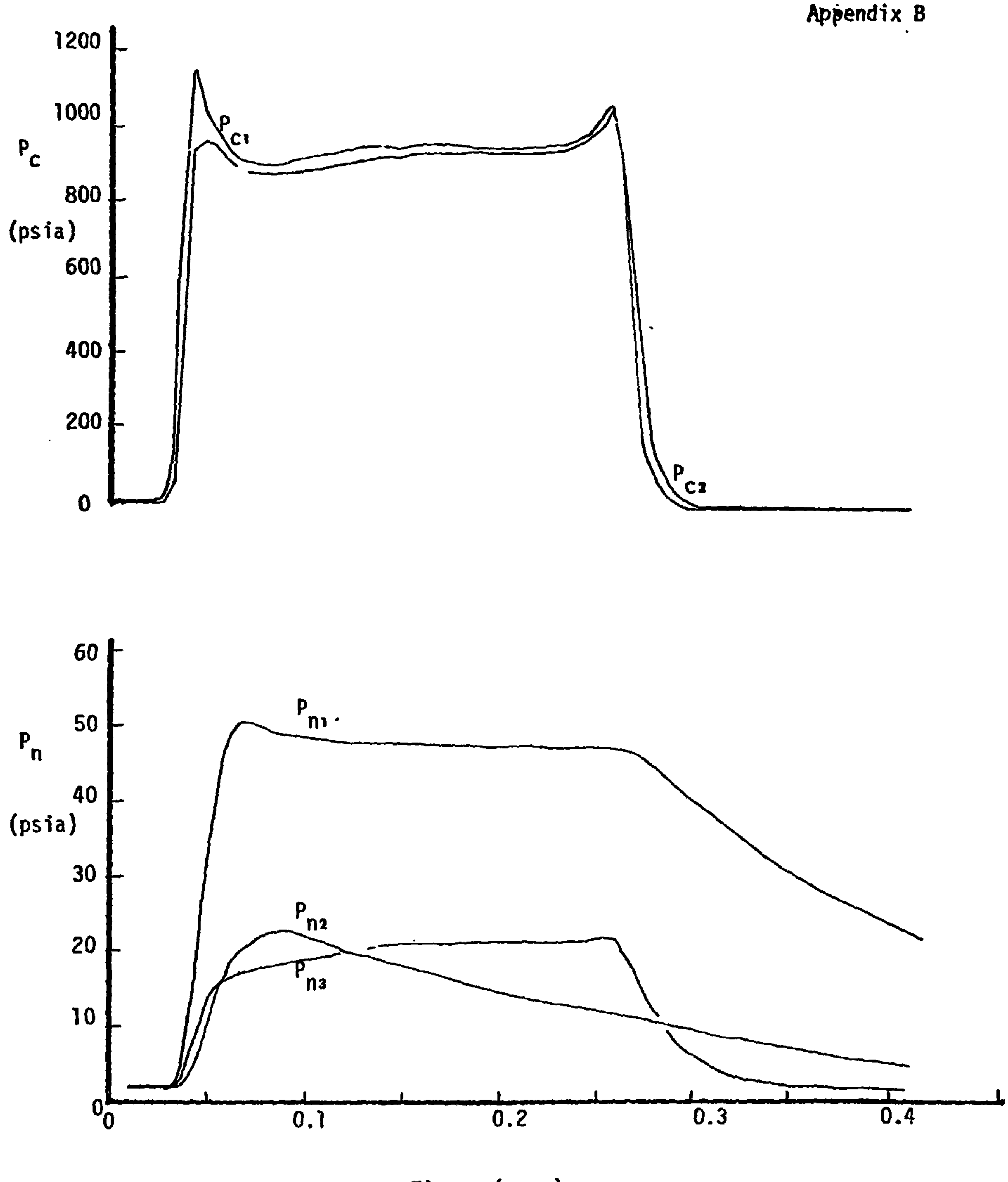
Plate @ X/D=5
ψ = 45°

Alt.=50,000'
%Aℓ =10





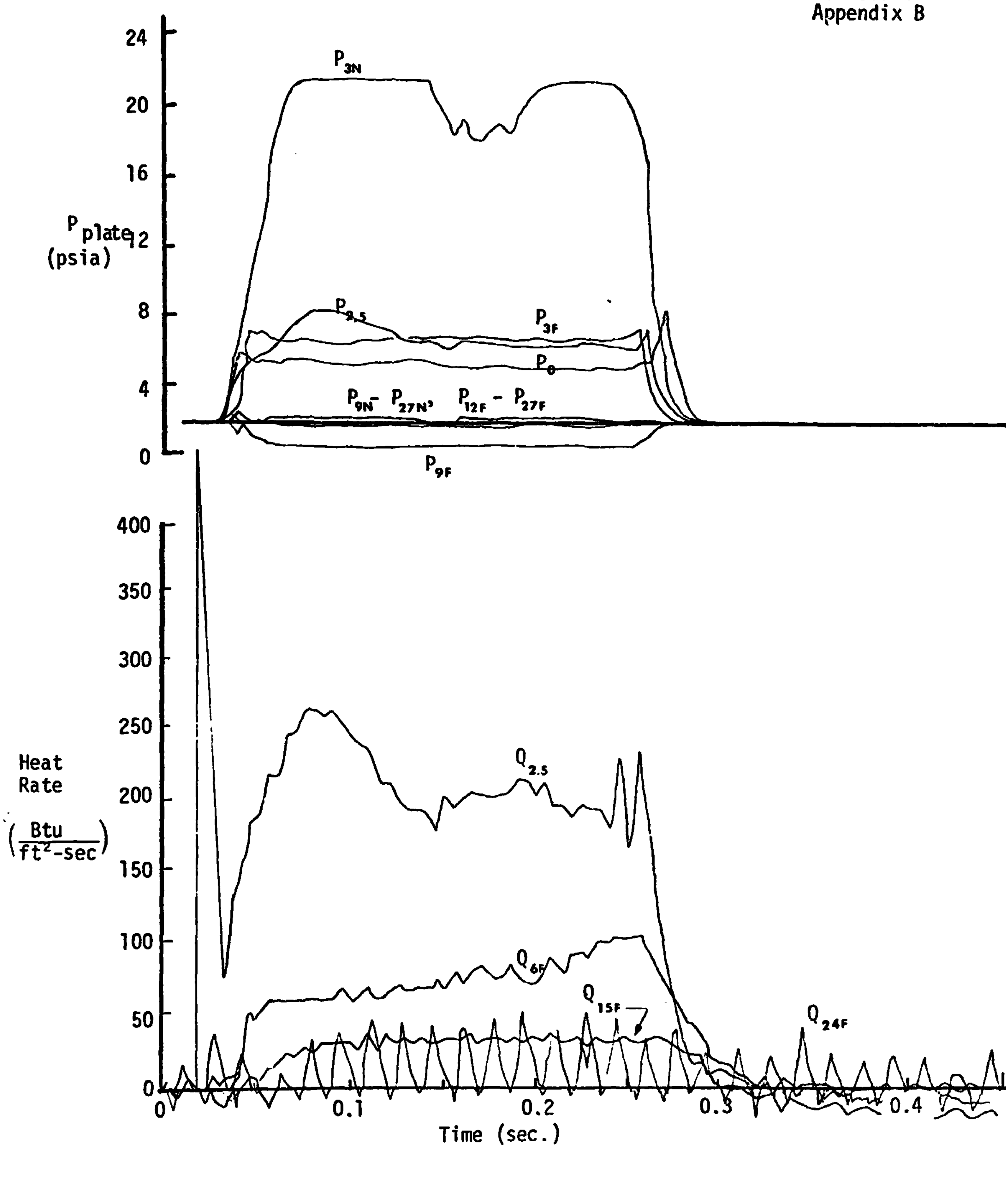
Run No. 23/1 (Concluded)



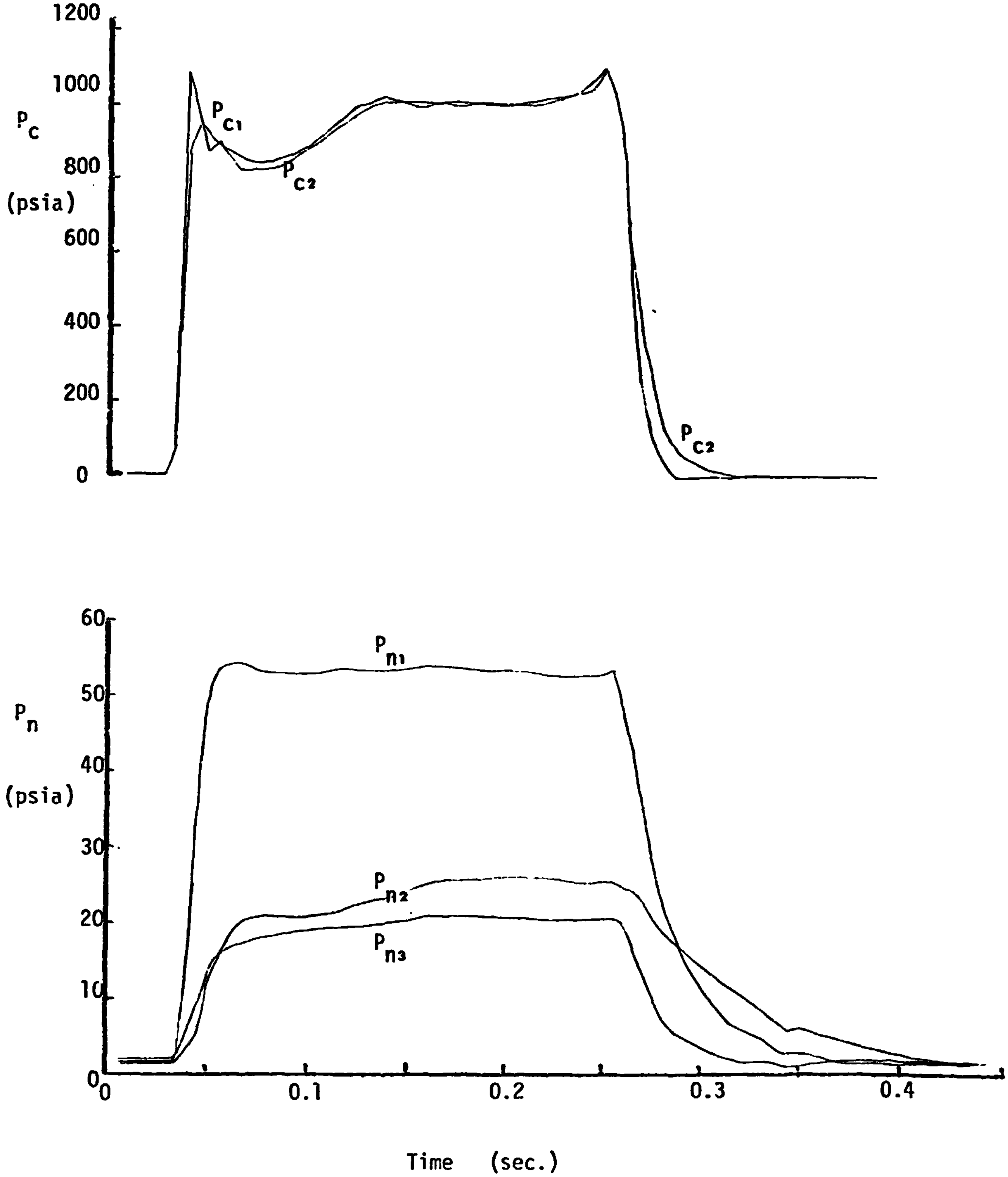
Run No. 23/2

Plate @ X/D=5
ψ = 45°

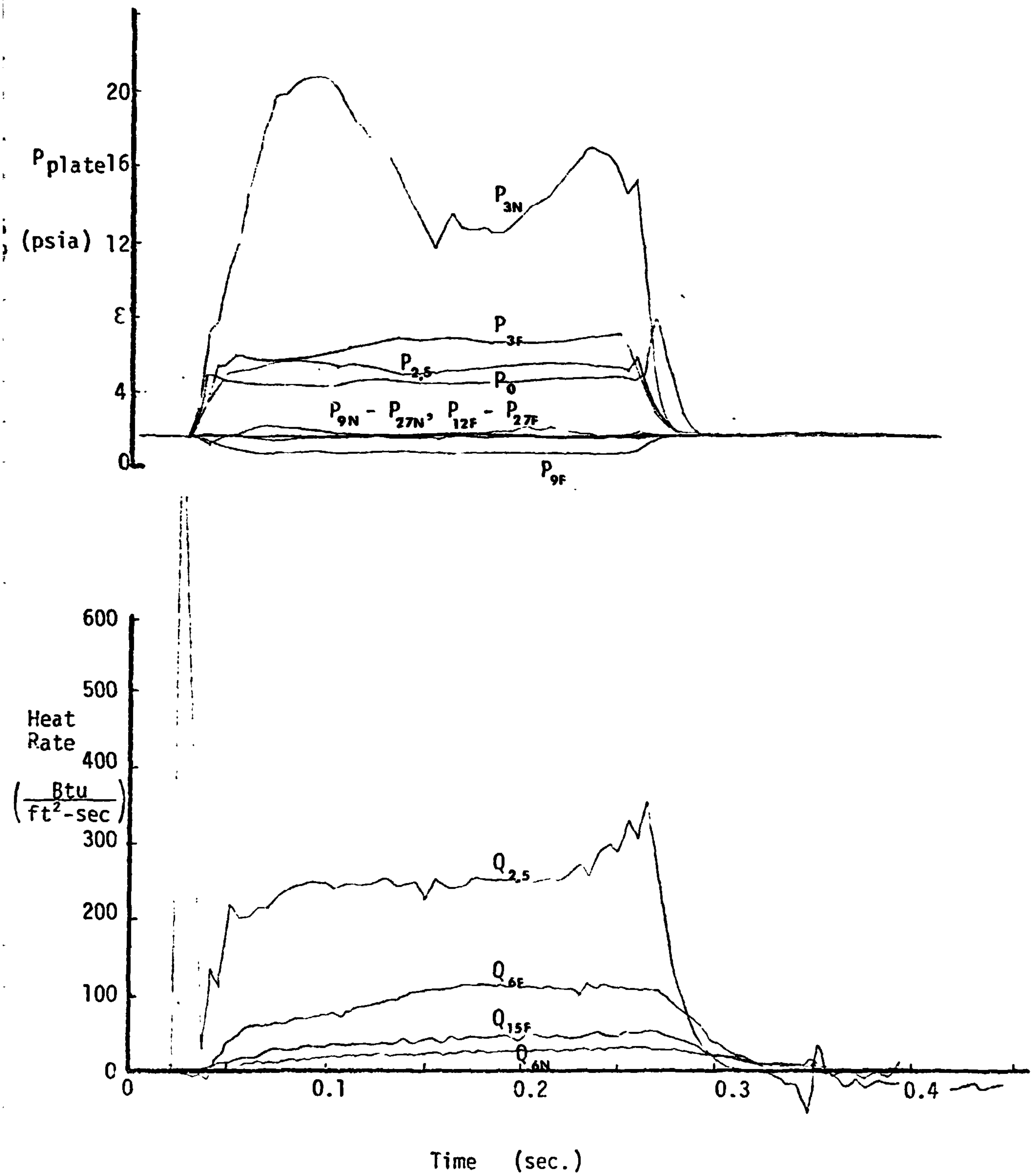
Alt.=50,000'
%Aℓ =10



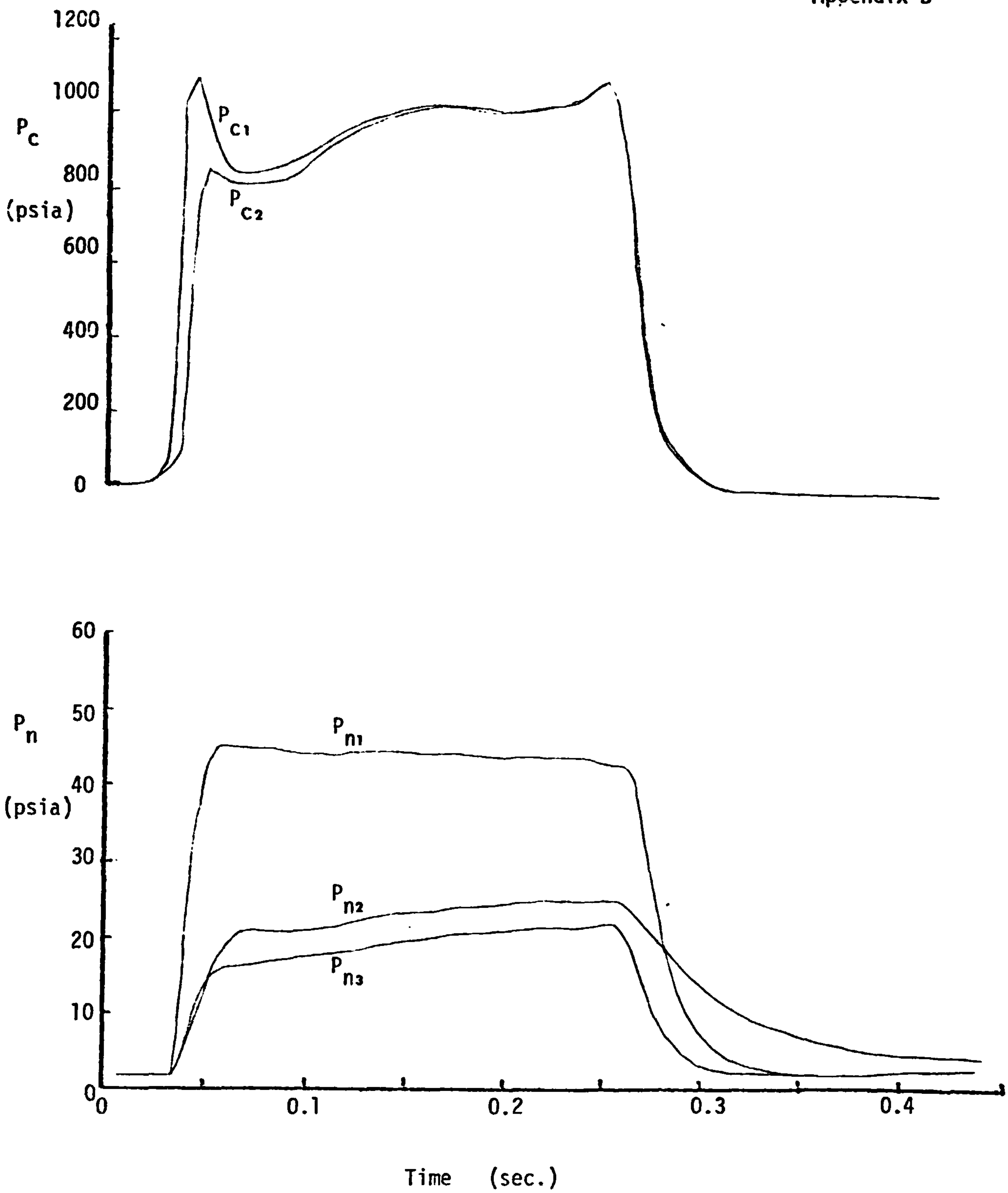
Run No. 23/2 (Concluded)



Run No. 24/1 Plate @ X/D=5 ψ = 45° Alt.=50,000' %Aℓ =15



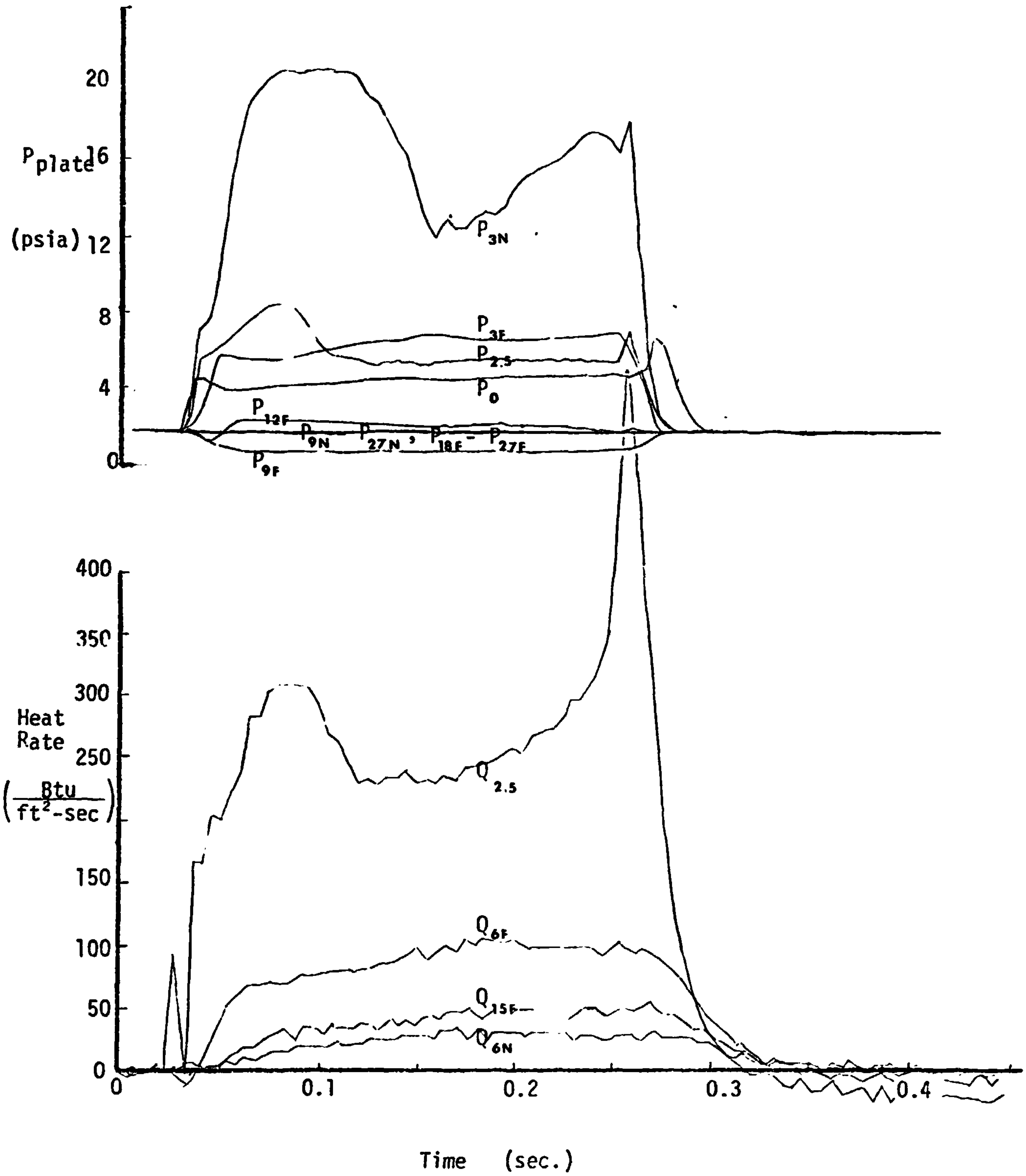
Run No. 24/1 (Concluded)



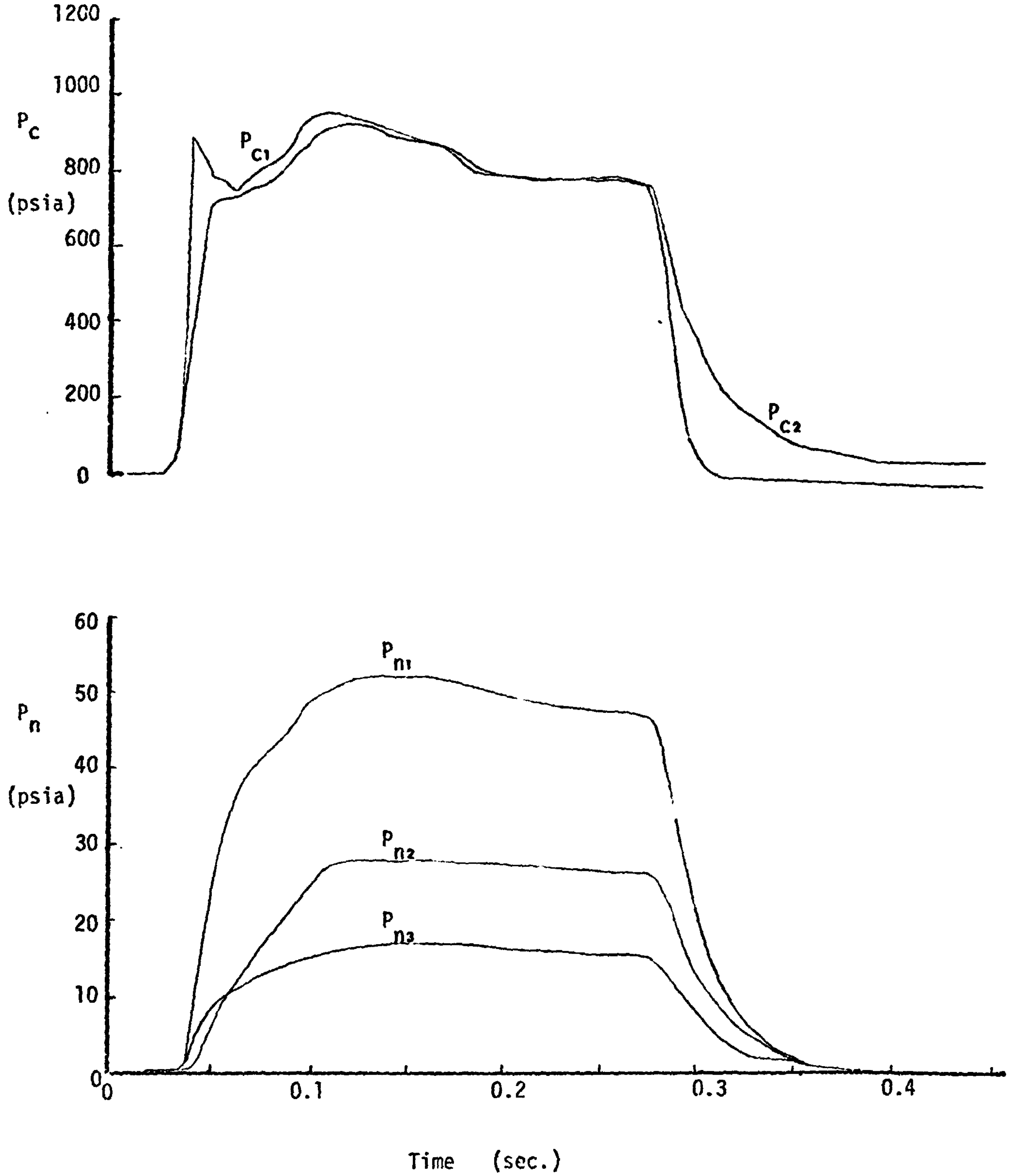
Run No. 24/2

Plate @ X/D=5
ψ = 45°

Alt.=50,000'
%Aℓ =15



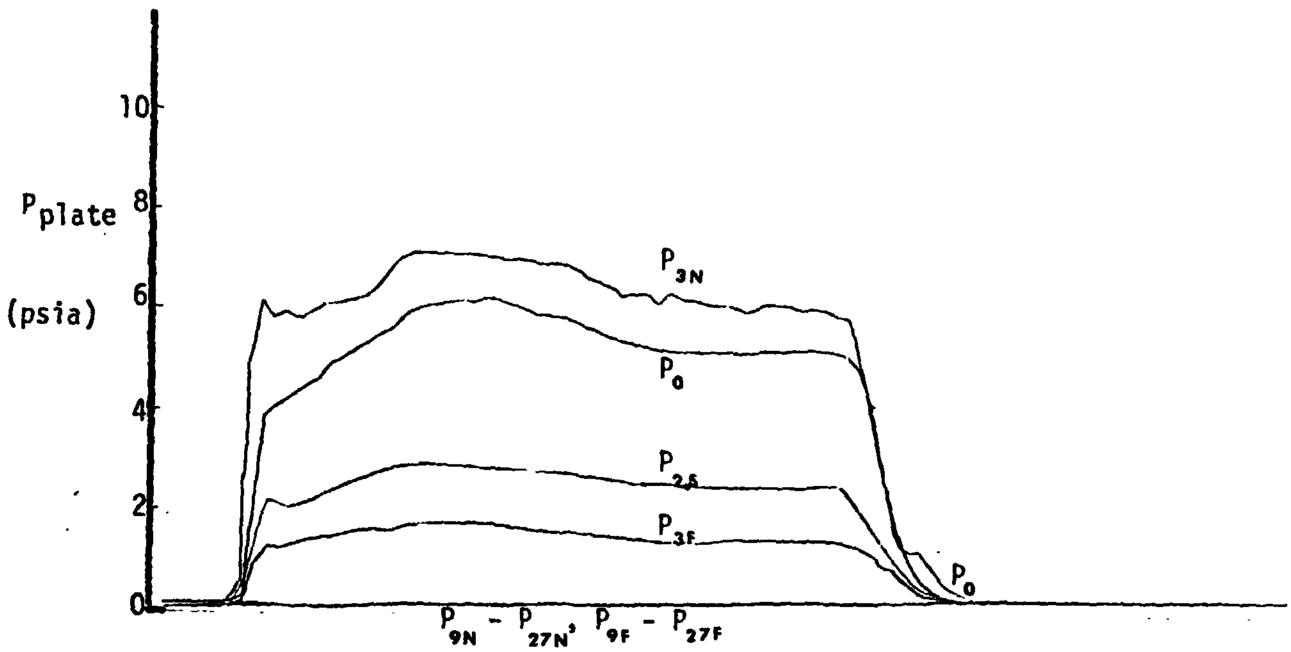
Run No. 24/2 (Concluded)

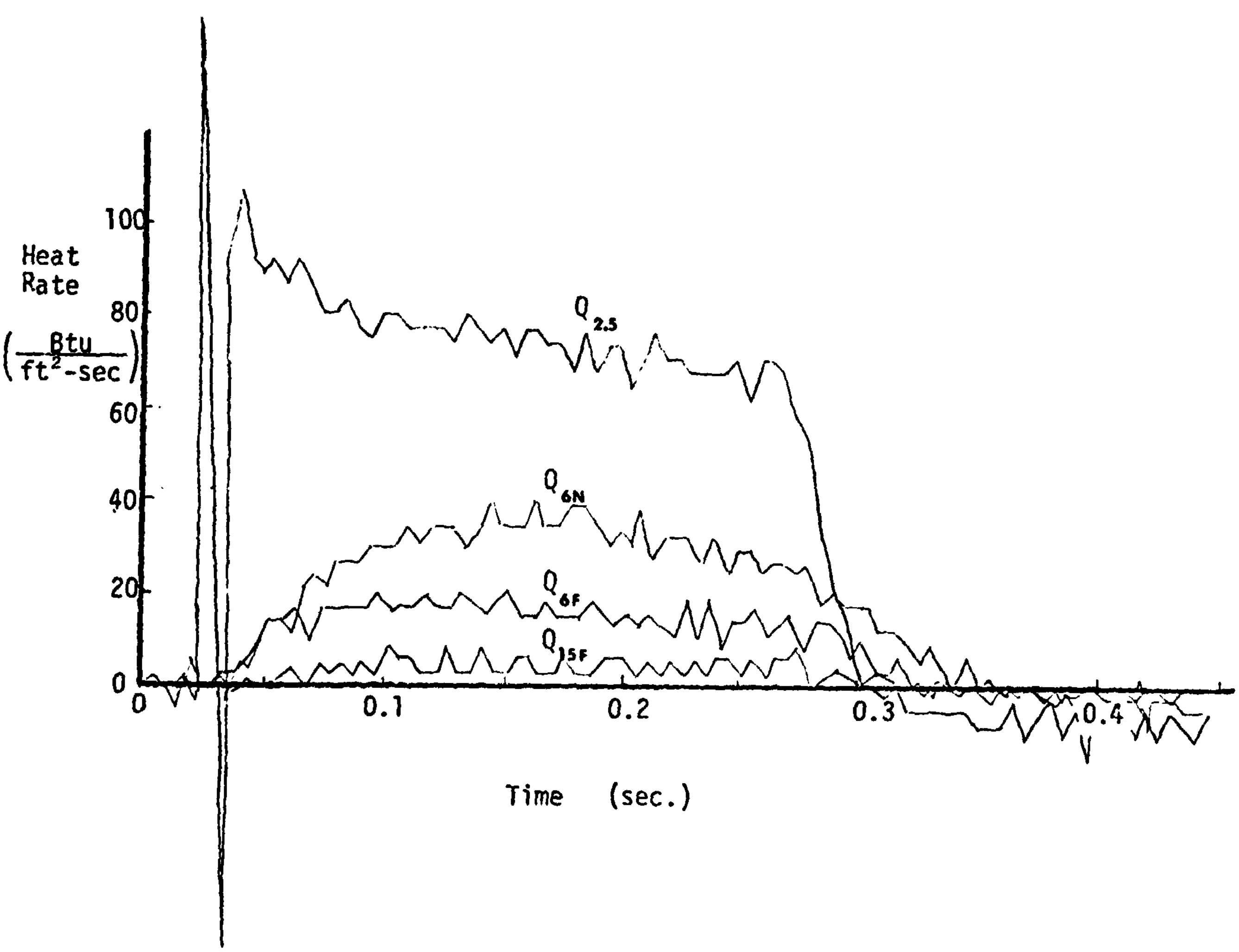


Run No. 25/1

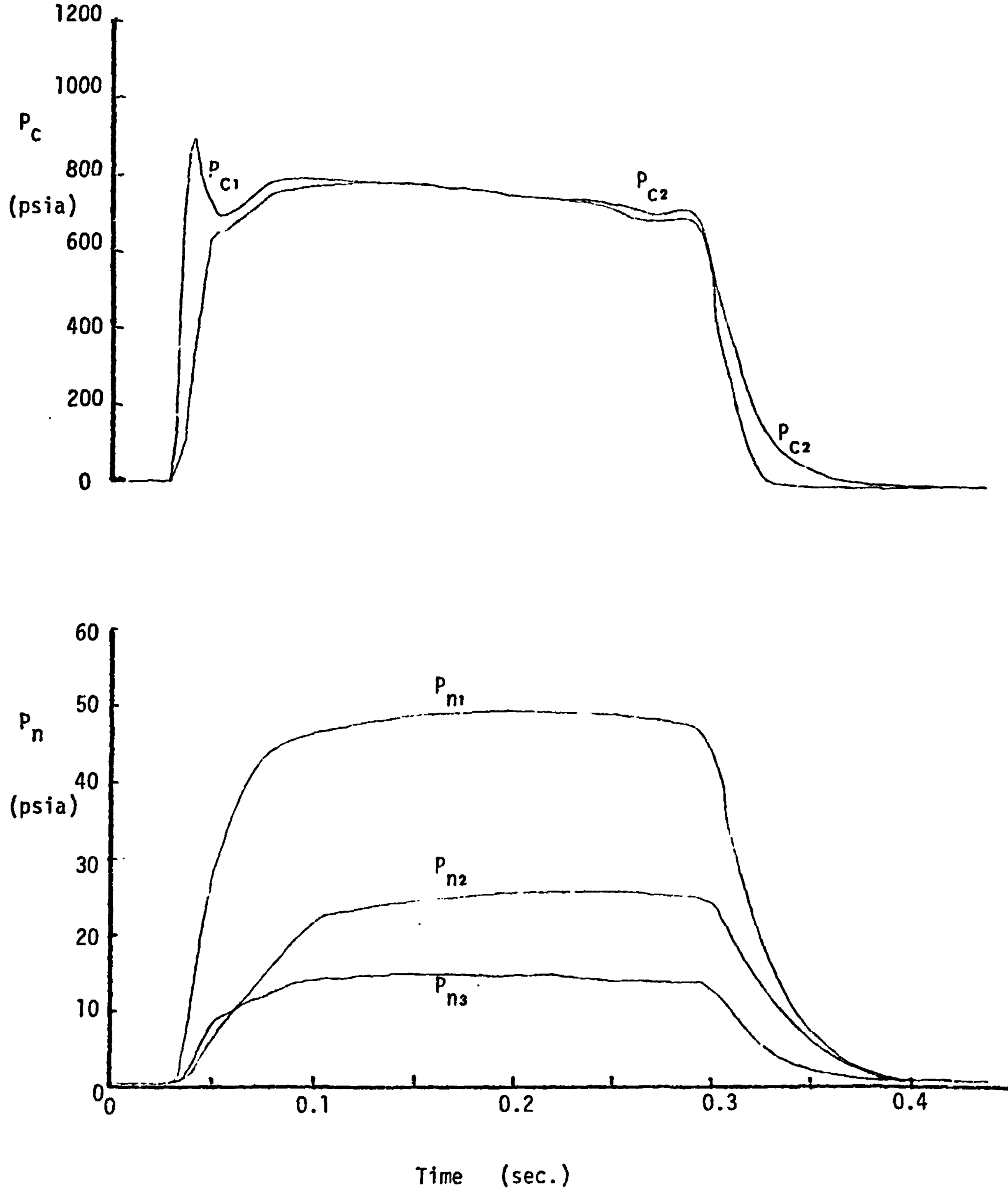
Plate @ X/D=5
ψ = 45°

Alt.=100,000'
%Aℓ = 2





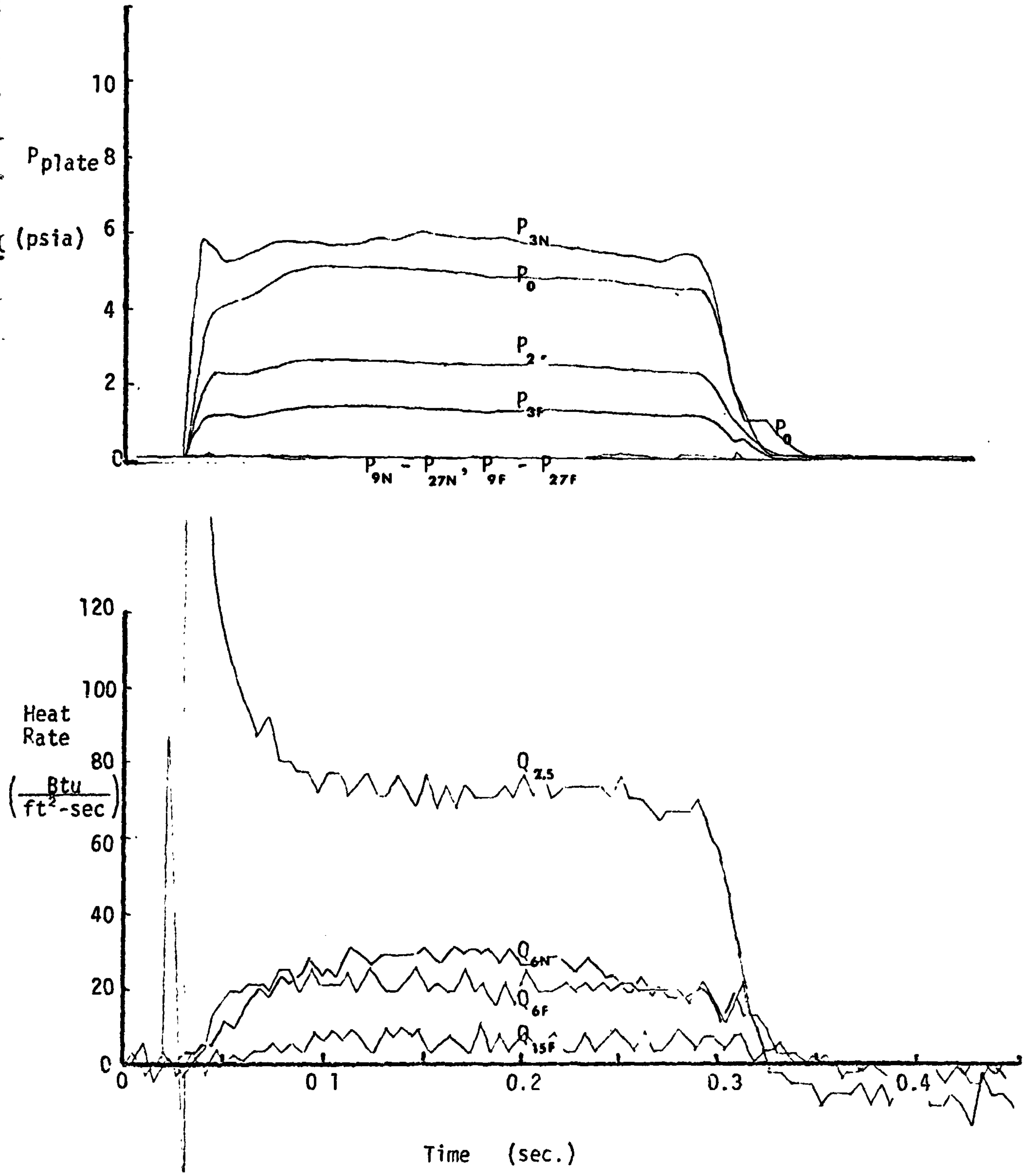
Run No. 25/1 (Concluded)



