Calspan

Technical Report

[redacted]

(NASA-CR-150216) RESULTS OF THE NASA/MSFC N77-20145
FA-23 PLUME TECHNOLOGY TEST PROGRAM
PERFORMED IN THE NASA/AMES UNITARY WIND
TUNNELS (Calspan Corp., Buffalo, N.Y.) 83 p Unclas
HC A05/MF A01 CSCL 01A G3/16 21751

APR 1977
RECEIVED
NASA STI FACILITY
INPUT BRANCH

Calspan Corporation
Buffalo, New York 14221

Calspan

RESULTS OF THE NASA/MSFC FA-23 PLUME TECHNOLOGY TEST PROGRAM PERFORMED IN THE NASA/AMES UNITARY WIND TUNNELS

K.C. Hendershot

Calspan Report No. XN-5798-A-2

Prepared For:
GEORGE C. MARSHALL SPACE FLIGHT CENTER
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
HUNTSVILLE, ALABAMA 35812

FEBRUARY 1977
CONTRACT NO. NAS8-31636

Prepared by: K.C. Hendershot
K.C. Hendershot

Approved by: A. Ritter
A. Ritter, Assistant Head
Aerodynamic Research Department

Calspan Corporation
Buffalo, New York 14221

TABLE OF CONTENTS

SUMMARY

A 2.25% scale model of the Space Shuttle external tank and solid rocket boosters was tested in the NASA/Ames Unitary 11 x 11-foot transonic and 9 x 7-foot supersonic tunnels under the sponsorship of NASA/MSFC to obtain base pressure data with firing solid propellant exhaust plumes.

Data system difficulties prevented the acquisition of any useful data in the 9 x 7 tunnel. However, 28 successful rocket test firings were made in the 11 x 11 tunnel during July/August 1976, providing base pressure data at Mach numbers of 0.5, 0.9, 1.05, 1.2, and 1.3 and at plume pressure ratios, Pc/P_{∞}, ranging from 11 to 89.

FOREWORD

This report summarizes the experimental results of the FA-23 Plume Technology Program performed by Calspan Corporation for the Aero-Astrodynamics Laboratory of NASA/MSFC under Contract NAS8-31636. The NASA Technical Monitor for this program is Mr. Kenneth Blackwell S&E-AERO-AAE, with Mr. Robert Goss as his designated alternate.

The experimental program was performed at the NASA/Ames Research Center in two separate phases; November/December 1975 in the 9 x 7 supersonic tunnel and July/August 1976 in the 11 x 11 transonic tunnel.

The successful operation of the model rockets and pressure instrumentation during the 11 x 11 tunnel tests was in a large measure due to the conscientious efforts of Ray Gostkowski of Calspan who supported the Calspan project engineer during all pretest and test activities at Ames.

I. INTRODUCTION

The FA-23 experimental program described herein constitutes one part of a continuing, multi-phase plume technology study being conducted by NASA/MSFC. The purpose of the present experiments was to obtain base pressure data on a Space Shuttle-like external tank (ET) solid rocket booster (SRB) configuration over a range of exhaust plume pressure ratios and freestream Mach numbers. These data, obtained with combusted, actual solid propellant exhaust plumes, are to be subsequently analyzed by NASA/MSFC and compared with similar data obtained under comparable test conditions with air and freon jets and other smaller solid propellant rockets. The primary objective of the NASA plume technology study is to establish conclusively the similarity parameters relating cold flow and hot combustion gas exhausts in order to provide a better basis for the simulation of rocket plumes with more easily provided cold gas flows than has heretofore been available.

A strut/sting-mounted ogive-cylinder model approximately 2.25% the size of the Space Shuttle external tank, equipped with two side-mounted solid propellant rockets, was employed for the present test program. A high aluminum content composite propellant of a type similar to that presently being developed for the Space Shuttle SRBs by Thiokol Corporation was burned in the rockets for a duration of approximately 200 milliseconds.

The tests were performed at the NASA/Ames Research Center, in two different wind tunnels. The initial test series was carried out in the Unitary 9 x 7 supersonic tunnel during December 1975, followed by tests in the Unitary 11 x 11 transonic tunnel during July/August 1976.

Test variables included rocket combustion pressure, test section static pressure (attitude) and freestream Mach number. Data measurements included model surface pressures, rocket combustion chamber and nozzle internal pressures, and test section conditions.

The subsequent sections of this report describe the facilities and test equipment employed for the program (wind tunnels, ET model, solid propellant rockets, and pressure instrumentation), discuss the 33 run test sequence, and finally present the data obtained and briefly comment on its quality and reasonableness.

II. TEST EQUIPMENT

A. TEST FACILITIES

The test program was performed in the 9 x 7 supersonic and 11 x 11 transonic legs of the NASA/Ames Research Center Unitary Plan Wind Tunnel complex illustrated in Figure 1. Both tunnels utilize a common compressor drive system and are of the closed return, variable density type. Test section Mach number in the 9 x 7 tunnel ranges from 1.6 to 2.5 and is varied by translating a fixed contour block which forms the floor of the tunnel. The 0.4 to 1.4 Mach number range for the 11 x 11 tunnel is generated by a combination of nozzle flexing and test section suction through porous walls.

Models are supported in the tunnel from a sting which, in turn, attaches to a wedge-shaped strut which spans the test section height (width)[*] as shown in Figure 2.

B. MODEL HARDWARE

The model consists of a cylinder-ogive body, mounted from a swept side strut (see Figures 3-4). This strut, in turn, attaches to a rectangular cross-section sting which is connected to the leading edge of the tunnel strut by means of a taper plug assembly. Model design and fabrication were performed under the cognizance of NASA/JSC.[**] Since copies of all drawings (Nos. SK-7519-1 through -9) and a model stress analysis report have previosuly been transmitted to the NASA/MSFC Project Engineer by JSC, these detials have been omitted from this document.

The model body, which simulates the Space Shuttle external tank (ET), is of aluminum construction, hollow, and consists of an ogive-shaped nose, cylindrical mid-section, and hemispherical aft dome. Two close-fitting top-side covers allow convenient access to the interior of the model.

---

[*] In the 9 x 7 tunnel, the strut runs horizontally across the 9-foot tunnel width, while being vertical in the 11-foot transonic tunnel.

[**] Messrs. Barney Roberts and Tom Grubbs.

A sharp-edged strut, also of aluminum, supports the ET body from the sting. Hollow leading and trailing-edge covers provide space for routing of instrumentation leads, control wiring, and plumbing.

Two solid rockets are symmetrically mounted on opposite sides of the ET. These units, shown in cross-section in Figure 5(a), each produce a thrust of approximately 775 pounds at a combustion pressure of 200 psia. The thrust and moment loads are resisted by a "foot-pad" which is recessed into a milled-out pocket in the ET side wall and a forward pin which is bolted into a recess in the ET wall. The SRBs were originally designed and fabricated by Calspan for use on the Rockwell International 2.25% scale 19-OTS Space Shuttle base heating model. For the present program, however, new larger throat nozzles were substituted for the normal SRB nozzles previously used by Rockwell.

As illustrated in Figure 5(a), the SRB assembly consists of a removable conical nose fairing, cylindrical body, aft skirt (shroud), and an expansion nozzle of area ratio $\epsilon = 3.1$. Details of the nozzle internal contour, which as specified by NASA/MSFC, are presented in Figure 5(b). The SRB internal components are comprised of a removable propellant holder, diaphragm assembly, and gimbal adapter (0° gimbal angle for the present program) to which the nozzle attaches. Design internal operating pressure for the original design was 600 psia, although the maximum nominal combustion pressure scheduled for the present program was only slightly over 200 psia. All internal components downstream of the propellant holder are thick-walled copper, for heat-sink cooling.

Since only a short burning duration (of order 200 msec) is allowable because of the heat-sink cooling, a minimum thickness propellant web was used. To prepare a propellant load, thin (0.100-inch thick) strips of solid propellant were bonded to the surface of a thin aluminum sheet with a commerically-available contact cement. These sheets were subsequently rolled up and inserted into the cylindrical propellant holder, providing an internal-burning, cylindrical grain configuration. For higher combustion pressures requiring more propellant burning area than is available on the cylindrical surface, an additional central cruciform blade is provided which spans the combustor I.D. and has propellant bonded to both faces. For the three nominal combustion pressures employed during the 11 x 11 tunnel tests (P_c = 125, 150, and 215 psia), propellant areas of 108, 129, and 155 sq. in., respectively, were used.* Propellant loads were prepared both at Calspan prior to the test as well as onside at Ames while the test was in progress.

Attached to the downstream end of the propellant holder is a diaphragm package containing an 0.028-inch thickness of mylar diaphragms [identified in Figure 5(a)]. Assembly of the diaphragm package and insertion of the rolled-up propellant load into the propellant holder was performed outside of the tunnel on the bench prior to tunnel entry. Hence, the actual motor loading process in the tunnel was quickly accomplished by simply first removing the spent propellant holder and then inserting the newly-prepared propellant holder assembly into the motor case from the upstream end. Re-installation of the conical nose places the propellant holder in compression, effecting all necessary gas seals(O-ring). With this procedure, removal of the nozzles or aft skirt between firings was not required.

Two propellant formulations (UTP-3001 and LPC-580C) were evaluated during combustor checkout at Calspan prior to the formal test program at Ames. However, the latter propellant was used exclusively during the 11 x 11 tunnel tests, when the only useful test data were obtained. Thus, LPC-580C is the only propellant considered in the present report; its physical characteristics and combustion properties are summarized in Table I.

To obtain simultaneous and rapid ignition of the two SRBs, the motor cases were filled with an oxygen-rich mixture of gaseous ethylene-oxygen at a pressure of one atmosphere just prior to firing. This ignition gas introduced

---

*A full cylindrical load was 129 sq. in. (6-in. circumference x 21-1/2 in. length). Thus, the larger 155 sq. in. case required the additional center blade, while the 108 sq. in. load was obtained by reducing the length of the cylinder to only 18-in.

into the motors from outside the tunnel through a copper tube which passes through the strut and sting and connects to a central manifold located in the external tank. Ignition (by means of pyrotechnic igniters)* and the resultant constant volume combustion of this gas mixture instantaneously exposes the propellant surface to an extremely hot (5000°F) oxidizing environment providing rapid (and more importantly, simultaneous) ignition of the two motors. Following ignition, the solid propellant products are contained in the individual motors (with pressure balancing occurring through the ignition gas inlet/cross-feed manifold) until the mylar diaphragms rupture somewhere near the desired operating pressure. During both previous Rockwell tests and the present program, reliable and repeatible ignition within 10 msec of igniter firing and nominal steady burn times of 150-200 msec have been observed.

C. PRESSURE INSTRUMENTATION

A total of 27 static pressure orifices are located on the model; 15 on the ET dome, three on the bases of each of the two SRB aft skirts (= 6 total), and three on each of the SRB nozzle internal surfaces (= 6 total). Locations of the pressure taps and corresponding Calspan identification numbers are shown in Figure 6, supplemented by Table II which correlates the Calspan and Ames numbering systems. In addition to model surface pressures, there is a pressure tap in each of the SRB combustion chambers, making a total of 29 model pressures in all.

Pressures on the ET dome are routed through 1/16-inch steel tubing to 15 Statham PM131TC, ±15 psid transducers located under the forward ET cover as shown in Figure 7(a). The six SRB aft skirt base pressures are similarly sensed through 1/16-inch steel tubing which is bent over the SRB surface (following the external contour) and into the ET at the dome/body junction. These tubes are connected to six additional Statham PM131TC differential

---

*For the 9 x 7 tests, separate igniters were installed in each SRB, while during the 11 x 11 phase of the program only a single igniter was employed, symmetrically located midway between the rockets in the cross-feed manifold.

pressure transducers which are installed on a bracket under the rear ET cover. Reference pressures for the 21 differential transducers are provided by plastic tubes connected to a multi-nipple manifold located under the forward cover, identified in Figure 7(a). The reference manifold connects, in turn, to an external vacuum source and precision manometer by means of a 1/4-inch tube which is routed out of the model along the forward edge of the strut. Tubing connections for all of the 21 differential transducer lines are made with slip-on plastic tubing.

Transducers for the nozzle internal pressures (6 Statham PA208TC, absolute type) are also installed under the ET rear cover and are attached to the nozzle pressures tubing with 1/16-inch Swagelok connectors as illustrated in Figure 7(b). Finally, the two SRB chamber pressures are measured with two Statham PA856-1M, 0-1000 psia transducers located under the forward cover and connected to the SRB pressure port via 1/8-inch steel tubing and Swagelok fittings. A tee and loop in each line allows purging, venting, and oil-filling of the P_c lines to minimize plugging (due to Al_2O_3) and exposure of the transducer diaphragm to corrosive (HCl) exhaust products. Both a P_c transducer and its tee/loop connecting plumbing are visible in Figure 7(a).

Transducer excitation and output signals were transmitted through shielded conductors terminating in a plug-in connector at the transducer end and spade lugs at the opposite end for attachment to permanent facility wiring inside the tunnel strut.

D. AUXILIARY EQUIPMENT

As noted earlier, ignition of the SRBs is effected by burning a mixture of gaseous ethylene and oxygen within the rocket chamber. Loading of this mixture into the rocket was carried out remotely from the control room, by means of the pre-fabricated ignition gas loading system shown schematically in Figure 8. A step-wise gas loading sequence in which the O_2 and C_2H_4 were introduced alternately into the rocket chambers assured adequate mixing of the ignition gases before firing. Additional details on the ignition gas loading system, operational procedures, and safety features may be found in Appendix A.

E. INSTRUMENTATION AND RECORDING

All 29 pressure transducers used in the program were provided by NASA/MSFC and are of the strain-gage, four-legged bridge type requiring an excitation voltage in the range of 5-6 V. Pressure calibrations were performed on the transducers by NASA/MSFC to verify output linearity prior to their delivery to Calspan for installation.

At Ames, signal conditioning for each transducer was provided by Newport power supply/balance/preamplifier/DVM readout modules, mounted in facility-supplied eight-channel rack mounts (see Figure 9). Output signals from the Newport units were recorded with the Ames NOVA digital data acquisition system, at a nominal sampling rate of once every two msec. Details of the operating characteristics of the NOVA have not been provided to the author, and thus the system will not be described further in this report.

A direct writing oscillograph was also provided by Ames to provide "quick-look" analog records of a number of pressures at representative locations to allow a rapid, on-line assessment of the data quality prior to proceeding to the next test condition.

III. TEST PROGRAM

A. TEST SCHEDULE

The test program was performed in two distinct phases separated by approximately eight months. The initial phase was conducted in the 9 x 7 tunnel during a two week period in December 1975, followed by the second phase which was carried out in the 11 x 11 tunnel during late July/early August 1976.

1. 9 x 7 Test Program

Following a number of delays in getting the program underway at Ames, including late arrival of hardware which had been lost during shipment from JSC and problems with the NOVA data system, a total of five rocket firing runs were made in the 9 x 7 tunnel at Mach 2 on 11-12 December 1976. However, during loading of propellant into the SRBs in preparation for Run No. 6, a forward gland nut on one of the rocket cases seized up and could not be loosened. Since extensive machining of the SRB appeared necessary to remove the nut, and remaining available tunnel occupancy time was limited, the MSFC Project Engineer elected to cancel the balance of this test phase. Subsequent detailed analysis of the model pressure measurements obtained during the five test firings by NASA/MSFC revealed excessive noise and scatter in the reduced data, attributed to anomolous operation of the NOVA data acquisition system. As a result, all of the data obtained during the 9 x 7 test phase was judged by the NASA/MSFC Project Engineer to be unreliable and not to warrant any further analysis or documentation. Thus, none of the results of the 9 x 7 tunnel phase are included herein.

2. 11 x 11 Tunnel Program

Jet-off testing for the 11 x 11 tunnel phase of the program was initiated on 28 July 1976 (Runs 1-4), following a relatively smooth and uneventful installation of the test model and assembly/activation of the NOVA data system. Hot firings commenced with Run 5 on 29 July, with a total of 28 successful rocket firings* being made by 4 August 1976 at which point all available propellant had been consumed and the scheduled test sequence was complete.

Tests were performed at nominal free stream Mach numbers of 0.5, 0.9, 1.05, 1.2, and 1.3, and rocket combustion pressures of 125, 150, and 215 psia. Nominal run conditions for all runs in the 11 x 11 tunnel are summarized in Table III, while Table IV compares the planned test parameters with the conditions actually achieved. Although the planned plume pressure ratios were generally not exactly achieved, the agreement between planned and actual is reasonable and the range of plume pressure ratios adequate to satisfy program objectives.

B. DESCRIPTION OF THE 11 x 11 TEST PROGRAM

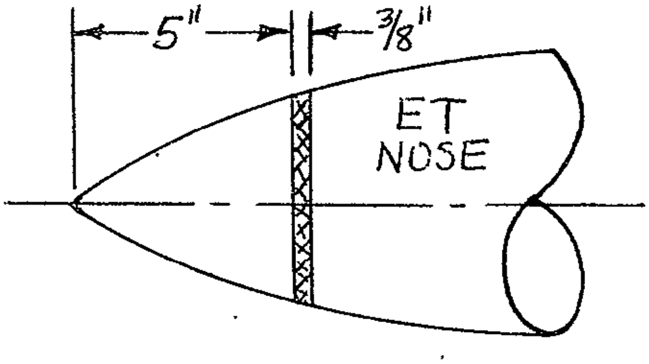
1. Pretest Activities

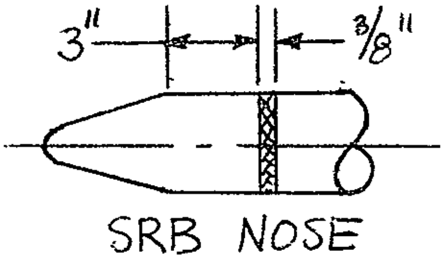
In general, model installation proceeded smoothly, with approximately one week being required to connect up all wiring, install the model in tunnel, assemble and pressure check the ignition gas system, checkout and calibrate all pressure instrumentation through the NOVA, and generally prepare for testing. During this pretest period, replacement of the SRB nozzle pressure tubes (which has been damaged during the 9 x 7 tests) was performed in the Ames machine shop. As a result of overheating the nozzle during the soldering processes, severe warping of the nozzle contour was experienced. This nozzle distortion was satisfactorily corrected, however, by remolding the nozzles over a 20° conical aluminum mandrel.

Boundary layer trips consisting of 0.03-inch (nominal) diameter glass beads, bonded to the model with Polaroid print coater, were provided on the SRB forward section and ET nose as shown in the following sketch and as identified in Figure 4(a).

---

*Out of 29 attempted; one firing was unsuccessful due to a faulty igniter.





Routing of the 1/16-inch steel tubing from the SRB skirts and nozzles into the ET near the hemisphere/cylinder junction unavoidably resulted in blockage of orifice P15, thus rendering any data from this tap questionable. Since P14 is in close proximity to P15, data from this pressure tap should also be regarded with suspicion. Problems with a nozzle pressure transducer (P23) could not be resolved, so this pressure tap was capped off and remained unused for the entire program.

Calibrations of the ET and SRB aft skirt differential pressure transducers (P1 → P21) were performed during the pretest period over a range of ±7 psid by leaving the pressure taps exposed to atmospheric pressure and varying the reference pressure both above and below atmospheric. Nozzle internal pressures (P22 → P27) were calibrated by sealing off the nozzle exits with special gasketed aluminum plates, and pressurizing the rocket interior up to 30 psia. The rocket Pc transducers (P28 and P29) were similarly calibrated by closing off the combustion chamber with a heavy mylar diaphragm at the diaphragm station and pressurizing the combustor to 200 psia. In both the latter cases, pressurization of the rocket interior was controlled through the ignition gas loading system (using N_2 as the test gas) and monitored with appropriate precision dial gages.

2. Test Operations

Formal testing commenced during late evening of 28 July, with wind-only data being obtained for comparison with comparable data previously acquired by NASA/MSFC personnel in the AEDC Tunnel 4T. Four runs were made at Mach numbers of 0.5, 0.9, 1.3 and 1.2 (Runs 1-4) all at a nominal free stream total pressure of 1415 psf. On the basis of an assessment of the data by the NASA/MSFC Project Engineer in attendance, a decision was made to proceed with the rocket firing portion of the test program during the afternoon of 29 July.

Following problems with an improperly operating ignition gas load gage,* the first hot firing (Run 5) was made at about 3:30 PM during the afternoon of 29 July 1976. Although the rockets operated satisfactorily, the run was voided because of an improperly set tunnel Mach number and total pressure.

Testing continued through the second shift of 29 July, with Runs 6-9 being made during the evening hours. The only difficulty encountered during this sequence of runs was plugging of the "leaky" check valve in the ignition gas line with solid propellant residue prior to Run 7, an occurrence which prevented normal loading of the ignition gas into the SRBs. The check valve was readily replaced with an available spare with only minimal delay.

During the second shift on Friday, 30 July, five more firings (Runs 10-14) were successfully completed prior to the weekend shutdown of the facility. In preparation for Run 10, the oil-filled Pc lines were purged and refilled with silicone oil, and measurements taken of the nozzle throat diameters. Nozzle throat dimensions obtained during this, and subsequent checks, are summarized in Table V.

Testing was resumed during the second shift on Monday, 2 August, with the Pc lines again being filled with fresh oil and the nozzle throat dimensions measured prior to the initial run. Four firings were successfully made (Runs 15, 16, 17, and 19) while Run 18 was aborted because the propellant

---

*This gage was a brand-new unit provided by Rockwell to replace one that had previously been used during the 9 x 7 tests, borrowed, and subsequently misplaced by Rockwell.

failed to ignite. Since subsequent checking disclosed no faults in the igniter electrical circuit and two identical igniters were successfully fired external to the model, it was concluded that the original igniter must have been faulty. Thus, a new igniter was installed and the run re-attempted using the same propellant load. This attempt was successful, and the run was re-numbered Run 19.

Testing continued during the afternoon and evening of 3 August, with Runs 20-28 being accomplished with some minor problems. Prior to this sequence, the Pc lines were again cleaned and re-filled with oil, while replacement of the ignition gas line check valve was found necessary between Runs 20 and 21. During assembly and installation of the propellant load for Run 26, the left SRB propellant holder was inadvertently reversed, end-for-end, from its normal arrangement. Since the combustion pressure is sensed through a series of holes in one end of this cylinder (normally at the downstream end, just ahead of the nozzle inlet), this backward installation resulted in the Pc being sensed at the upstream end of the combustion chamber instead. The combustion pressure is considerably higher at the forward end of the chamber, and the discrepancy was immediately apparent upon examination of the data following the run. It was concluded by the NASA/MSFC Project Engineer that the data could be salvaged, however, and thus the run was not repeated.

Following the (now) routine Pc line refilling, throat measurement, and ignition gas-line check valve replacement, testing commenced around noon on 4 August, with five firings (Runs 29-33) being made to complete the test program.* During this series of runs, the incident of Run 26 was unfortunately repeated during Run 30 when the propellant holder was mistakenly again assembled backwards (this time in the right hand SRB), resulting in P29 recording the

---

*It is noted that through Run 28, all propellant charges were assembled from loads which had been prepared (glued) in Buffalo several weeks in advance of their use in the program. Propellant loads for the last five runs, however, were prepared onsite at Ames only a day before their use. Their somewhat erratic behavior (e.g., slightly lower than anticipated Pc) may be attributable to their lack of aging.

SRB forward end, rather than aft end, combustor pressure. Again, it was decided by the NASA Project Engineer that the data could be used and the test schedule proceeded on uneventfully through the remaining runs.

In summary, a total of 28 successful combustion runs was made during five tunnel operating periods, with nine firings being made during one 12-hour shift. Only one firing malfunction occurred, attributed to a faulty igniter rather than any of the rocket hardware or its support equipment.

Operation of the tunnel appeared to be quite compatible with a rocket test of this type. Post-run purging and access to the tunnel to prepare for the next run was performed on a cycle consistent with the rate at which fresh propellant loads could be assembled by Calspan support personnel. Samples of the tunnel air routinely obtained by NASA/Ames personnel following an appropriate purging cycle revealed no evidence of HCl in the atmosphere and confirmed the safety of the tunnel environment for working personnel.

The NASA/JSC-designed model functioned quite well, providing adequate accessibility for transducer/component installation during pretest and on a run-to-run basis during the test program.

3. Test Sequence

After the rockets were loaded and leak-checked and the tunnel was closed ready for testing, all pressures were scanned by the NOVA system to obtain WIND-OFF, JET-OFF reference data at tunnel static pressure conditions ("initial zero reading"). Electrical calibrations were also obtained for every channel at the start of each run by introducing a pre-determined electrical signal ("initial calibration reading") which effectively calibrated all system electronics.

The tunnel was then turned on and while tunnel flow conditions were being set, the SRBs were loaded with ignition gas to one atmosphere. When tunnel conditions became stable, a NOVA scan was made to obtain WIND-ON, JET-OFF pressure data for all transducers ("initial tunnel readings"). Upon notification that the ignition system was armed and ready to fire, the tunnel engineer started the following test sequence via the NOVA computer:

(1) Direct writing oscillograph turned on (chart speed $\approx$32 inches/second);

(2) After a suitable delay to allow the oscillograph to reach operating speed, NOVA started sampling pressure transducers to obtain WIND-ON, JET-OFF baseline data for a total of 10 samples (20 msec nominal time duration);

(3) At 20 msec, NOVA transmitted a signal to the rocket igniter system to fire the rockets while data sampling continued;

(4) The rockets reached steady conditions in approximately 40 msec; data sampling continued for a total duration of 400 msec, well beyond the end of combustion;

(5) Subsequent to rocket firing, the pre-run data sampling sequence was repeated (in reverse order), obtaining first WIND-ON, JET-OFF post-run baselines ("final tunnel readings"), followed by "final calibration readings" and "final zero readings".

IV. PRESENTATION AND DISCUSSION OF THE DATA

A. DATA PRESENTATION

All data were collected (sampled), reduced to absolute, ratio, and coefficient form, and printed out in the tabular format illustrated in Figure 10* by the Ames-supplied and operated NOVA data acquisition system. Since a complete set of the data tabulations has been transmitted by Ames to the MSFC Project Engineer, and reproduction of the entire 500+ pages of data printouts in this report would be prohibitively costly, tabulated data have not been included herein. However, some supplementary data must be provided in order to correlate clock times and calendar dates during which the actual calibration and run events occurred with the clock times and dates shown on the data tabulations which correspond to the times at which the data were actually reduced (approximately one month after the test was completed). For example, Run 20 actually started at 13:40:52 on August 1976, whereas the data printout for Run 20 which was received by Calspan (not shown in this report) defines the run start time as 20:18:54 on 2 September 1976, which is (presumably) the time at which the data were reduced by Ames from the tape record. Table VI is included to provide the necessary correlations between actual times/dates and those shown on the data tabulations. The information provided in this table was transmitted to Calspan by the NASA/MSFC Project Engineer during September 1976, and is reproduced exactly as received to avoid any possibility of transcribing or typographical errors.

As an aid to data interpretation and evaluating flow steadiness with time, the SRB rocket chamber pressures are plotted as a function of time in Figure 11 for all valid data runs between Runs 6 → 33. It is seen from these plots that the chamber pressures were, in most cases, acceptably steady, normally varying no more than 5 to 10% during the test event. Burn duration

---

*The edited records illustrated in Figure 10 are taken from Run 18, a run in which the SRBs failed to fire. Thus, these particular data have no significance in themselves. However, the format is identical to that employed for all good data runs.

varied with chamber pressure (since the propellant thickness was constant), but was at least 250 msec for all runs. Chamber pressures in the two rockets were consistently well matched, illustrating both adequate quality control and similarity between propellant loads and the effectiveness of the cross-feed tube in balancing any pressure variations between the two SRBs.

An examination of the abscissas in Figure 11 shows two time scales, "actual" and "computer". It is Calspan's understanding that the nominal time interval of 2 msec between data samples was, in fact, actually 2.3 msec. This longer interval appears to be confirmed by a comparison of the overall rocket firing duration as indicated by the oscillograph analog records and the NOVA tabulated printouts. Thus, although the data were plotted in the 2 msec steps provided in the tabulations for convenience, actual corresponding real times are also included.

B. DISCUSSION OF THE DATA

In view of the large amount of data collected during the test program (i.e., approximately 150 samples per run x 30 transducers x 32 data runs 150,000 data points), it would be physically impossible and beyond the scope of the program to examine and evaluate every data point for consistency and/or reasonableness. Further, since none of the data previously obtained in the AEDC 4T tunnel with a similar configuration (albeit jet-off) or other relevant NASA cold jet data have been made available to the writer for data comparisons, the present report includes only samples of the data to illustrate behavior and leaves the detailed analysis of the data to the user.

For purposes of discussion, the pressure at the center of the ET dome, PET1 has been selected as being representative of the base pressures. To illustrate the rise characteristic and time to equilibrate, Figure 12 compares the pressure-time histories of the SRB combustion pressures, PCL and PCR, and PET1 during Run 33. It can be seen that PET1 achieves a nominally steady pressure level within approximately 100 msec after the start of pressure rise, in phase with PCL and PCR, and remains essentially constant for another 100 msec.

This time appears quite adequate to insure steady state, equilibrium pressure levels have been achieved in the base region. To illustrate the behavior of other representative pressures as a function of time, the on-line oscillograph record from Run 11 has been reproduced in Figure 13. It is seen that all ET dome (ET1 and ET4) and aft fairing pressures (L1 and L3) stabilized within 20-30 msec during this run, whereas the nozzle internal pressures (NL3 and NR3) took somewhat longer. In any event, however, all pressures were equilibrated for a sufficiently long period to assure attainment of steady state levels.

In Figure 14, the variation in ET1 pressure with plume pressure ratio, Pc/P_∞, and free stream Mach number is illustrated. The behavior appears reasonable, with base pressures increasing as plume pressure ratio increases (i.e., more plume spreading).

V. CONCLUSIONS

A 2.25% scale pressure model of the Space Shuttle external tank and hot-firing solid rocket boosters was successfully tested in the Ames Research Center 11- x 11-foot transonic tunnel. The model, solid propellant rockets, instrumentation, and data recording system functioned extremely well, allowing 28 successful rocket firings to be made during five tunnel operating periods, with nine runs being achieved in a single 12-hour test period.

Pressure data were obtained over a range of transonic Mach numbers (0.5 to 1.3) and plume pressure ratios ranging from 11 to 89.