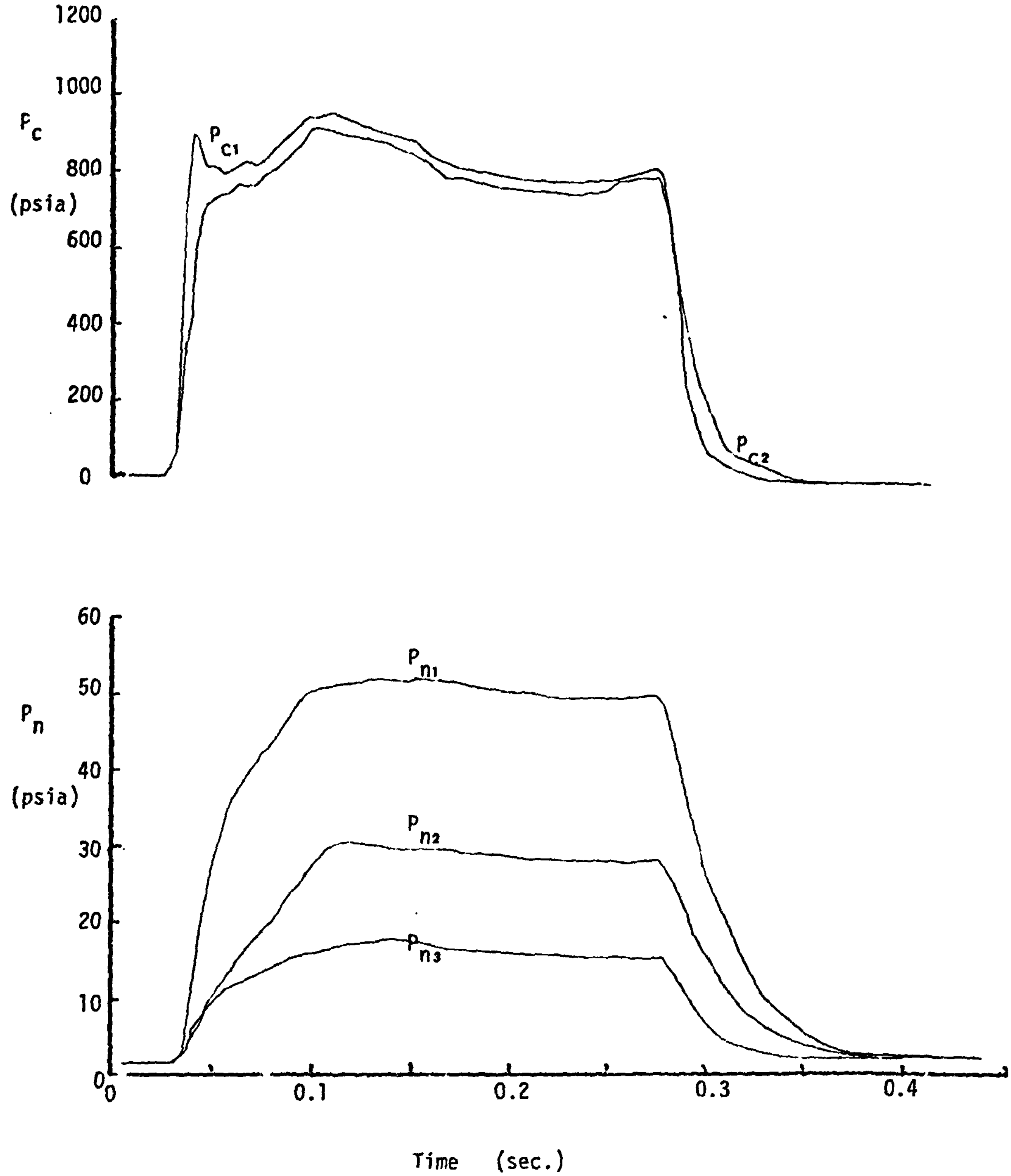
Run No. 25/2

Plate @ X/D=5
ψ = 45°

Alt.=100,000'
%Aℓ = 2



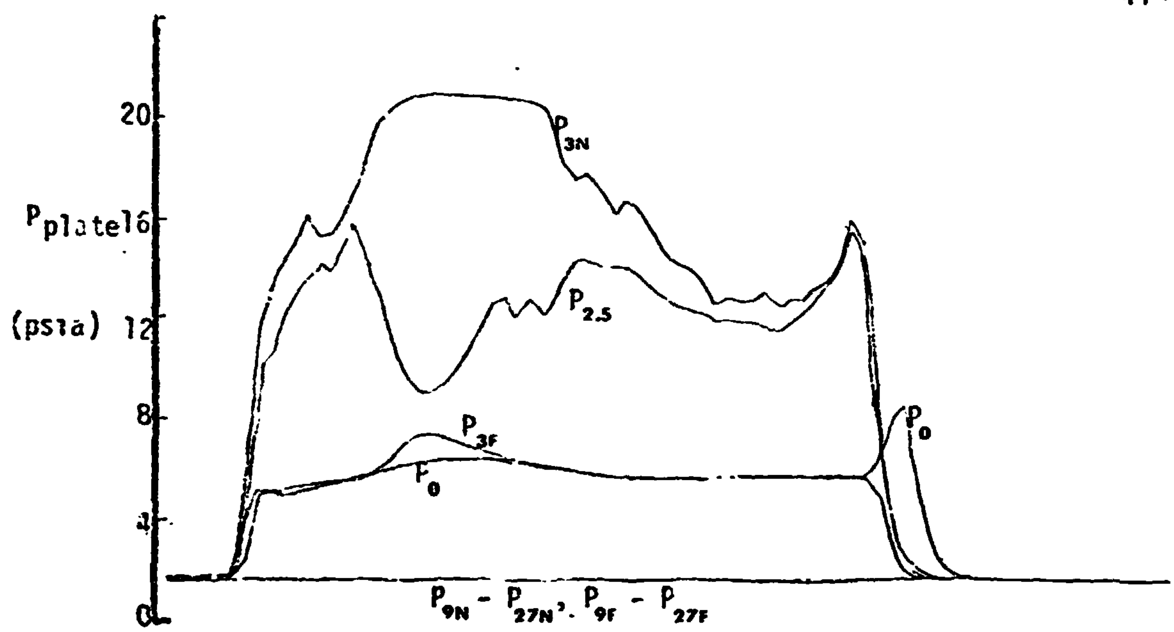
Run No. 25/2 (Concluded)

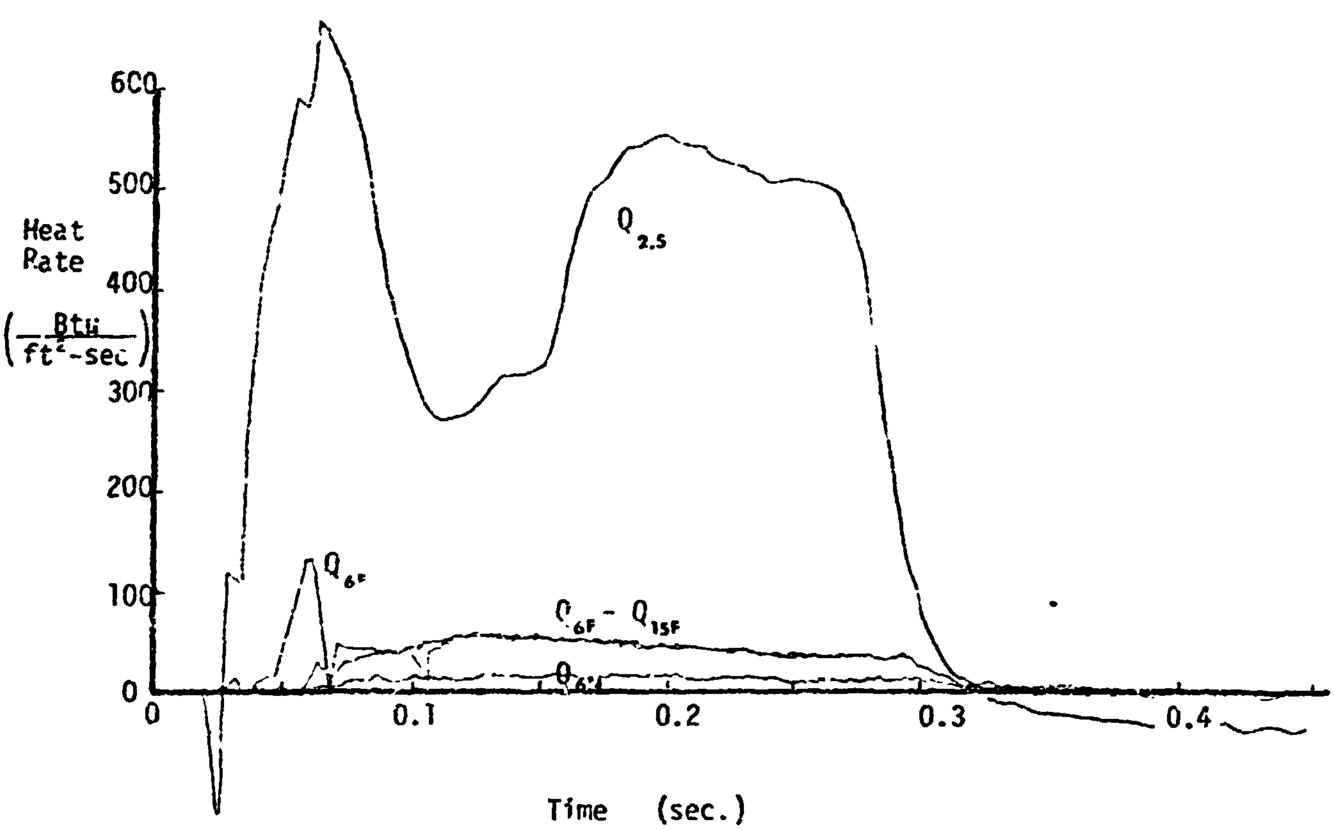


Run No. 26/1

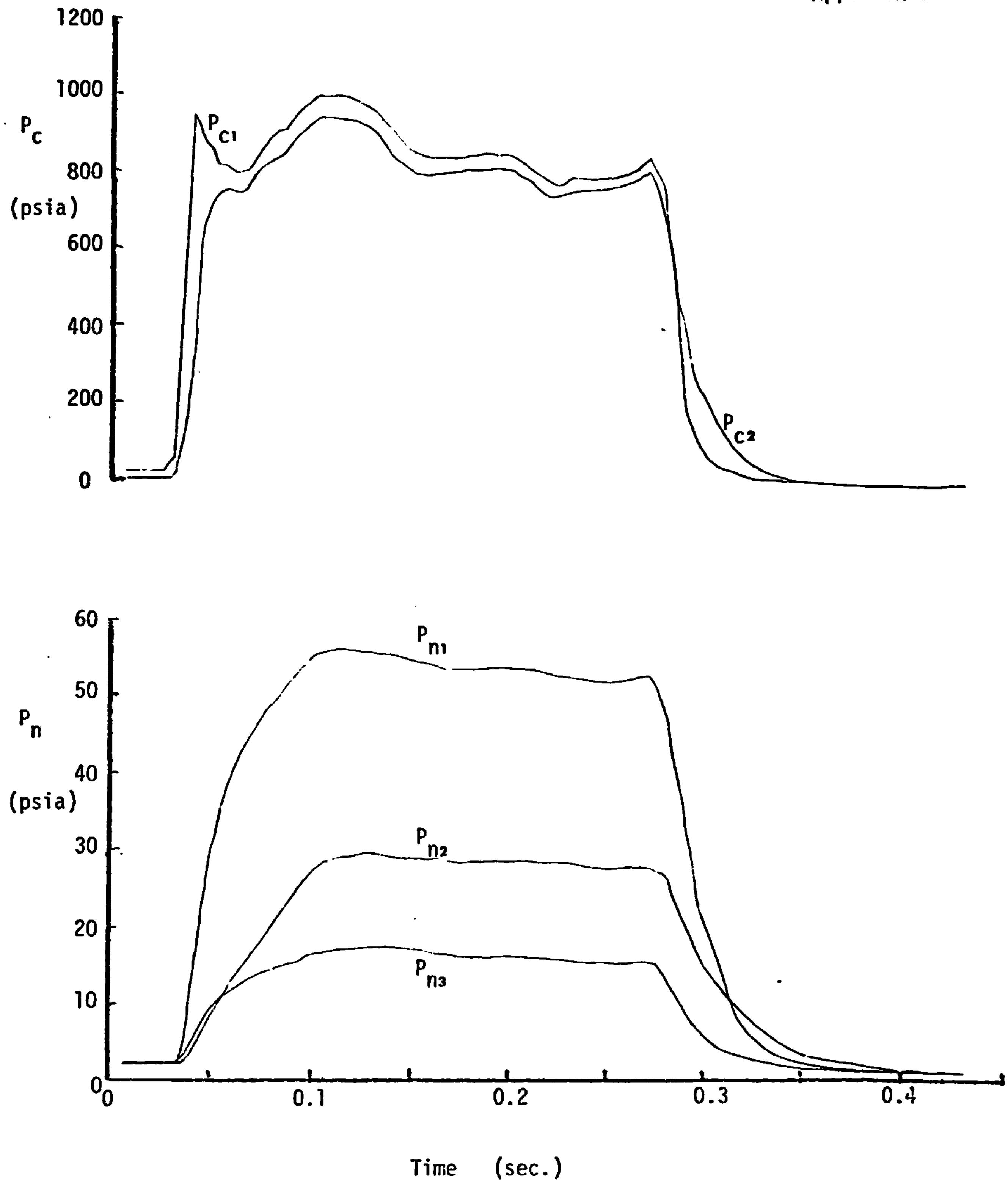
Plate @ X/D=5
ψ = 45°

Alt.=50,000'
%Aℓ =2





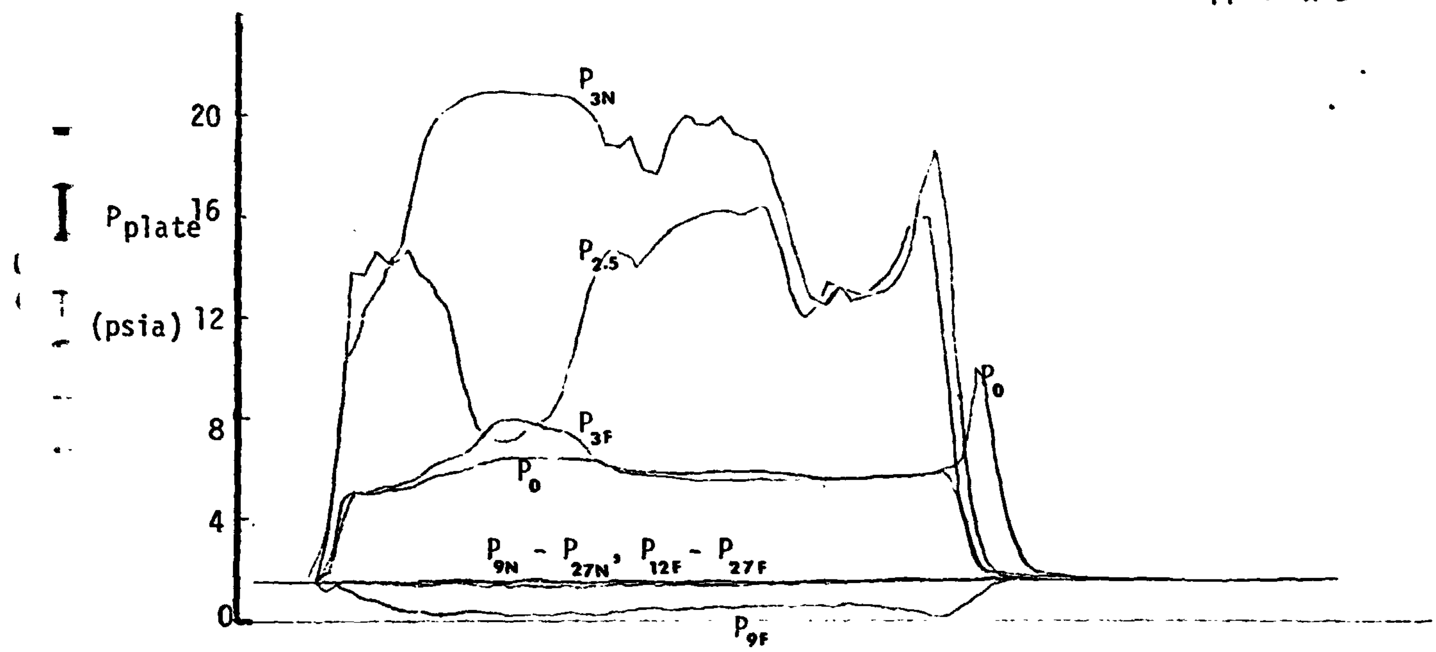
Run No. 26/1 (Concluded)

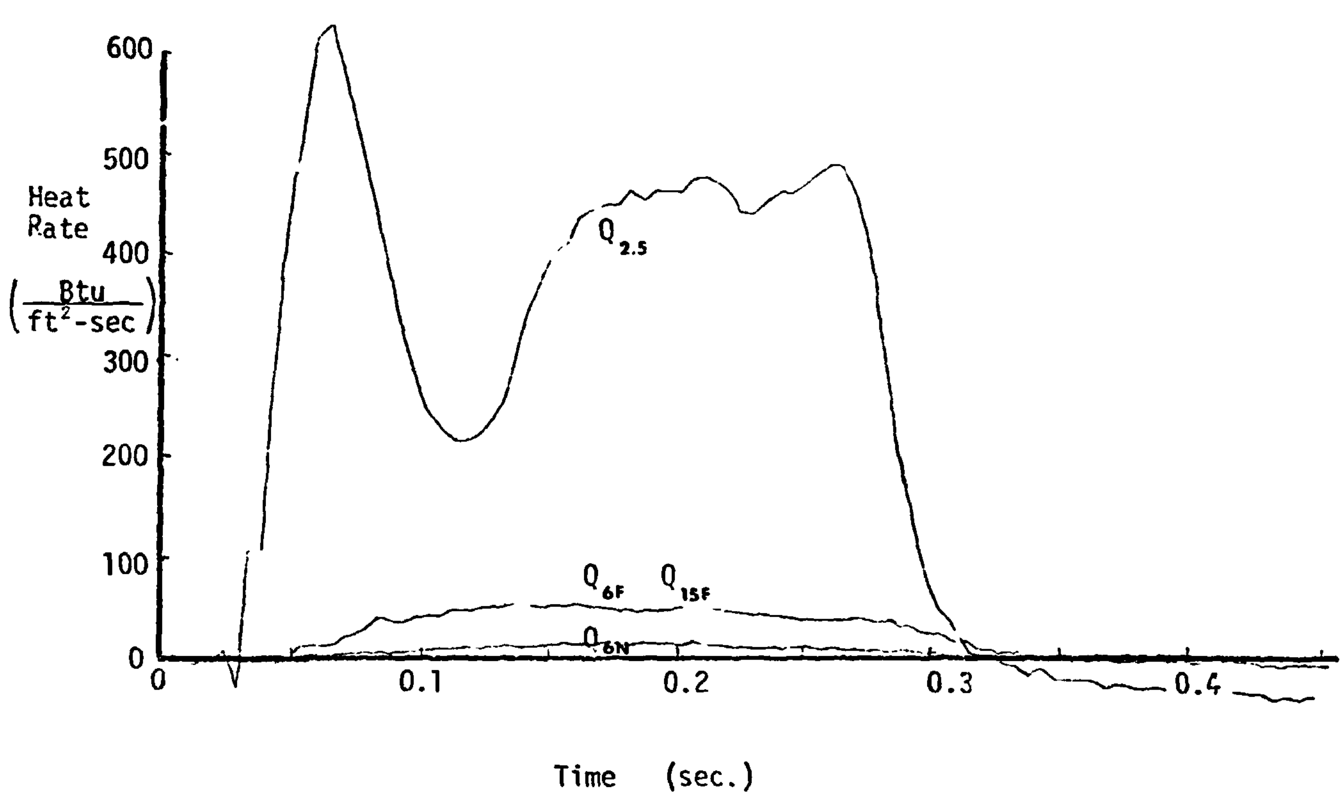


Run No. 26/2

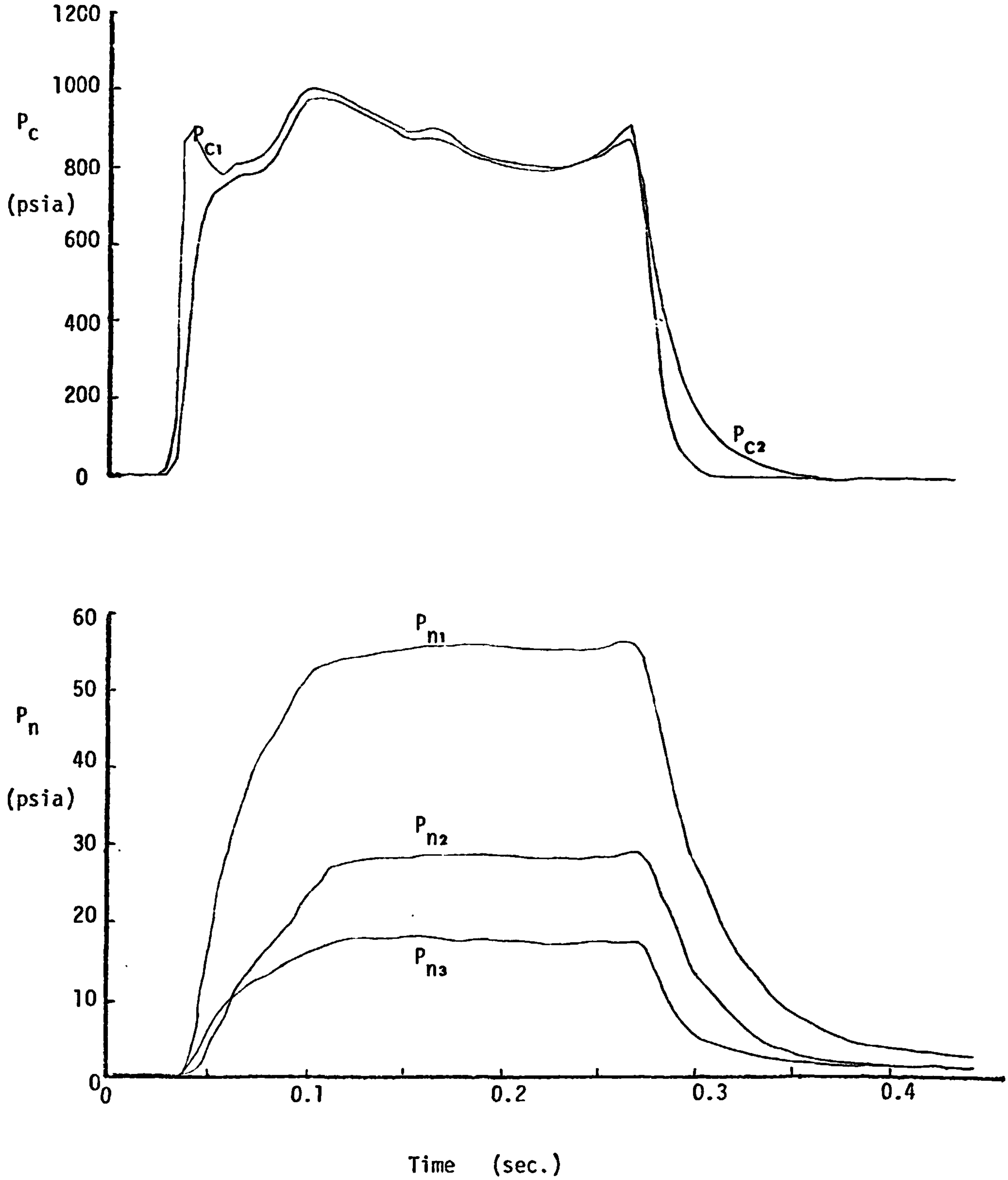
Plate @ X/D=5
ψ = 45°

Alt.=50,000'
%Aℓ =2





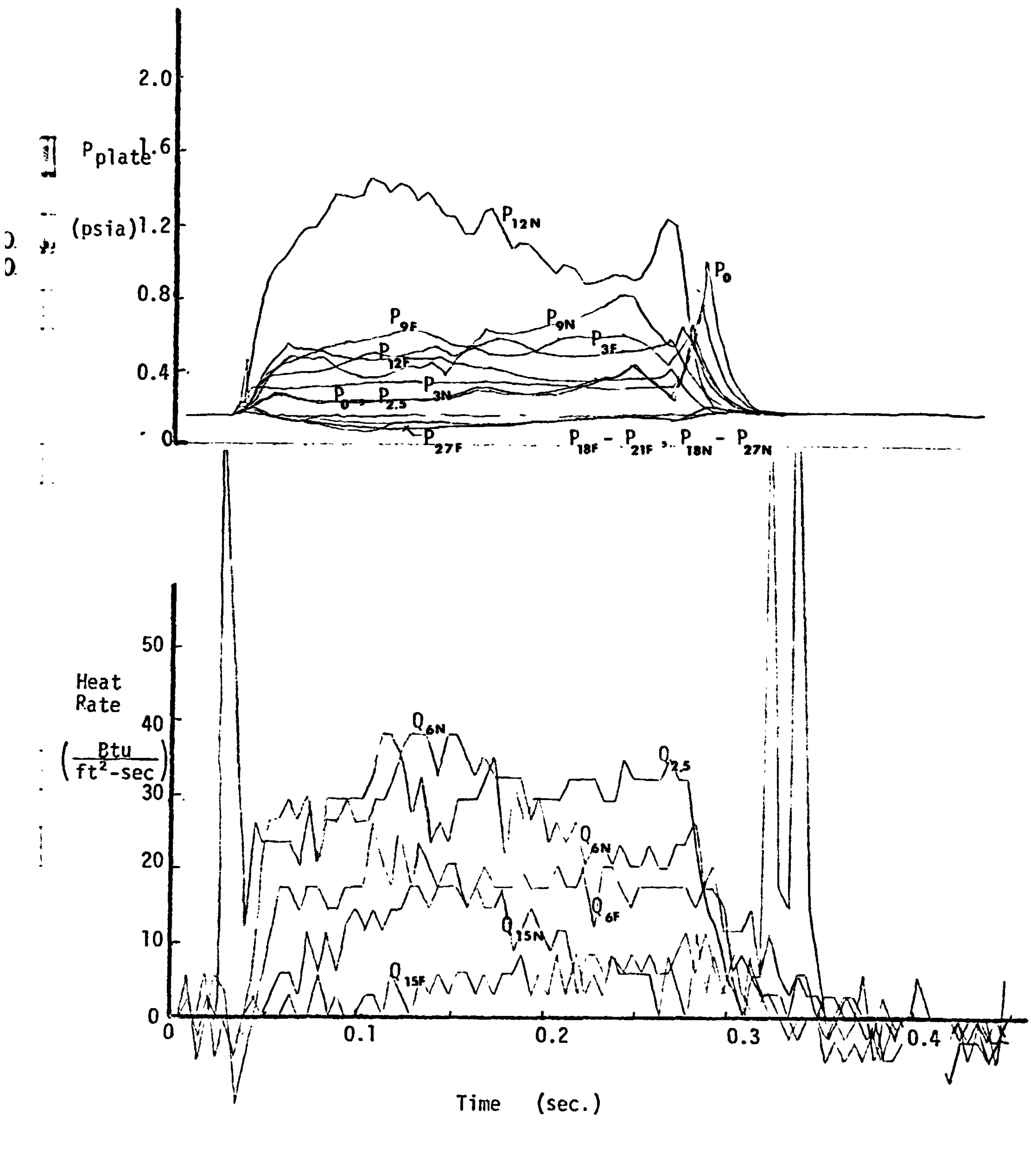
Run No. 26/2 (Concluded)



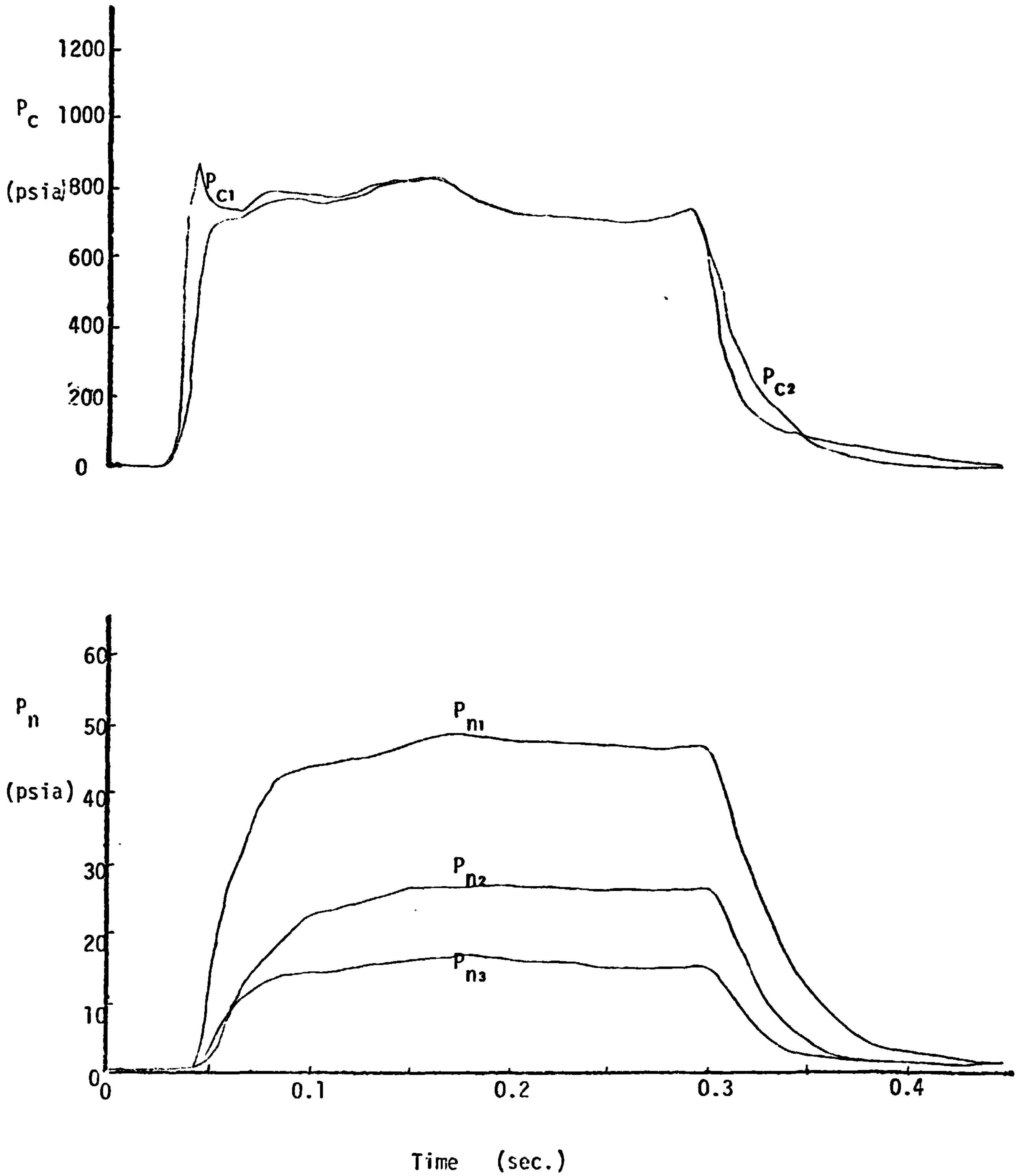
Run No. 27/1

Plate @ X/D=20
ψ = 45°

Alt.=100,000'
%Aℓ = 2



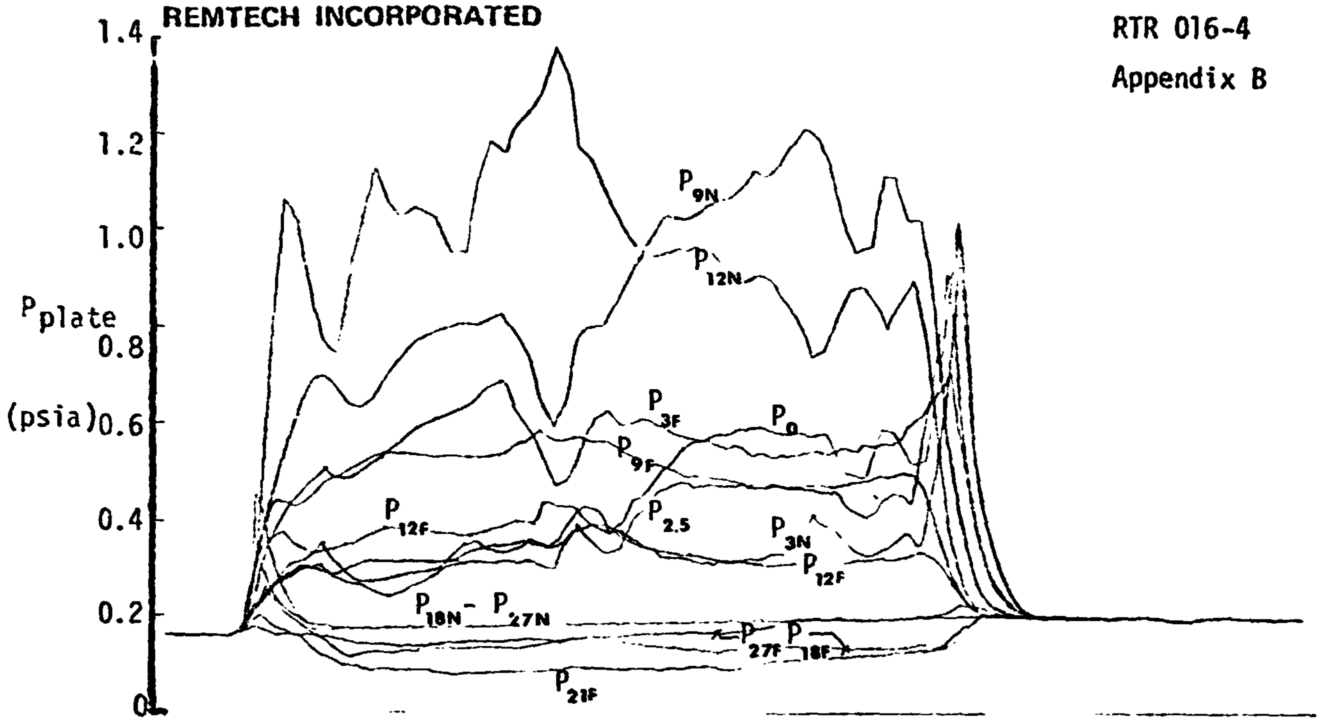
Run No. 27/1 (Concluded)