The model solid rocket boosters operated satisfactorily, demonstrating reliable ignition, good pressure matching, and over 200 msec of steady combustion pressure.

A limited number of test runs performed earlier in the Ames 9- x 7-foot supersonic tunnel produced no useful data because of data acquisition system problems.

VI. REFERENCES

1. Anon., "Ames Research Facilities Summary - 1974".

APPENDIX A
IGNITION GAS SYSTEM

A. Background

The SRB solid propellant is ignited by the rapid combustion of a flammable mixture of gaseous ethylene (C_2H_4) and oxygen (O_2) whose ignition is, in turn, effected by a Holex 1196A pyrotechnic igniter. The following paragraphs briefly describe the basis for the ignition gas technique and the loading procedures employed to introduce the gases into the SRBs.

It has been conclusively demonstrated during extensive checkout firings at Calspan during early 1975 in preparation for the Rockwell 19-OTS Space Shuttle base heating tests in the LeRC 10 x 10 wind tunnel that reliable and rapid ignition of the SRBs cannot be achieved by the use of commercially available (or enhanced) pyrotechnic igniters alone. From these studies, it was concluded that the available igniters simply do not provide sufficient energy to rapidly and uniformly heat the propellant surface and initiate combustion on the millisecond time scale necessary to assure simultaneous ignition of two rockets.

It had previously been shown by Calspan, however, that rapid and repeatible ignition can be achieved by pre-loading the closed rocket combustion chamber with an oxidizer-rich combustible gas mixture (typically C_2H_4/O_2, with of order 200% excess oxygen) and igniting the mixture with a spark plug or, as in the present case, pyrotechnic igniter. Such a technique has been routinely used at Calspan for many years and was employed on the present FA-23 program.

B. Ignition Gas Loading Procedure

Coincident with loading of propellant into the SRBs, the discharge end of the SRB combustion chamber is sealed off with mylar diaphragms. This allows the ignition gas mixture to be retained within the chamber and, subsequent to propellant ignition, allow a rapid pressurization of the combustion chamber which also aids in the attainment of repeatable start transients. The diaphragm fails at, or near, the design operating pressure.

As shown schematically in Figure A-1, the two SRBs are pneumatically connected at their midpoint by a 1/2-inch I.D. tube which spans the interior of the external tank. This duct provides a path for pressure equalization between the two rockets during burning as well as an inlet for the C_2H_4/O_2 ignition gas mixture. Introduction of the ignition gas into the rockets proceeds as follows:

(1) Following installation of the propellant load and igniters, and evacuation of personnel from the tunnel test section, the SRBs are leak-checked with N_2 at a pressure of $\approx$60 psia. Pressurization is provided from the ignition gas manifold and monitored on the compound "load gage" shown in Figure A-1. If no leakage is detected (i.e., no pressure drop in a valved-off system after a reasonable waiting period), the test section is secured and tunnel start-up commences.

(2) While test conditions are being established, residual gases in the SRBs are evacuated by means of the vacuum pump in the ignition gas system.

(3) Approximately 5-10 minutes prior to the time of rocket firing, ignition gas is introduced into the SRBs (remotely from the control room by actuating solenoid valves "fuel" and "oxidizer" on the ignition gas panel and the "load line" solenoid valve inside the model just ahead of the equalization duct). The sequence of events is as follows:

    (a) The rockets are initially pressurized to 2.0 psia with C_2H_4, followed with O_2 to 10 psia (total pressure), then by C_2H_4 again to 11.2 psia (total pressure), and finally with O_2 to 20 psia (total pressure);

    (b) After waiting $\approx$5 minutes for mixing to occur, the system is vented to atmospheric pressure (nominally 14.7 psia) through the vent valve;

    (c) The "load line" solenoid valve in the model is then closed, trapping the combustible C_2H_4/O_2 mixture in the SRB chambers at one atmosphere pressure;

    (d) To preclude any possibility of ignition gas burning in the load line (due to leakage through the "load line" solenoid valve, for example), the load line is purged by loading the line to $\approx$60 psia with N_2 and venting to atmosphere several times, followed by evacuation, and finally, filling with N_2 to 1 atmosphere.

(4) The SRBs are fired by igniting the ignition gas with the pyrotechnic igniters.

C. Gas Panel and Control Functions

Major features of the ignition gas system, which is assembled on a board for mounting adjacent to the tunnel, are shown schematically in Figure A-1 and are as follows:

(1) Standard welding-bottle size N_2, O_2, and C_2H_4 cylinders, equipped with conventional hand-actuated pressure regulators provide the working gases (line pressures of $\approx$50-60 psia are employed);

(2) Check valves are installed in each gas line to prevent possible backflow of gases;

(3) Gas flows are actuated from the control room by remotely controlled ON-OFF solenoid valves;

(4) All gas feed lines connect to a common manifold equipped with a relief valve, and vent lines (solenoid valve actuated), needle throttling valve, and pressure monitoring gage;

(5) The "load line" monitoring gage, a precision dial gage of the solid front, "blowout" type is mounted remote from the gas panel, adjacent to the outer control room wall and directly visible to the gas panel operator through the control room windows;

(6) The system consists of tubing, fitting, valves, and other components all rated for operation at 3000 psi and was completely assembled, pressure/leak checked, and cleaned for oxygen service at Calspan prior to shipment to ARC;

(7) Routing of the ignition gas between the control panel and SRBs occurs via a 1/4-inch line which passes through the tunnel strut, down the model sting, and into the external tank where it connects to the "load line" solenoid valve;

(8) Protection of the seat of the "load line" valve against burning ignition gases and hot combustion products from the SRBs is afforded by a "leaky" check valve between the equalization duct and valve inlet. This valve allows initial evacuation of the SRBs over a 30 minute time scale while minimizing the reverse flow of hot gases during the 200 msec rocket burn. Such a technique has been frequently used at Calspan and found to function well.

D. Safety Features

(1) Oxidizer and fuel valve switches are interlocked and of an automatic return push button type to prevent the two gases from being turned on simultaneously or inadvertently left on;

(2) The vacuum valve is interlocked with the oxidizer and fuel valves to avoid loading of undiluted oxidizer or fuel gases directly into the vacuum pump;

(3) The vent and vacuum valves are energized from a common double throw CENTER OFF switch to avoid the possibility of vacuum pumping with the vent valve open. A mechanical stop which must be deliberately repositioned by the operator minimizes the possibility of inadvertently exhausting low pressure oxygen which has been previously loaded into the system through the vacuum pump;

(4) An electrical interlock prevents igniter firing with the "load line" solenoid valve inside the ET in the open position.

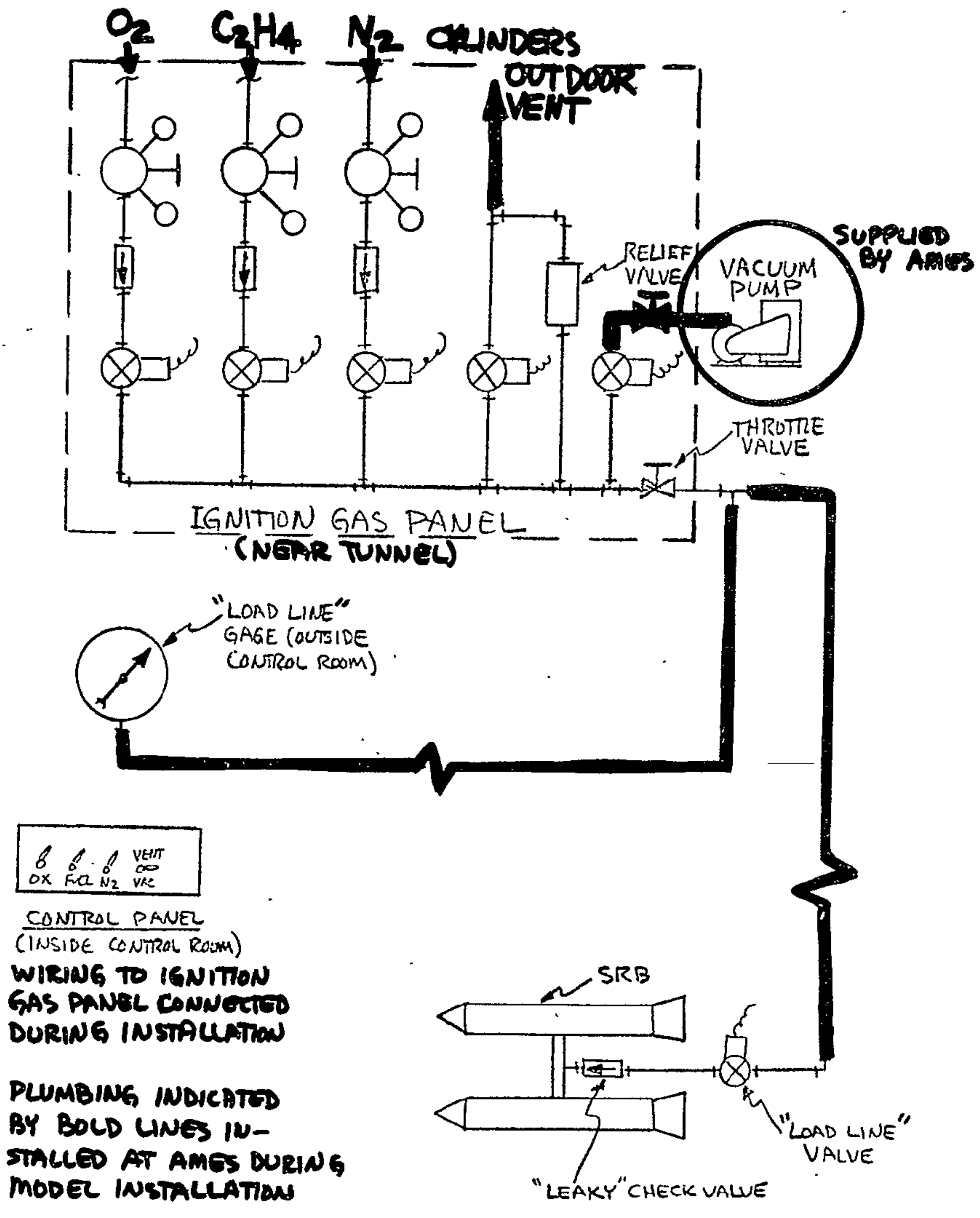


Figure A-1 IGNITION GAS SYSTEM — SCHEMATIC

TABLE I

PROPERTIES OF LPC-580C SOLID PROPELLANT

Physical Characteristics

Composition	AP/PBAN/16% Al Composite
Thickness	0.100 inches
Density	0.065 lb/in^3
Autoignition Temperature	420°F

Combustion Properties (theoretical calculation)

Combustion Temperature	6330°R
Molecular Weight	26.8
γ effective	1.17
Combustion Products	mole %
CO_2	2
H_2	28
H_2O	12
N_2	8
CO	22
HCl	12
Al_2O_3	8
Other (H, Cl, OH, $AlCl_2$, etc.)	8

TABLE II

PRESSURE TAP IDENTIFICATION

Location	Calspan Designation	Ames Designation
ET dome	P1	ET1
	P2	ET2
	P3	ET3
	P4	ET4
ET body	P5	ET5
	P6	ET6
	P7	ET7
ET dome	P8	ET8
	P9	ET9
	P10	ET10
	P11	ET11
	P12	ET12
	P13	ET13
	P14	ET14
	P15	ET15
SRB aft skirt	P16	L1
	P17	L2
	P18	L3
	P19	R1
	P20	R2
	P21	R3
Nozzle internal surface	P22	NR1
	P23	NR2
	P24	NR3
	P25	NL1
	P26	NL2
	P27	NL3
SRB chamber	P28	PCL
	P29	PCR
Tunnel sidewall	P30	PSWALL

TABLE III

11 x 11 TUNNEL NOMINAL TEST CONDITIONS

Run	M	P_T (psf)	P_c (psia)	Comments
1	0.5	1413	-	Wind only - no rocket firing
2	0.9	1417	-	
3	1.3	1413	-	
4	1.2	1415	-	
5	1.1	2000	175	Tunnel conditions improperly set - invalid run
6	0.9	1550	215	Rocket firing
7	0.9	2502	125	
8	0.9	1063	215	
9	1.2	1519	150	
10	1.2	3000	125	
11	1.2	992	215	
12	1.3	1768	150	
13	1.3	1359	150	
14	0.5	2397	150	
15	1.05	2773	150	
16	1.3	1002	215	
17	1.05	1075	150	
18	1.05	870	215	No rocket firing - igniter malfunction
19	1.05	870	215	Rocket firing
20	0.5	954	150	
21	0.5	699	215	
22	1.2	848	125	
23	1.2	1111	150	
24	0.9	1804	150	
25	0.9	885	150	
26	1.3	1895	150	
27	1.05	1711	150	

TABLE III (Concluded)

Run	M	P_T (psf)	P_c (psia)	Comments
28	1.05	814	150	Rocket firing
29	1.3	961	150	↓
30	1.3	2122	150	↓
31	0.5	1378	150	↓
32	1.3	1357	150	↓
33	0.5	1048	215	↓

TABLE IV

11 x 11 TUNNEL TEST PARAMETERS

Mach No.	δ_J(deg) Planned	Plume Pressure Ratio, P_c/P_∞		Run No.
		Planned	Actual*	
0.5	34	42.3	56.2	21
	32	35.1	32.0	33
	28	27.0	28.0	20
	22	18.6	17.2	31
	12	10.6	11.0	14
0.9	40.5	54.4	48.6	8
	35	36.9	45.6	25
	32.5	31.5	32.8	6
	25.5	20.3	23.0	24
	17	12.2	11.8	7
1.05	42	71.5	74.2	19
	38	53.2	57.6	28
	32	40.3	42.4	17
	27	25.3	26.8	27
	19	15.6	16.6	15
1.2	45	75.8	80.2	11
	40.5	47.4	53.1	23
	36.5	34.5	36.6	9
	29	21.4	21.0	22
	22	14.5	14.5	10
1.3	46.5	85.5	88.8	16
	42.5	62.5	58.0	29
	37.5	44.0	47.8	13
			41.6	32
			36.5	26
	31	31.6	30.9	30
	23	28.3	29.5	12

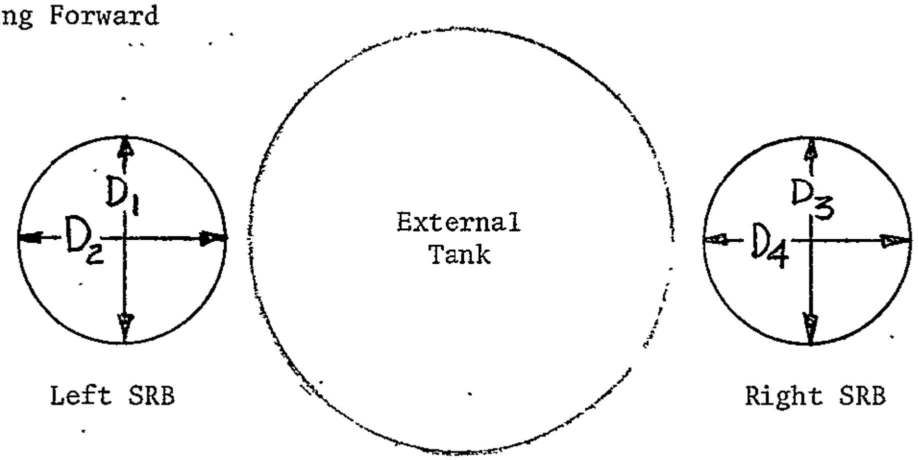
---

*These values are based on an average of PCL and PCR and were taken from the data tabulations at 160 msec $\leq t \leq$ 220 msec.

TABLE V

SRB NOZZLE THROAT DIMENSIONS

View Looking Forward



Measurement taken prior to:	Inches			
	D_1	D_2	D_3	D_4
Run 10	1.753	1.753	1.756	1.754
Run 15	1.754	1.753	1.753	1.754
Run 20	1.754	1.755	1.754	1.755
Run 29	1.755	1.756	1.753	1.753

Nominal throat diameter (as machined) = 1.757 ± .001

NOTE: These data provided
by NASA/MSFC Project
Engineer

TABLE VI

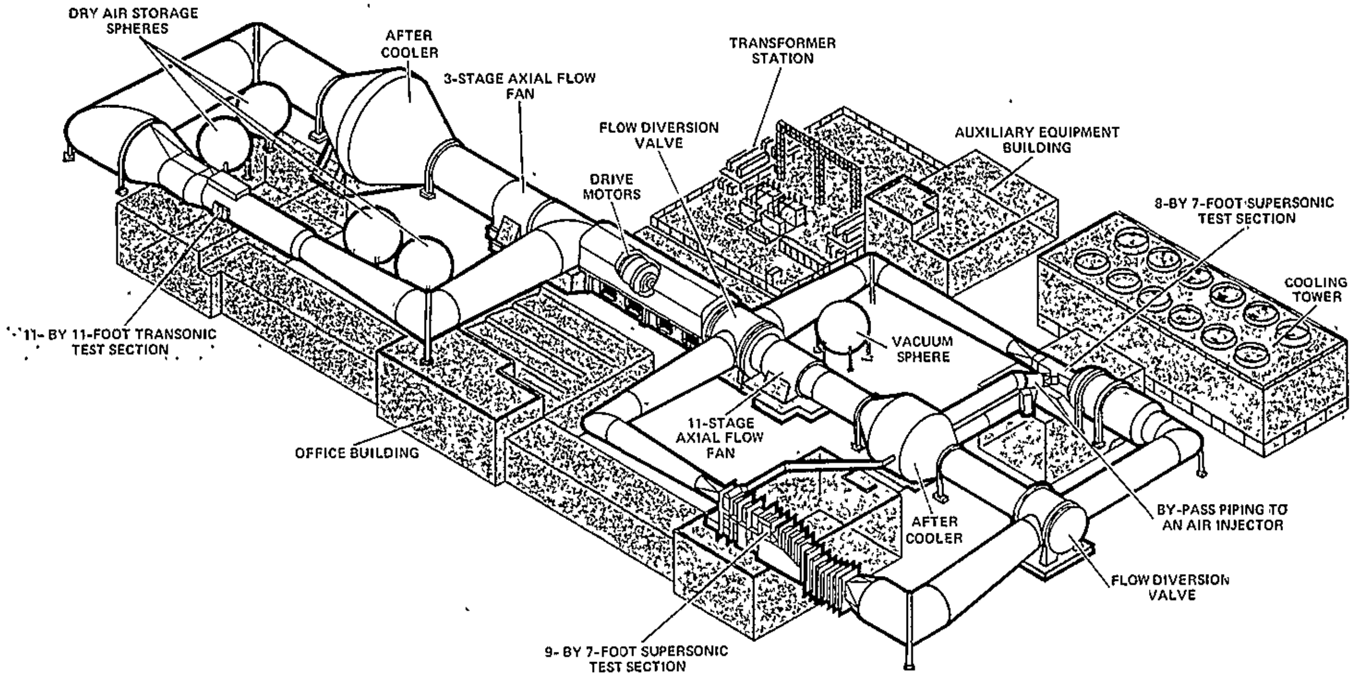
DATA ACQUISITION TIMES

Run	INITIAL			START	FINAL			(RUN)
	ZERO	CAL	READ	RUN	READ	ZERO	CAL	DATE
1.	22:13:47	22:14:02	22:14:02	22:55:29	22:55:54	23:02:45	23:02:54	07/28/76
2	23:13:22	23:13:39	23:13:39	23:23:45	23:25:12	23:30:49	23:31:11	07/28/76
3	10:15:34	10:15:56	11:06:17	11:10:15	11:11:04	11:22:12	11:22:39	07/29/76
4	12:17:22	12:17:38	12:17:38	12:32:53	12:33:41	12:43:03	12:43:21	07/29/76
5	14:54:42	14:55:07	14:55:07	15:31:40	:36:34 15:~~34:52~~	16:15:04	16:15:43	07/29/76
6	17:05:01	17:05:15	17:05:15	17:24:07	17:25:45	17:47:42	17:47:59	07/29/76
7	19:36:23	19:36:53	19:36:53	19:50:17	19:52:10	20:07:14	20:07:34	07/29/76
8	20:54:03	20:59:17	20:59:17	21:13:36	21:15:34	21:34:40	21:34:59	07/29/76
9	22:06:17	22:06:34	22:06:34	22:22:23	———	22:40:43	22:41:03	07/29/76
10	15:19:13	15:19:31	15:19:31	15:48:14	15:50:00	16:09:57	16:10:12	07/30/76
11	17:01:31	17:01:54	17:01:54	17:17:58	17:19:41	17:40:35	17:41:09	07/30/76
12	18:36:25	18:36:43	18:36:43	18:55:18	18:57:03	19:17:52	19:18:22	07/30/76
13	19:57:18	19:57:37	19:57:37	20:15:18	20:17:11	20:38:46	20:39:12	07/30/76
14	21:09:39	21:09:53	21:09:53	21:24:24	21:26:02	21:39:42	21:39:59	07/30/76
15	17:00:57	17:01:15	17:01:15	17:14:44	17:16:27	17:28:25	17:28:44	08/02/76
16	18:01:26	18:01:45	18:01:45	18:22:18	18:24:03	18:51:51	18:52:09	08/02/76
17	19:21:33	19:21:48	19:21:48	19:42:43	19:44:36	20:03:03	20:03:21	08/02/76
18	20:10:51	22:11:04	22:11:04	22:28:30	22:30:15	22:50:52	22:51:14	08/02/76
20	13:10:21	13:10:35	13:10:35	13:40:52	13:43:04	14:08:30	14:08:45	08/03/76
21	14:56:14	14:56:29	14:56:29	15:16:32	15:18:16	15:43:38	15:43:59	08/03/76
22	16:20:42	16:20:55	16:20:55	16:45:01	16:48:38	17:03:12	17:03:27	08/03/76
23	17:36:12	17:36:25	17:36:25	17:51:51	17:53:38	18:12:55	18:13:09	08/03/76
24	18:43:01	18:43:13	18:43:13	18:56:06	18:57:49	19:09:32	19:09:48	08/03/76
25	19:32:13	19:38:26	19:32:26	19:55:04	19:56:47	20:18:11	20:18:35	08/03/76
26	20:47:52	20:48:11	20:48:11	21:05:00	21:06:51	21:21:35	21:21:50	08/03/76
27	22:01:13	22:01:26	22:01:26	22:13:03	22:14:51	22:29:25	22:29:41	08/03/76

TABLE VI (Concluded)
DATA ACQUISITION TIMES

Run	INITIAL			Start Run	FINAL			(RUN) DATE
	ZERO	CAL	READ		READ	ZERO	CAL	
28	22:57:28	22:57:42	22:57:42	23:16:03	23:17:48	23:34:03	23:34:22	08/03/76
29				12:35:25		13:02:27	13:02:51	08/04/76
30	13:38:56	13:39:11	13:39:11	13:54:26	13:56:14	14:15:36	14:15:54	08/04/76
31	14:55:01	14:55:15	14:55:15	15:14:46	15:16:28	15:34:10	15:34:25	08/04/76
32	16:05:50	16:06:03	16:06:03	16:20:38	16:22:20	16:40:36	16:40:50	08/04/76
33	17:06:57	17:07:10	17:07:10	17:22:04	17:23:46	17:52:27	17:52:42	08/04/76

(REPRODUCED FROM REF. 1)

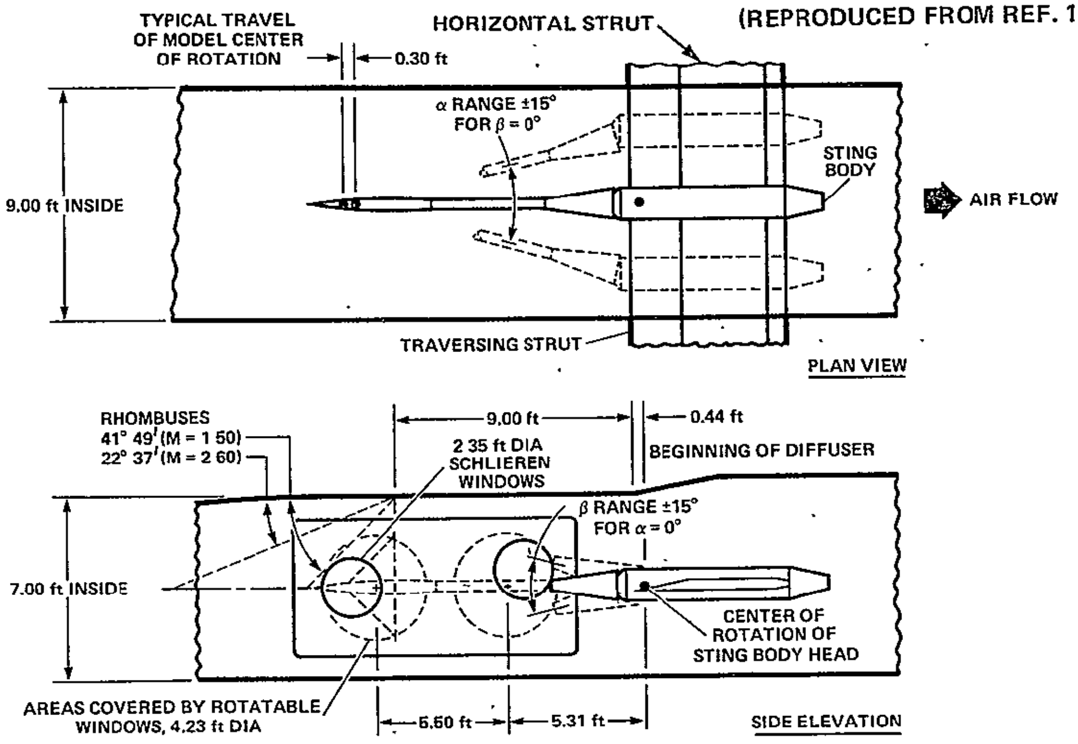


MAJOR COMPONENTS OF THE UNITARY PLAN WIND TUNNELS

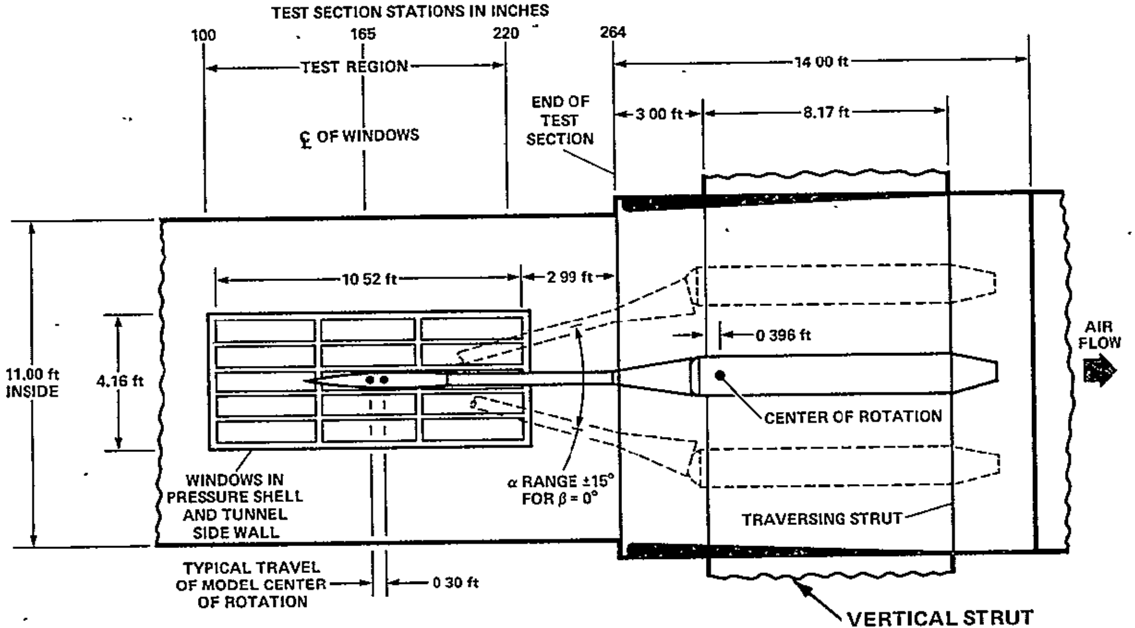
Unitary Test Sections	Height and Width, ft	Speed Range	Stagnation Press, atm	Stagnation Temp, °R	Reynolds No./ft	Dynamic Pressure, lb/ft^2	Special Features
Eleven Foot Transonic	Eleven by Eleven	0.4 to 1.4 M	0.5 to 2.25	580	1.7 to 9.4 X 10^6	250 to 2000	Slotted Test Section, 4 Walls
Nine-by Seven-Foot Supersonic	Seven by Nine	1.55 to 2.5 M	0.3 to 2.0	580	1.5 to 6.5 X 10^6	200 to 1450	
Eight-by Seven-Foot Supersonic	Eight by Seven	2.45 to 3.5 M	0.3 to 2.0	580	1.0 to 5.0 X 10^6	200 to 1000	

Figure 1 NASA/AMES UNITARY TUNNEL

(REPRODUCED FROM REF. 1)