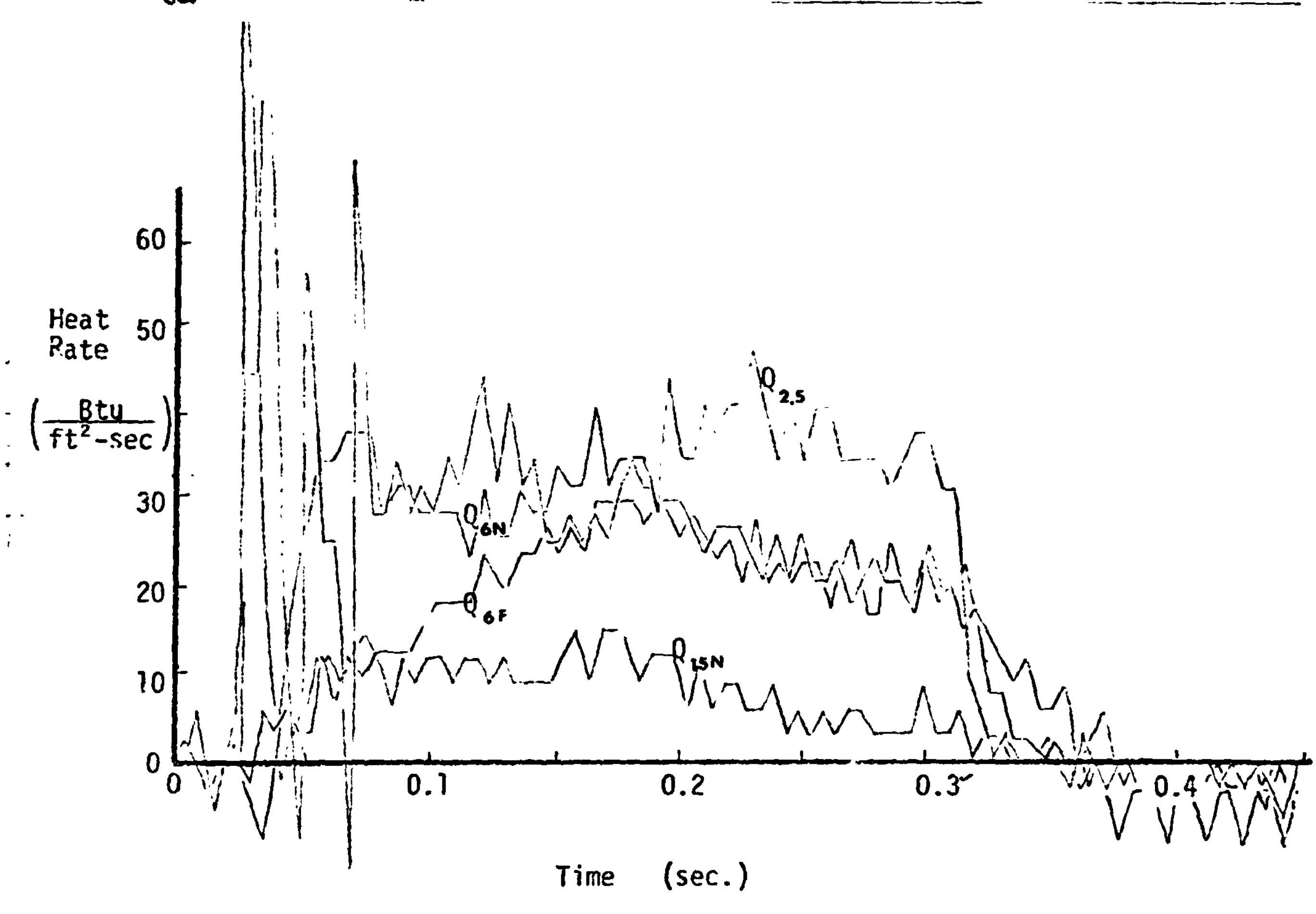


Run No. 27/2

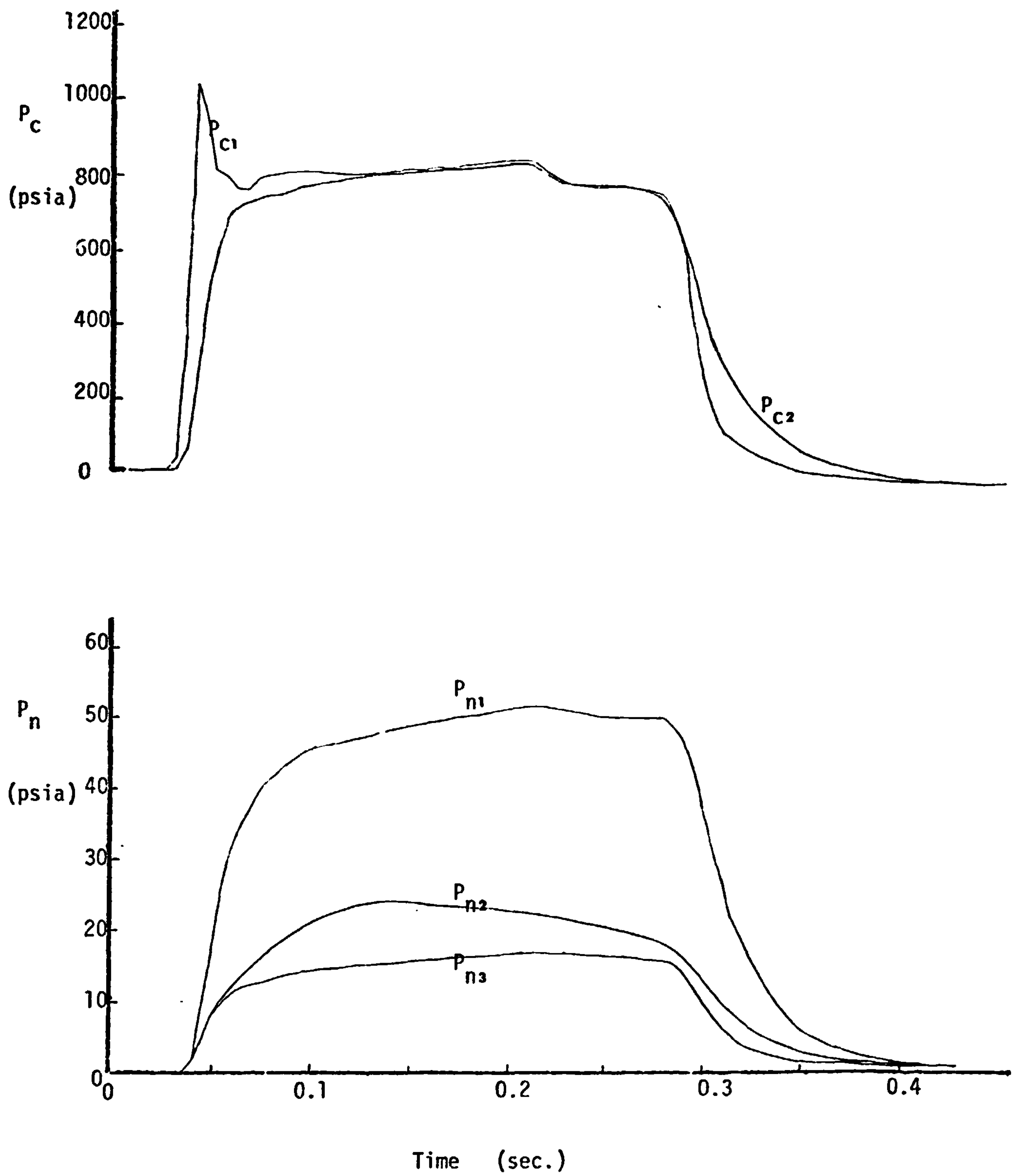
Plate @ X/D=20
ψ = 45°

Alt.=100,000'
%Aℓ = 2





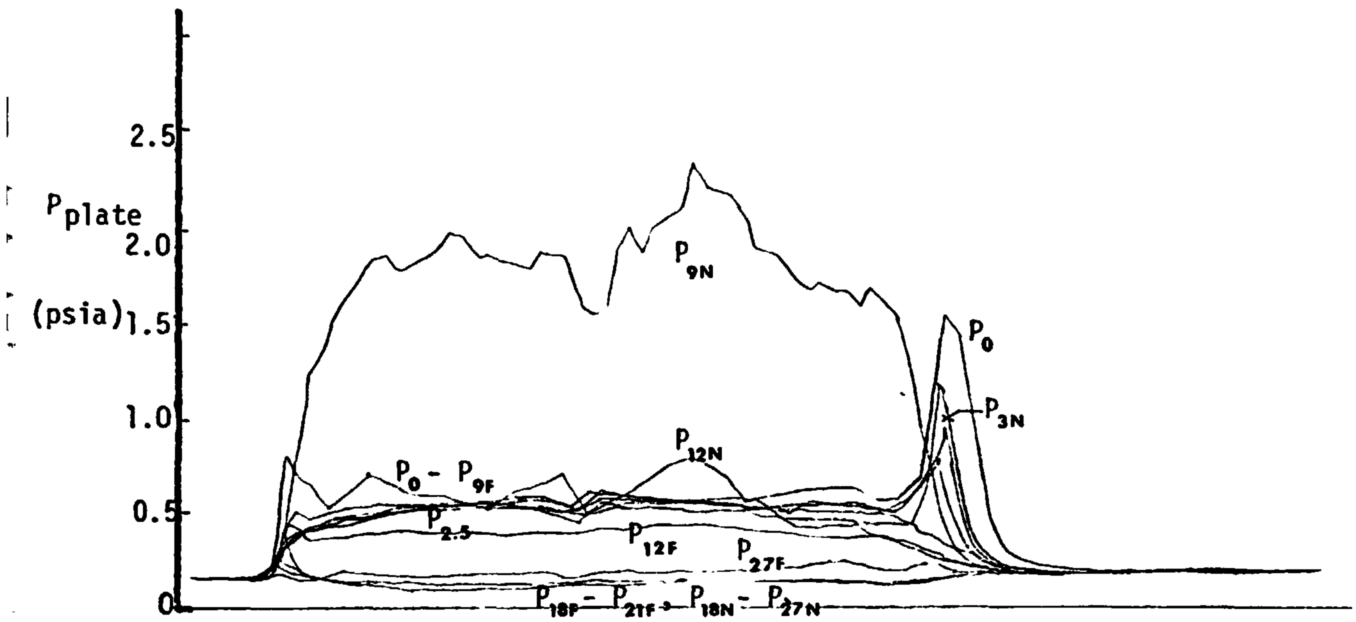
Run No. 27/2 (Concluded)

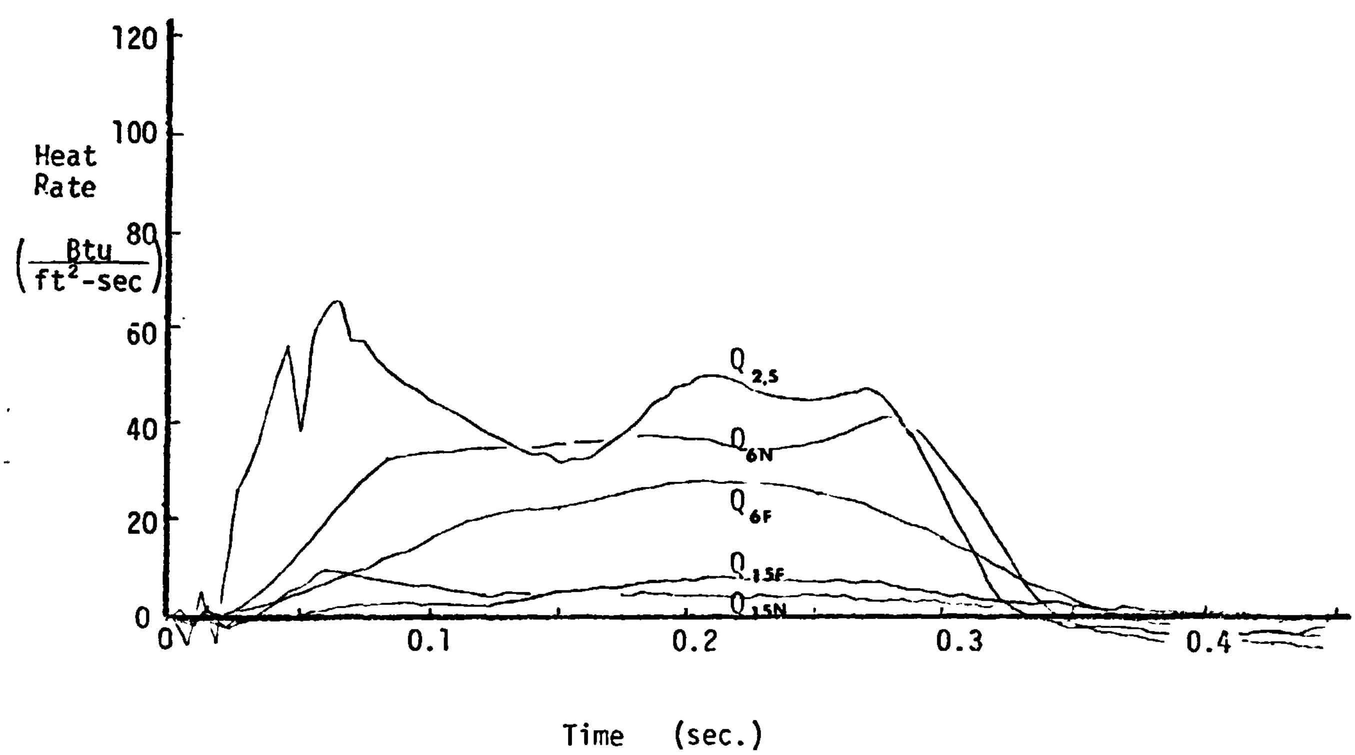


Run No. 28/1

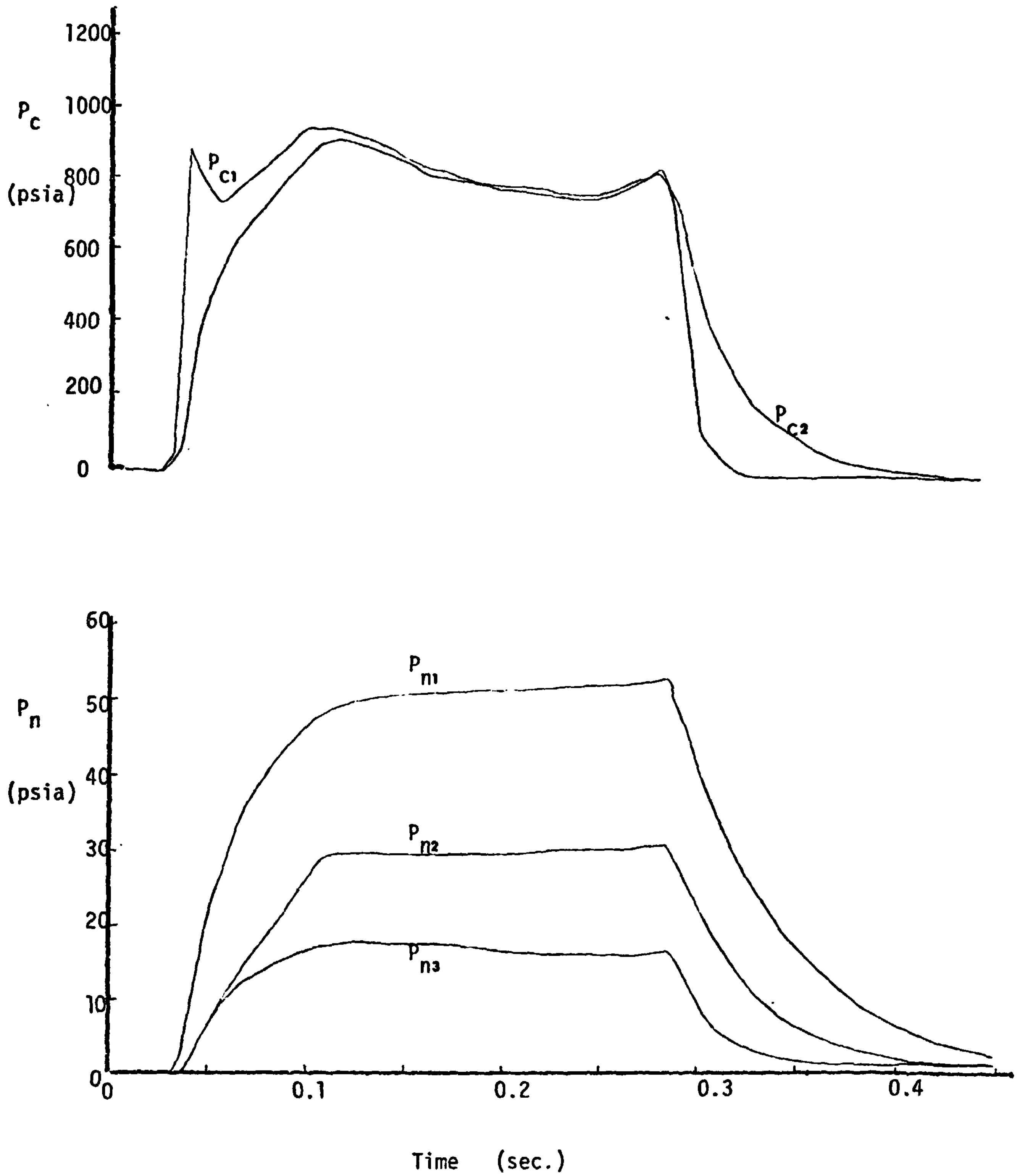
Plate @ X/D=20
ψ = 60°

Alt.=100,000'
%Aℓ = 2





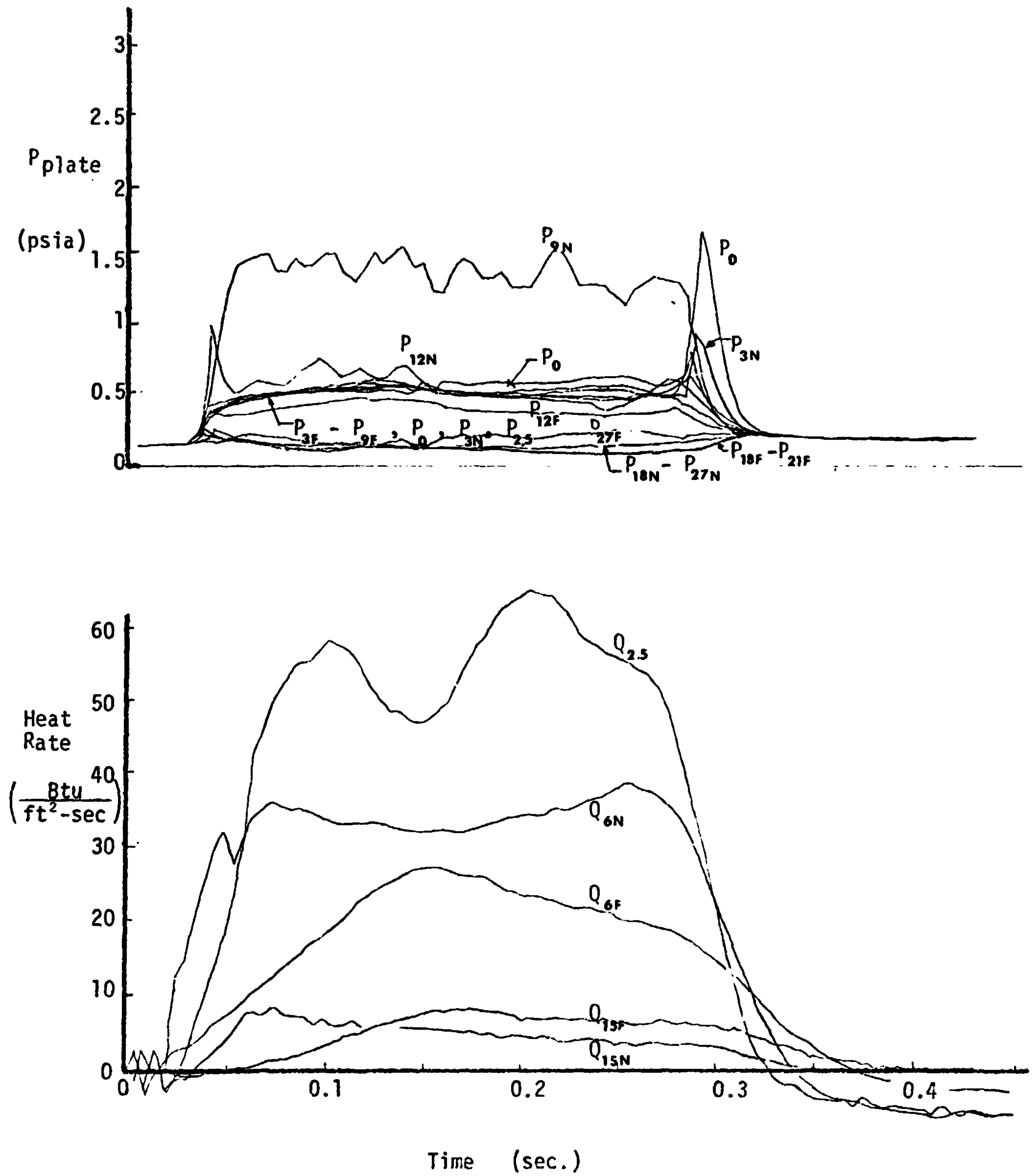
Run No. 28/1 (Concluded)



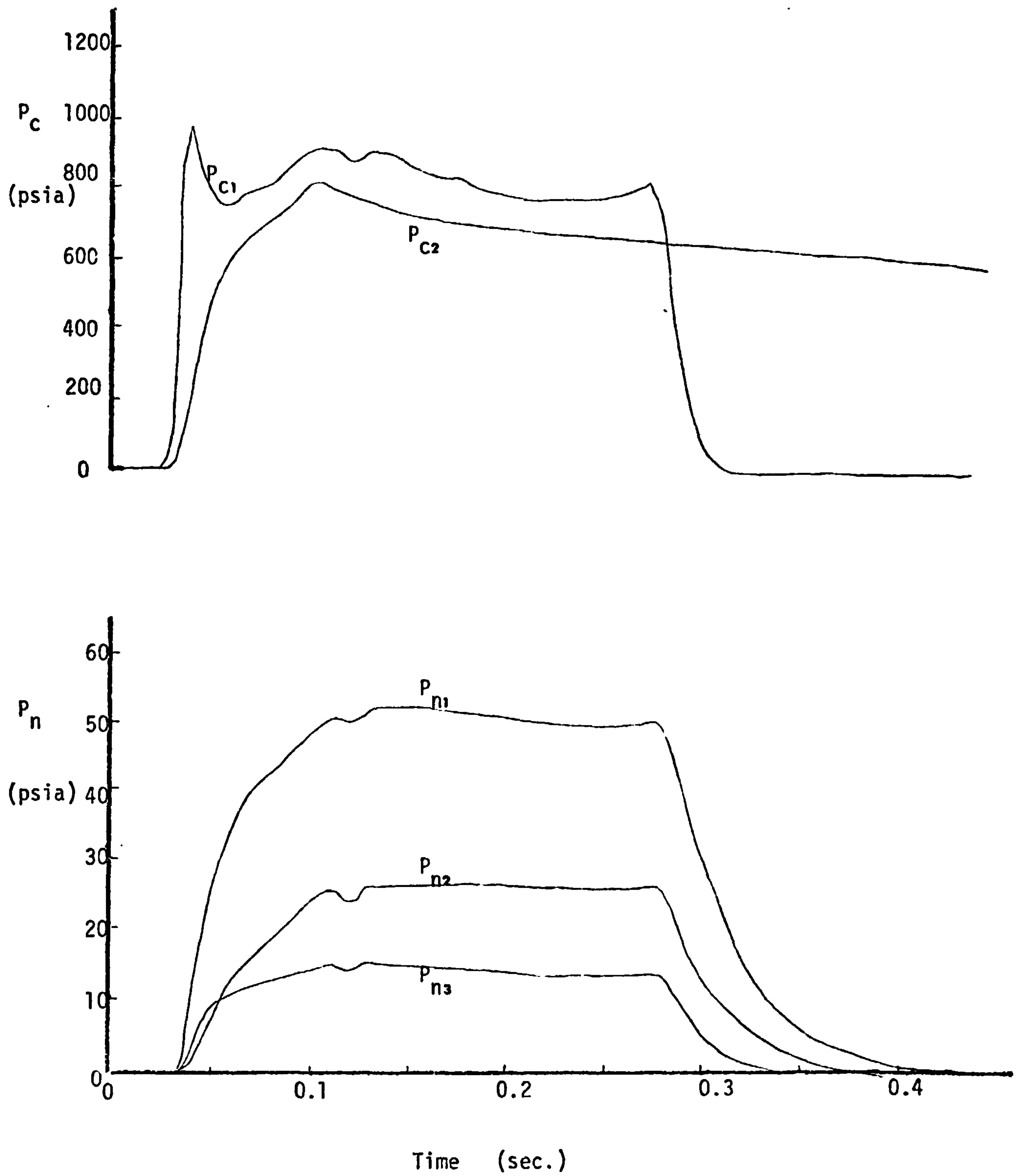
Run No. 28/2

Plate @ X/D=20
ψ = 60°

Alt.=100,000'
%Aℓ = 2



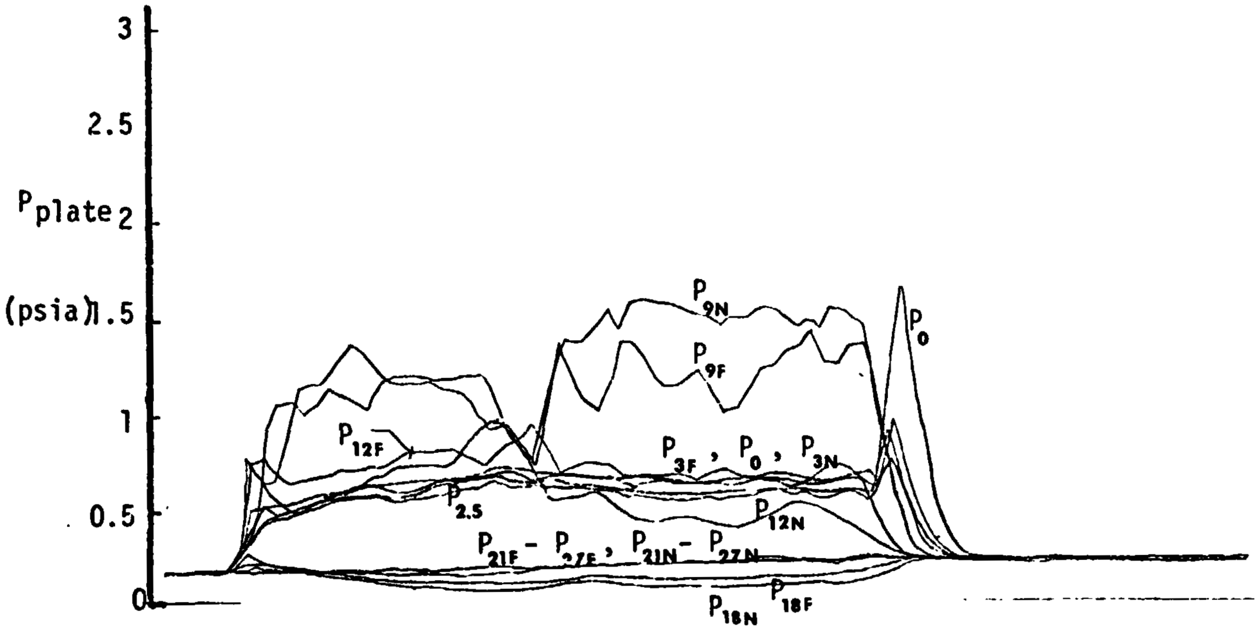
Run No. 28/2 (Concluded)

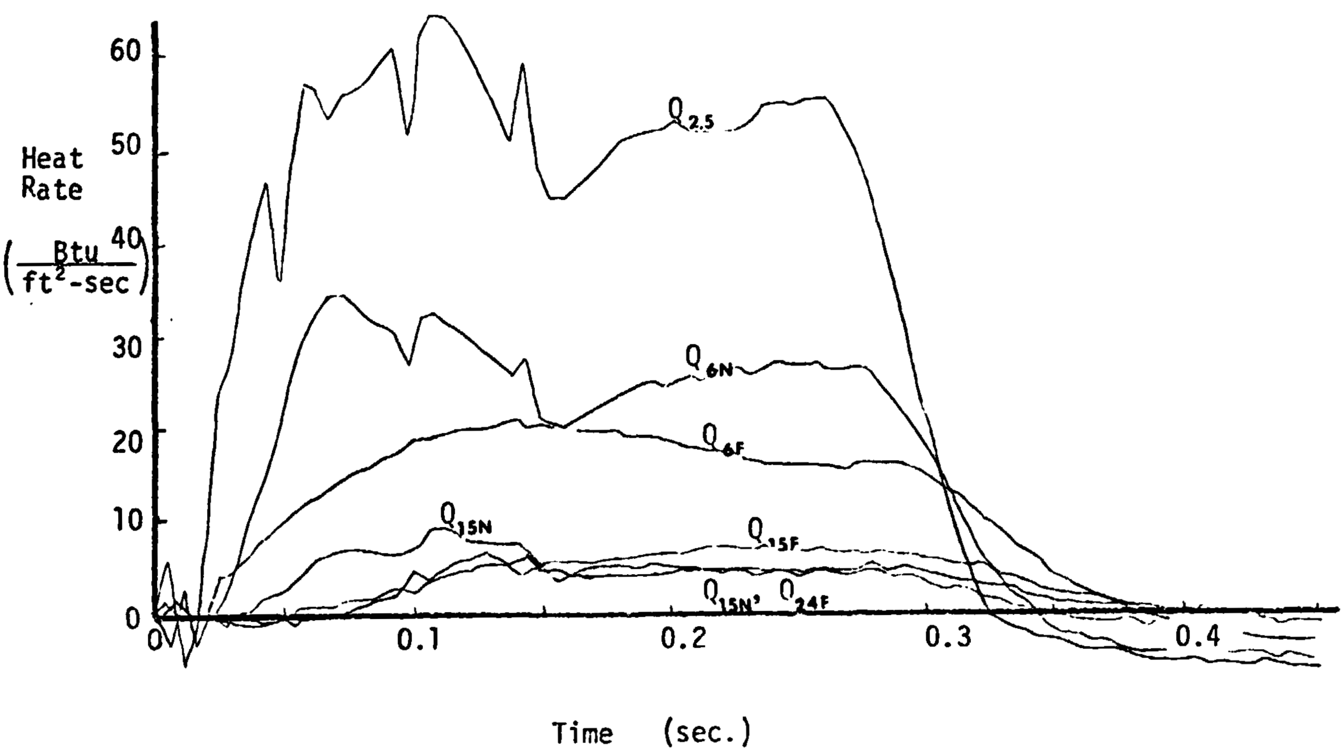


Run No. 29/1

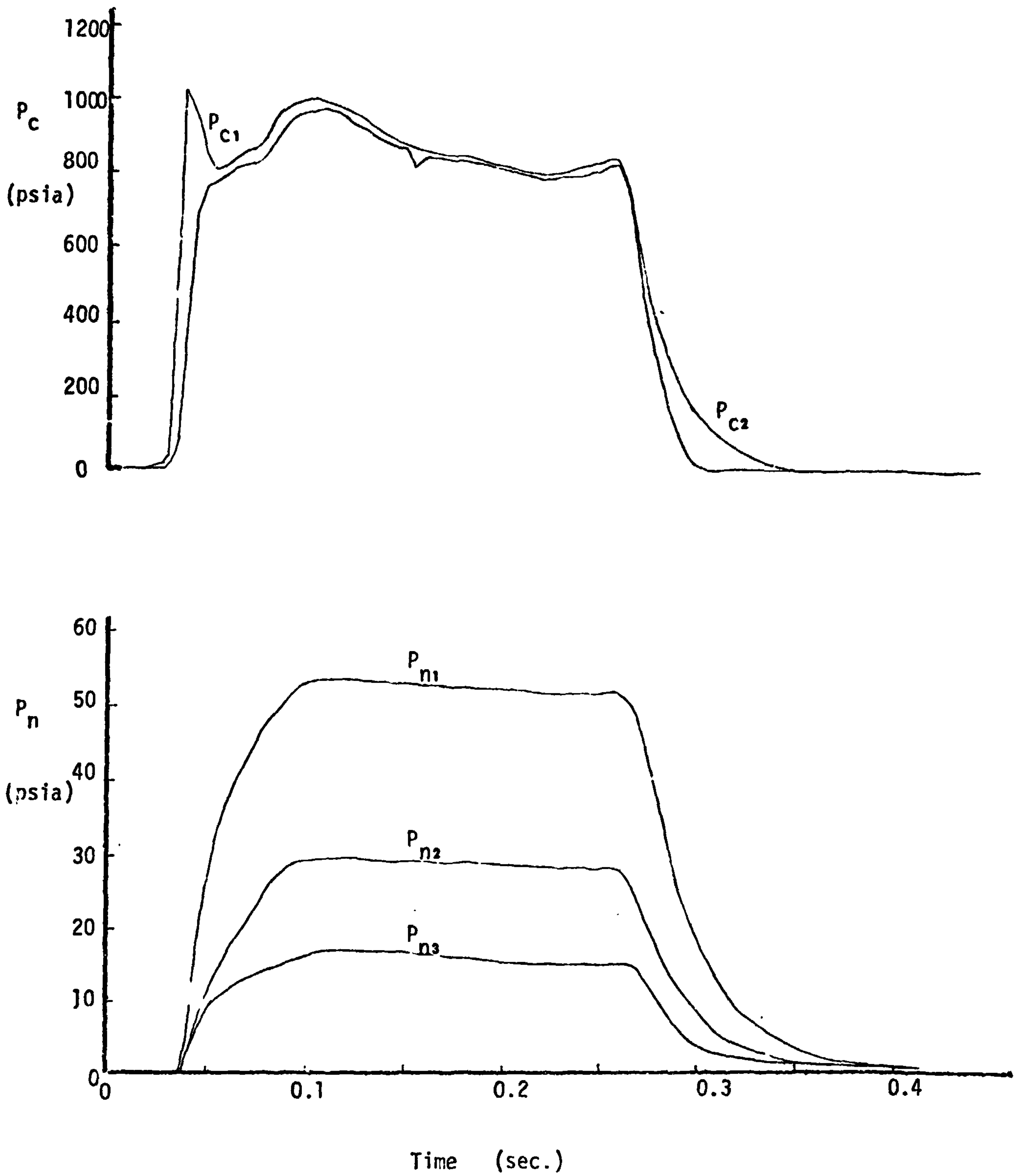
Plate @ X/D=20
ψ = 90°

Alt.=100,000'
%Aℓ = 2





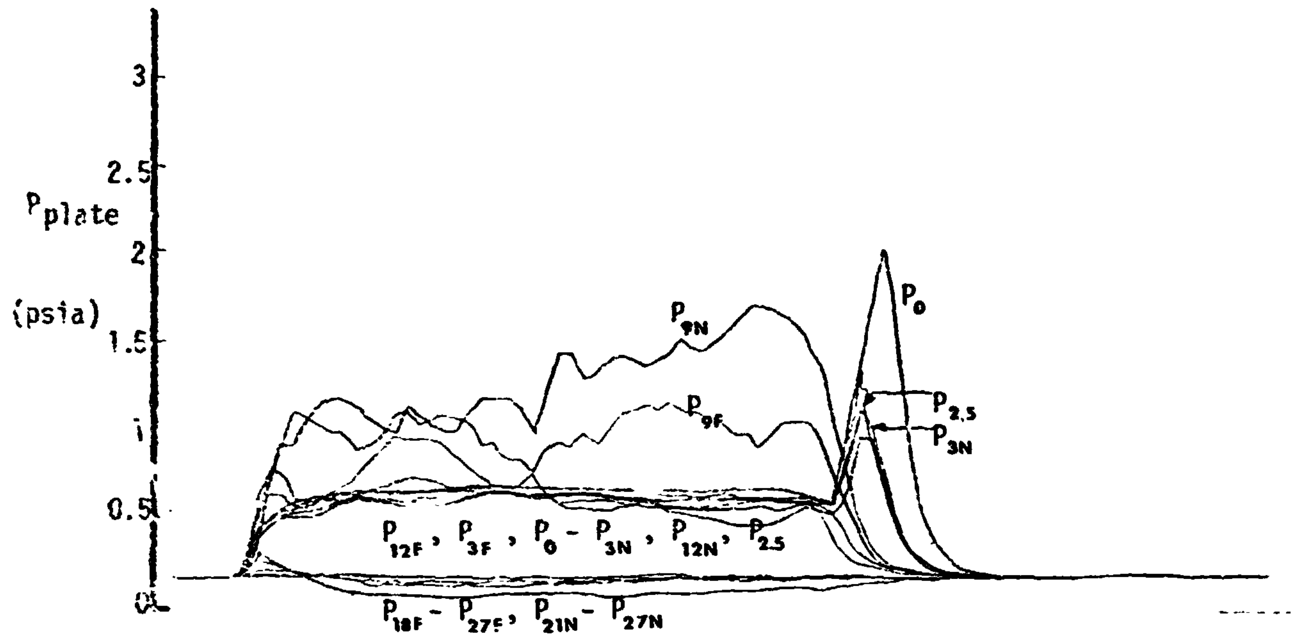
Run No. 29/1 (Concluded)