9 x 7 SUPERSONIC TUNNEL



11 x 11 TRANSONIC TUNNEL

Figure 2 UNITARY WIND TUNNEL TEST SECTION CONFIGURATIONS

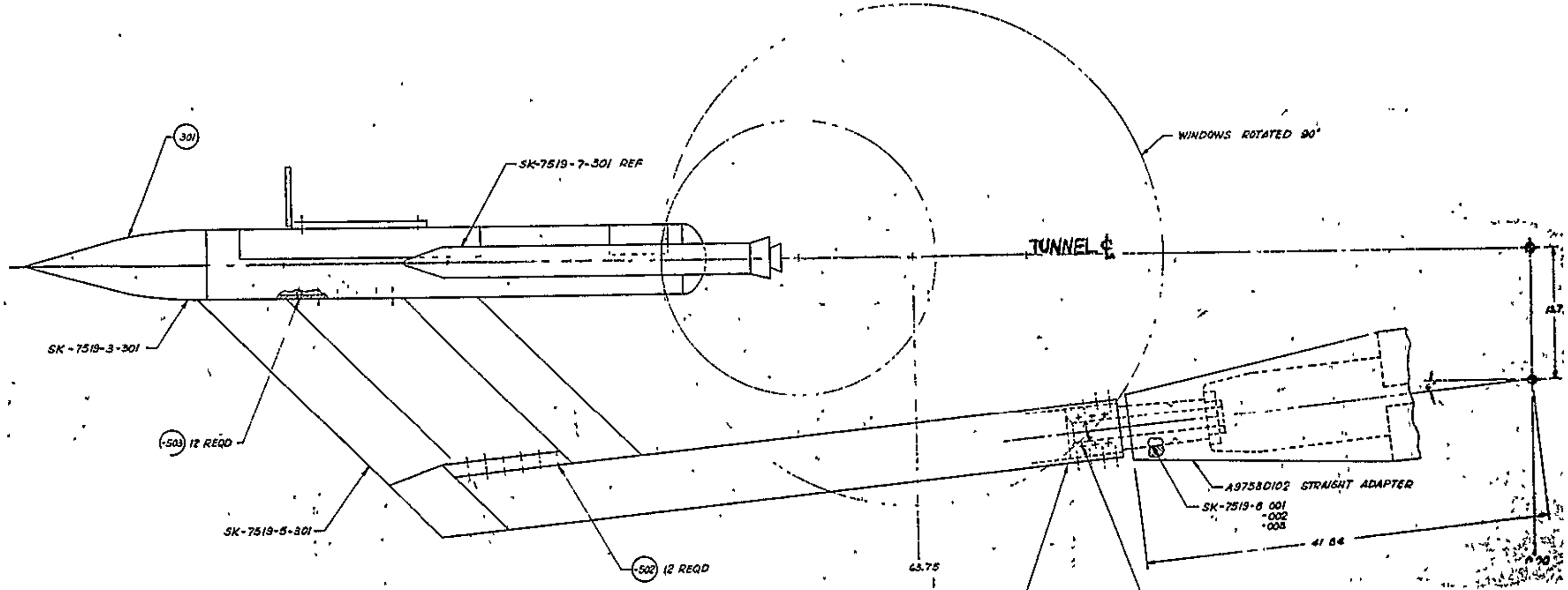


Figure 3 (a) MODEL INSTALLATION IN 9x7 TUNNEL (PLAN VIEW)

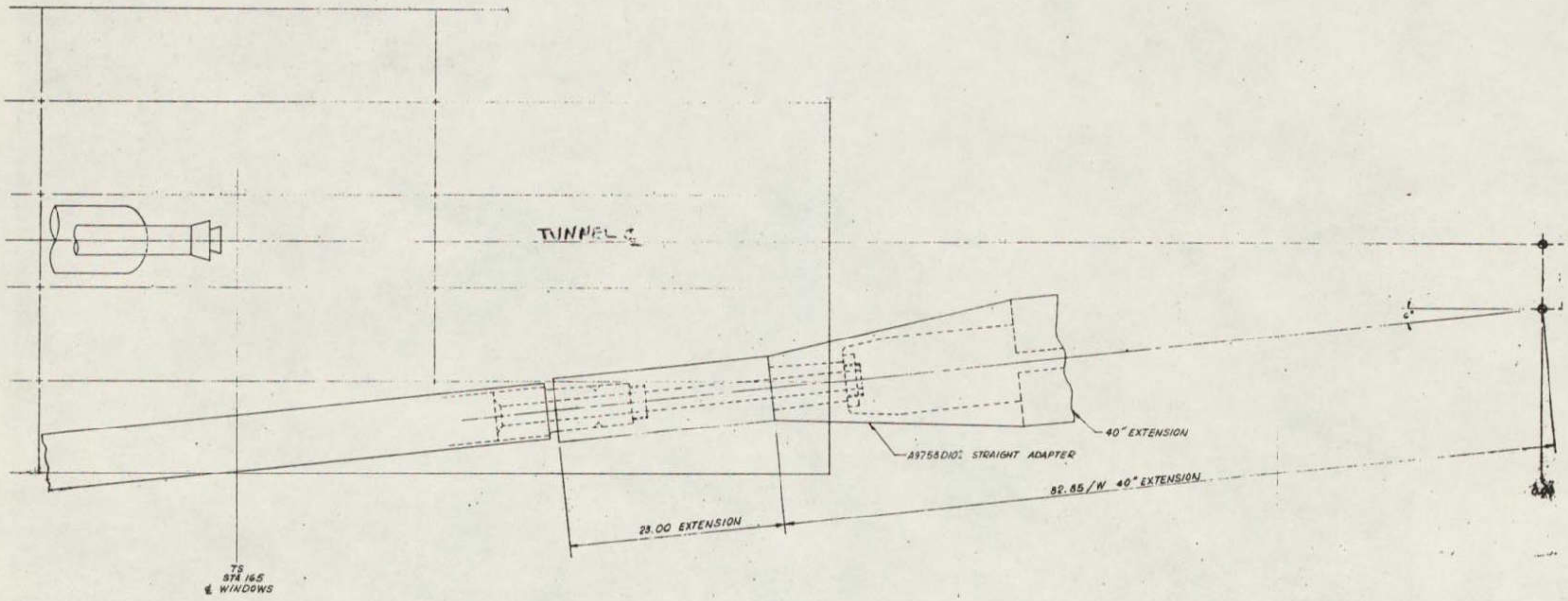


Figure 3(b) MODEL INSTALLATION IN 11x11 TUNNEL (ELEVATION VIEW)