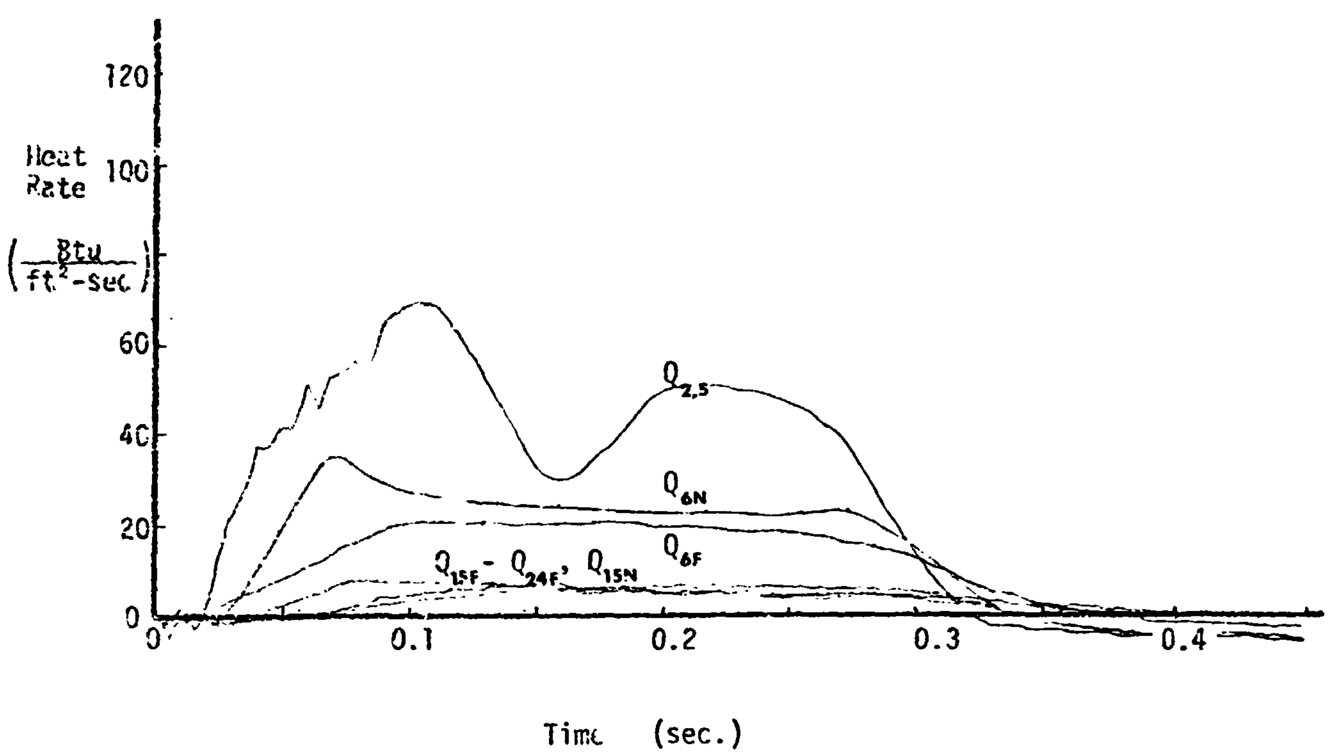


Run No. 29/2

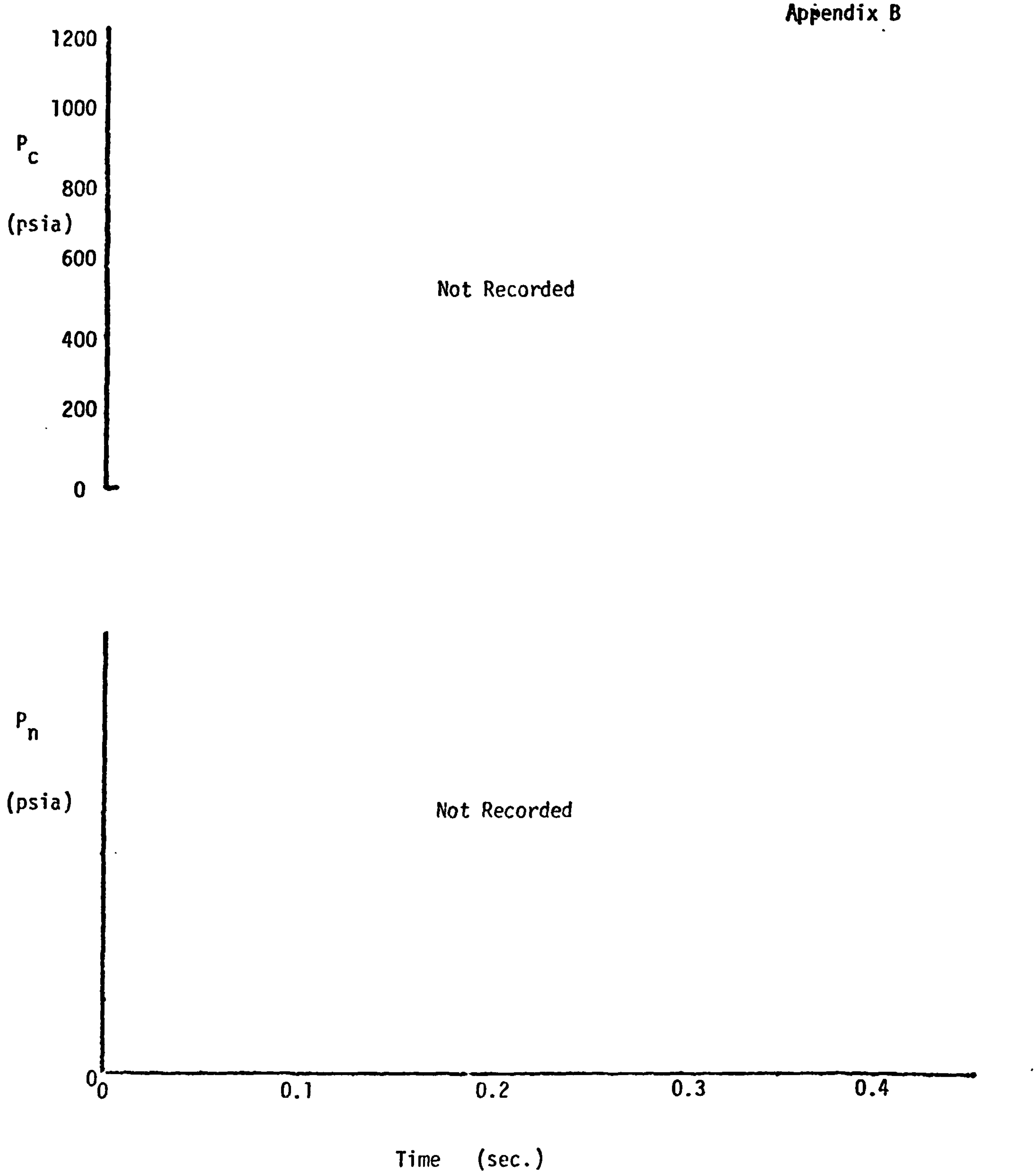
Plate @ X/D=20
ψ = 90°

Alt.=100,000'
%Aℓ = 2





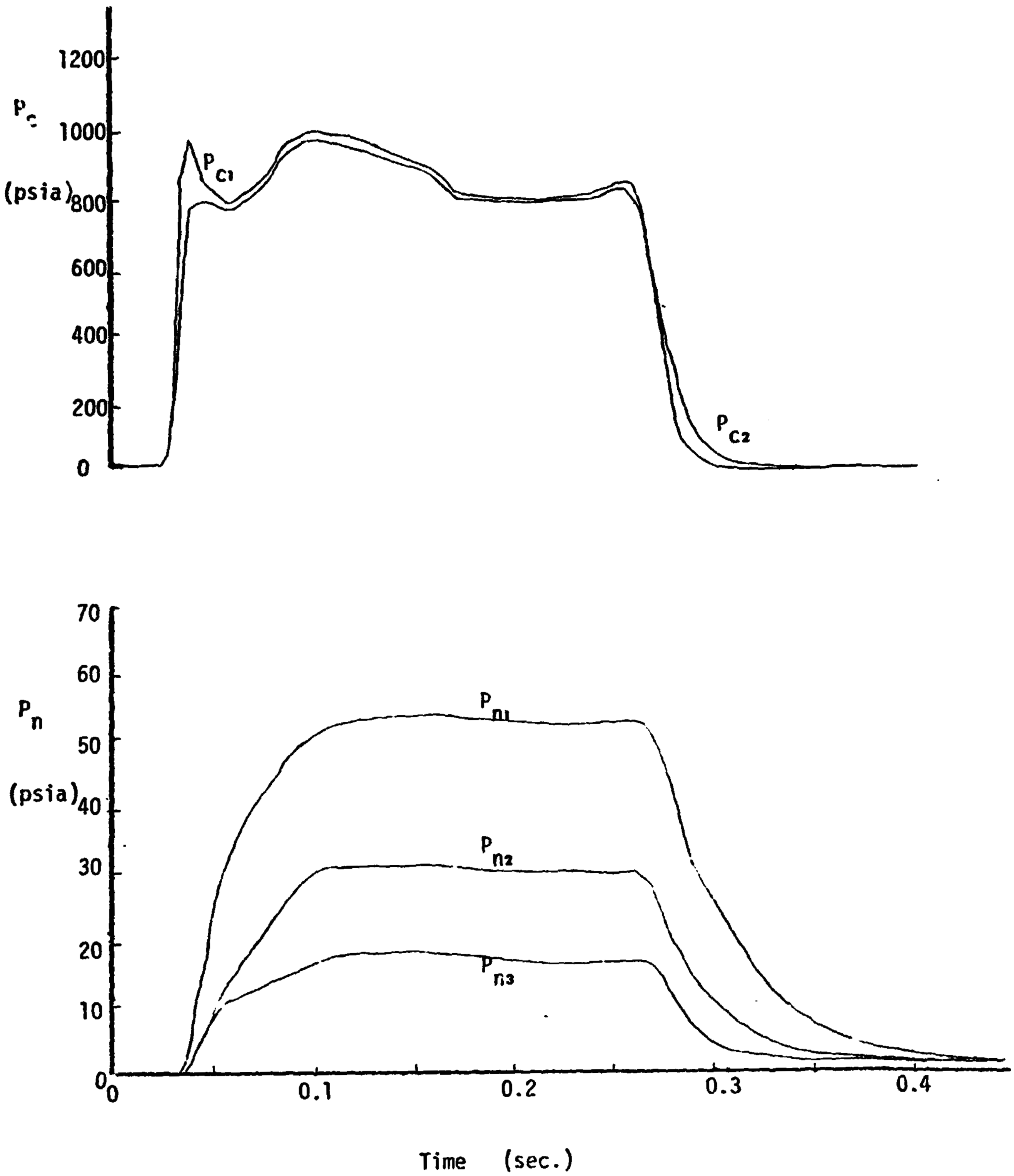
Run No. 29/2 (Concluded)



Run No. 30/1

Particle
X/D=20

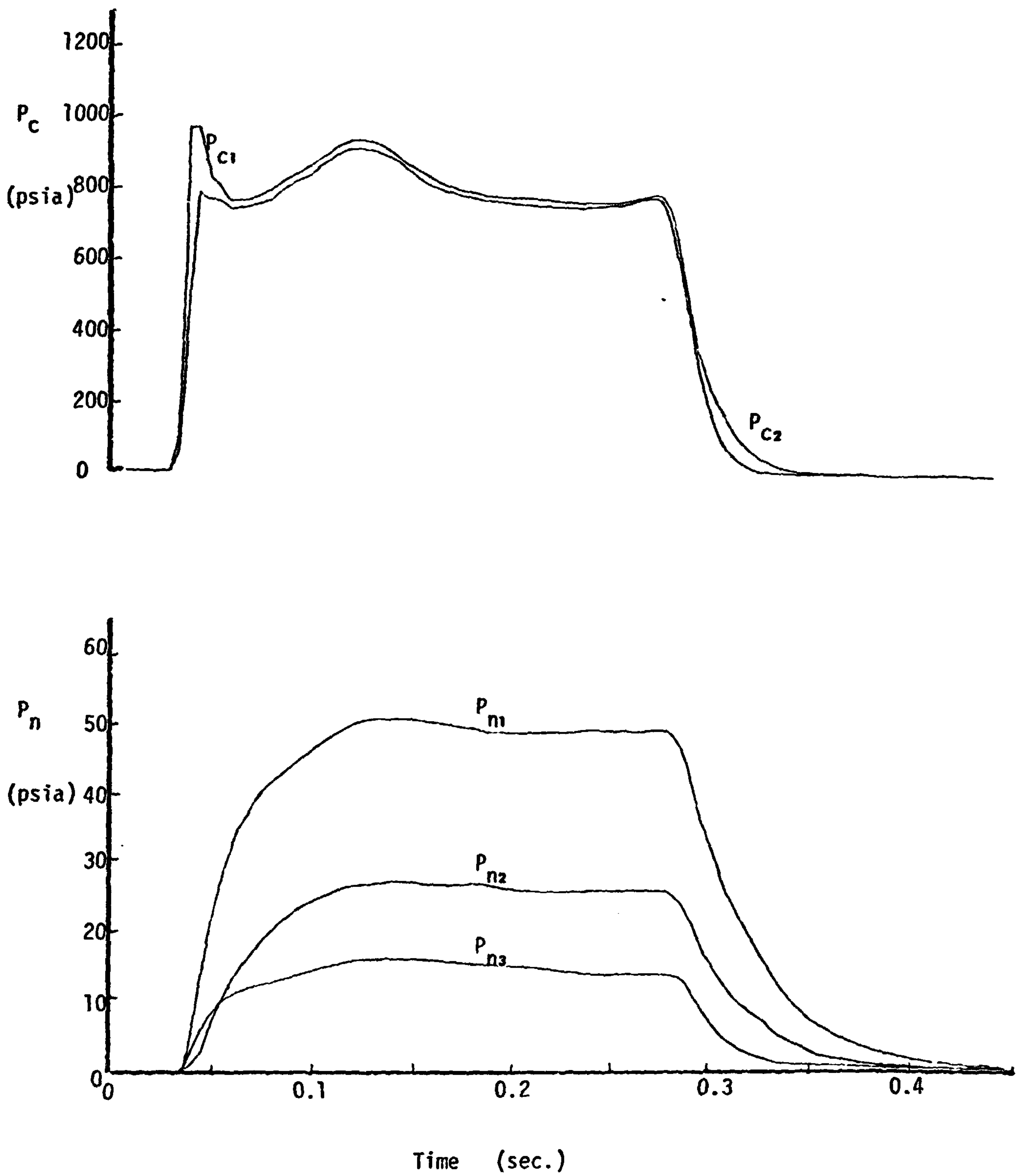
Alt.=100,000'
%Aℓ = 2



Run No. 30/2

Particle
X/D=20

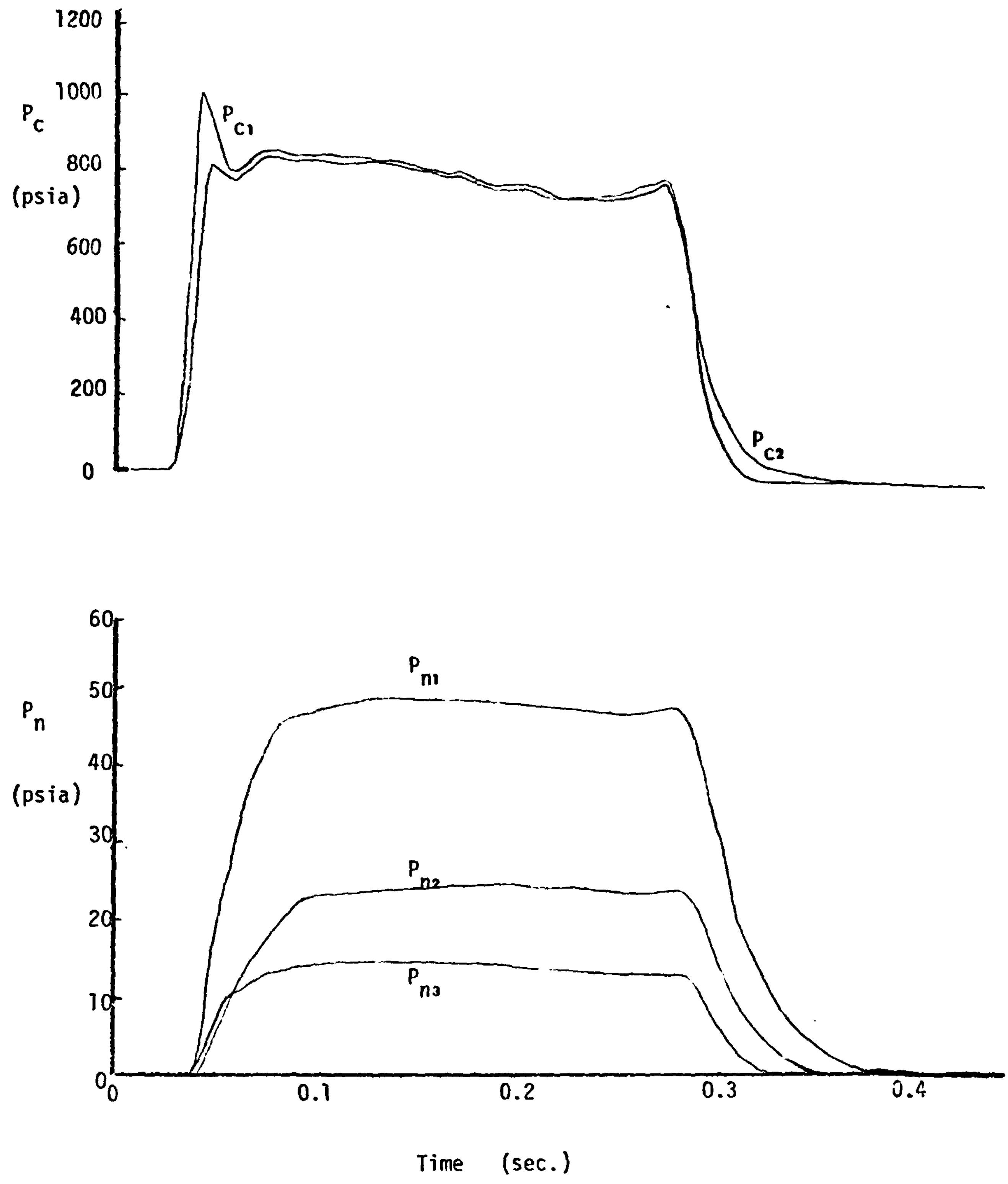
Alt.=100,000'
%Aℓ = 2



Run No. 31/1

Particle
X/D=12

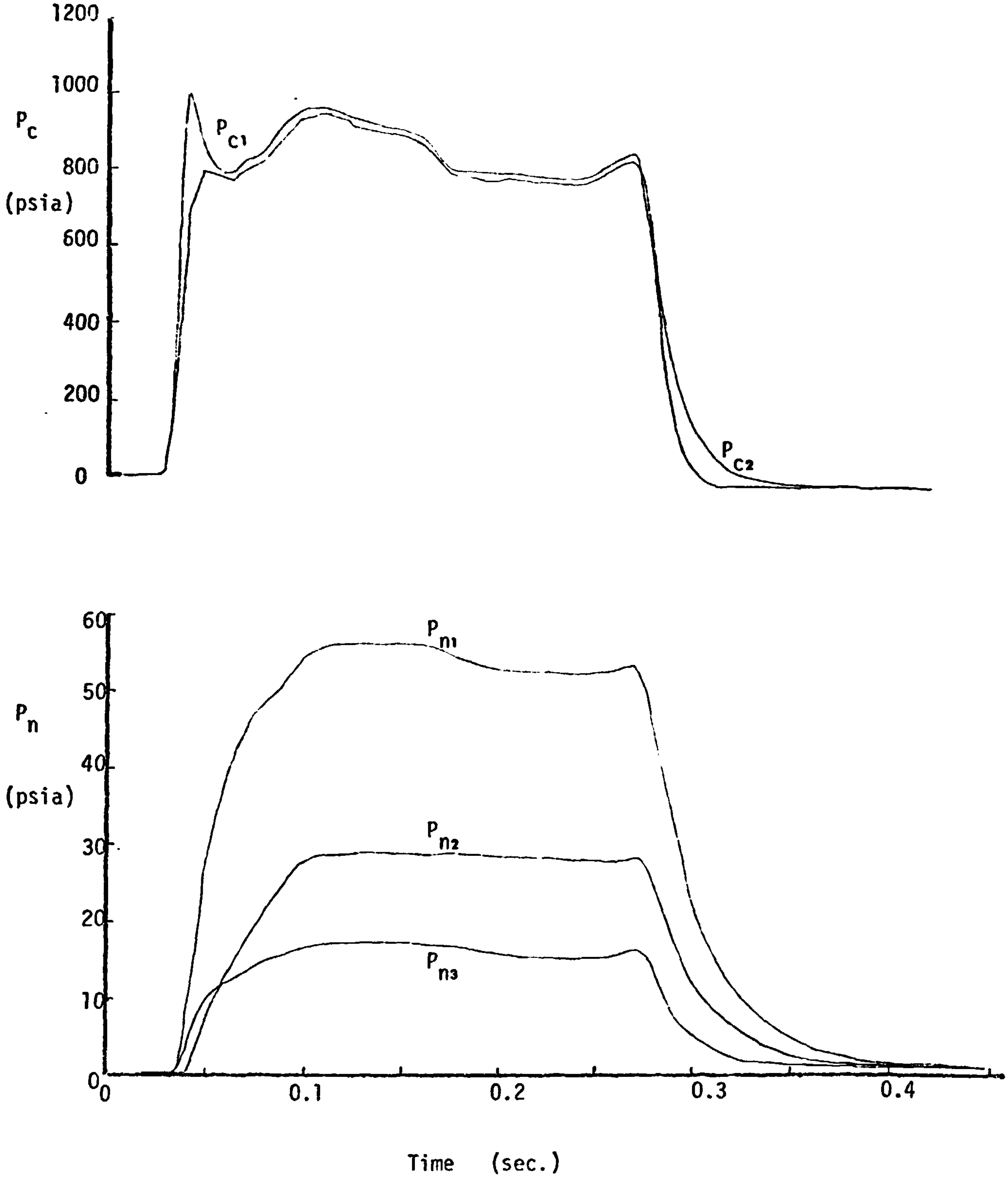
Alt.=100,000'
%Aℓ = 2



Run No. 31/2

Particle
X/D=12

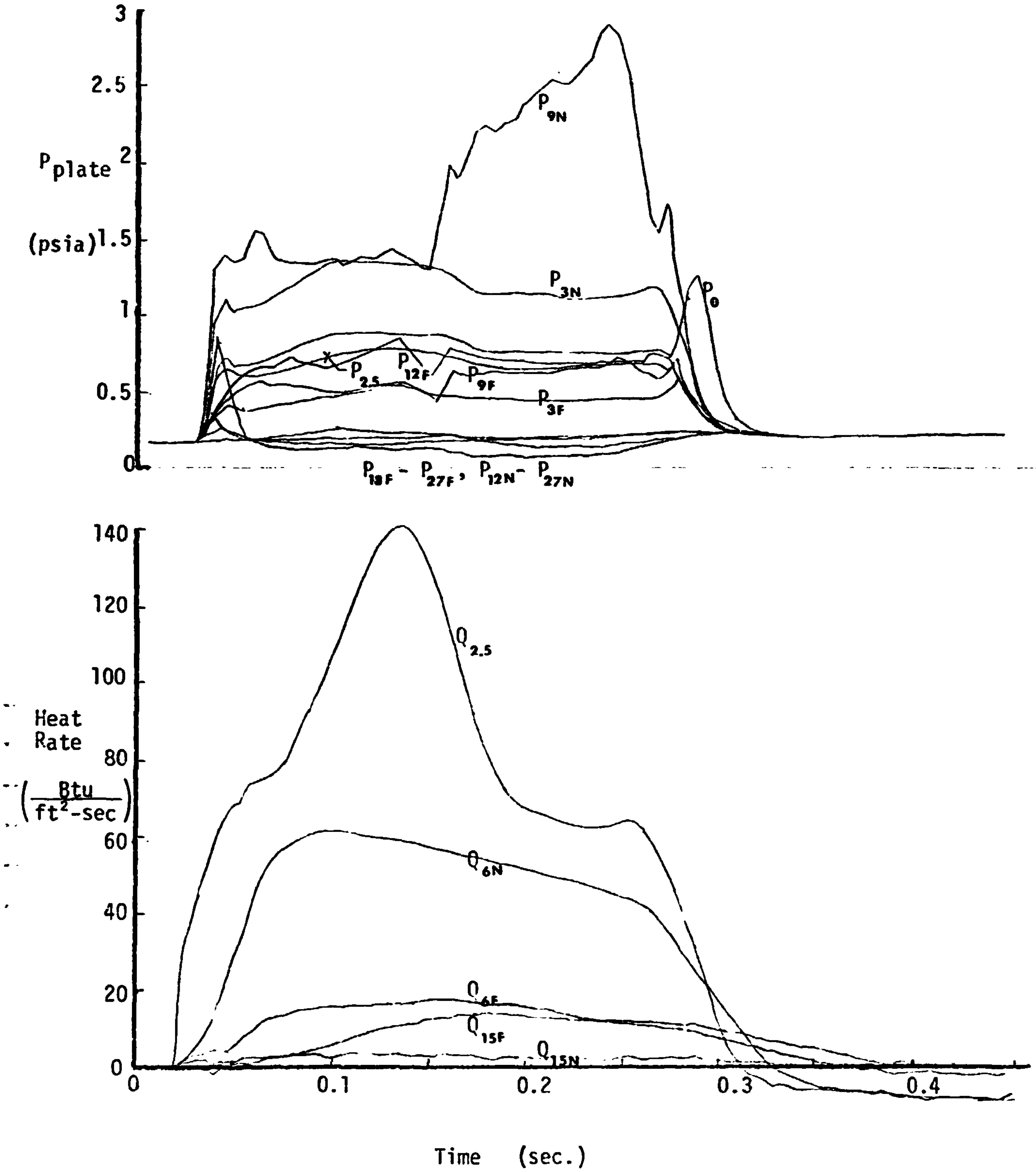
Alt.=100,000'
%Aℓ = 2



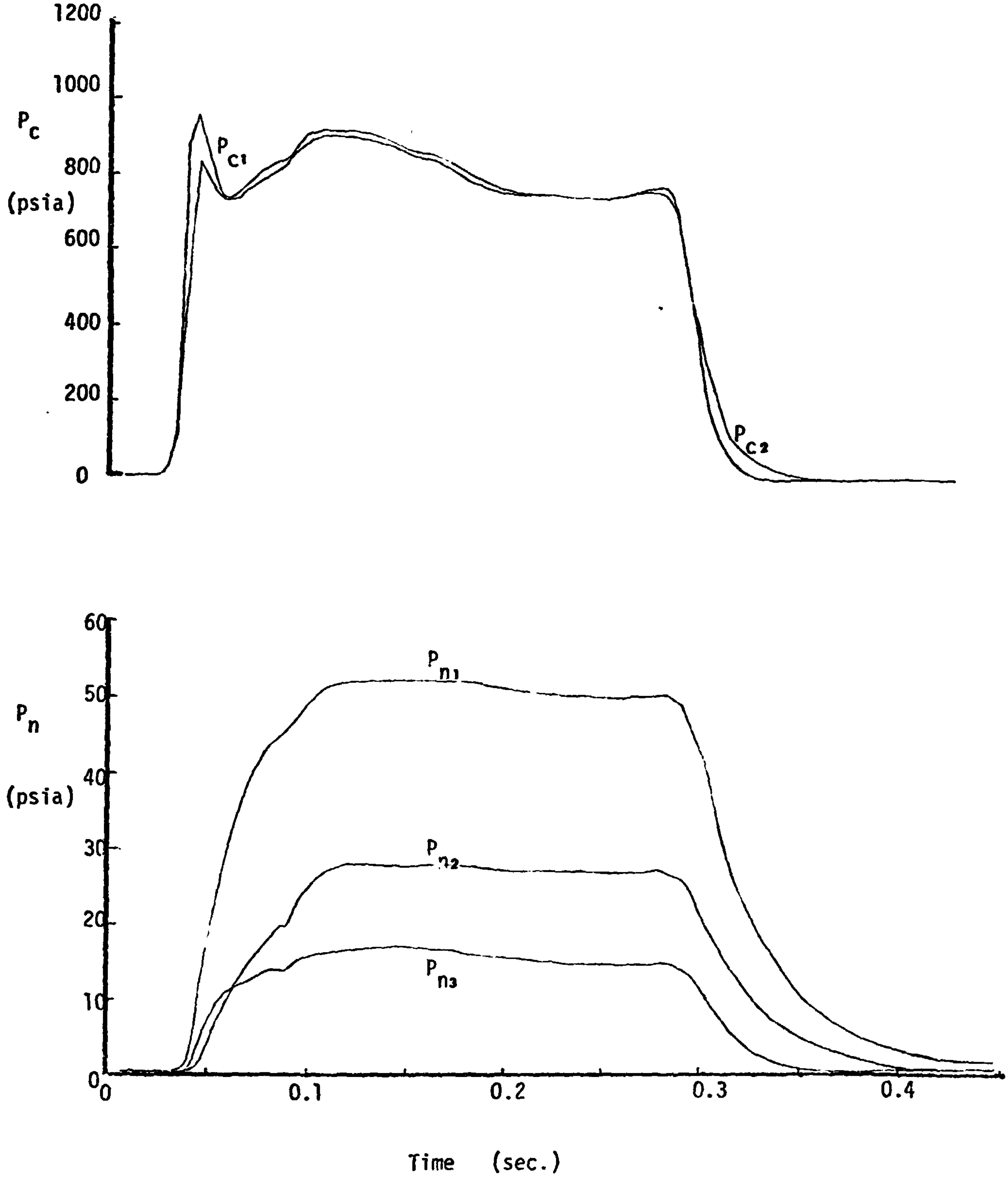
Run No. 32/1

Plate @ X/D=12
ψ = 45°

Alt.=100,000'
%Aℓ = 2



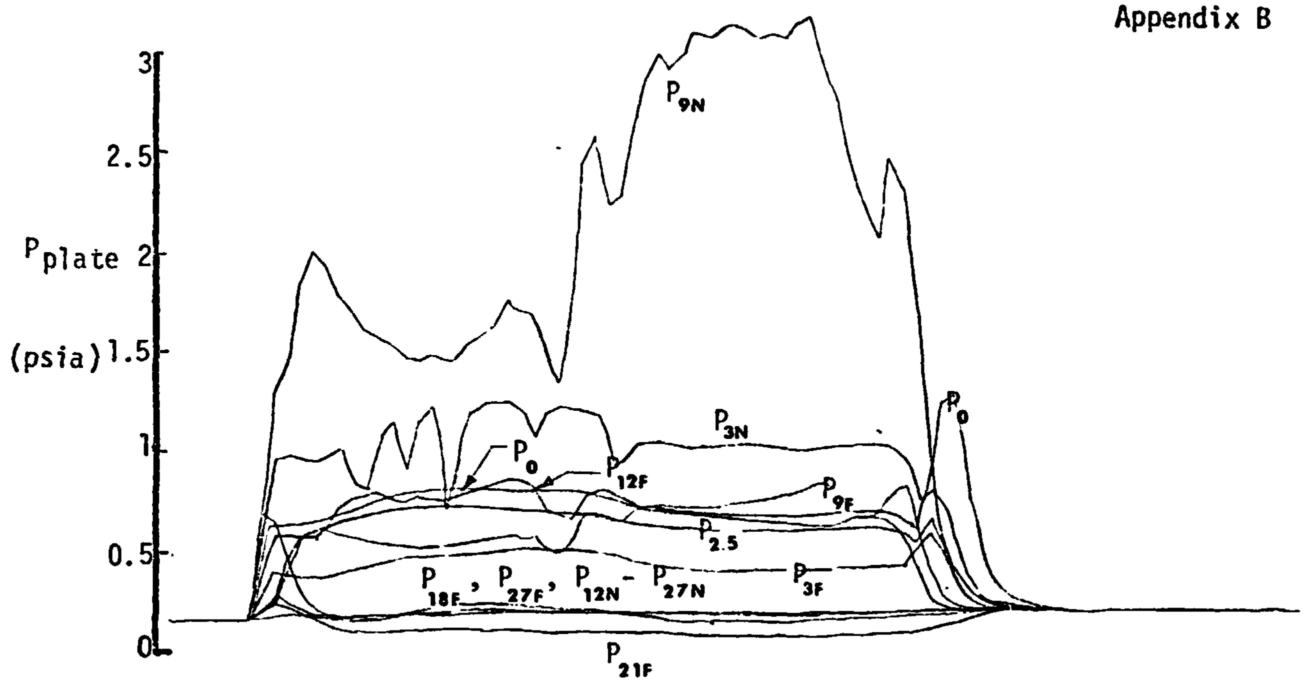
Run No. 32/1 (Concluded)