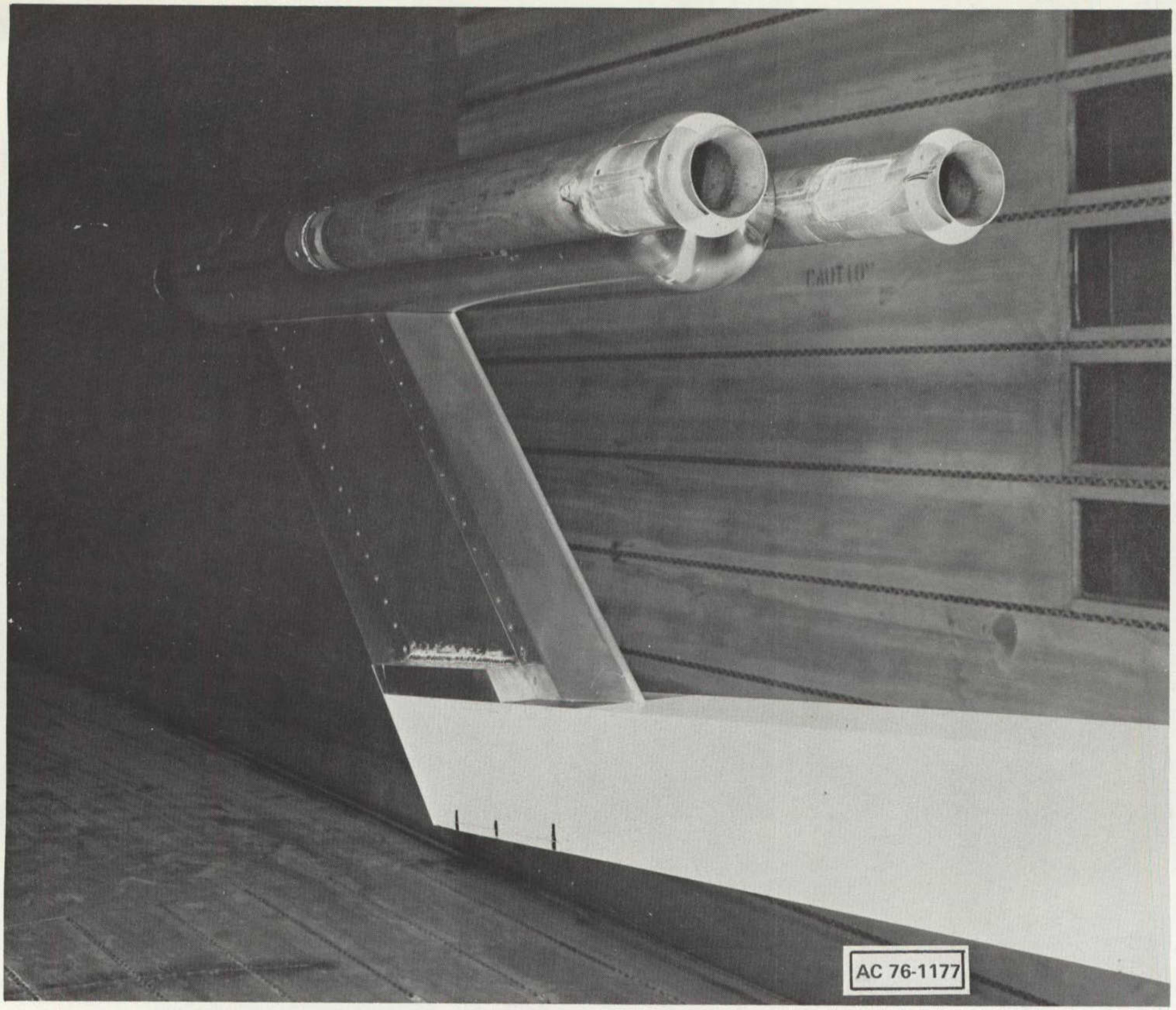


Figure 4(a) TEST MODEL INSTALLED IN ARC 11x11 TUNNEL

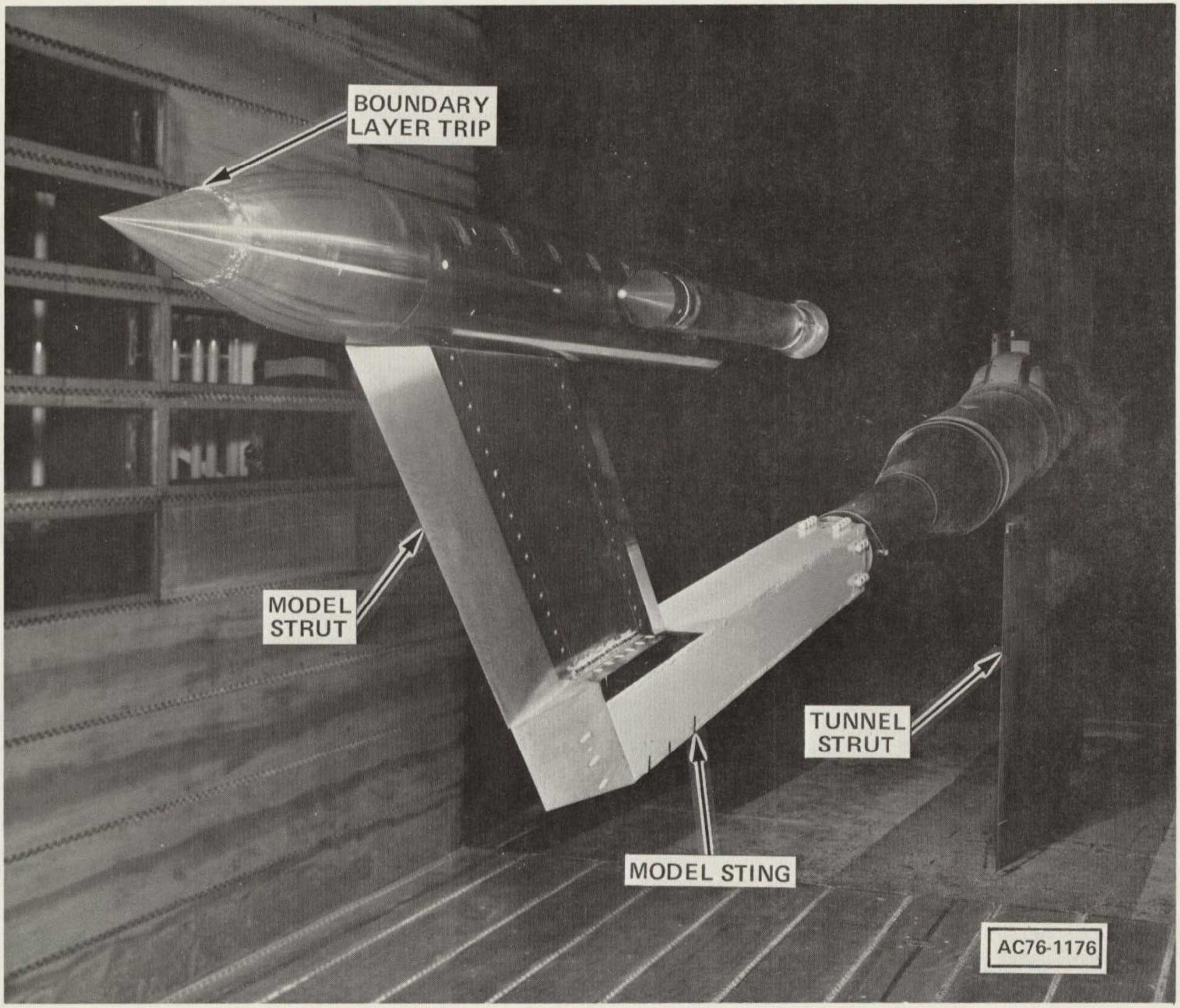


Figure 4(b) TEST MODEL INSTALLED IN ARC 11x11 TUNNEL

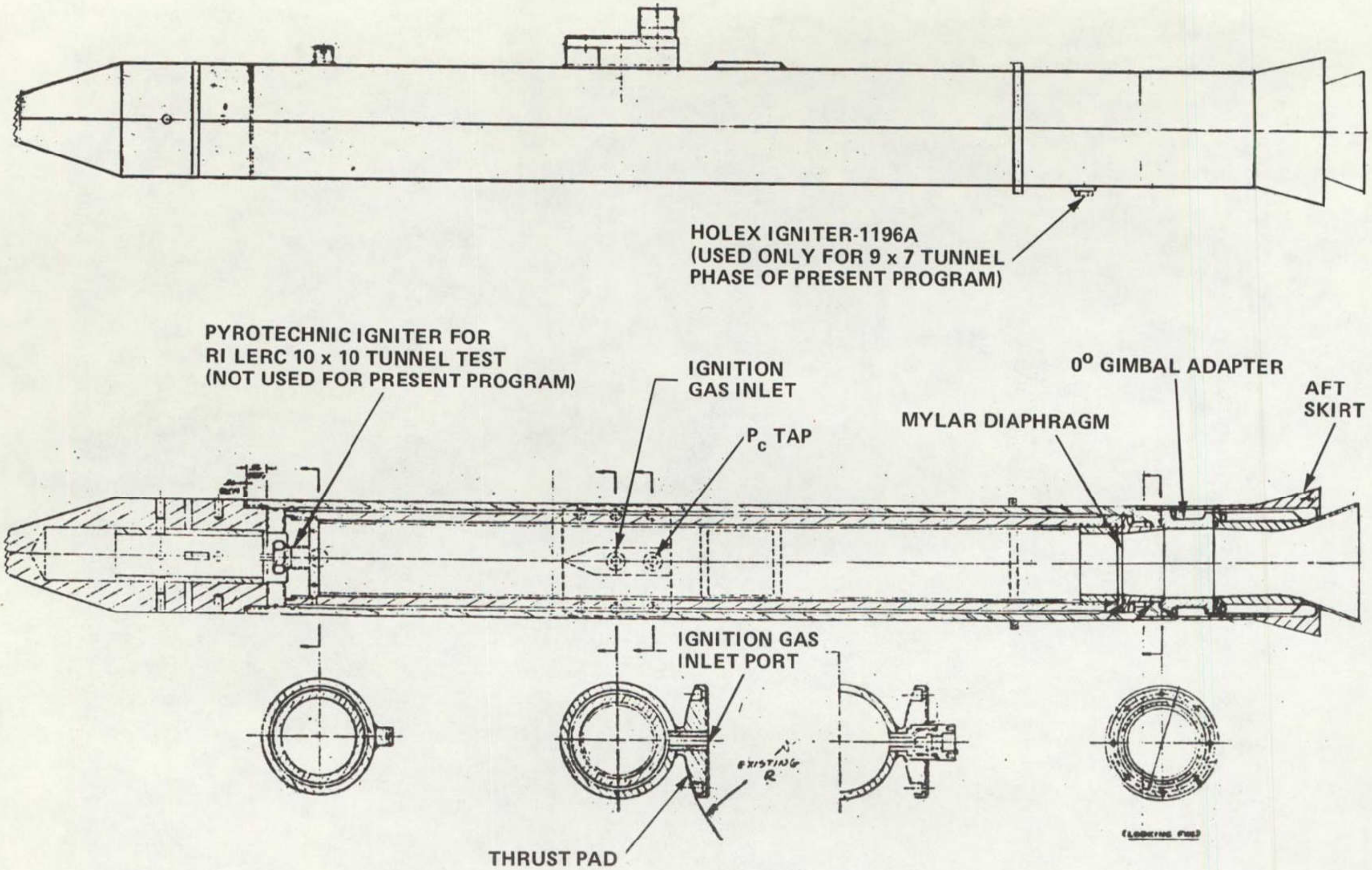


Figure 5(a) SRB CONFIGURATION

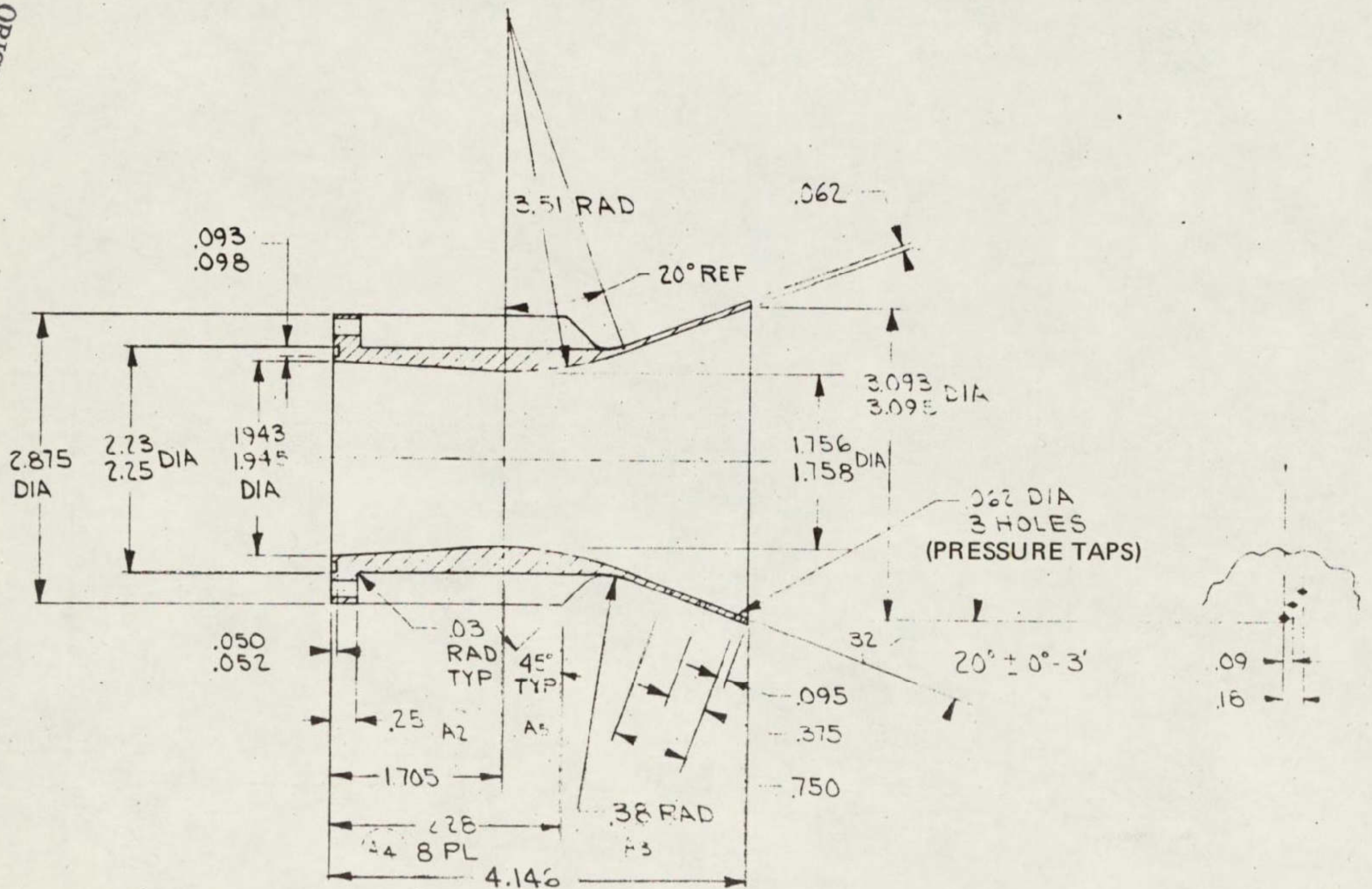


Figure 5(b) SRB NOZZLE DETAILS

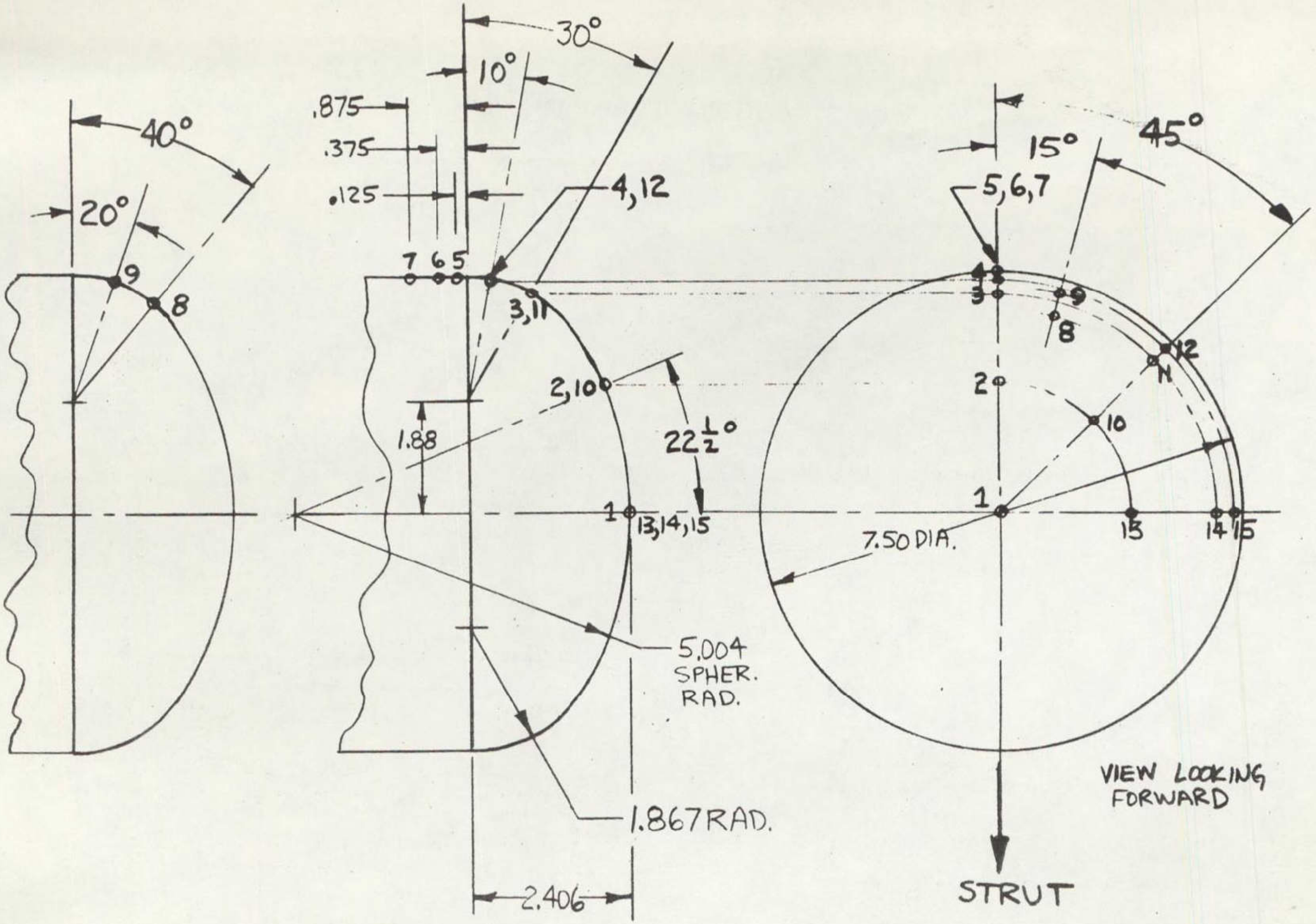


Figure 6(a) PRESSURE ORIFICE LOCATIONS (ET DOME, PI-P15)

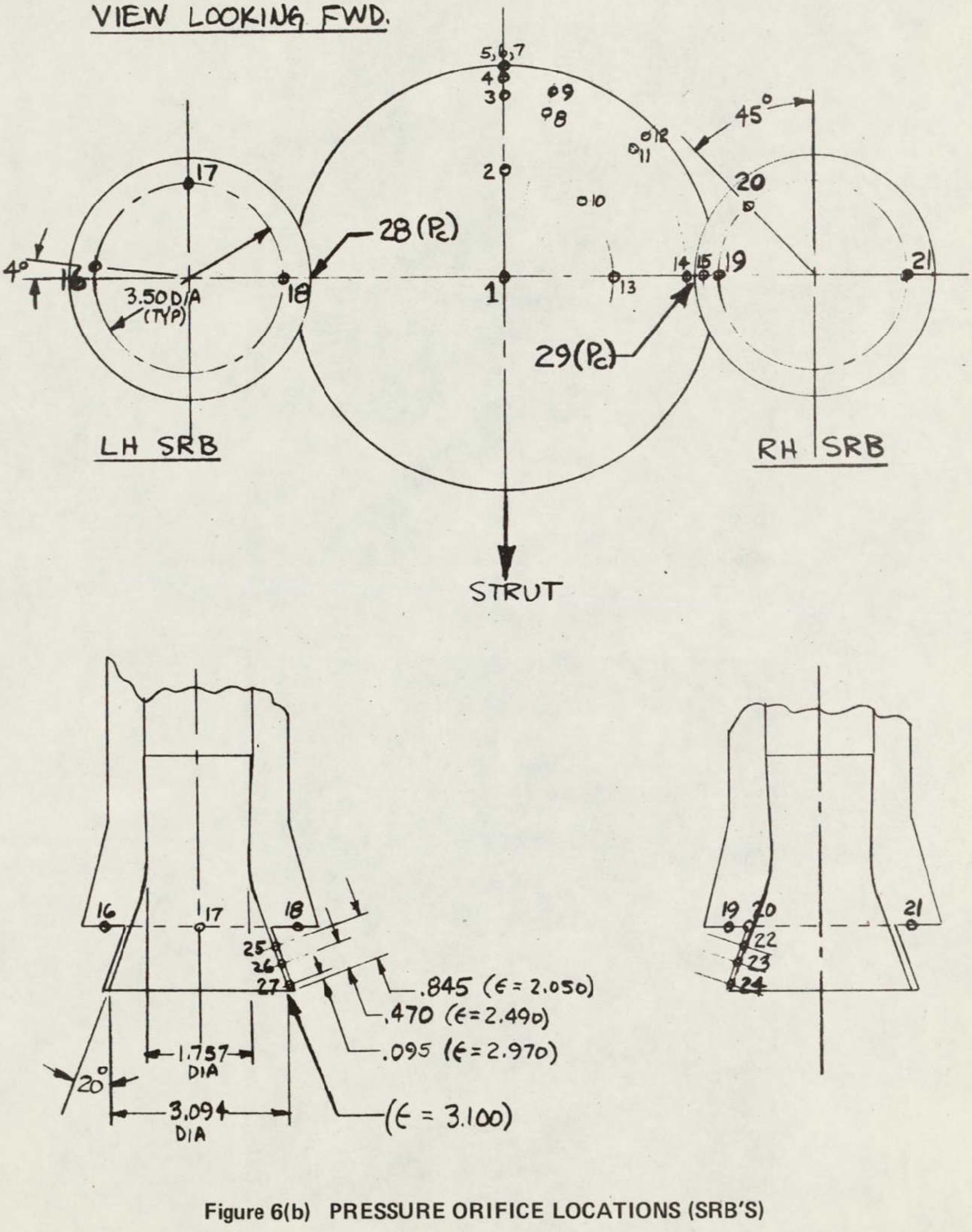
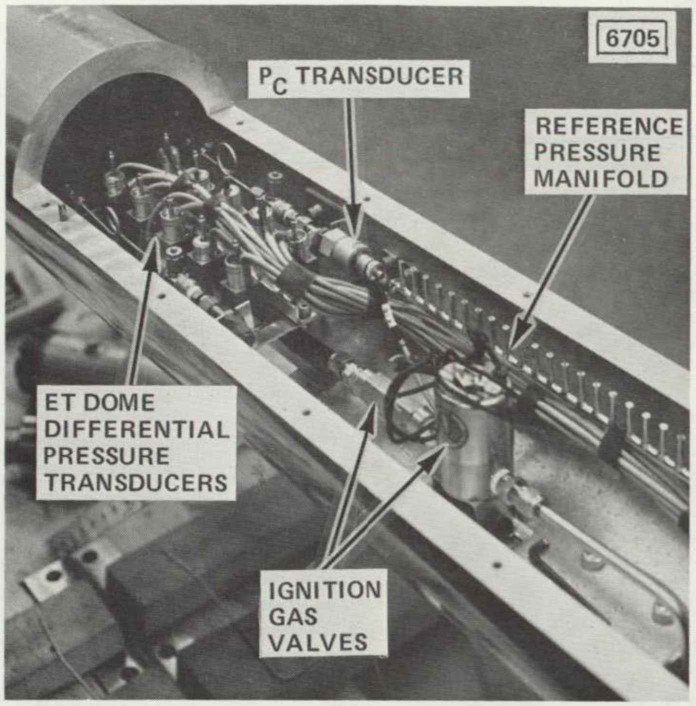
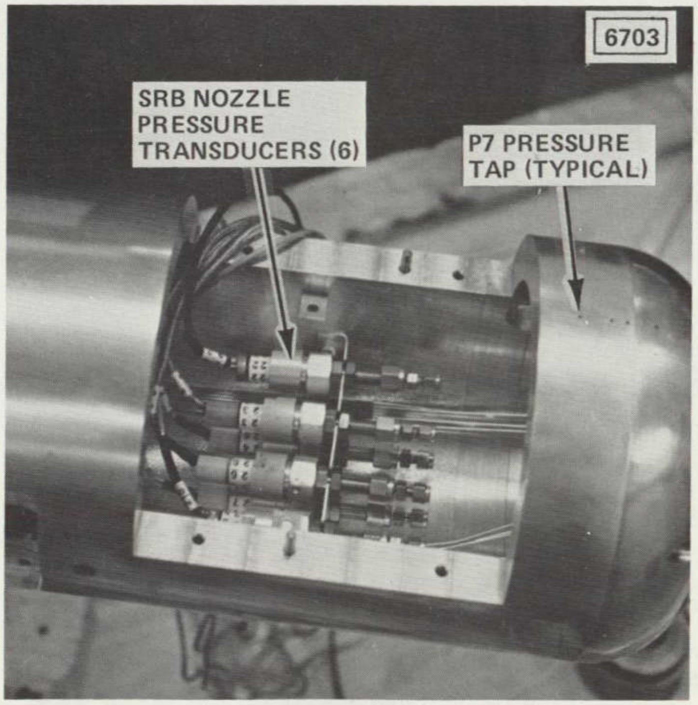