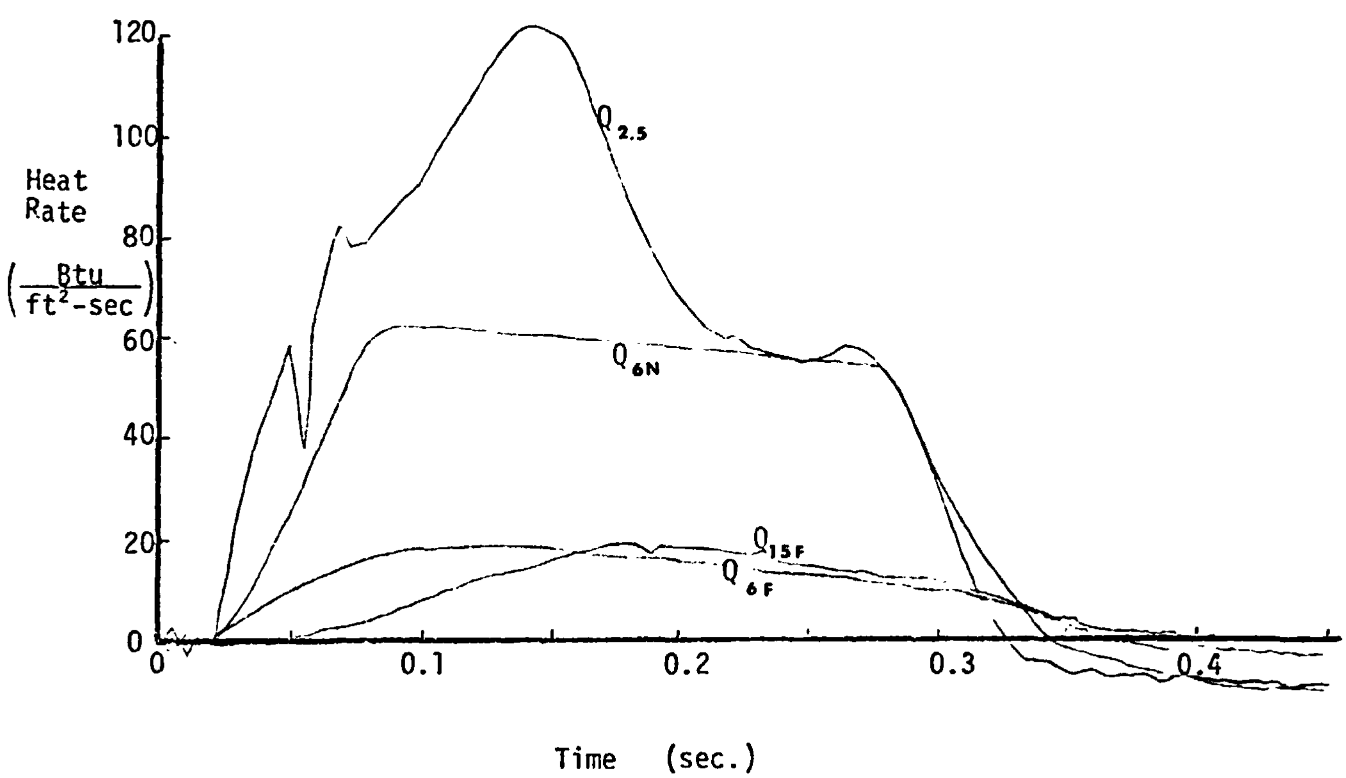


Run No. 32/2

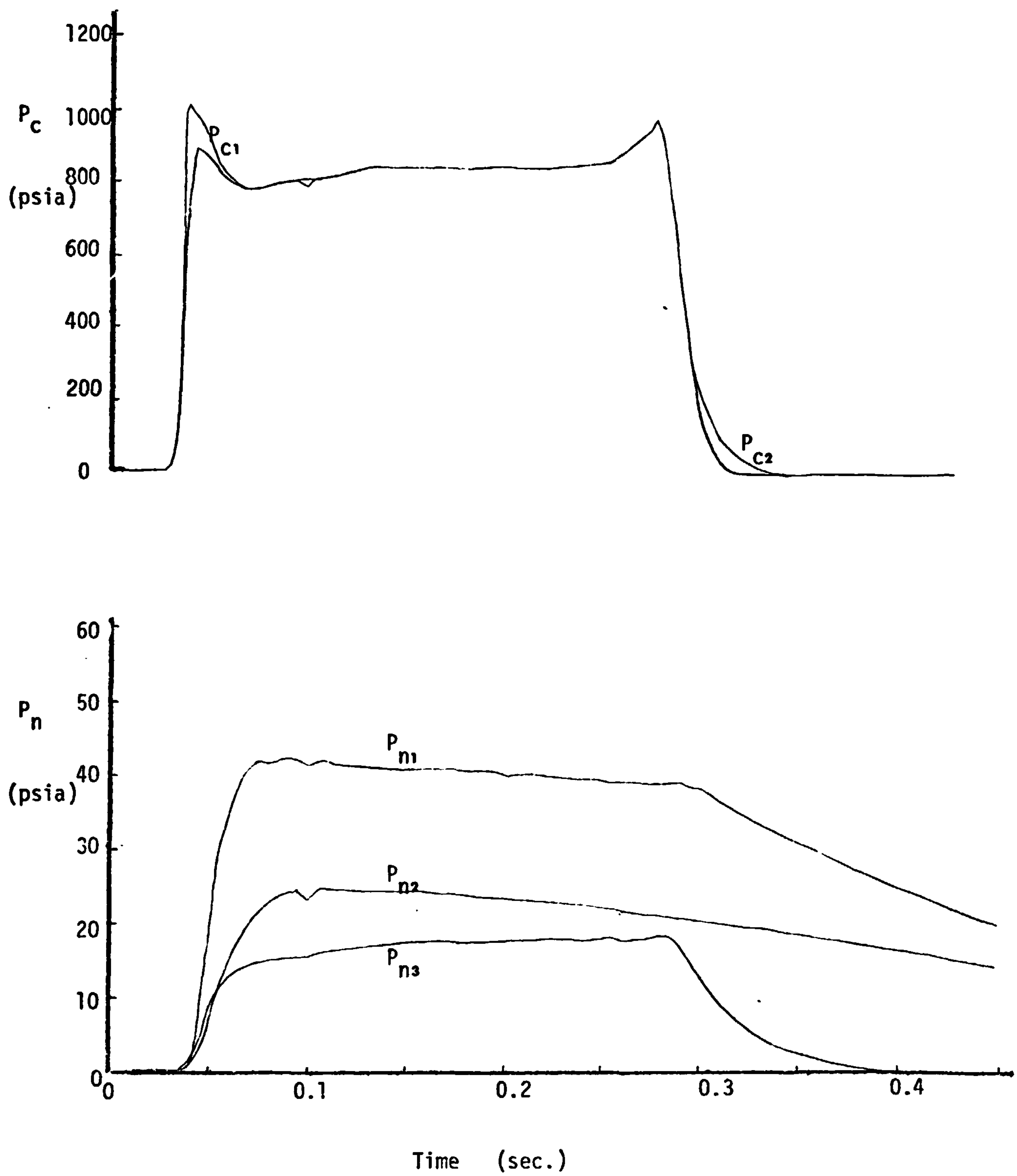
Plate @ X/D=12
ψ = 45°

Alt.=100,000'
%Aℓ = 2





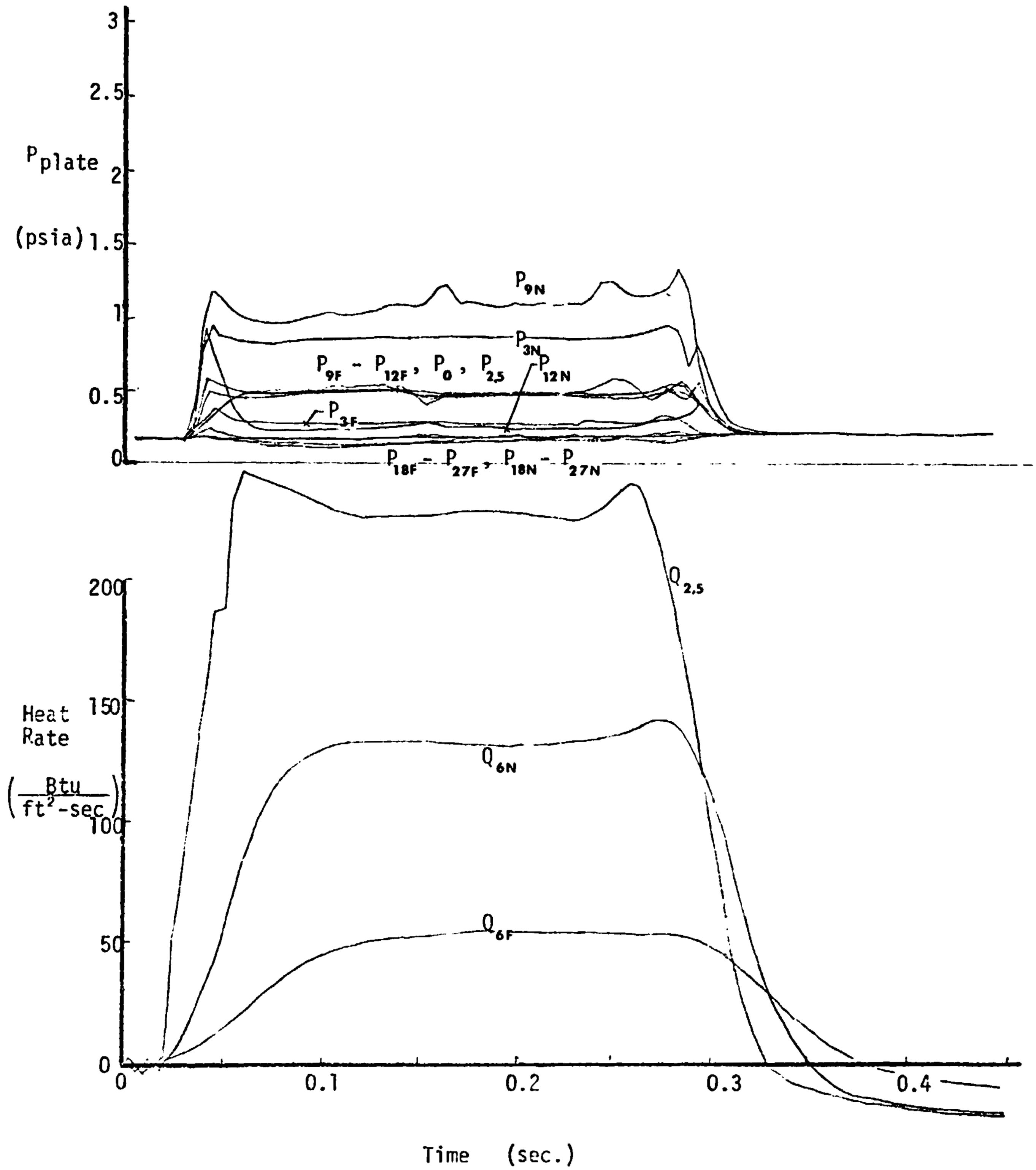
Run No. 32/2 (Concluded)



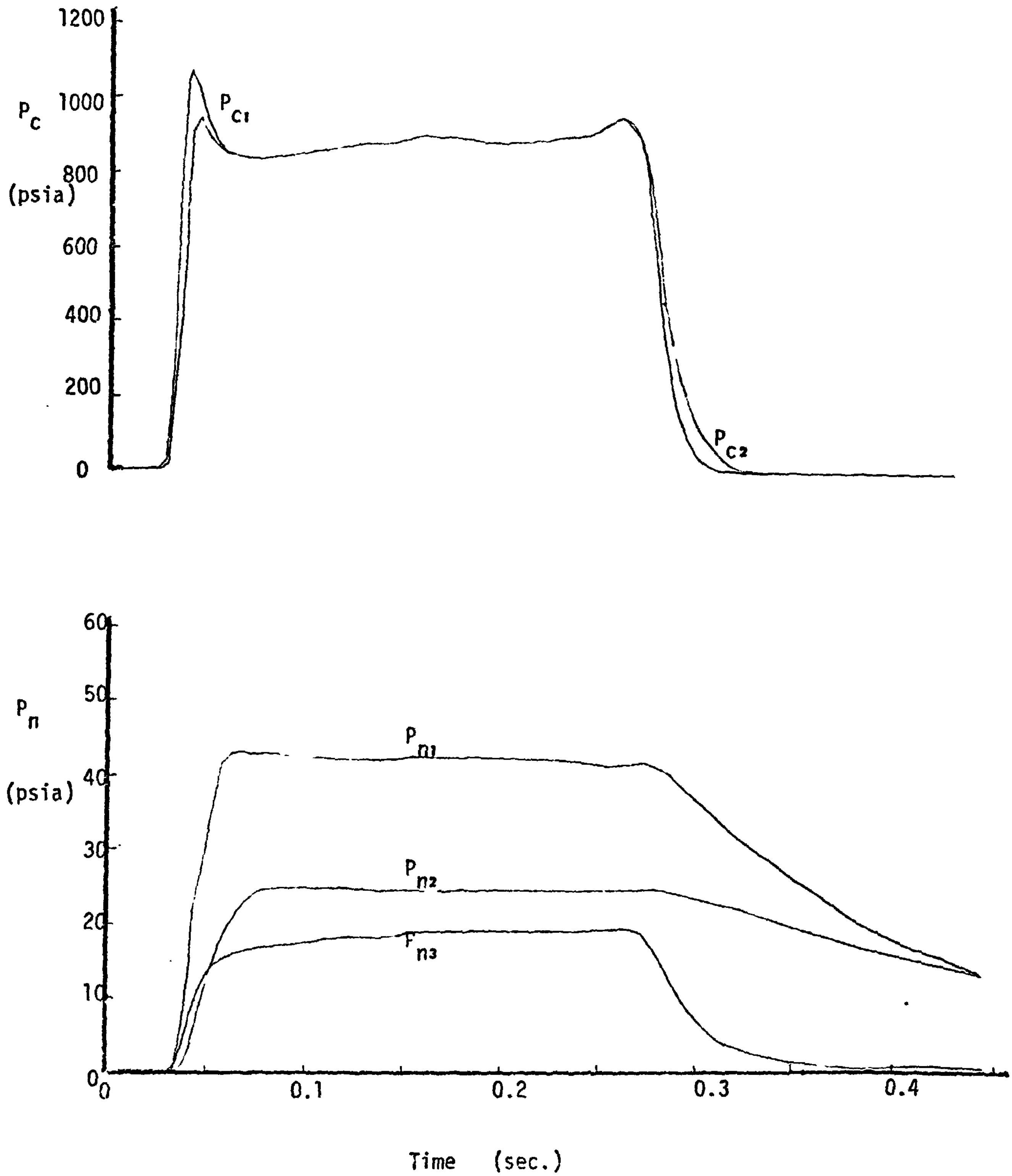
Run No. 33/1

Plate @ X/D=12
ψ = 45°

Alt.=100,000'
%Aℓ =10



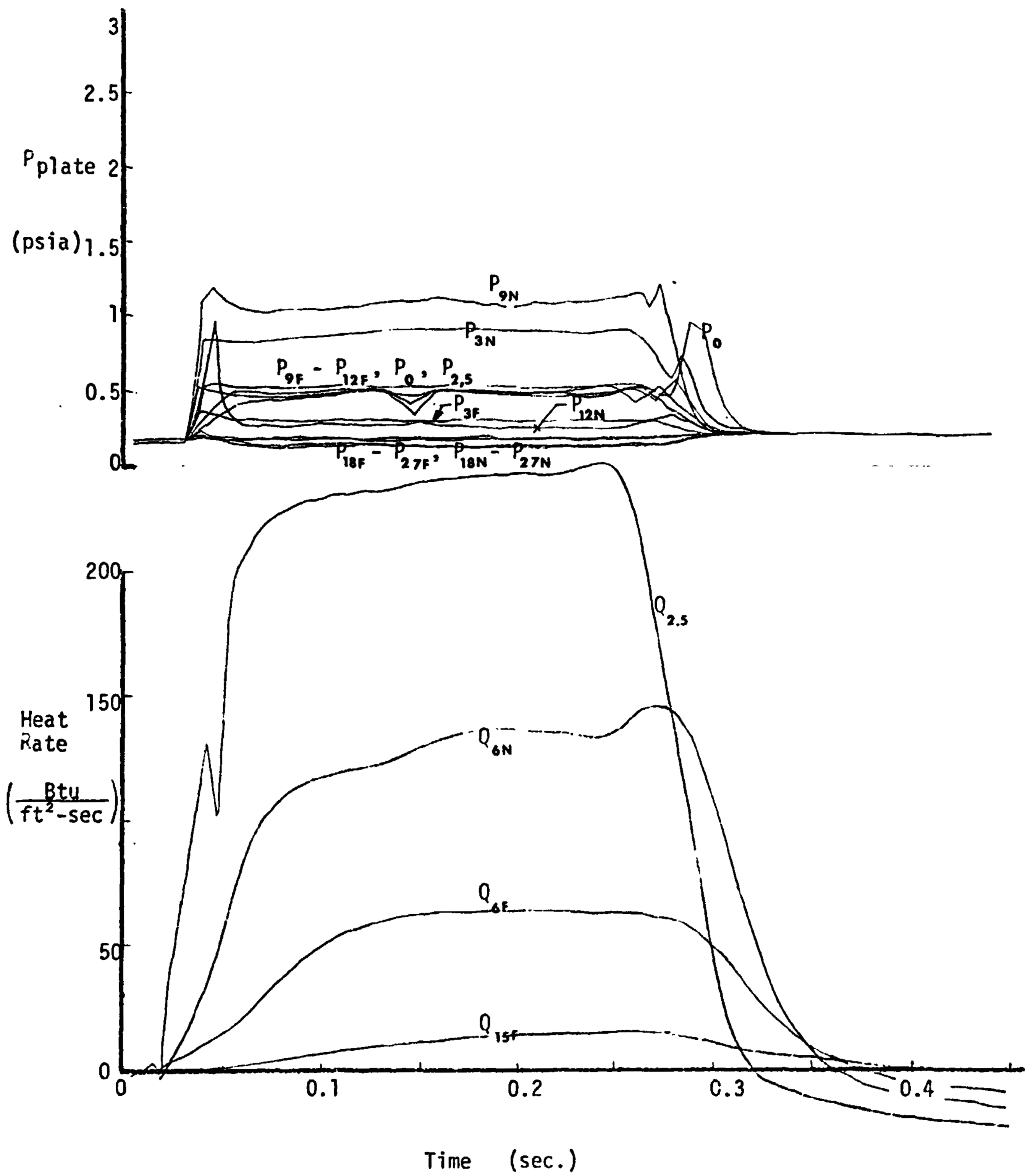
Run No. 33/1 (Concluded)



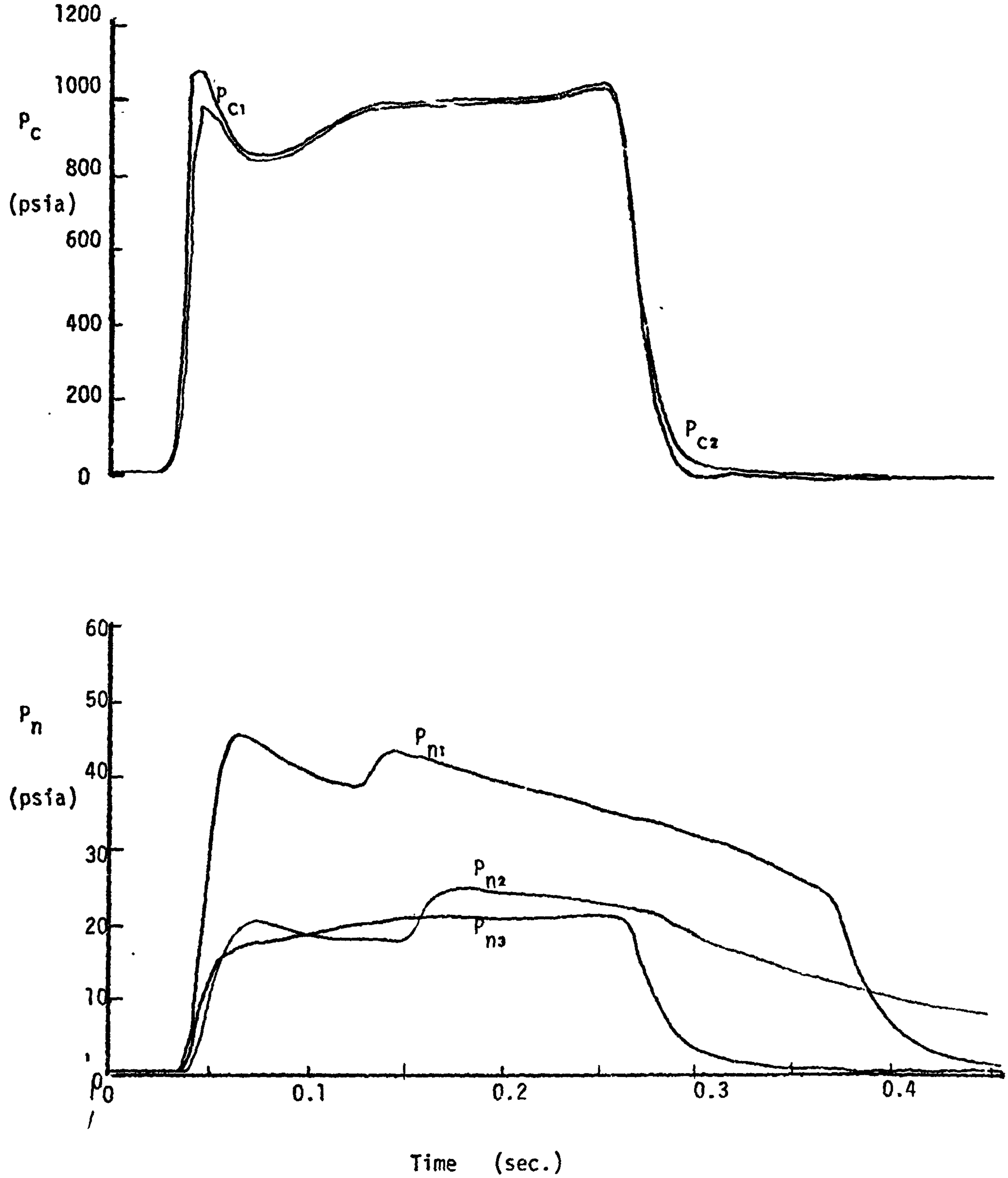
Run No. 33/2

Plate @ X/D=12
ψ = 45°

Alt.=100,000'
%Aℓ = 10



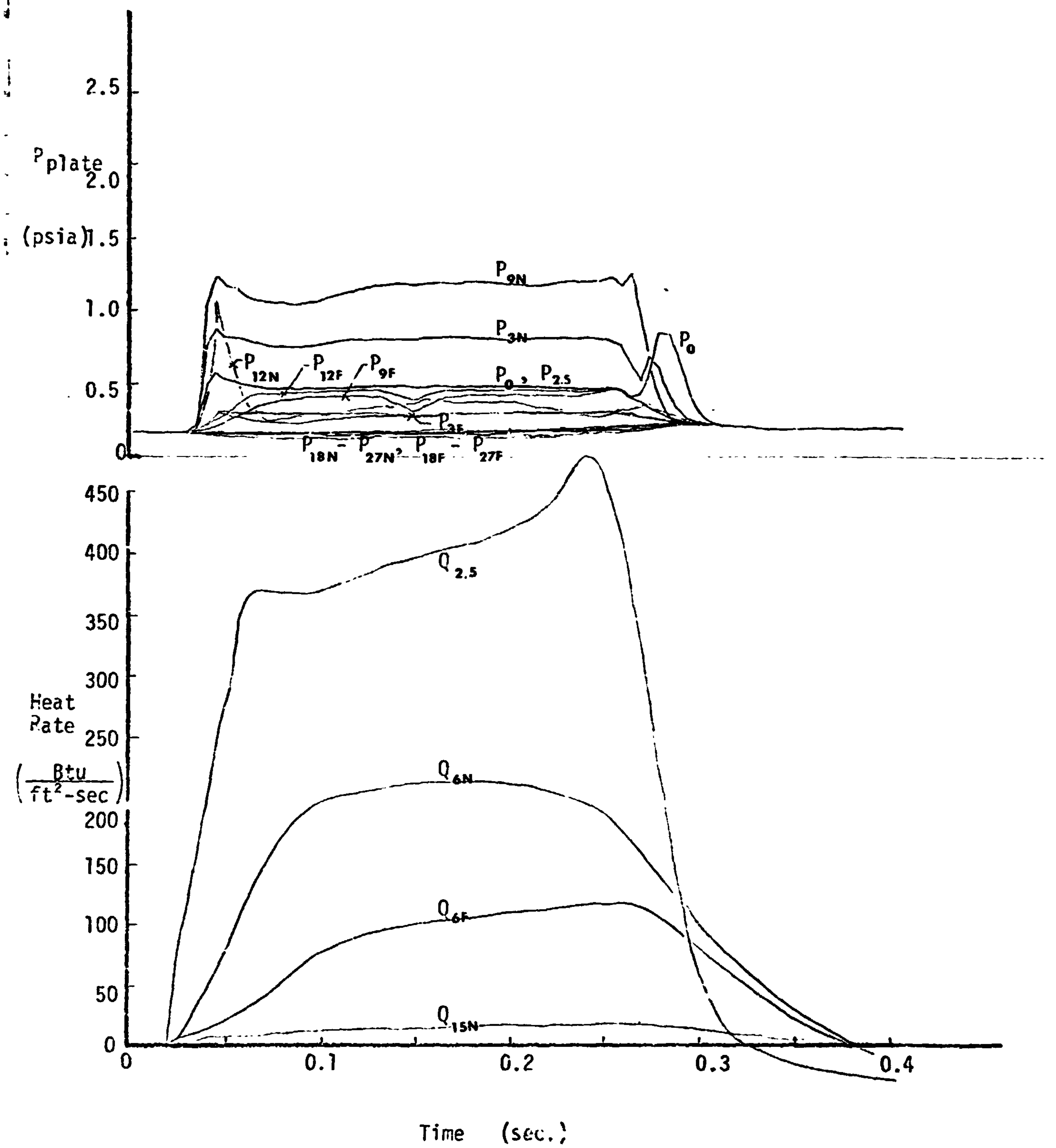
Run No. 33/2 (Concluded)



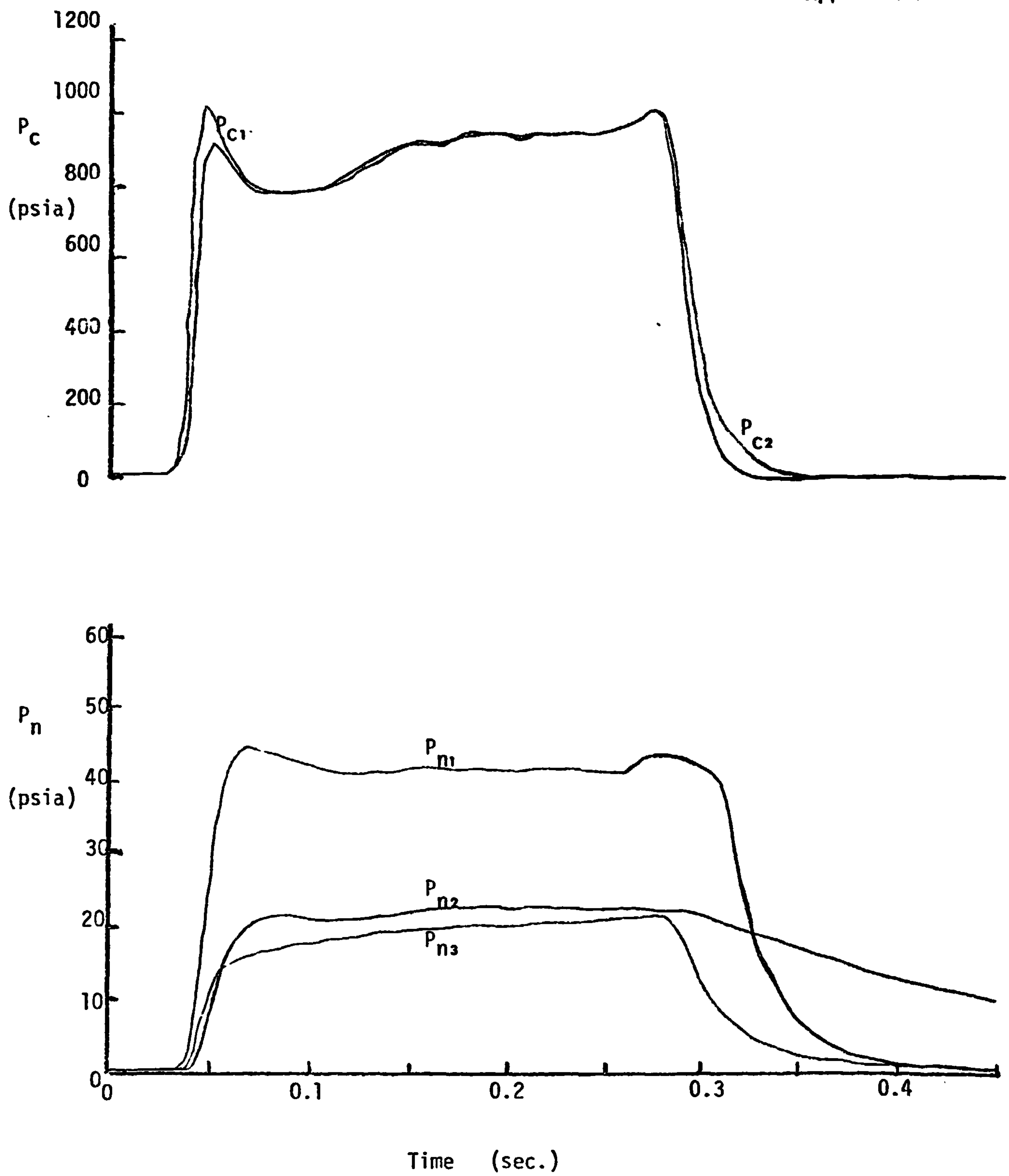
Run No. 34/1

Plate @ X/D=12
ψ = 45°

Alt.=100,000'
%Aℓ = 15



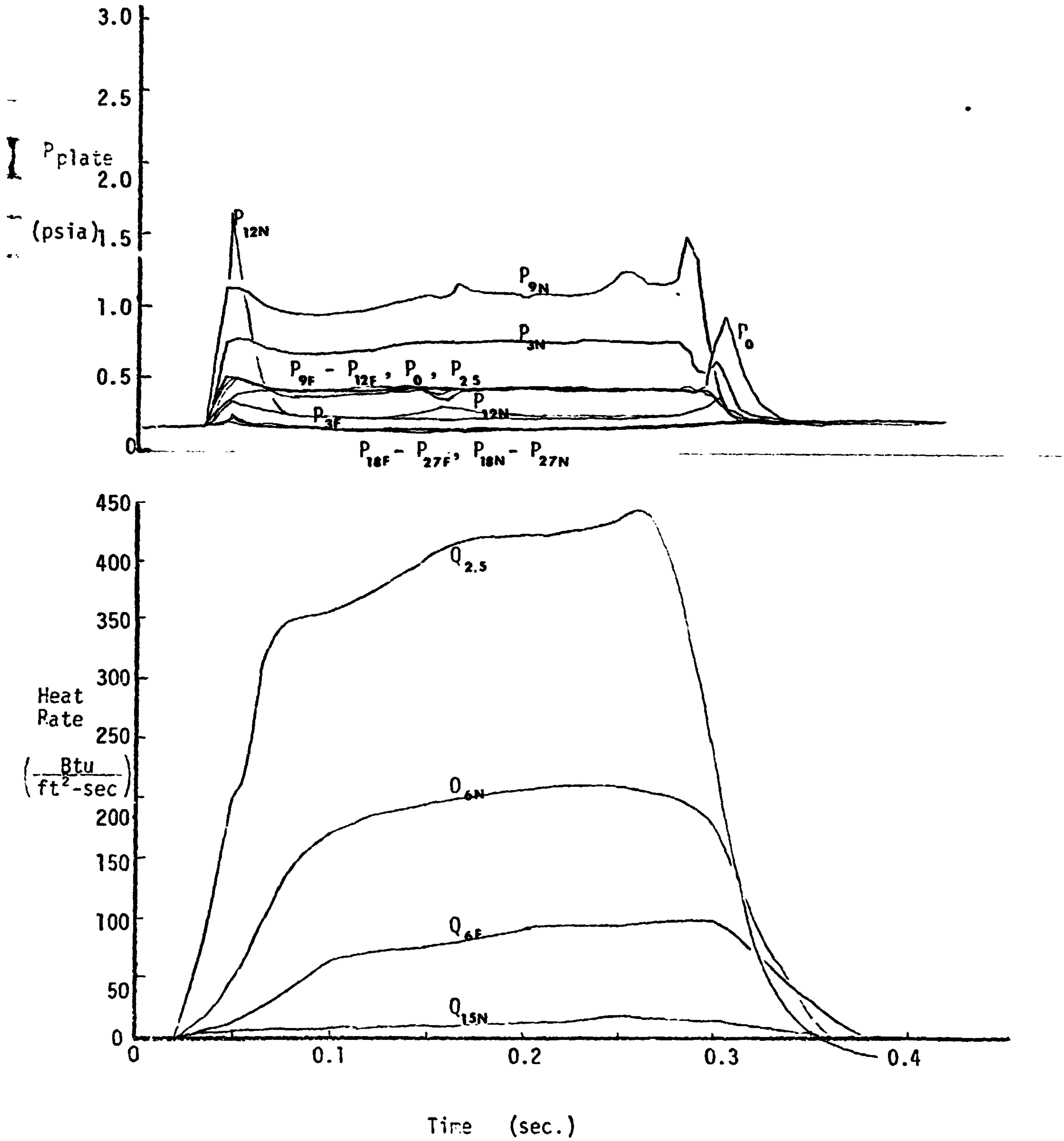
Run No. 34/1 (Concluded)



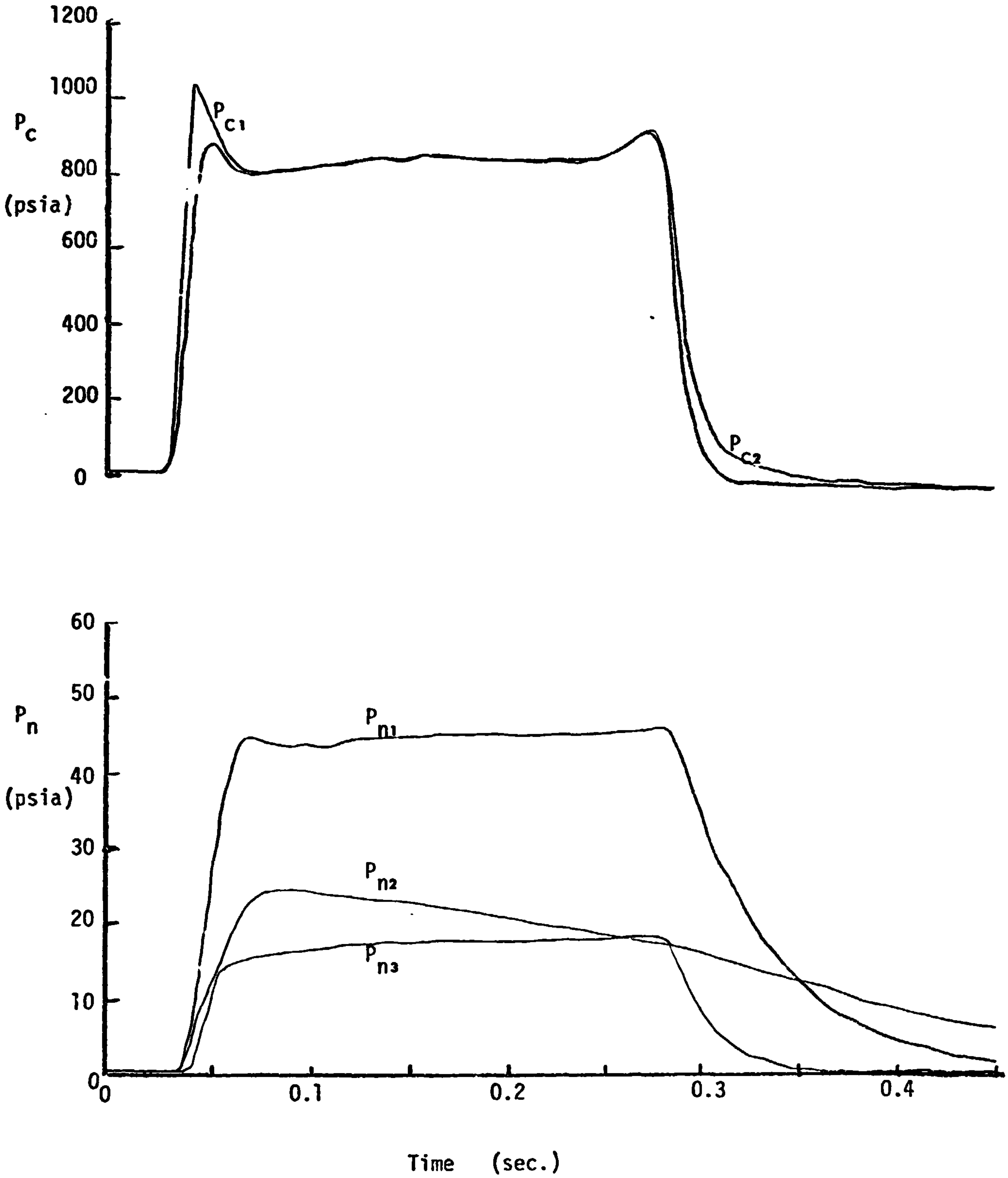
Run No. 34/2

Plate @ X/D=12
ψ = 45°

Alt.=100,000'
%Aℓ = 15



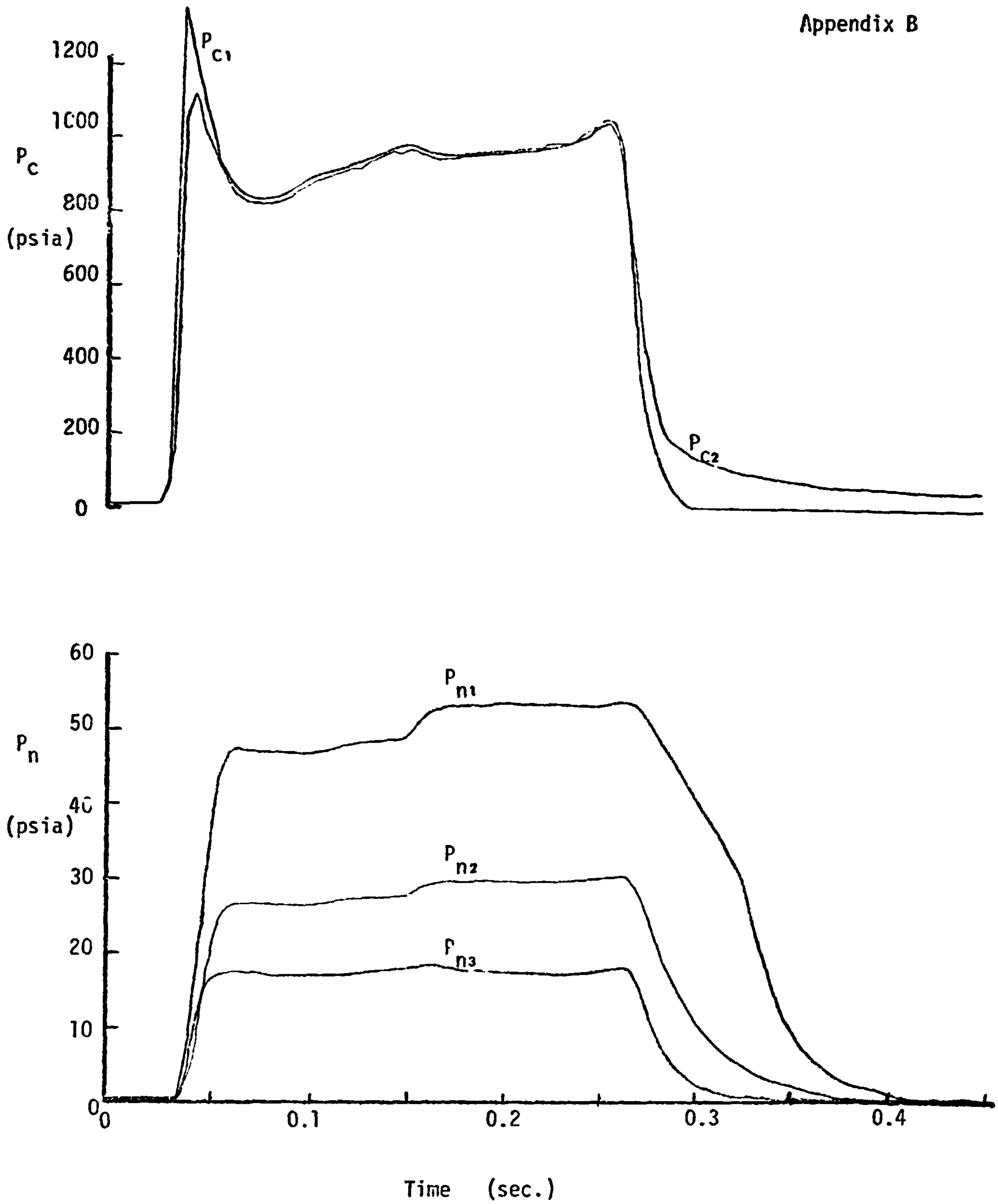
Run No. 34/2 (Concluded)



Run No. 35/1

Particle
X/D=12

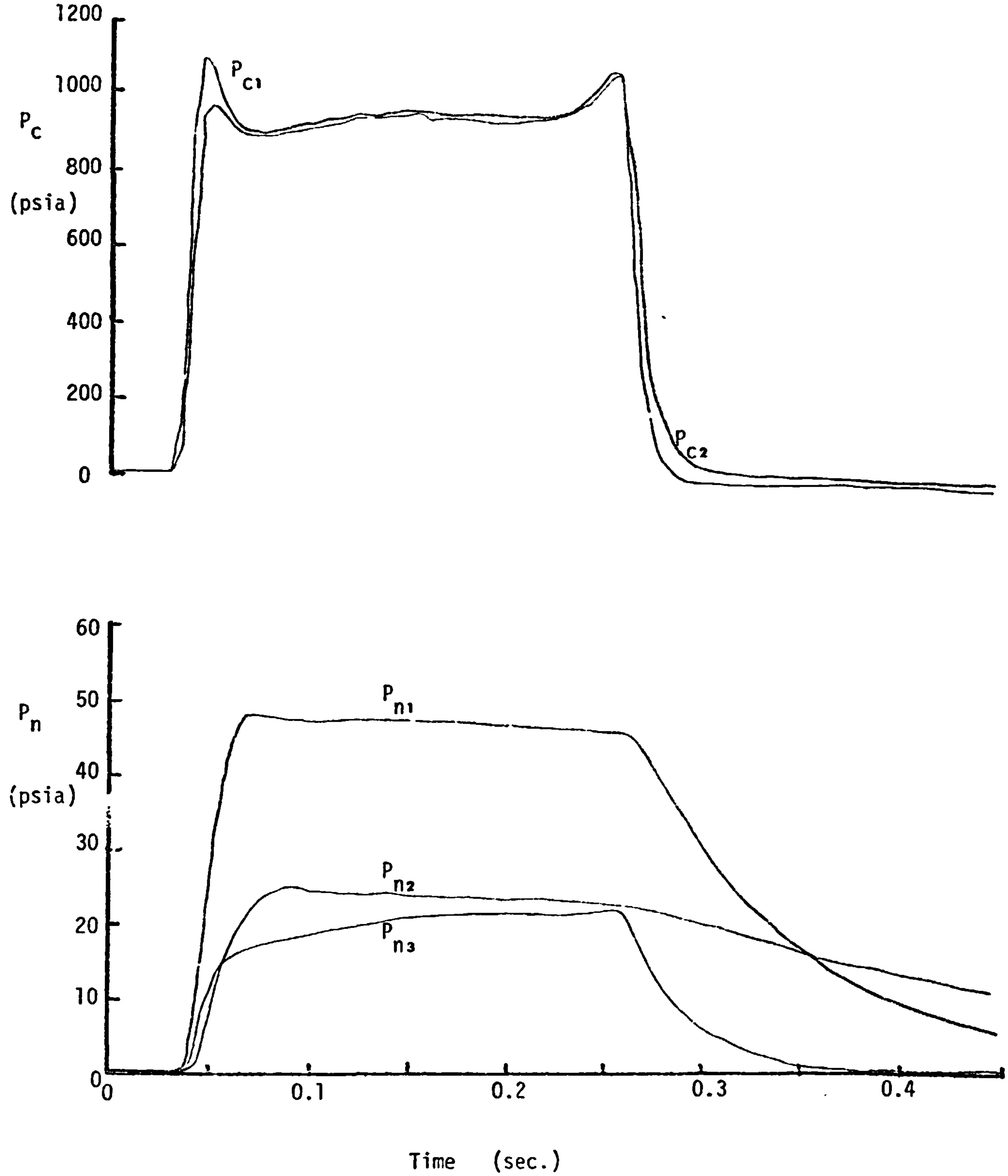
Alt.=100,000'
%Aℓ = 10



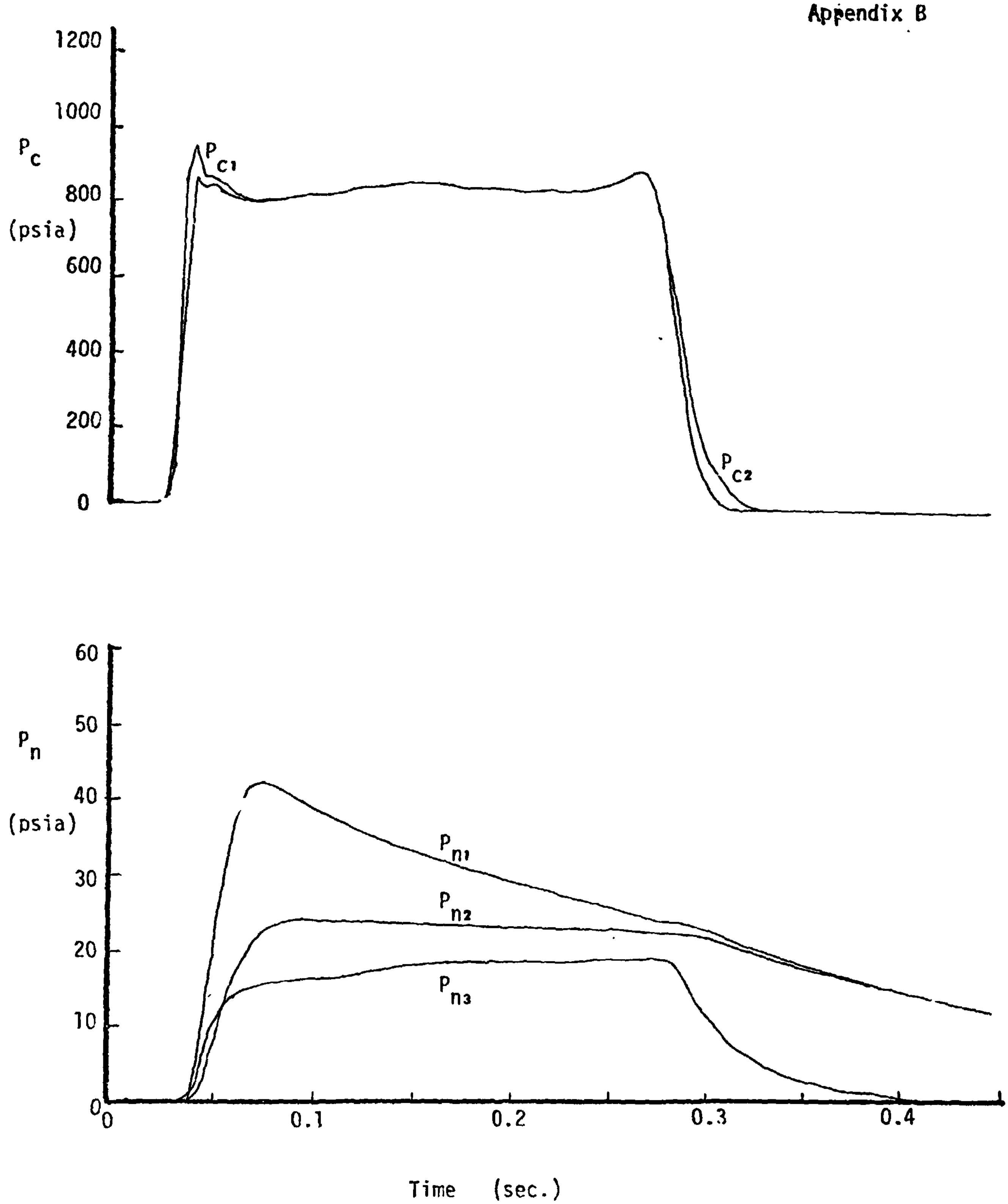
Run No. 36/1

Particle
X/D=12

Alt.=100,000'
%Aℓ = 15



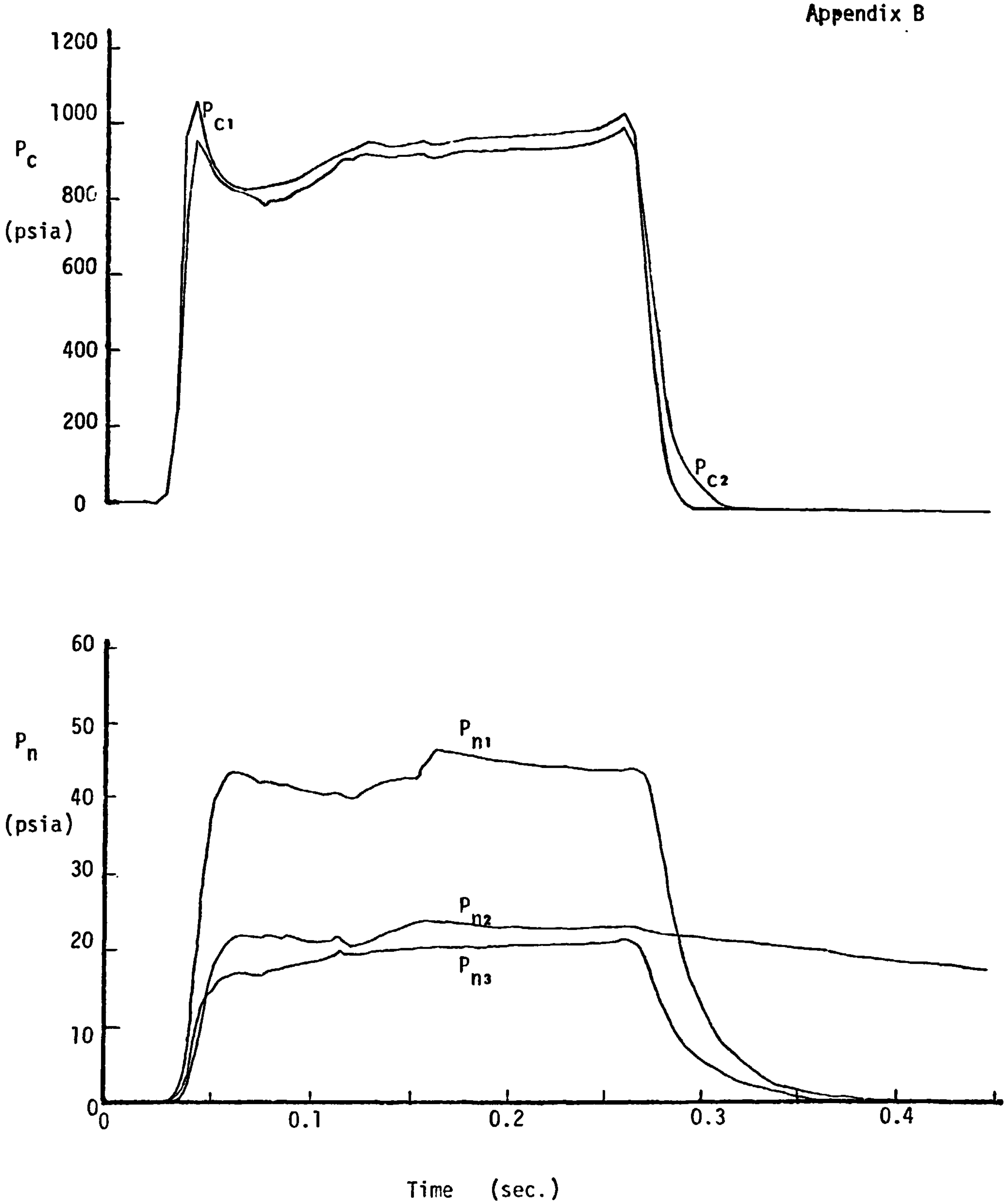
Run No. 37/1 Particle X/D=20 Alt.=100,000' %Aℓ = 10



Run No. 37/2

Particle
X/D=20

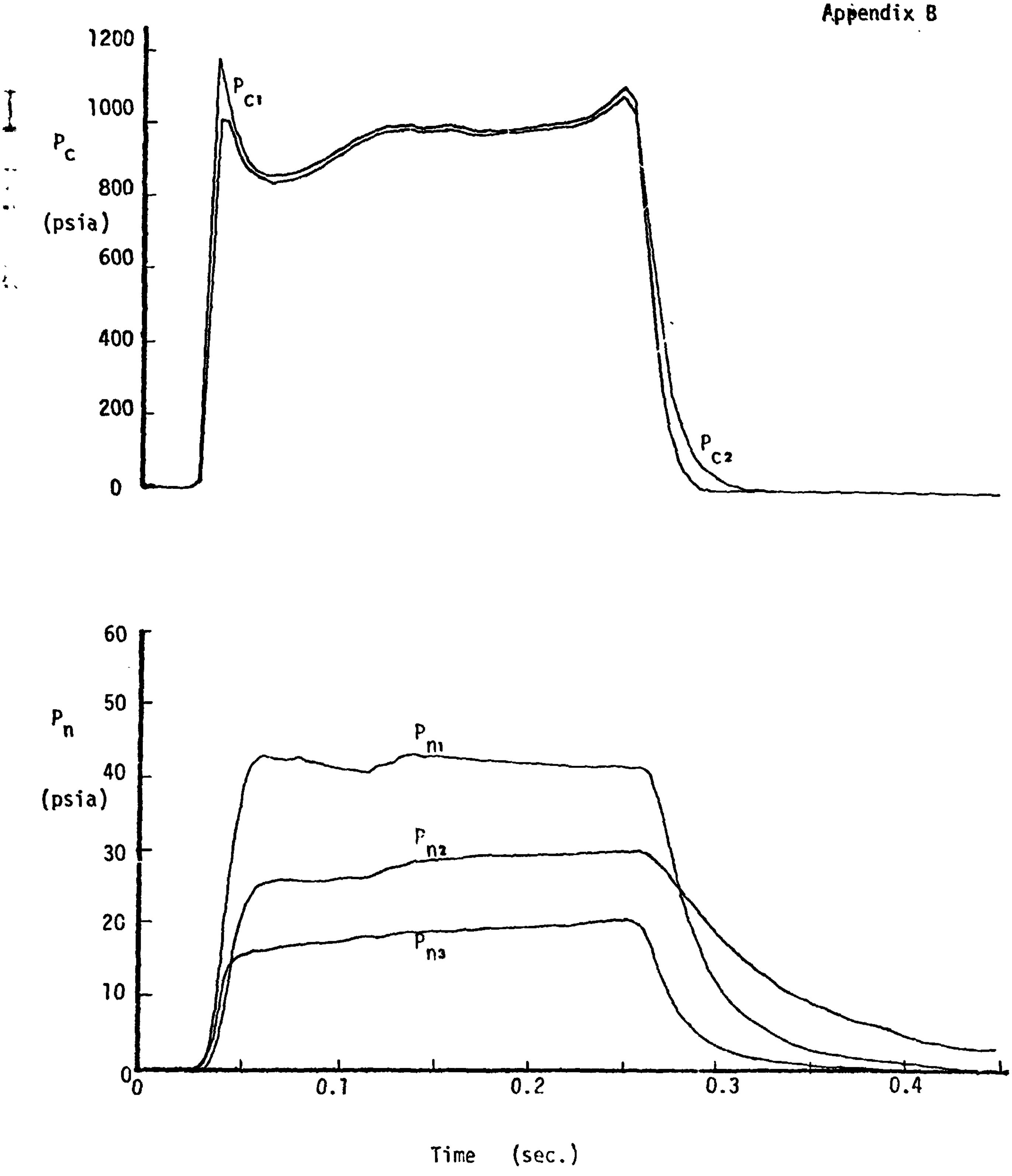
Alt.=100,000'
%Aℓ = 10



Run No. 38/1

Particle
X/D=20

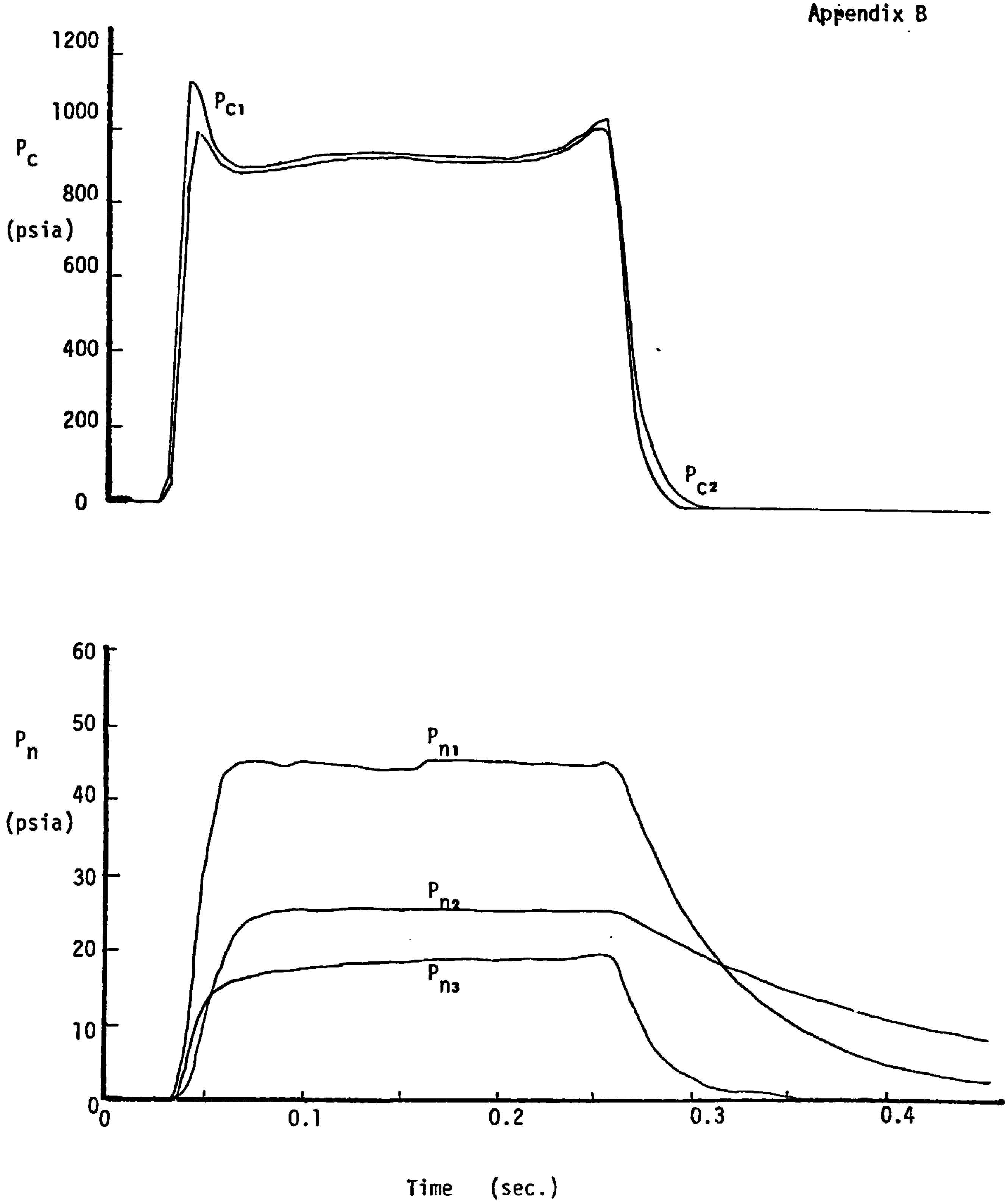
Alt.=100,000'
%Aℓ = 15



Run No. 38/2

Particle
X/D=20

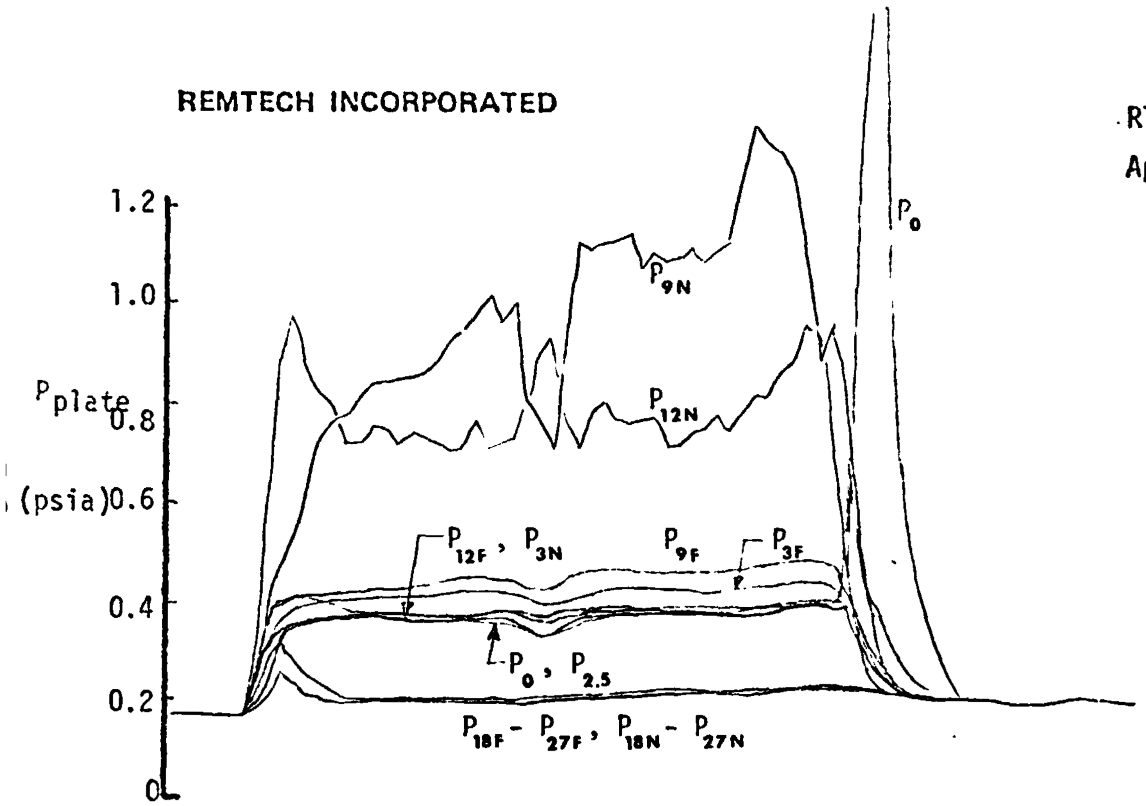
Alt.=100,000'
%Aℓ = 15

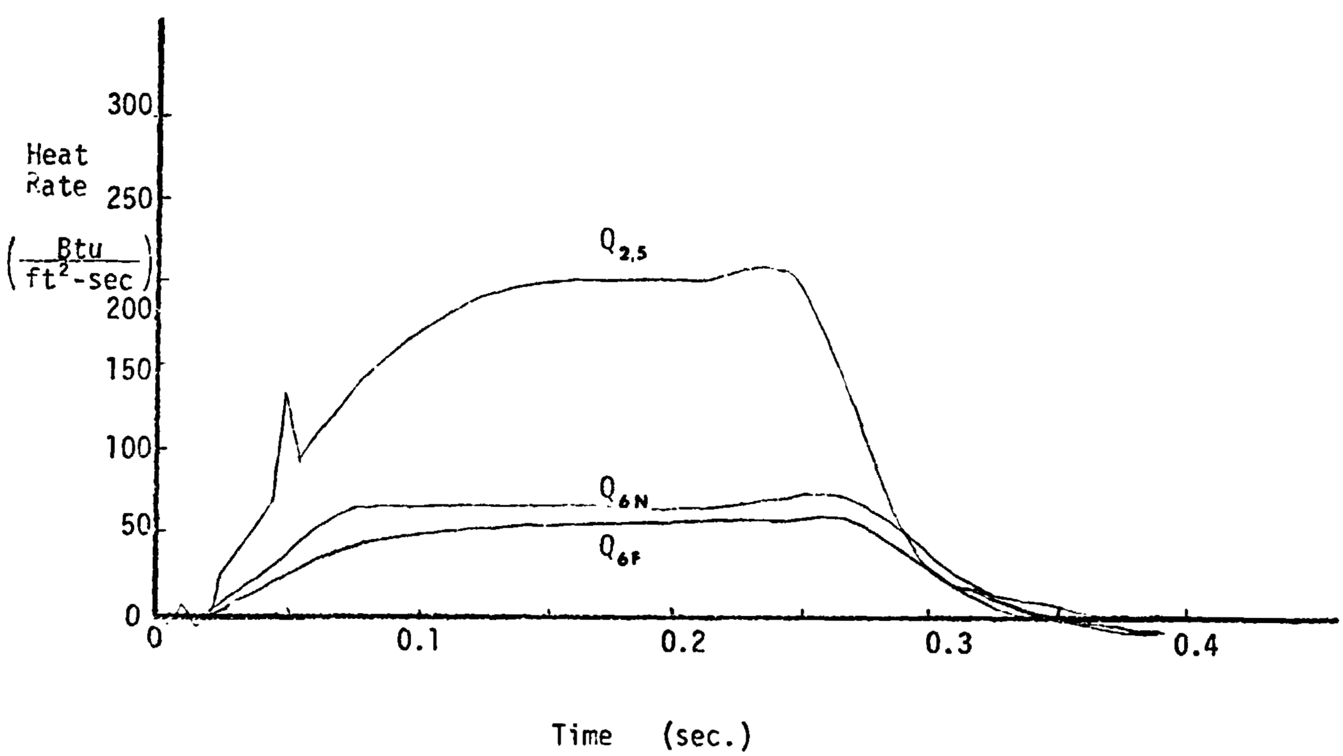


Run No. 39/1

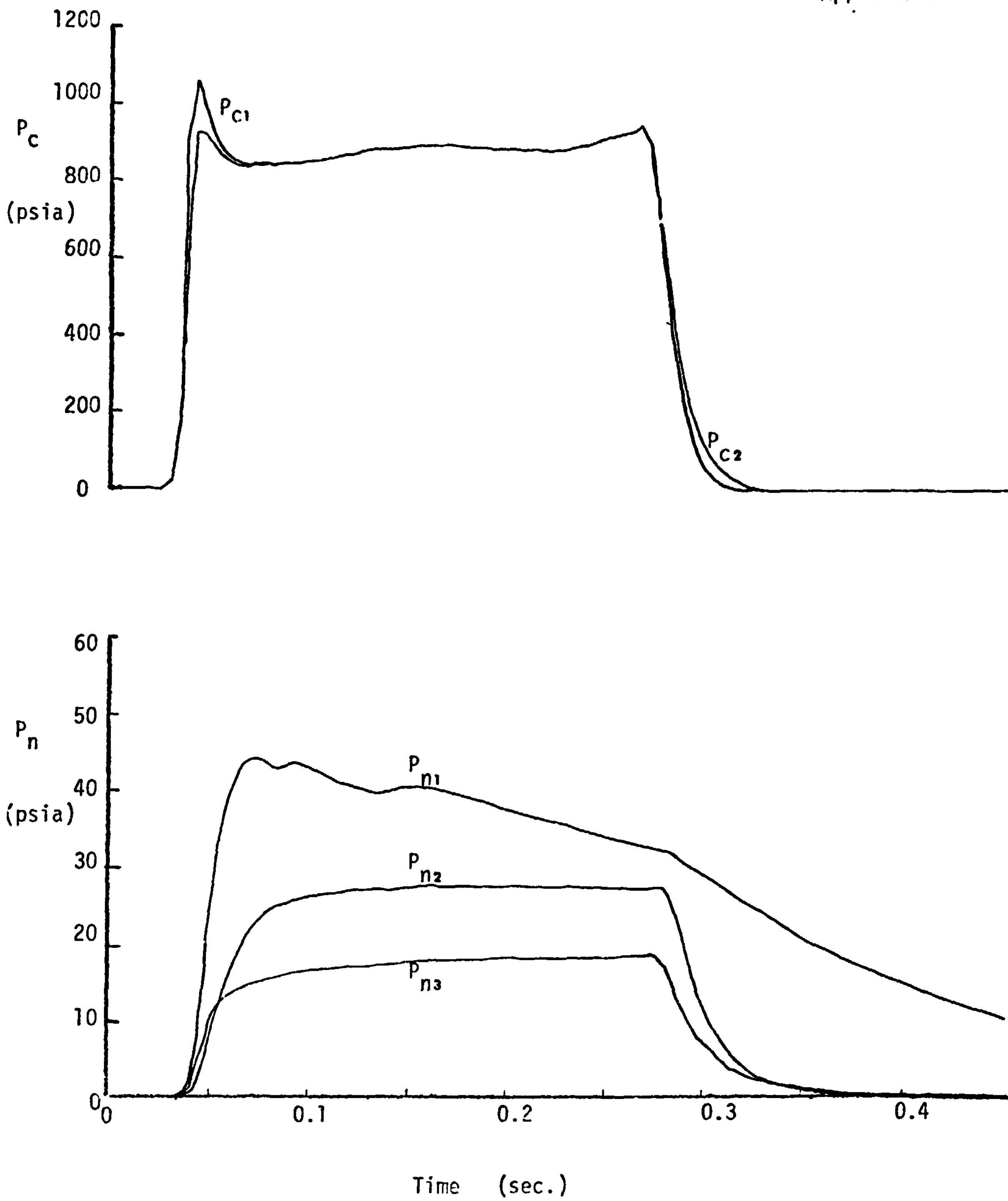
Plate @ X/D=20
ψ = 60°

Alt.=100,000'
%Aℓ = 10





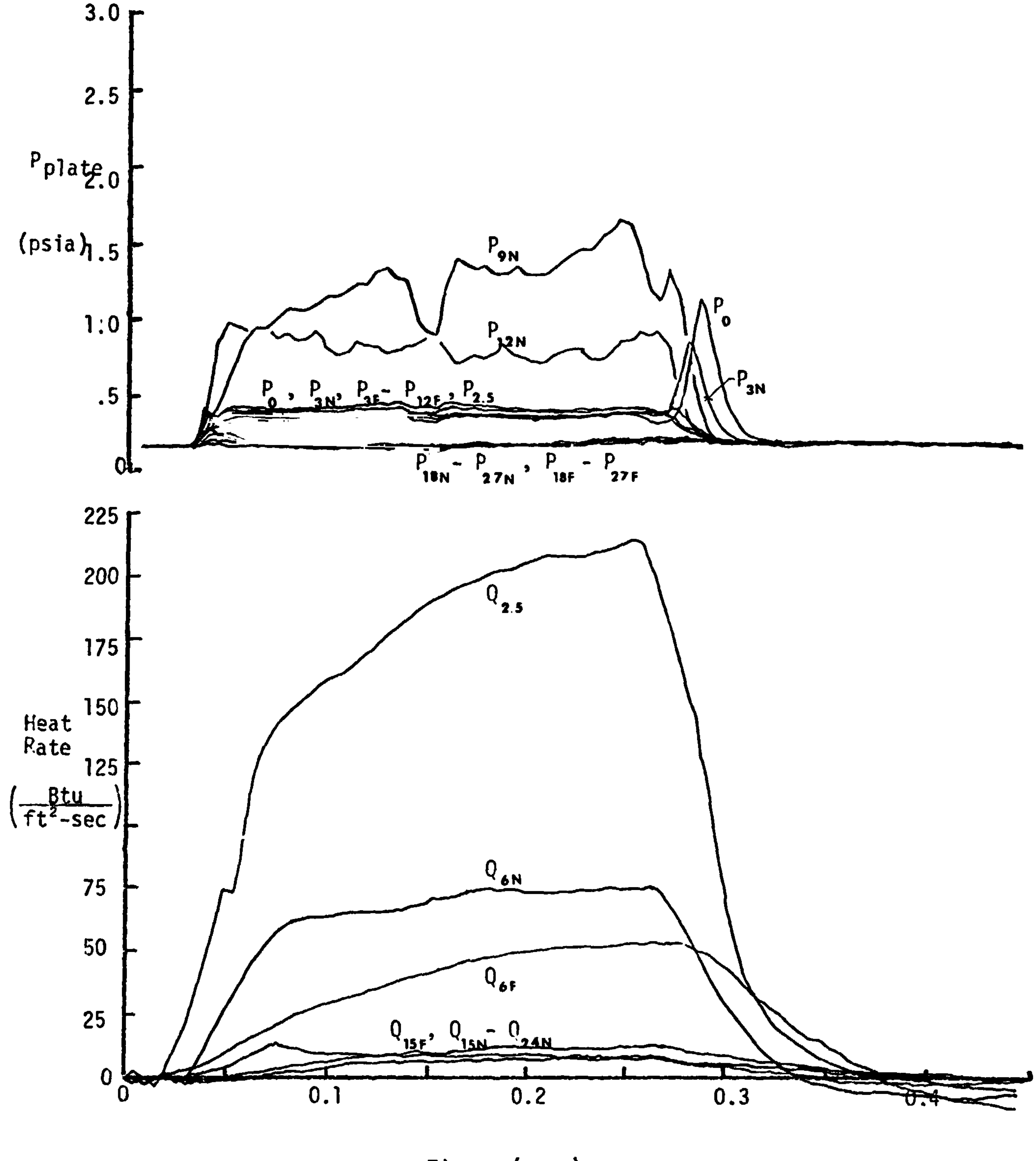
Run No. 39/1 (Concluded)