Figure 6(b) PRESSURE ORIFICE LOCATIONS (SRB'S)

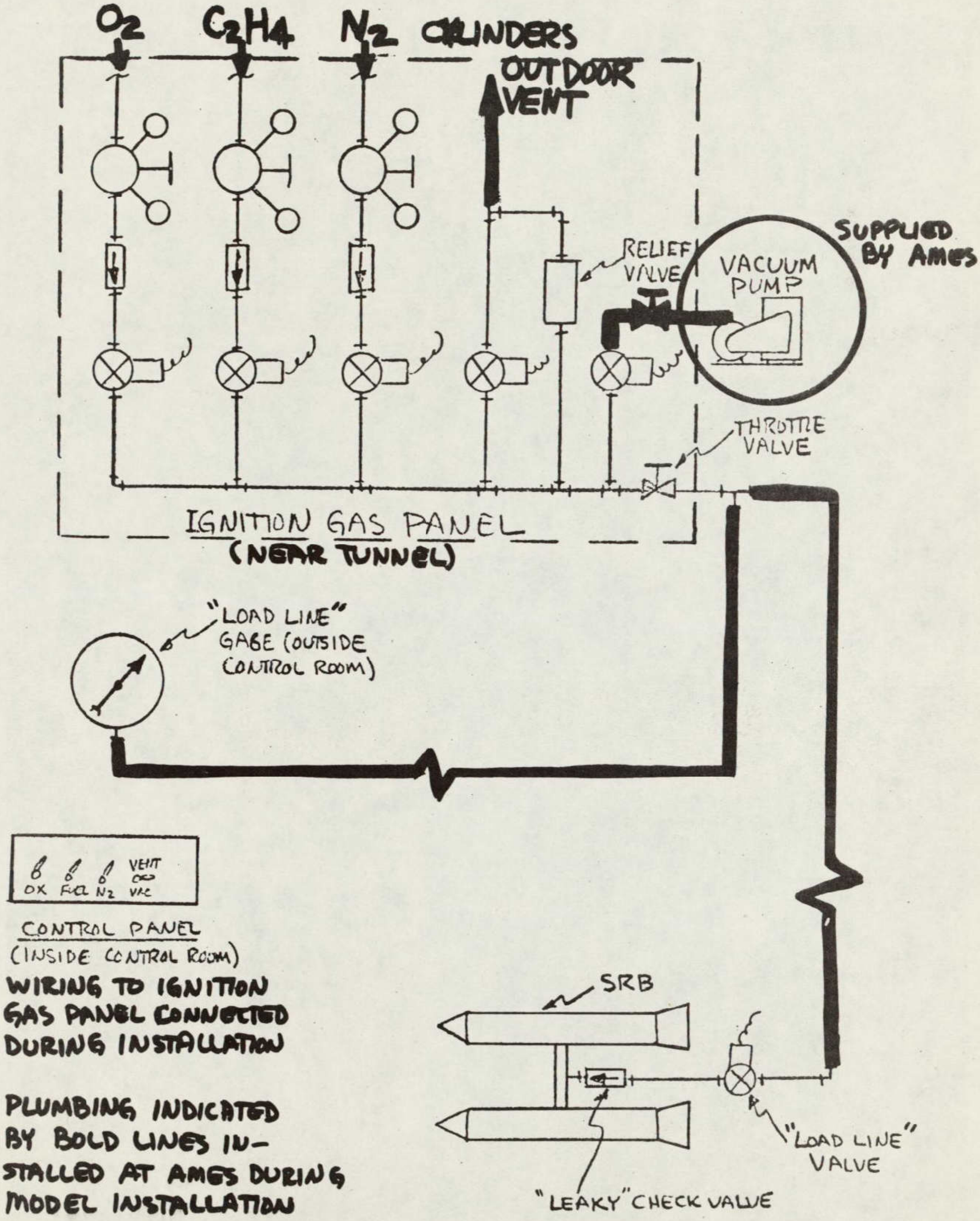


(a) BENEATH FORWARD COVER



(b) BENEATH AFT COVER

Figure 7 INTERIOR VIEWS OF EXTERNAL TANK



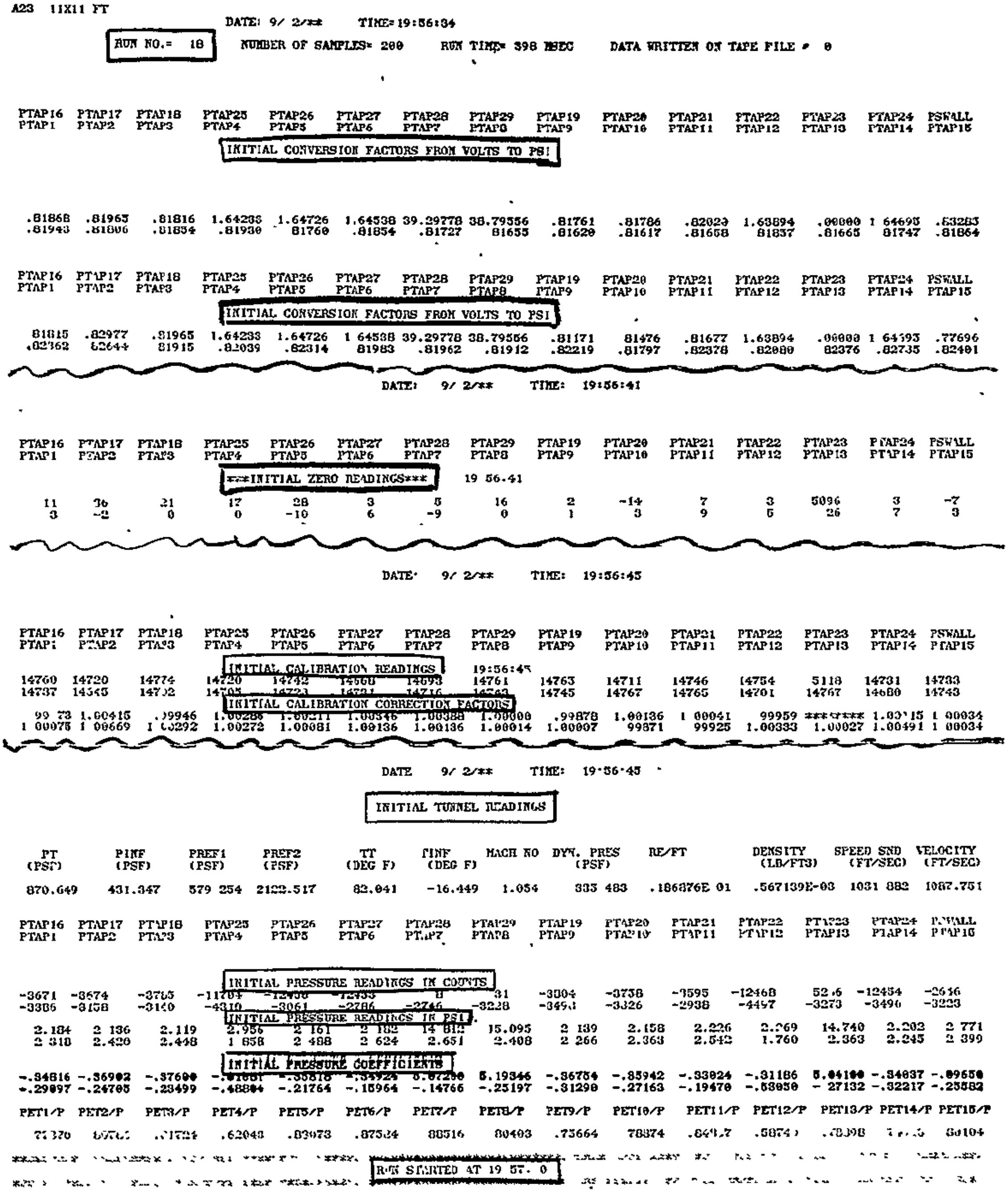
WIRING TO IGNITION GAS PANEL CONNECTED DURING INSTALLATION

PLUMBING INDICATED BY BOLD LINES INSTALLED AT AMES DURING MODEL INSTALLATION

Figure 8 IGNITION GAS SYSTEM – SCHEMATIC

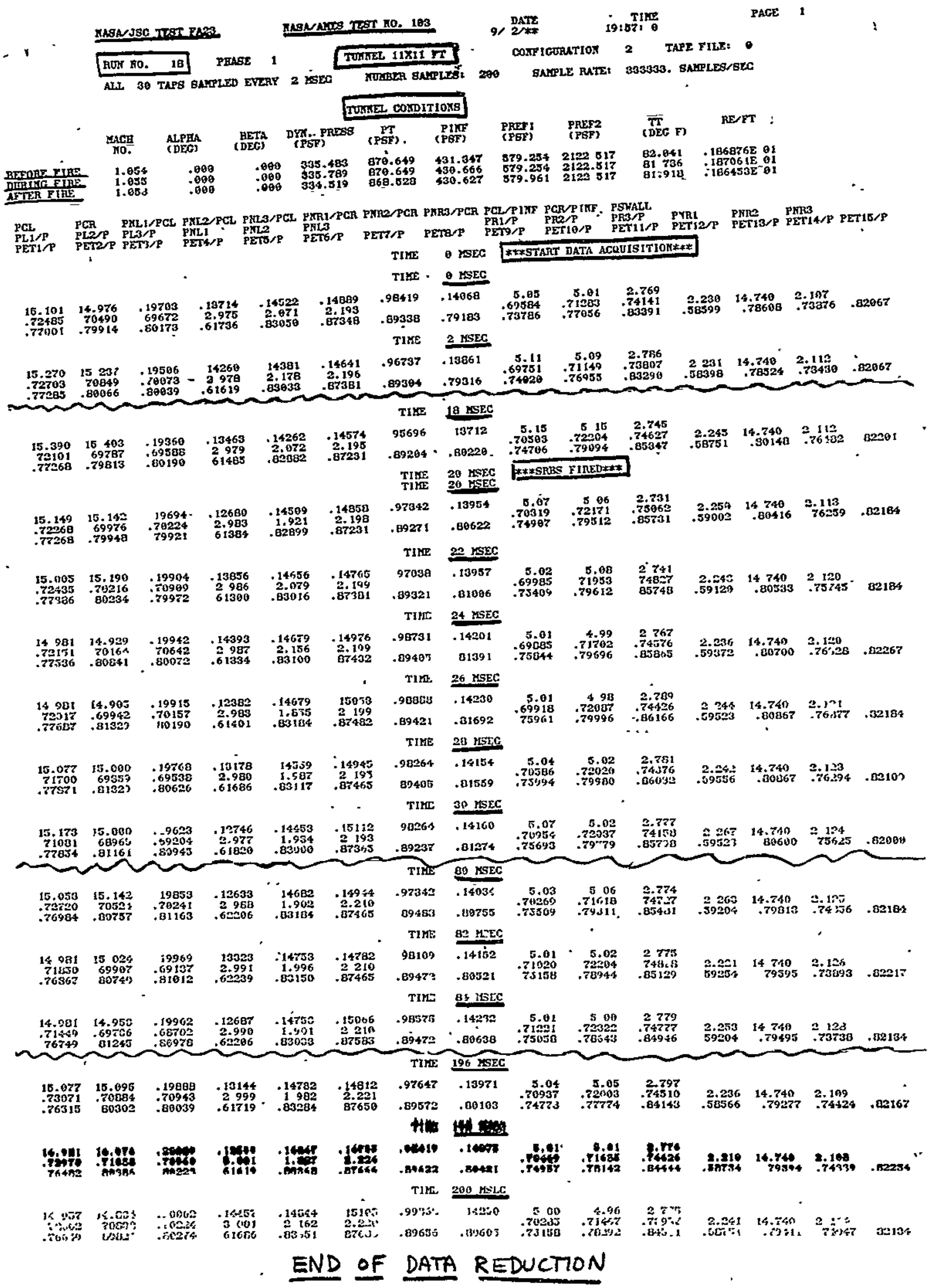
Figure 9 VIEW OF AMES 11 X 11 TUNNEL CONTROL ROOM