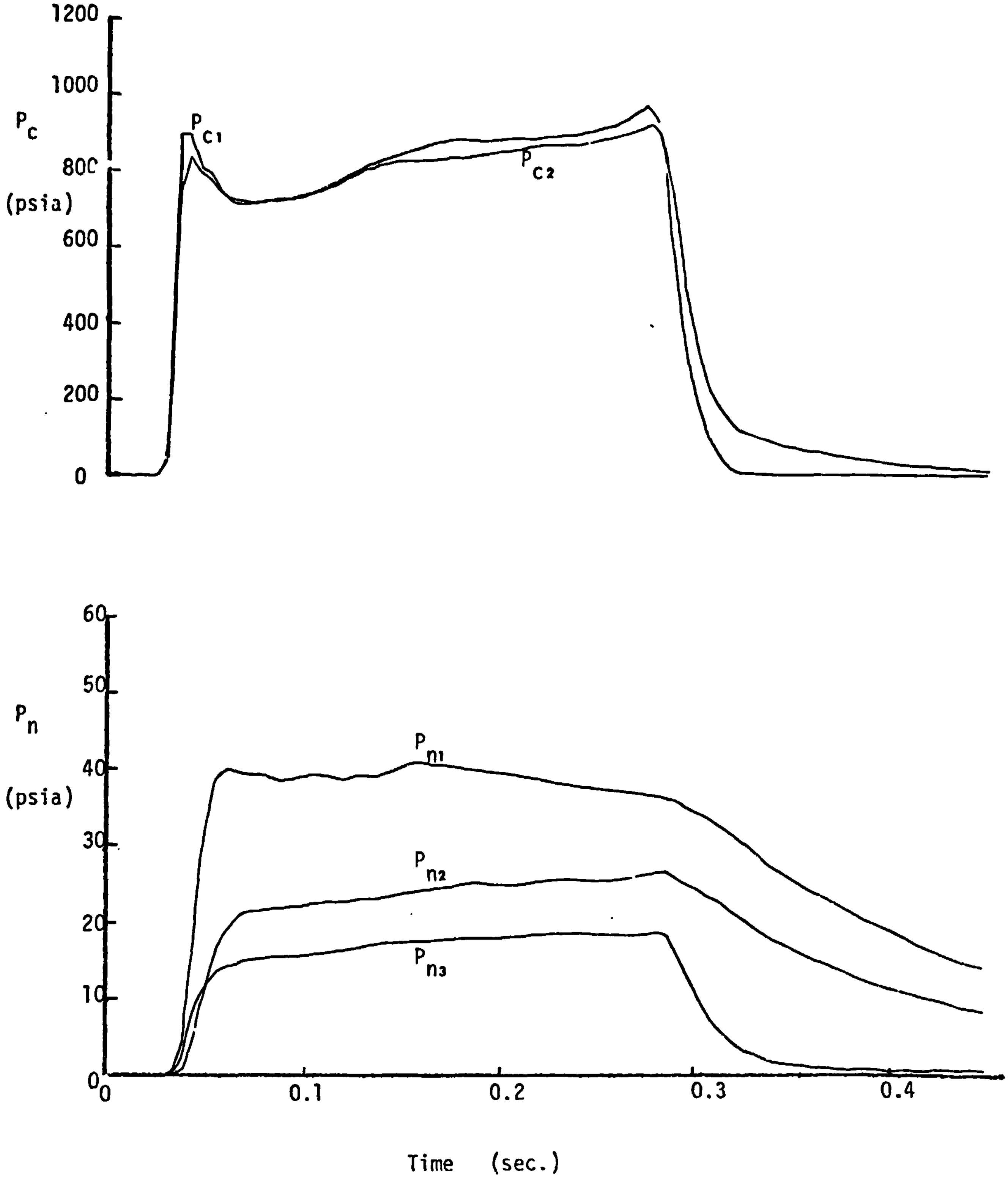
Run No. 39/2

Plate @ X/D=20
ψ = 60°

Alt.=100,000'
%Aℓ = 10



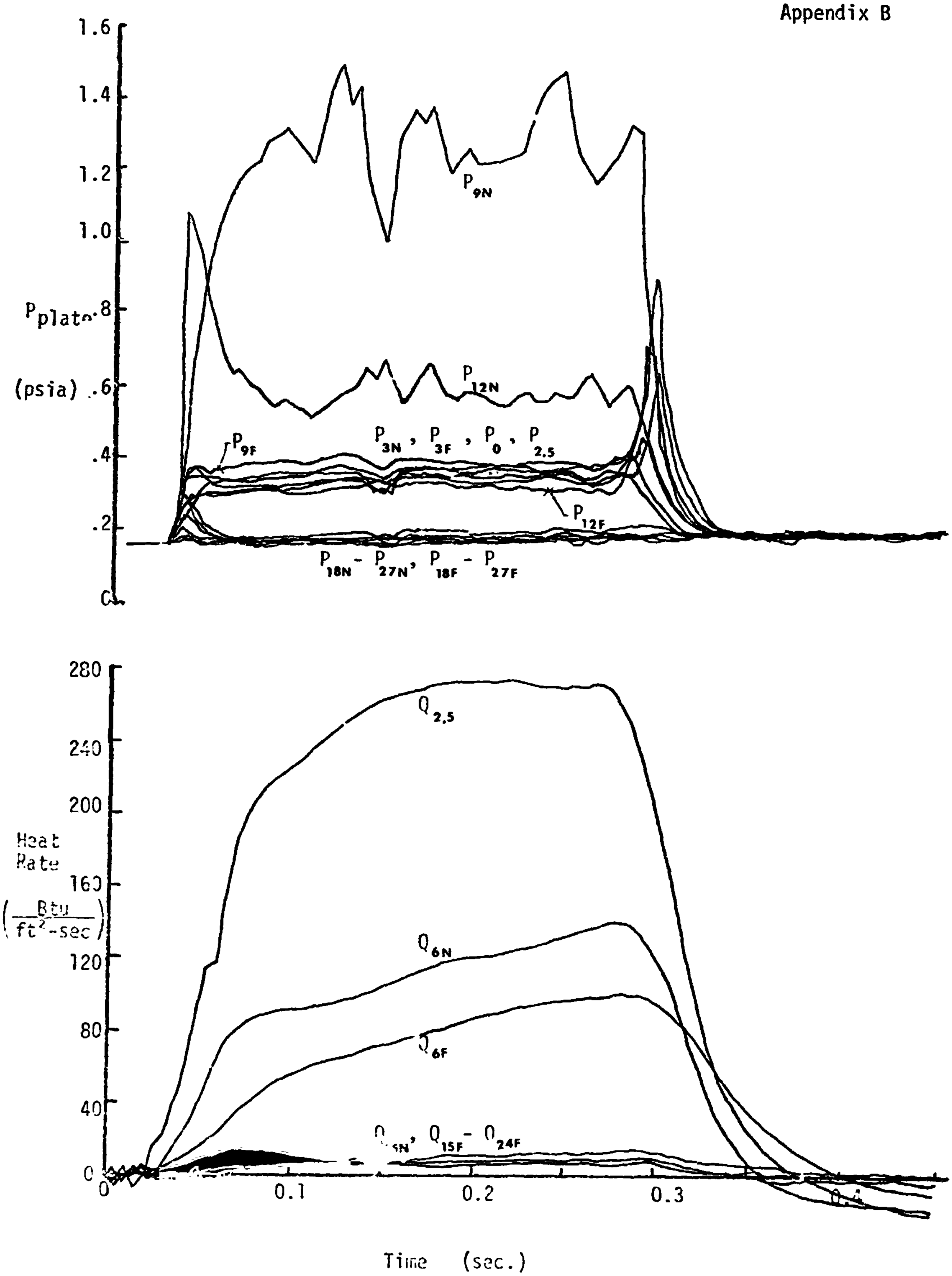
Run No. 39/2 (Concluded)



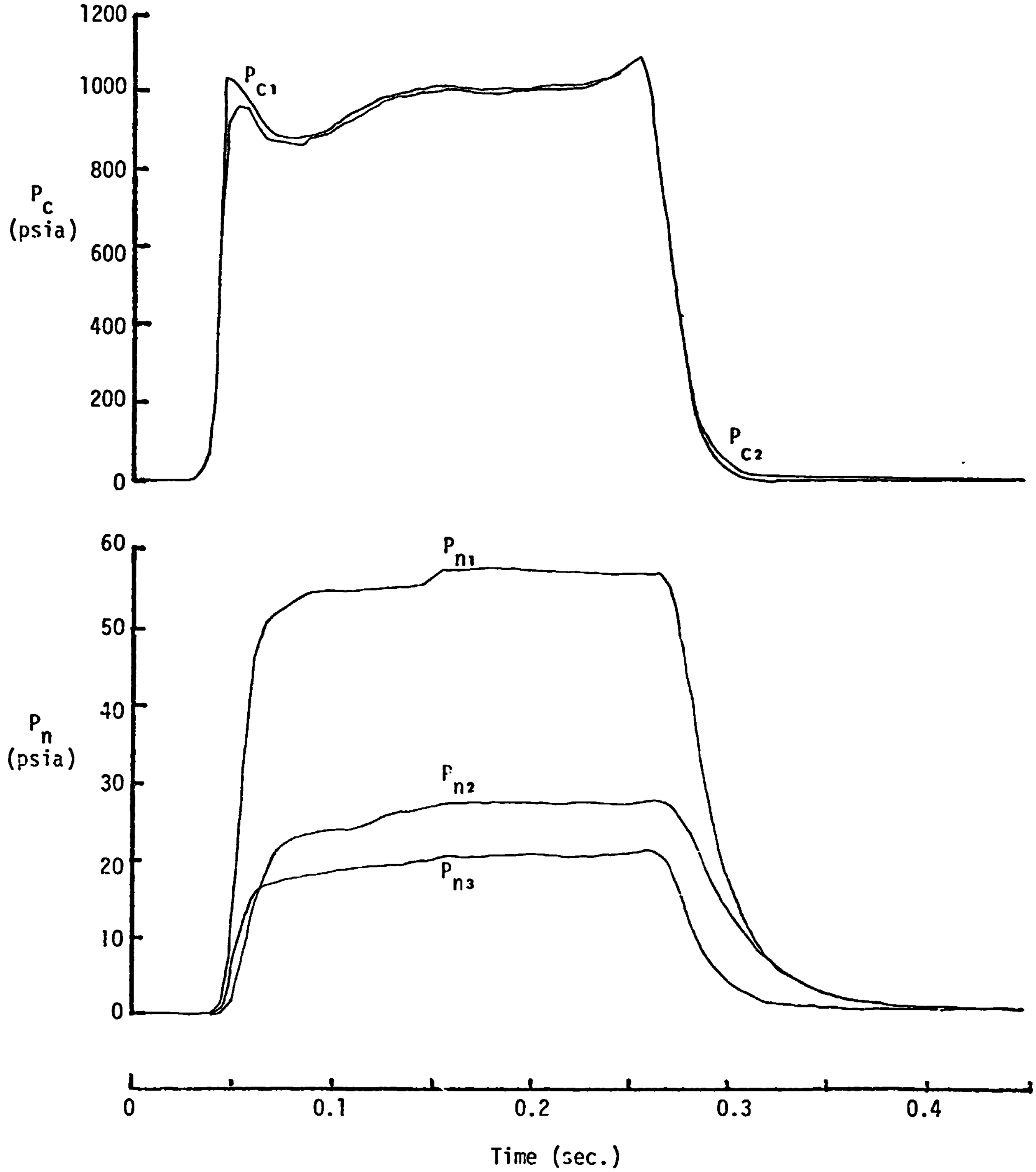
Run No. 40/1

Plate @ X/D=20
ψ = 60°

Alt.=100,000'
%Aℓ = 15



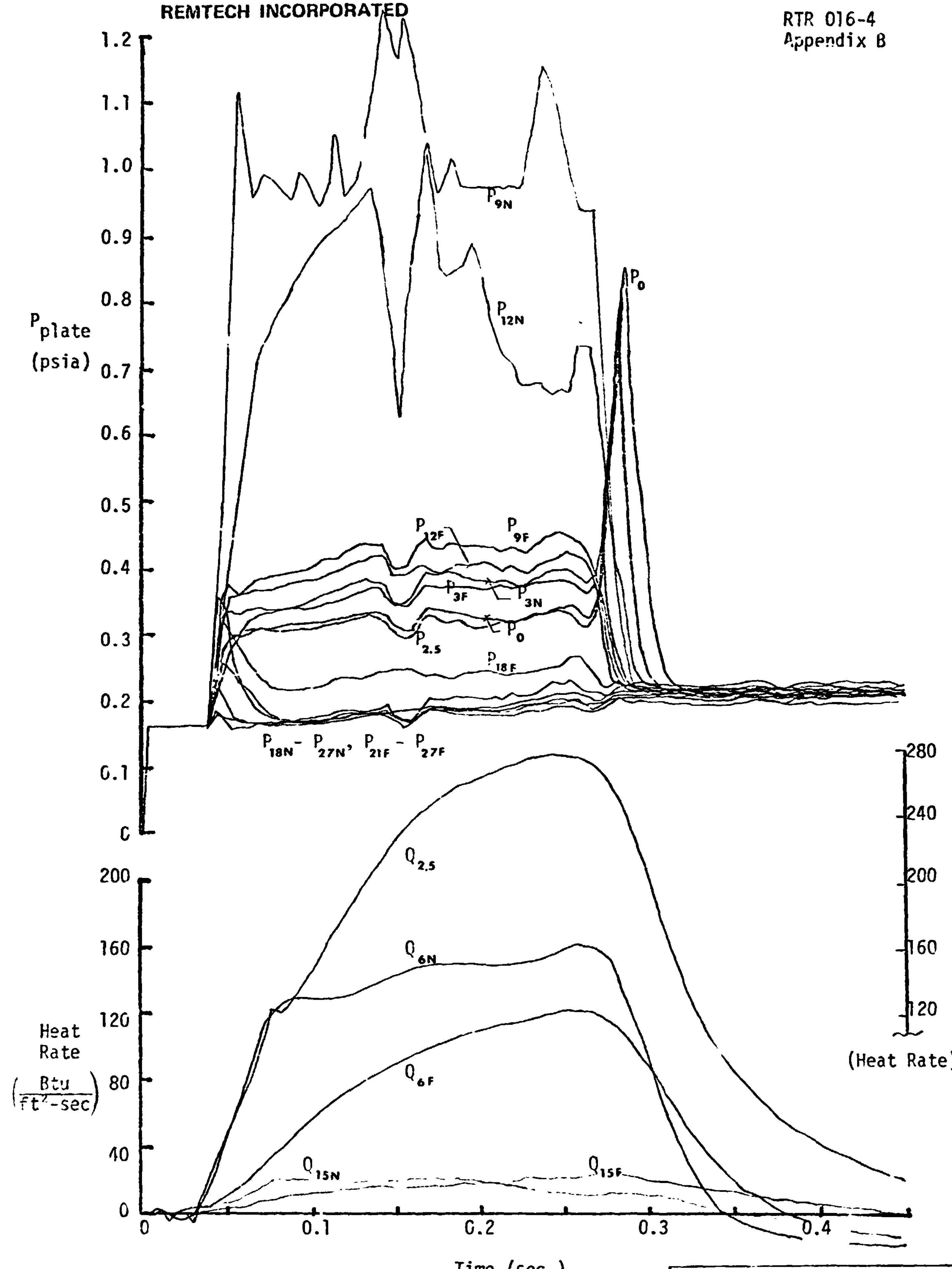
Run No. 40/1 (Concluded)



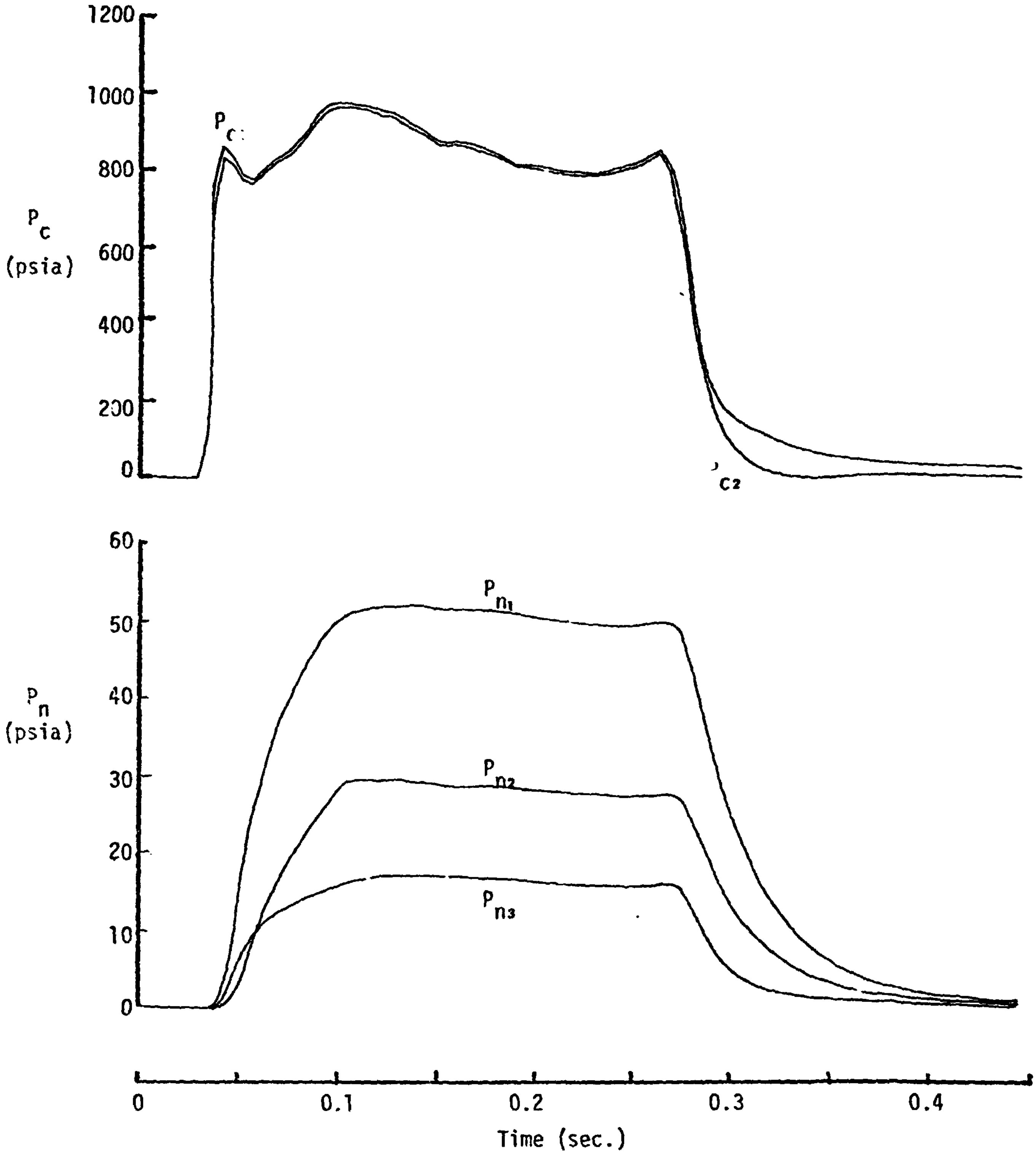
Run No. 40/2

Plate @ X/D=20
ψ = 60°

Alt.=100,000'
%Aℓ = 15



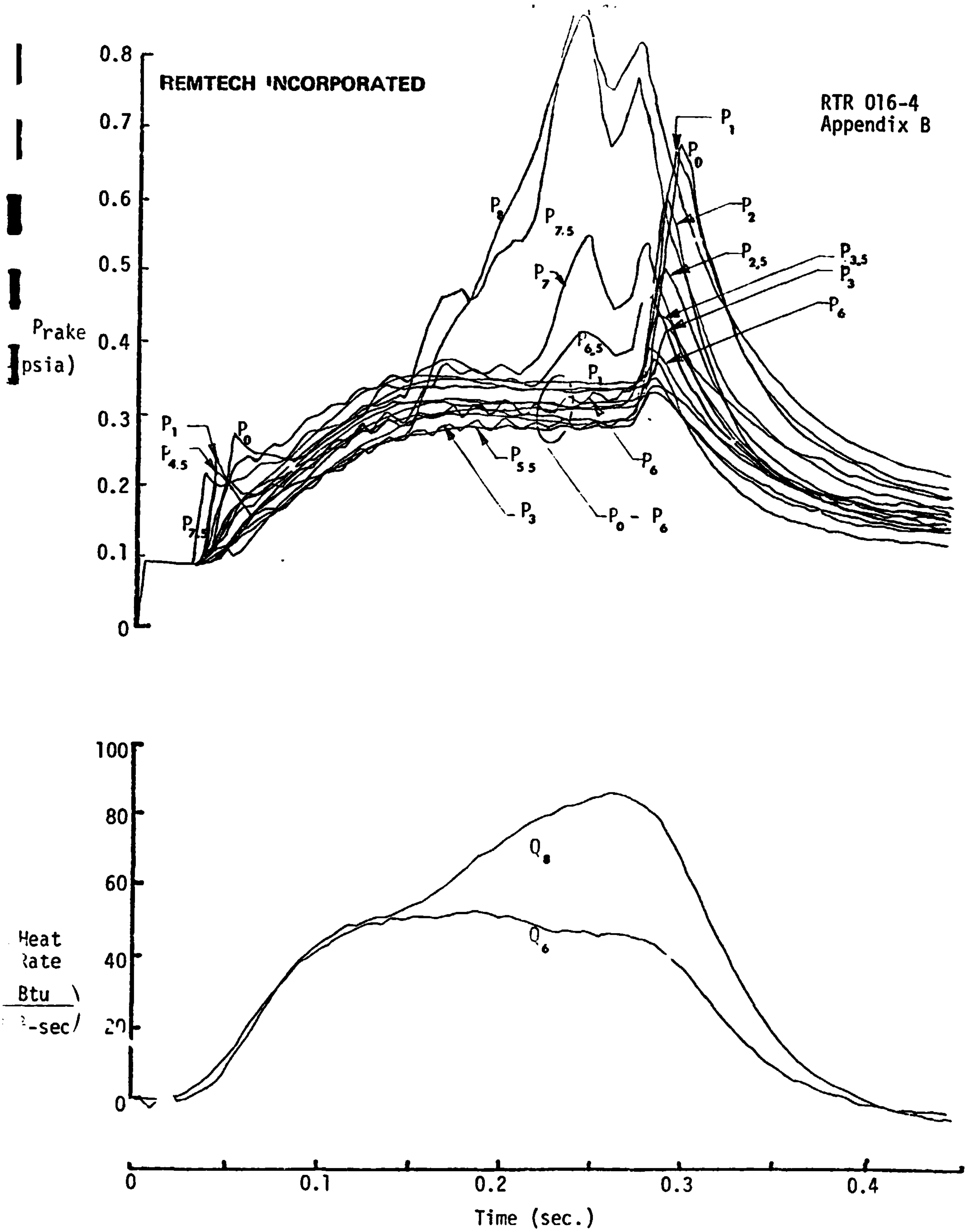
Run No. 40/2 (Concluded)



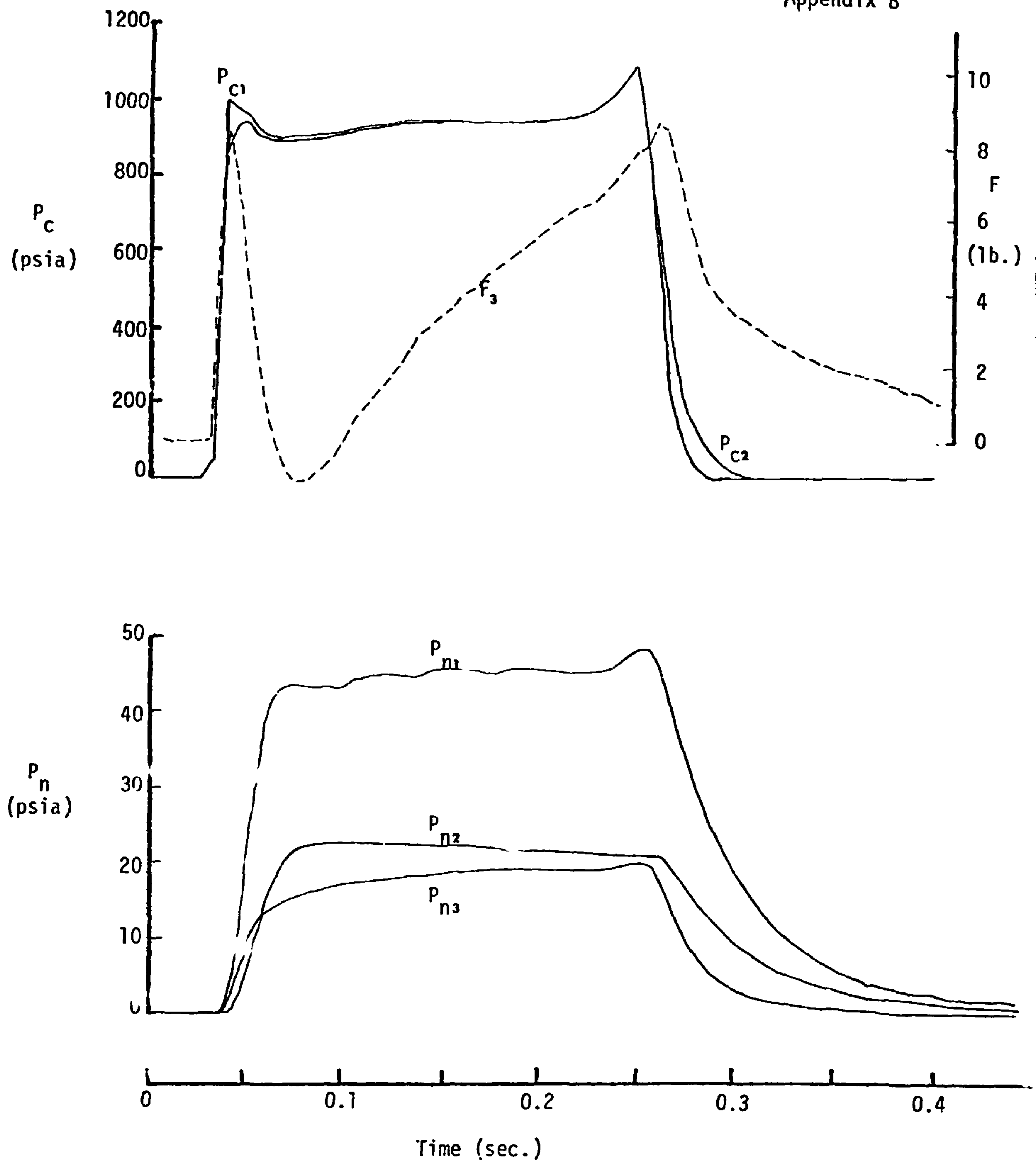
Run No. 41/1

Rake @ X/D=20

Alt.=112,000'
%Al = 2



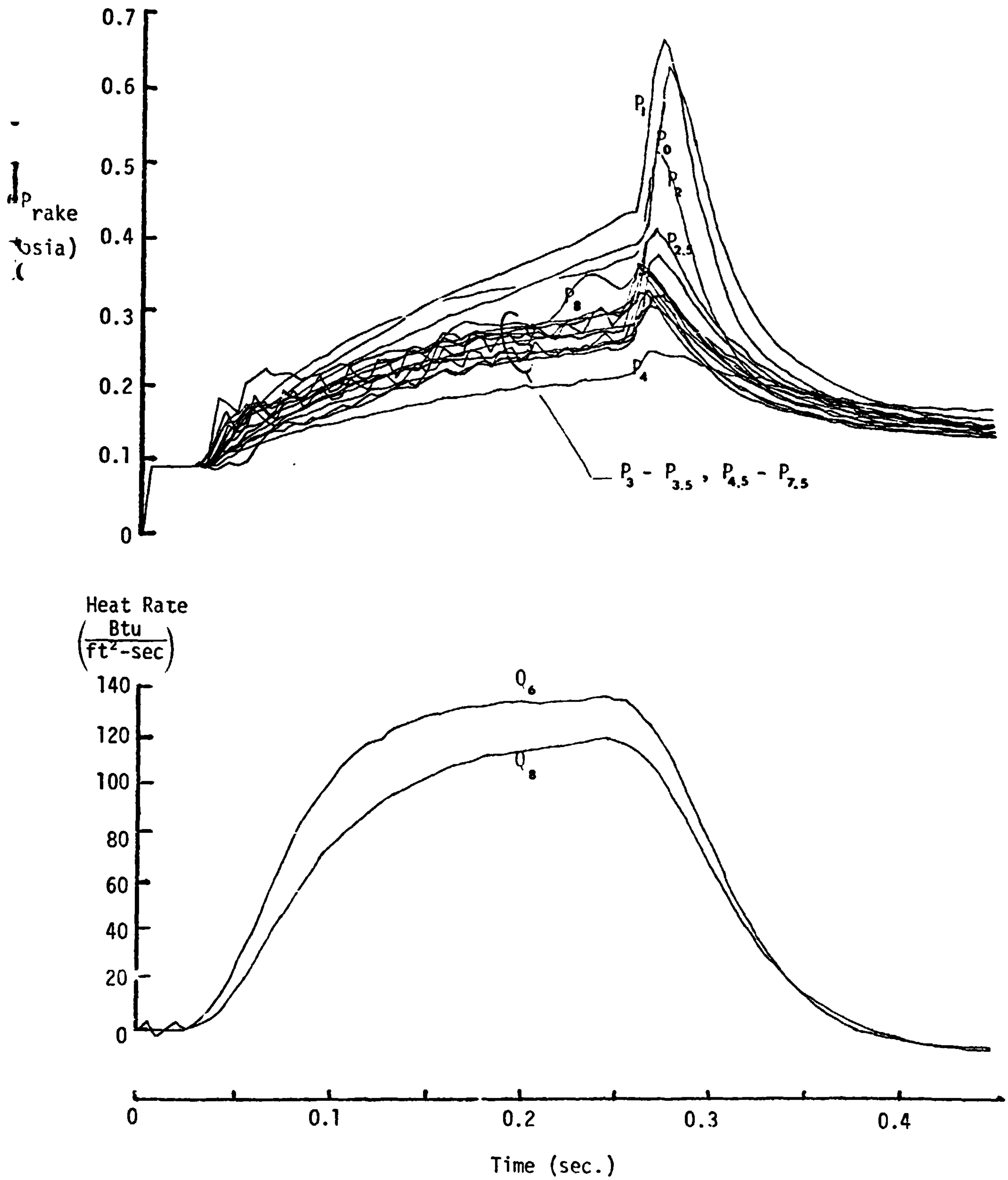
Run No. 41/1 (Concluded)



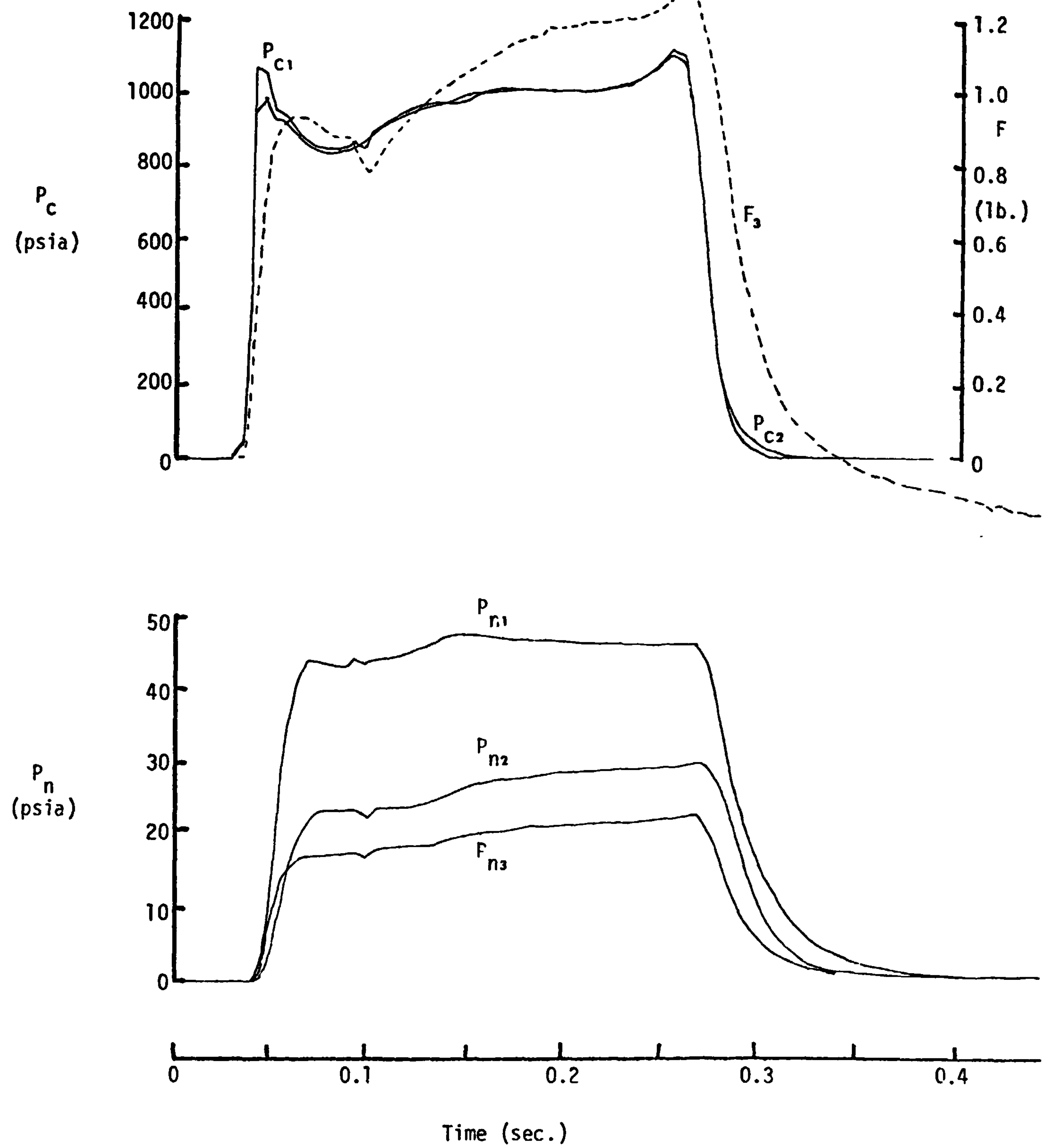
Run No. 42/1

Rake @ X/D=20

Alt.=112,000'
%Aℓ = 10



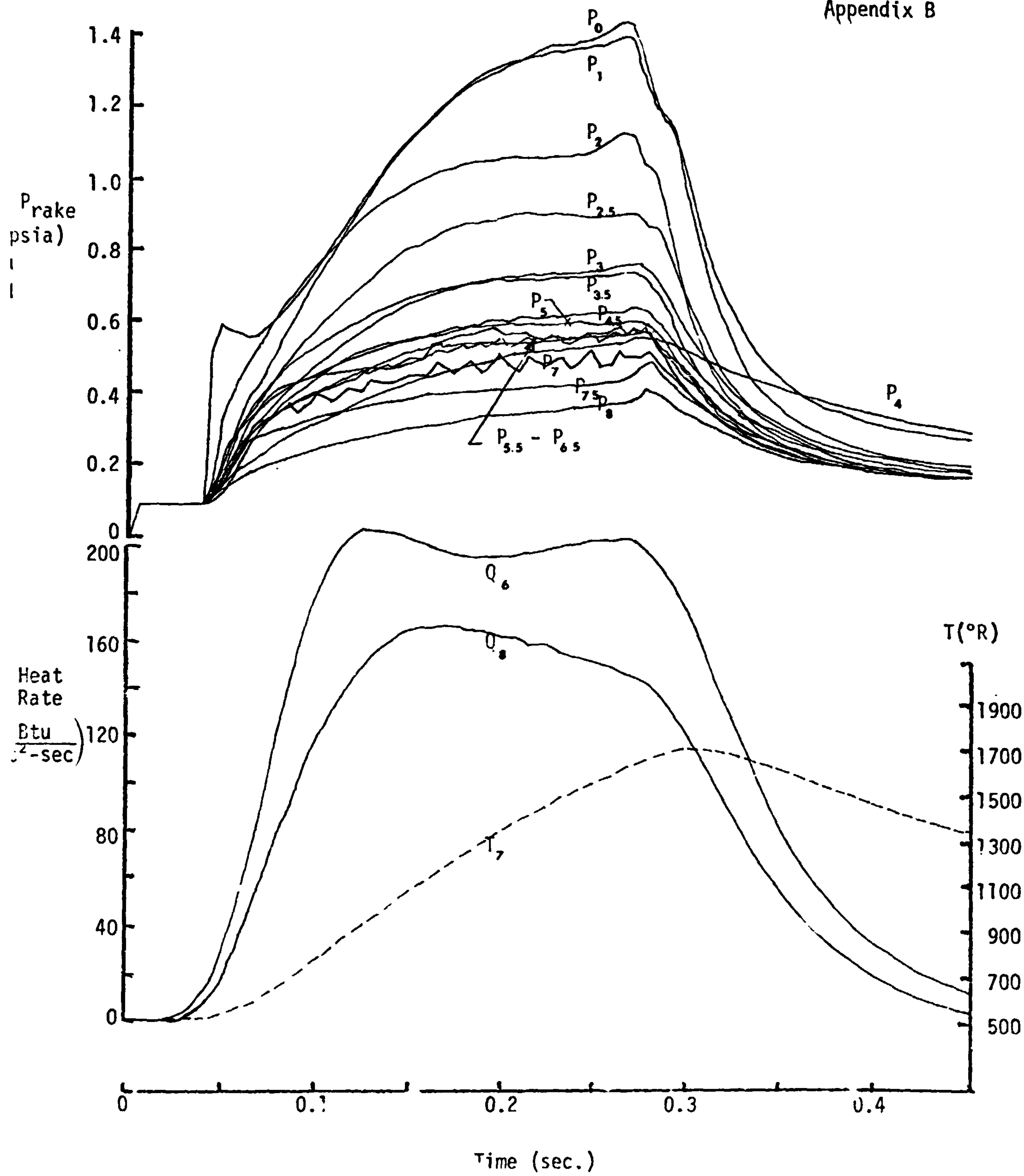
Run No. 42/1 (Concluded)



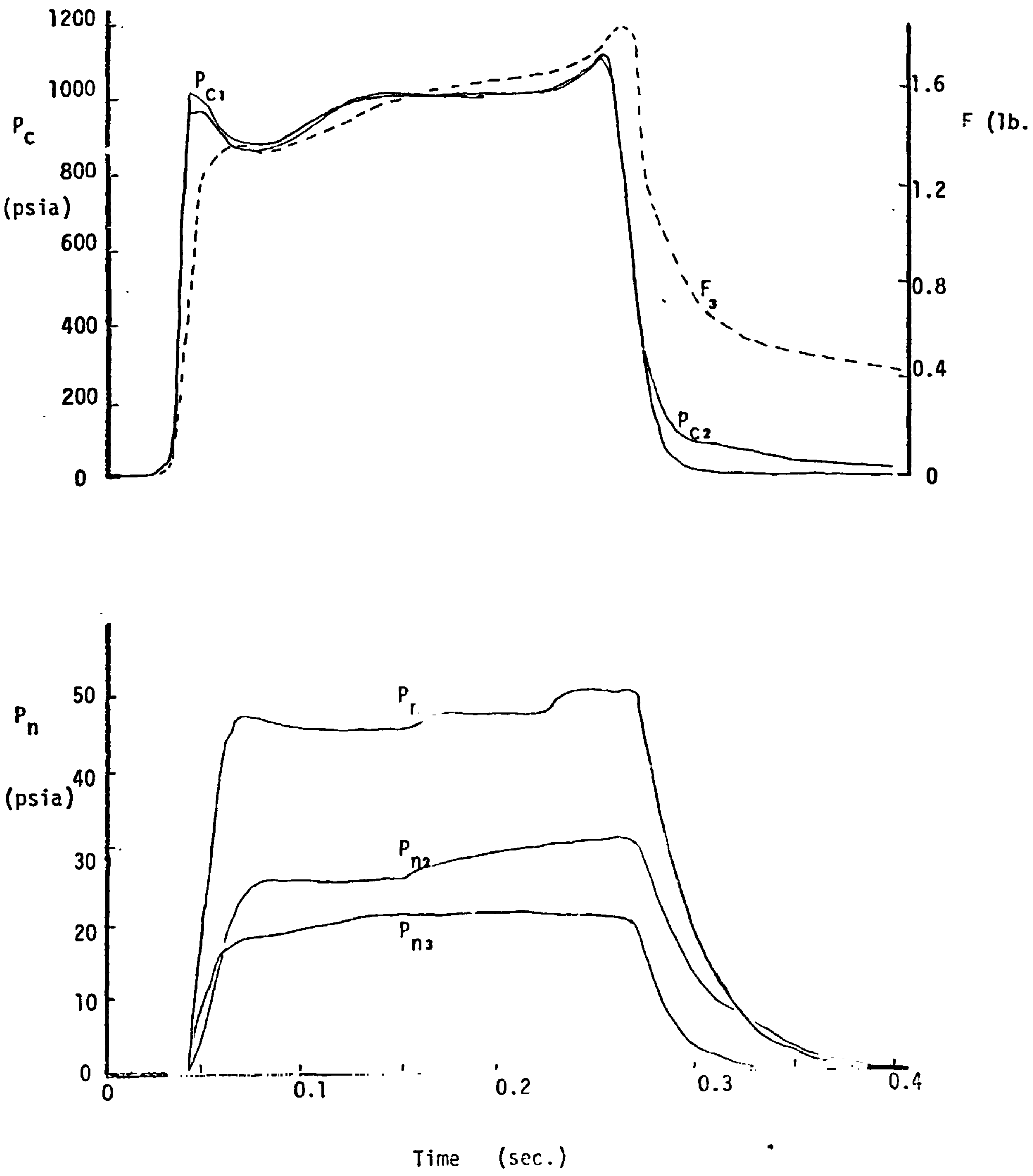
Run No. 43/1

Rake @ X/D=12

Alt.=112,000'
%Al = 15



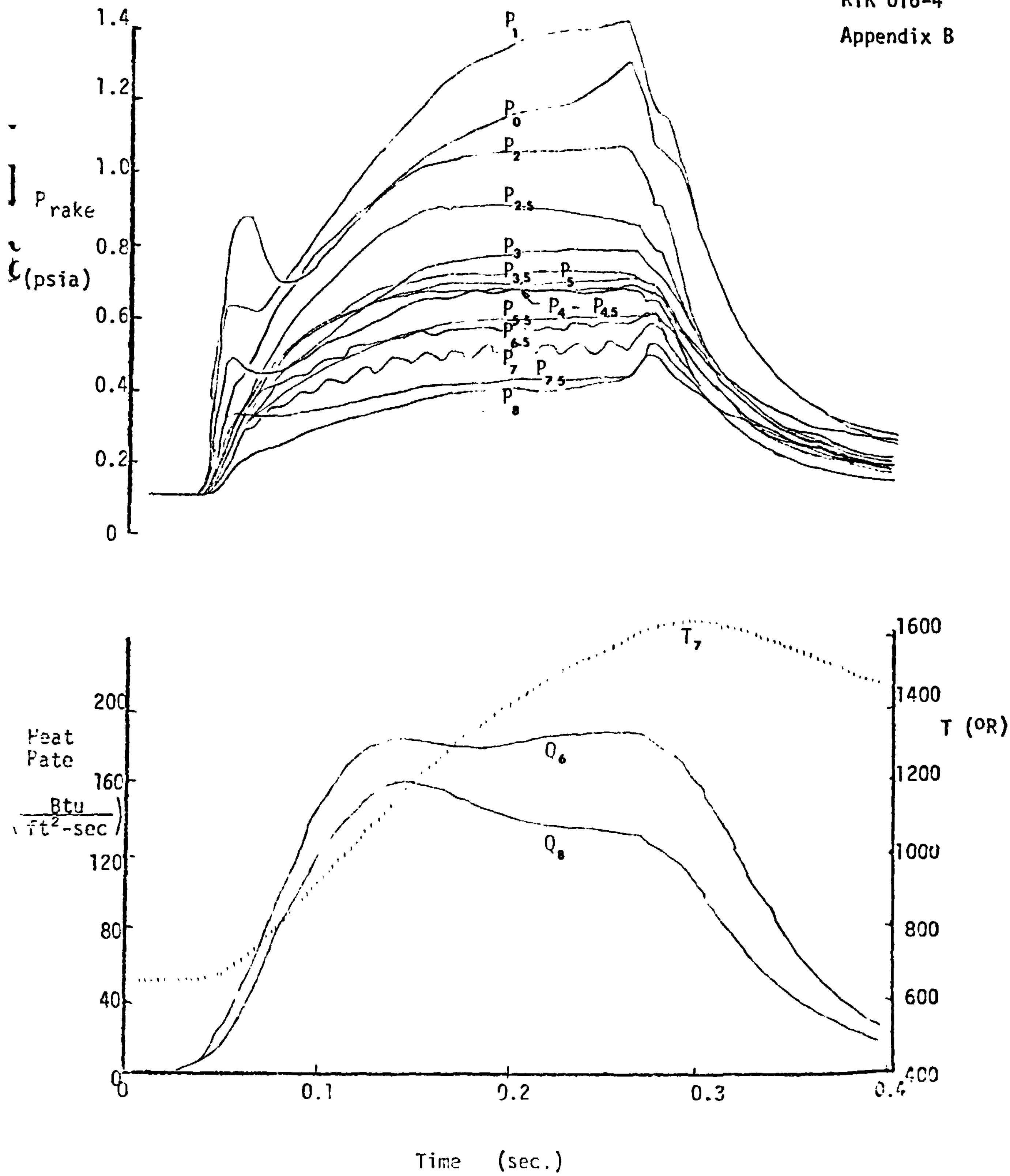
Run No. 43/1 (Concluded)



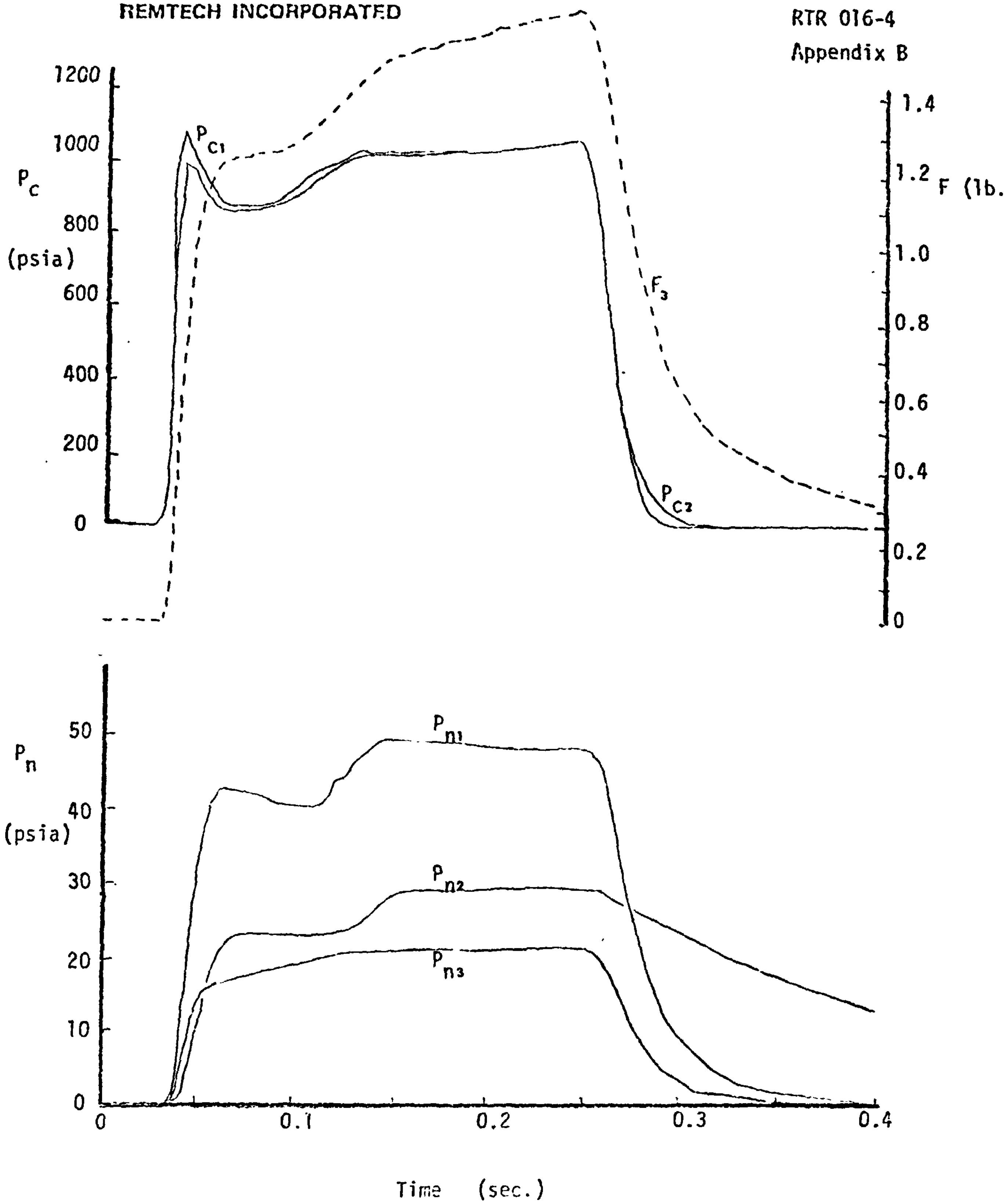
Run No. 43/2

Rake @ X/D=12

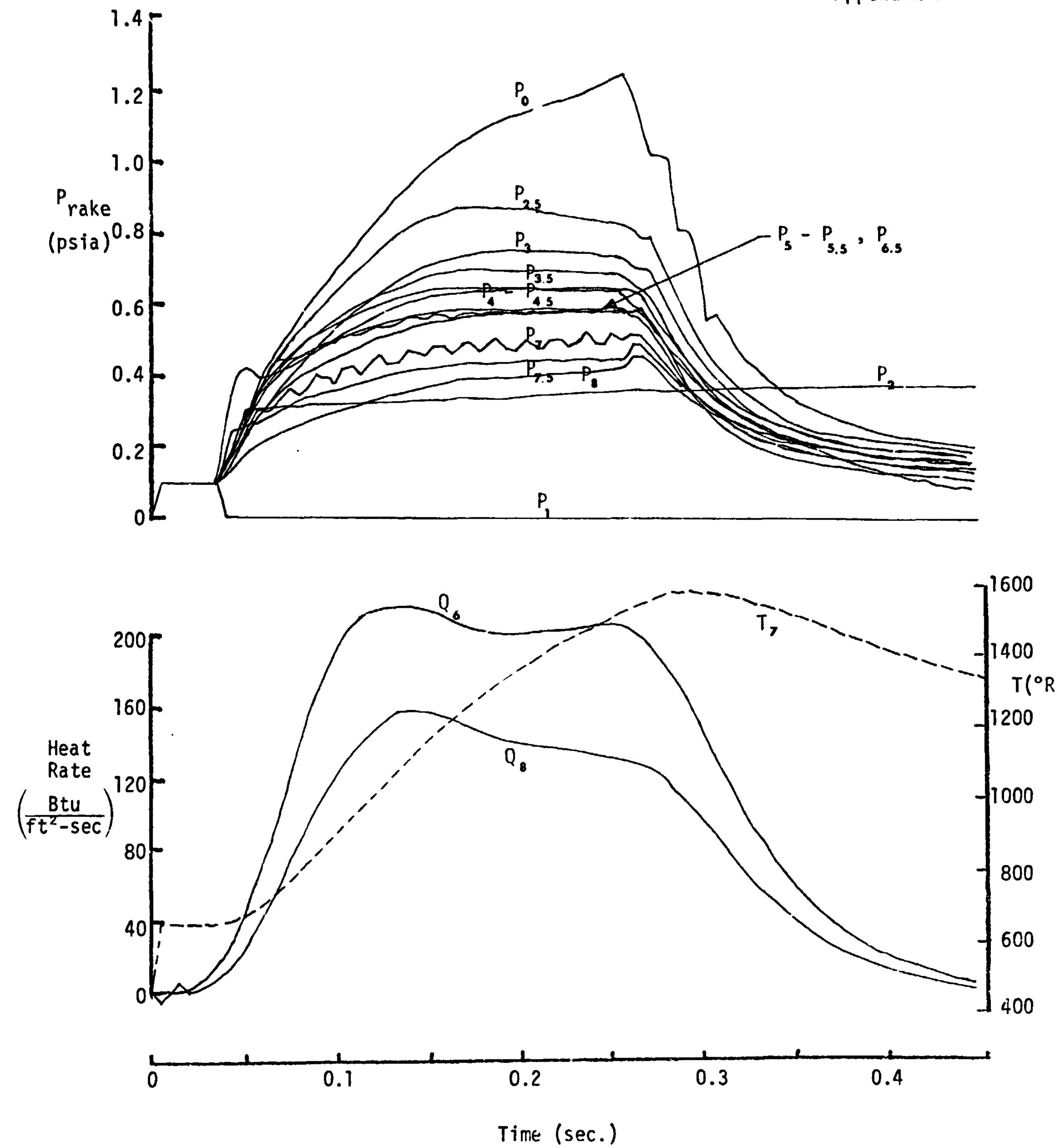
Alt.=112,000'
%Aℓ = 15



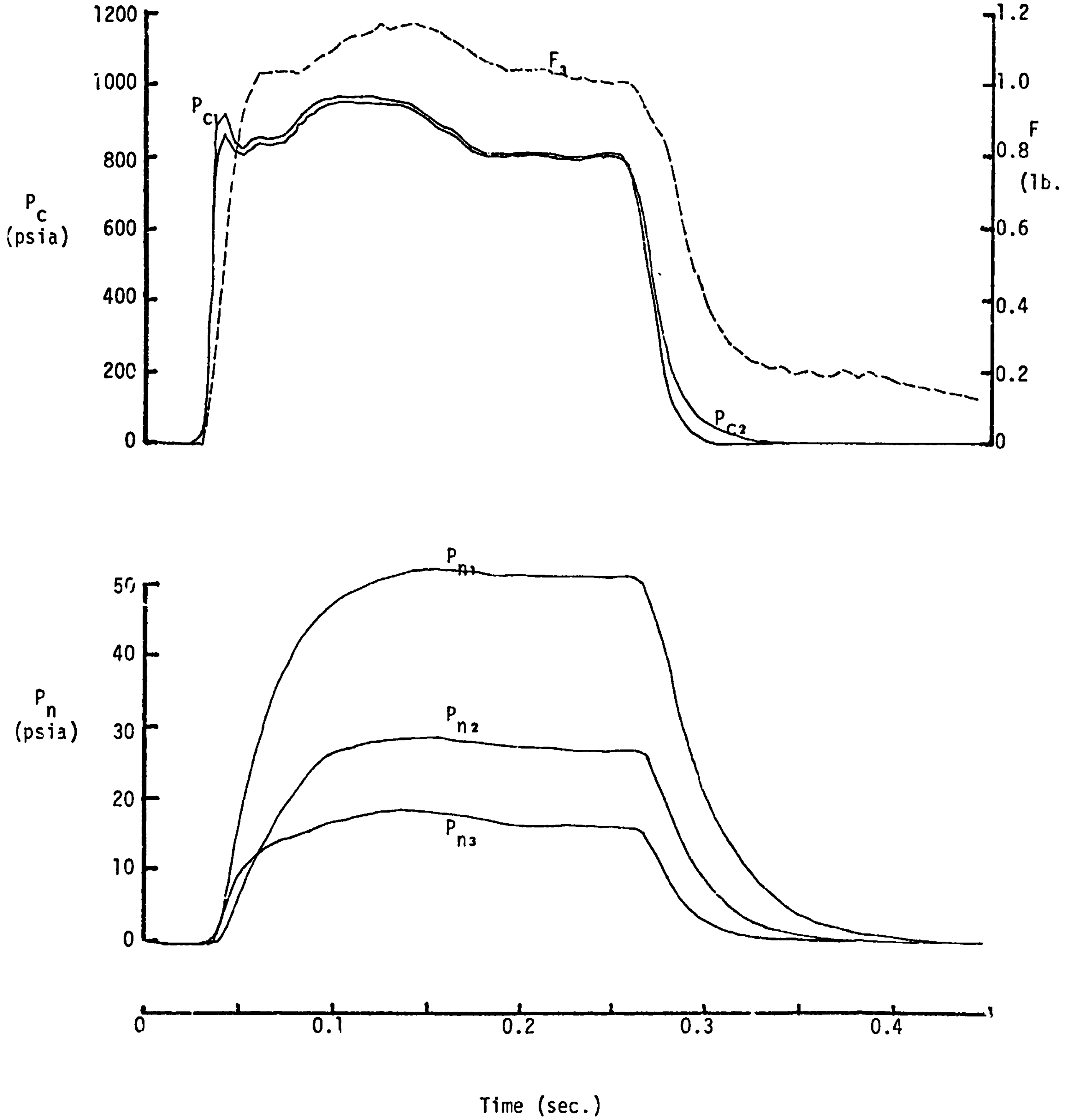
Run No. 43/2 (Concluded)



Run No. 43/3
Rake @ X/D=12
Alt.=112,000' %Aℓ = 15



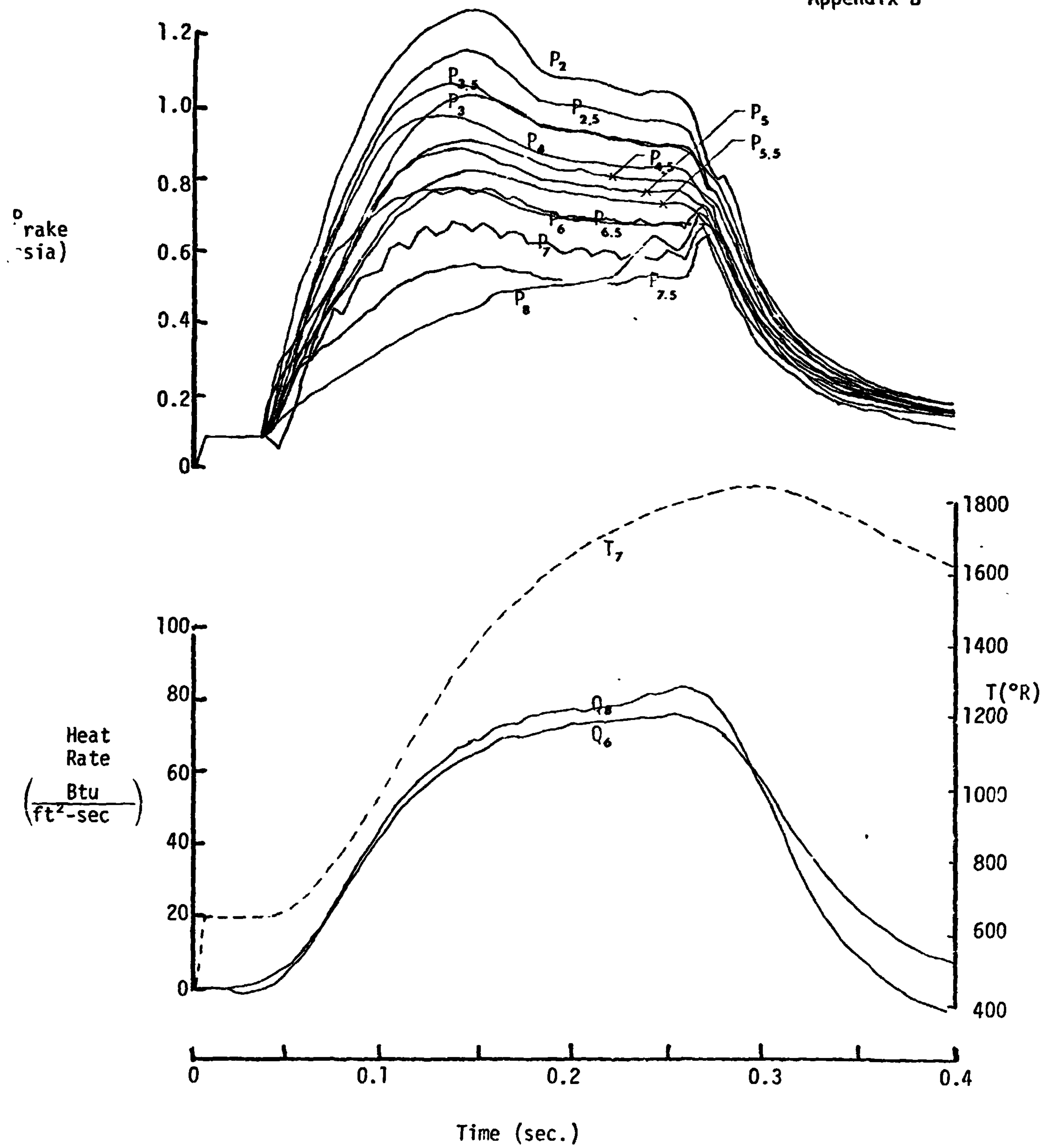
Run No. 43/3 (Concluded)



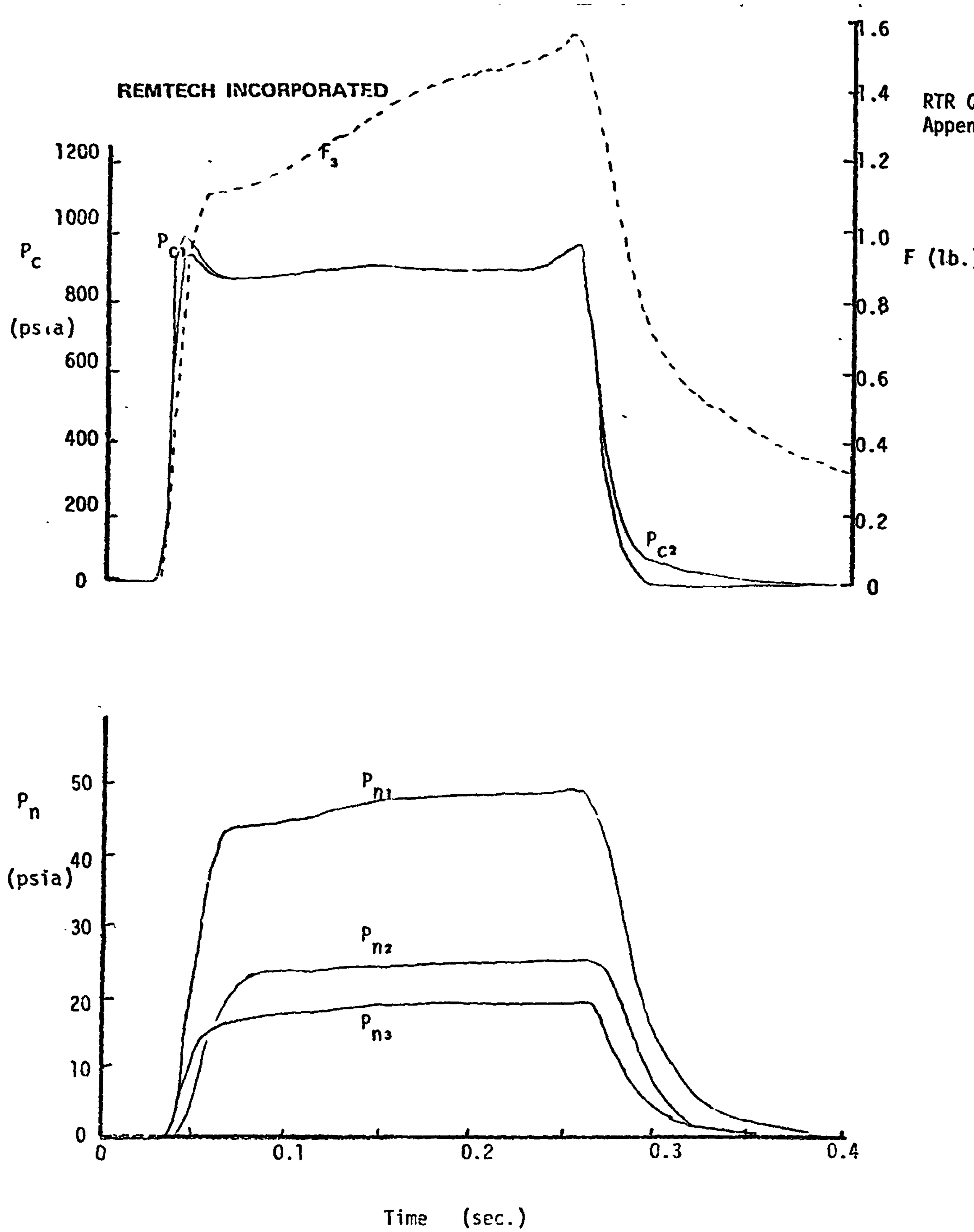
Run No. 44/1

Rake @ X/D=12

Alt.=112,000'
%Aℓ = 2



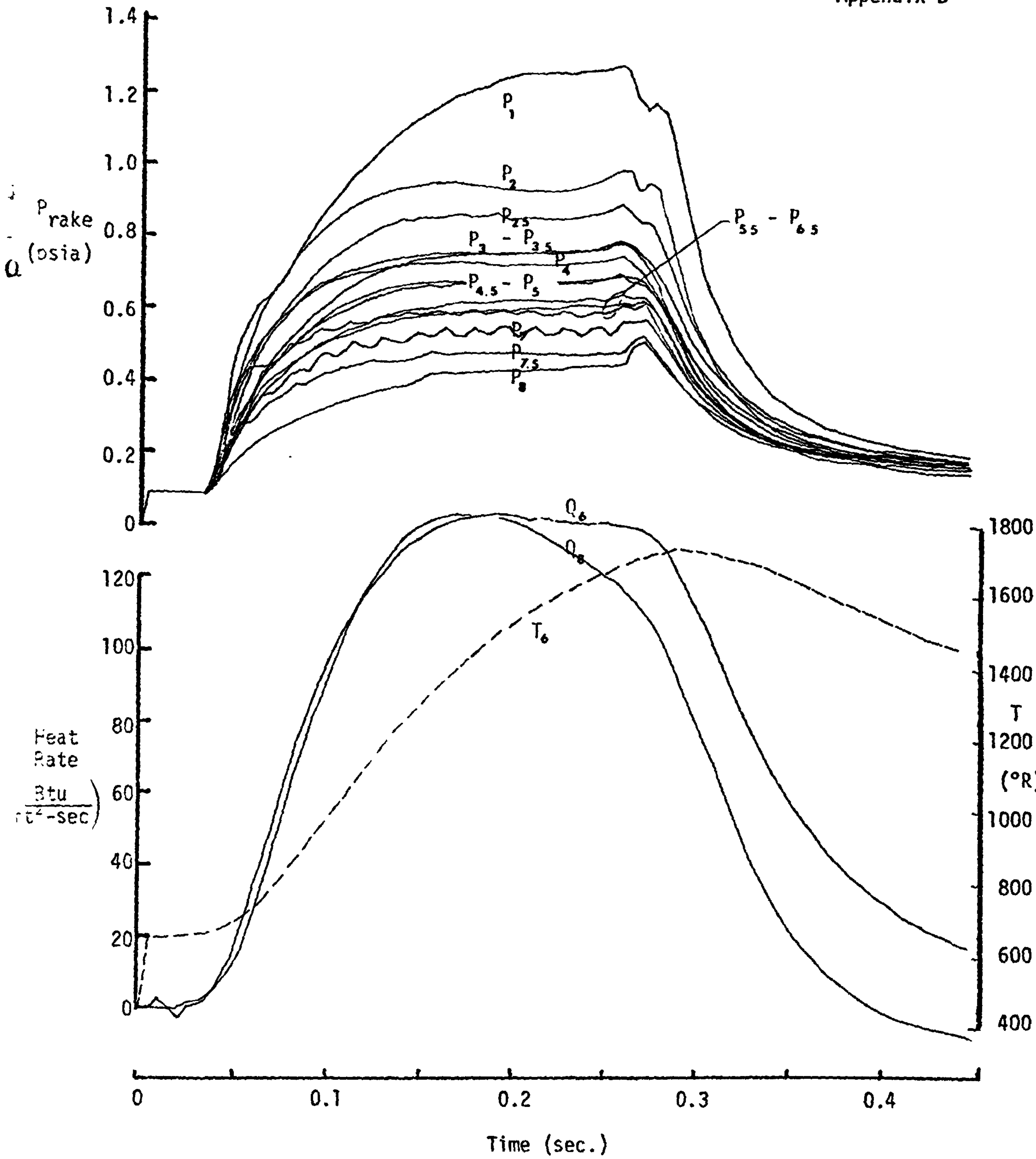
Run No. 44/1 (Concluded)



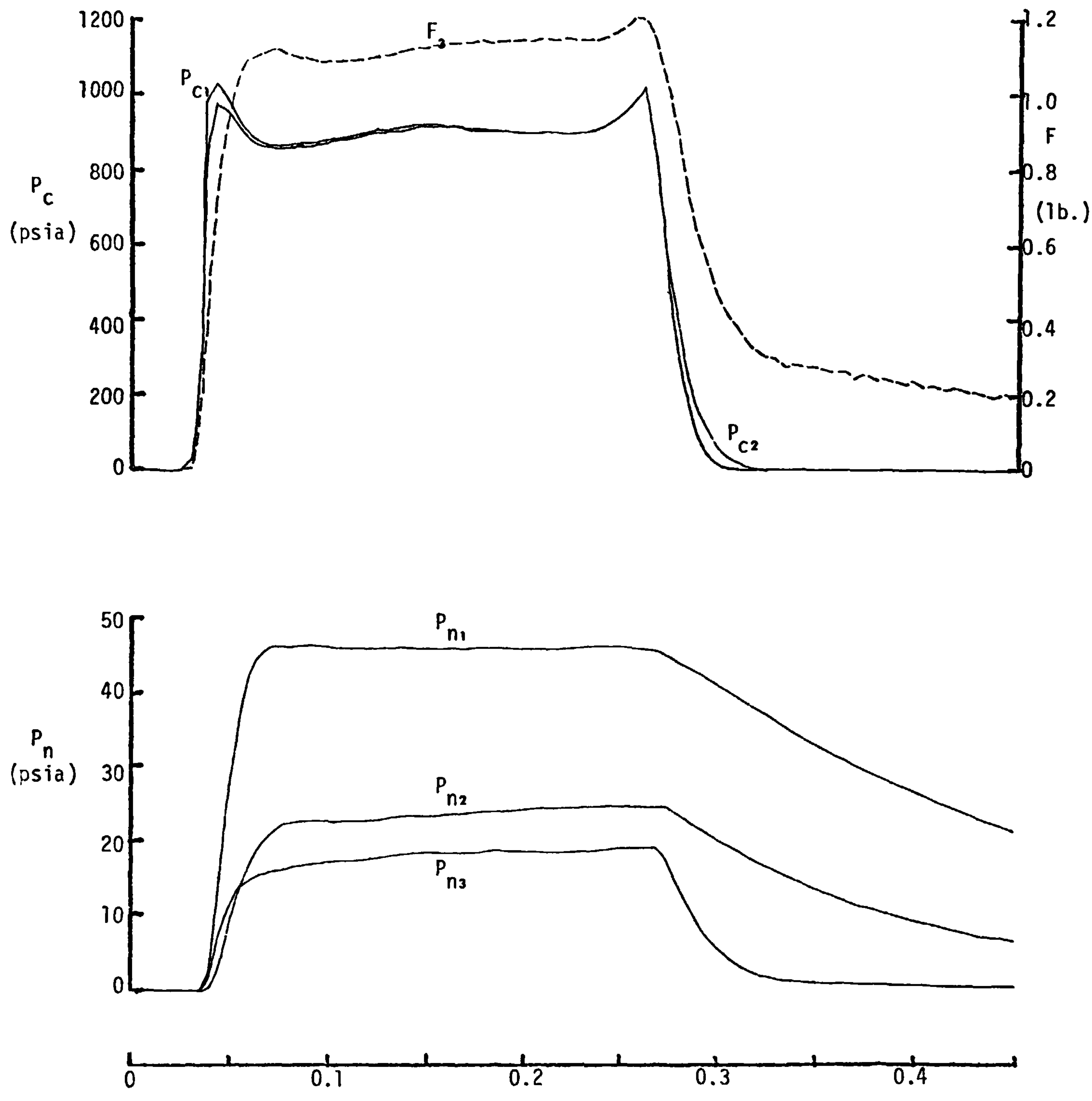
Run No. 45/1

Rake @ X/D=12

Alt.=112,000'
%Al = 10



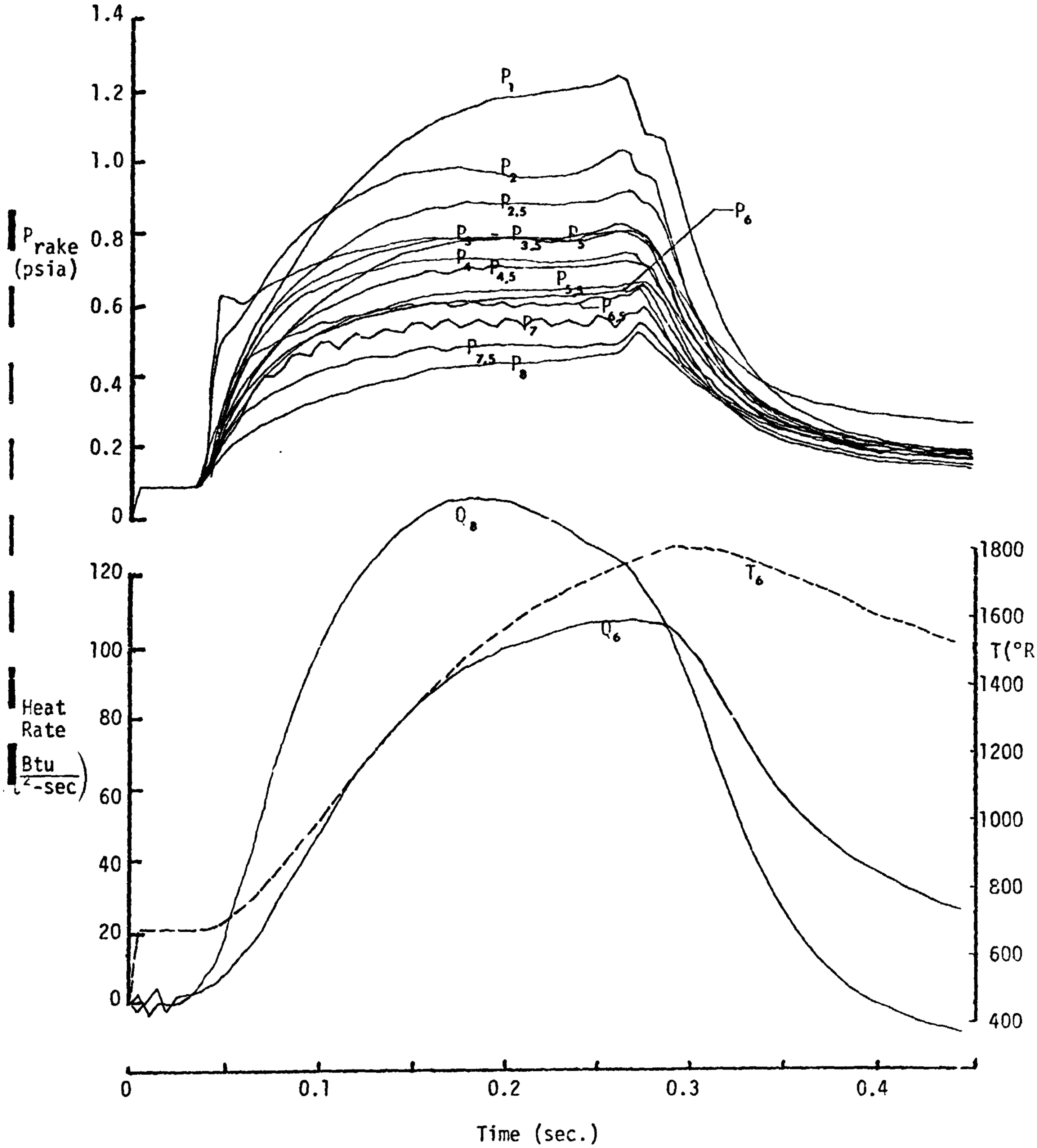
Run No. 45/1 (Concluded)



Run No. 45/2

Rake @ X/D=12

Alt.=112,000'
%Aℓ = 10



Run No. 45/2 (Concluded)