ORIGINAL PAGE IS
OF POOR QUALITY



```
A23   11X11 FT
                          DATE: 9/ 2/**       TIME=19:56:34
           RUN NO.=  18     NUMBER OF SAMPLES= 200      RUN TIME= 398 MSEC      DATA WRITTEN ON TAPE FILE #  0


PTAP16  PTAP17  PTAP18   PTAP25   PTAP26   PTAP27   PTAP28   PTAP29   PTAP19   PTAP20   PTAP21   PTAP22   PTAP23   PTAP24  PSWALL
PTAP1   PTAP2   PTAP3    PTAP4    PTAP5    PTAP6    PTAP7    PTAP8    PTAP9    PTAP10   PTAP11   PTAP12   PTAP13   PTAP14  PTAP15
                          INITIAL CONVERSION FACTORS FROM VOLTS TO PSI


 .81868  .81965   .81816  1.64233  1.64726  1.64538 39.29778 38.79556   .81761   .81786   .82023  1.63894   .00000 1 64695  .53283
 .81943  .81806   .81854   .81930   81760   .81854   .81727   81655   .81620   .81617   .81658   81837   .81665   81747  .81864

PTAP16  PTAP17  PTAP18   PTAP25   PTAP26   PTAP27   PTAP28   PTAP29   PTAP19   PTAP20   PTAP21   PTAP22   PTAP23   PTAP24  PSWALL
PTAP1   PTAP2   PTAP3    PTAP4    PTAP5    PTAP6    PTAP7    PTAP8    PTAP9    PTAP10   PTAP11   PTAP12   PTAP13   PTAP14  PTAP15
                          INITIAL CONVERSION FACTORS FROM VOLTS TO PSI
  81815  .82977   .81965  1.64233  1.64726  1 64538 39.29778 38.79556   .81171    81476   .81677  1.63894   .00000 1 64393  .77696
 .82362   82644    81915   .82039   .82314    81983   .81962   .81912   .82219   .81797   .82378   .82080    82376  .82735  .82401

                                              DATE:   9/ 2/**      TIME:   19:56:41


PTAP16  PTAP17  PTAP18   PTAP25   PTAP26   PTAP27   PTAP28   PTAP29   PTAP19   PTAP20   PTAP21   PTAP22   PTAP23   PTAP24  PSWALL
PTAP1   PTAP2   PTAP3    PTAP4    PTAP5    PTAP6    PTAP7    PTAP8    PTAP9    PTAP10   PTAP11   PTAP12   PTAP13   PTAP14  PTAP15
                          ***INITIAL ZERO READINGS***        19 56.41
   11      36       21       17       28        3        5       16        2      -14        7        3     5096        3      -7
    3      -2        0        0      -10        6       -9        0        1        3        9        5       26        7       3

                                              DATE:   9/ 2/**      TIME:   19:56:45


PTAP16  PTAP17  PTAP18   PTAP25   PTAP26   PTAP27   PTAP28   PTAP29   PTAP19   PTAP20   PTAP21   PTAP22   PTAP23   PTAP24  PSWALL
PTAP1   PTAP2   PTAP3    PTAP4    PTAP5    PTAP6    PTAP7    PTAP8    PTAP9    PTAP10   PTAP11   PTAP12   PTAP13   PTAP14  PTAP15
                          INITIAL CALIBRATION READINGS        19:56:45
14760   14720    14774    14720    14742    14660    14693    14761    14763    14711    14746    14754     5118    14731   14733
14737   14545    14702    14705    14723    14731    14716    14763    14745    14767    14765    14701    14767    14680   14743
                          INITIAL CALIBRATION CORRECTION FACTORS
  99 73 1.00415   .99946  1.00286  1.00211  1.00346  1.00388  1.00000   .99878  1.00136  1 00041    99959 ******* 1.00315 1 00034
1 00075 1 00669  1 00292  1.00272  1.00081  1.00136  1.00136  1.00014  1.00007    99871    99925  1.00333  1.00027 1.00491 1 00034

                                              DATE    9/ 2/**      TIME:   19:56:45

                                                INITIAL TUNNEL READINGS

   PT          PINF       PREF1      PREF2         TT        TINF      MACH NO  DYN. PRES     RE/FT          DENSITY     SPEED SND  VELOCITY
  (PSF)       (PSF)      (PSF)      (PSF)       (DEG F)    (DEG F)               (PSF)                     (LB/FT3)     (FT/SEC)   (FT/SEC)

870.649     431.347     579 254   2122.517      82.041     -16.449     1.054      335 483    .186876E 01    .567139E-03   1031 882   1087.751

PTAP16  PTAP17  PTAP18   PTAP25   PTAP26   PTAP27   PTAP28   PTAP29   PTAP19   PTAP20   PTAP21   PTAP22   PTAP23   PTAP24  PSWALL
PTAP1   PTAP2   PTAP3    PTAP4    PTAP5    PTAP6    PTAP7    PTAP8    PTAP9    PTAP10   PTAP11   PTAP12   PTAP13   PTAP14  PTAP15


                          INITIAL PRESSURE READINGS IN COUNTS
-3671   -3674    -3765   -11704   -12458   -12433        8       31    -3004    -3738    -3595   -12468     52.6   -12454   -2616
-3306   -3158    -3140    -4310    -3061    -2786    -2746    -3228    -3493    -3326    -2938    -4497    -3273    -3496   -3223
                          INITIAL PRESSURE READINGS IN PSI
  2.184   2 136    2.119    2.956    2 161    2 182   14 812   15.095    2 139    2.158    2.226    2.269   14.740    2.202   2 771
  2 318   2.420    2.448    1 658    2 488    2 624    2.651    2.408    2 266    2.363    2.542    1.760    2.363    2.245   2 399

                          INITIAL PRESSURE COEFFICIENTS
-.34816 -.36902  -.37600  -.31681  -.35818  -.34924  5.07200  5.19346  -.36754  -.35942  -.33024  -.31186  5.04100 -.34037 -.09650
-.29097 -.24705  -.23499  -.48804  -.21764  -.15964  -.14766  -.25197  -.31290  -.27163  -.19470  -.53050  - 27132 -.32217 -.25582

PET1/P  PET2/P   PET3/P   PET4/P   PET5/P   PET6/P   PET7/P   PET8/P   PET9/P   PET10/P   PET11/P  PET12/P  PET13/P PET14/P PET15/P

  77370   60761   .51724   .62043   .83073   .87534    88516    80403   .75664    78374   .84917   .58743   .78398 [illegible]  80104

                                         RUN STARTED AT 19 57. 0
```

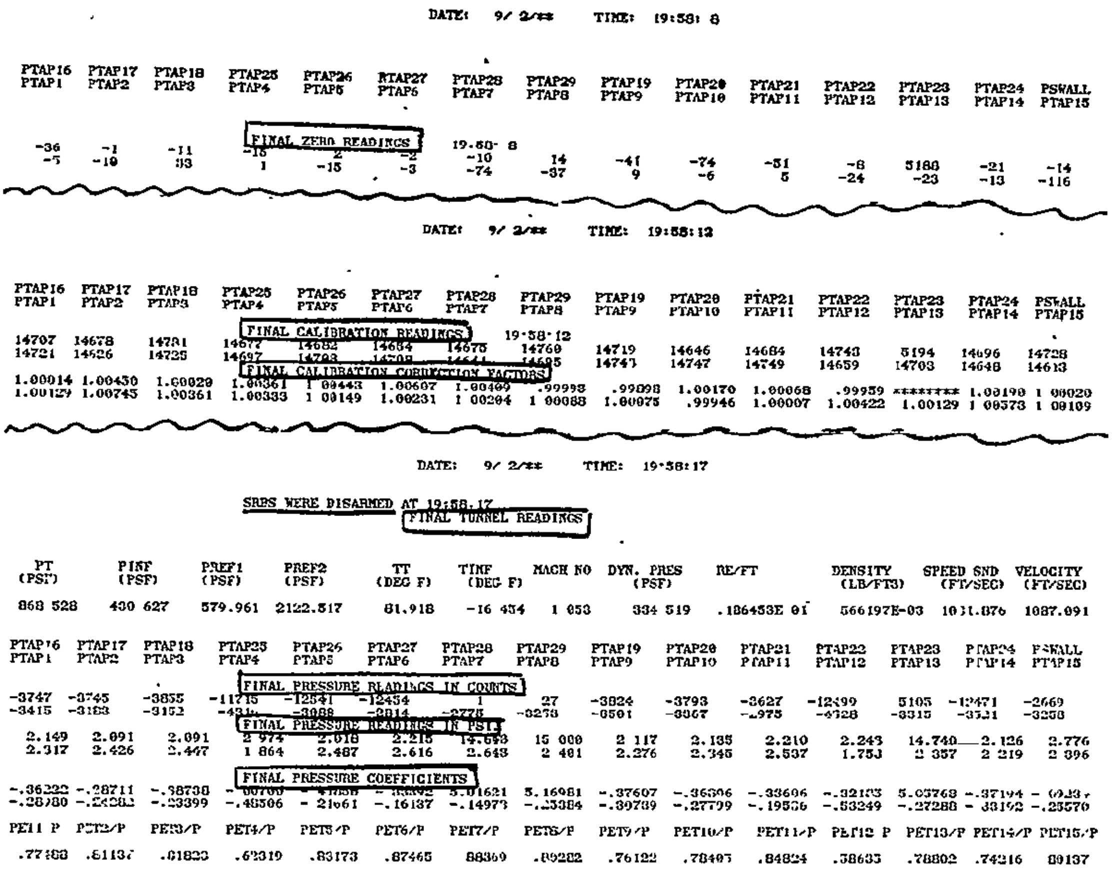
Figure 10a NOVA DATA PRINTOUT FORMAT - PRE-RUN REFERENCE DATA



```
                                                                          DATE              TIME                  PAGE  1
        NASA/JSC TEST FA23.       NASA/AMES TEST NO. 183           9/ 2/**           19:57: 0

        RUN NO.    18     PHASE   1          TUNNEL 11X11 FT            CONFIGURATION    2     TAPE FILE:  0
         ALL  30 TAPS SAMPLED EVERY  2 MSEC        NUMBER SAMPLES:  200       SAMPLE RATE:  333333. SAMPLES/SEC

                                                  TUNNEL CONDITIONS
                                                                                                   __
                                                                                                   TT            RE/FT
                 MACH      ALPHA      BETA    DYN.. PRESS     PT        PINF     PREF1     PREF2   (DEG F)
                  NO.      (DEG)      (DEG)     (PSF)       (PSF).    (PSF)     (PSF)     (PSF)
                                                                                                 82.041      .186876E 01
BEFORE FIRE      1.054      .000       .000    335.483    870.649    431.347   579.254   2122 517   81 736     .187061E 01
DURING FIRE      1.055      .000       .000    335.789    870.649    430.666   579.254   2122.517   81.918     .186453E 01
AFTER FIRE       1.053      .000       .000    334.519    868.528    430.627   579.961   2122 517

                PNL1/PCL PNL2/PCL PNL3/PCL PNR1/PCR PNR2/PCR PNR3/PCR PCL/PINF PCR/PINF. PSWALL
PCL      PCR                                                           PR1/P    PR2/P    PR3/P     PYR1     PNR2     PNR3
PL1/P    PL2/P    PL3/P    PNL1     PNL2     PNL3                      PET9/P   PET10/P  PET11/P   PET12/P  PET13/P  PET14/P  PET15/P
PET1/P   PET2/P   PET3/P   PET4/P   PET5/P   PET6/P   PET7/P   PET8/P
                                              TIME      0 MSEC    ***START DATA ACQUISITION***

                                              TIME      0 MSEC

                                              .98419   .14068    5.85     5.01     2.769
15.101   14.976   .19703   .13714   .14522   .14889                .69584   .71283   .74141    2.230   14.740   2.107   .82067
.72485    70490    69672    2.975    2.071    2.193                .73786   .77056   .83391    .58599   .78608  .73376
.77001   .79914   .60173   .61736   .83050   .87348   .89338   .79183
                                              TIME      2 MSEC

                                              .96737   .13861    5.11     5.09     2.786
15.270   15 237   .19506    14260    14381   .14641                .69751   .71149   .73807    2 231   14.740   2.112   .82067
.72703    70849   .70073 -  2 978    2.178    2.196                .74920   .76955   .83290    .58398   .78524  .73430
.77285   .80066   .80039   .61619   .83033   .87381   .89304   .79316
~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
                                              TIME     18 MSEC

                                               95696    13712    5.15     5 15     2.745
15.390   15 403   .19360   .13463   .14262   .14574                .70503   .72204   .74627    2.245   14.740   2 112   82201
 72101    69787   .69588    2 979    2.072    2.195                .74706   .79094   .85347    .58751   .80148  .76182
.77268   .79813   .80190    61485   .82882   .87231   .89204   .80220
                                              TIME     20 MSEC   ***SRBS FIRED***
                                              TIME     20 MSEC

                                              .97342   .13954    5.07     5 06     2.731
15.149   15.142    19694-  .12680   .14509   .14858                .70319   .72171   .75062    2.259   14 740   2.113   .82184
.72268    69976   .70224    2.983    1.921    2.198                .74987   .79512   .85731    .59002   .80416   76259
.77268   .79948    79921    61384   .82899   .87231   .89271   .80622
                                              TIME     22 MSEC

                                               97038   .13957    5.02     5.08     2 741
15.005   15.190   .19904   .13856   .14656   .14765                .69985    71953    74827    2.243   14 740   2 120    82184
.72435   .70216   .70909    2 986    2.079    2.199                .75409   .79612    85748    .59129   .80533  .75745
.77386    80234   .79972    61300   .83016   .87381   .89321   .81086
                                              TIME     24 MSEC

                                              .98731   .14201    5.01     4.99     2 767
14 981   14.929   .19942   .14393   .14679   .14976                .69085   .71702   .74576    2.236   14.740   2.120   .82267
.72151    70164    70642    2 987    2.156    2.109                .75844   .79696   .85865    .59372   .80700  .76628
.77536   .80841   .80072   .61334   .83100    87432   .89405    81391
                                              TIME     26 MSEC

                                              .98888   .14230    5.01     4 98     2.789
14 981   14.905   .19915   .12382   .14679    15038                .69918   .72087   .74426    2 244   14.740   2.1?1   .32184
 72017   .69942   .70157    2.983    1.835    2 199                 75961   .79996  -.86166    .59523   .80867  .76877
.77687   .81329    80190   .61401   .83184   .87482   .89421   .81692
                                              TIME     28 MSEC

                                              .98264   .14154    5.04     5.02     2.781
15.077   15.000   .19768   .13178    14359   .14945                .70586   .72020   .74376    2.242   14.740   2.123   .82109
 71700    69359   .69538    2.980    1.587    2 193                .75994   .79980   .86092    .59556   .80867  .76294
.77871   .81329   .80626   .61686   .83117   .87465    89405   .81559
                                              TIME     30 MSEC

                                               98264   .14160    5.07     5.02     2.777
15.173   15.000   .-9623   .12746   .14453   .15112                .70954   .72937    74158    2 267   14.740   2 124   .82000
 71081    68965   .59204    2.977    1.934    2 193                .75693   .79?79   .85778    .59523    80600   75625
.77834   .81161   .80943   .61820   .83000   .87365   .89237   .81274
~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
                                              TIME     80 MSEC

                                              .97342   .14034    5.03     5 06     2.774
15.058   15.142    19853   .12633    14682   .14944                .70269   .71618    747?7    2 263   14.740   2.1?7   .82184
.72720    70524   .70241    2 968    1.902    2.210                .73509   .79311   .85431    .59204   .79813  .74356
.76984   .80757   .81163   .62206   .83184   .87465    89483   .80755
                                              TIME     82 MSEC

                                               98109   .14152    5.01     5.02     2 775
14 981   15 024    19969    13323   .14753   .14782                .71020    72204    748.8    2.221   14 740   2.126   .82217
 71830    69907   .69137    2.991    1.996    2 210                 73158   .78944   .85129    59254    79595  .73893
.76367    80749   .81012   .62239   .83150   .87465   .89473   .80521
                                              TIME     84 MSEC

                                              .98575   .14232    5.01     5 00     2 779
14.981   14.958   .19962   .12687   .14750   .15066                .71221   .72322   .74777    2.253   14 740   2 128   .82134
.71449   .69766   .68702    2.990    1.901    2 210                .75058   .78543   .84946    59204   .79495  .73738
 76749    81245   .80978   .62206   .83033   .87583   .89472   .80638
~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
                                              TIME    196 MSEC

                                              .97647   .13971    5.04     5.05     2.797
15.077   15.095   .19888   .13144   .14782   .14812                .70937   .72003   .74510    2.236   14.740   2.109   .82167
.73071   .70884   .70943    2 999    1 982    2.221                .74773   .77774   .84143    .58566   .79277  .74424
.76315    80302   .80039   .61719   .83284    87650   .89572   .80103
                                              TIME    [illegible]

                                              [illegible] [illegible] 5.01   5.01     [illegible]
14.981   [illegible] [illegible] [illegible] [illegible] [illegible]  [illegible] .71658 .74426  2.210   14.740   2.108   .82234
[illegible] .71658 [illegible] [illegible] 1.[illegible] [illegible]  .74957   .78142   .84444    [illegible] 79394  .74339
 76482   [illegible] [illegible] 61419  [illegible] .87444  [illegible] .80421
                                              TIME    200 MSEC

                                              .9993?   14250     5 00     4.96     2 7?5
1? 957   1?.0??   ..0062   .1645?   .14544    1510?                .70283   .71457   .7?9?2    2.241   14.740   2 ???    32134
[illegible] 70899  ..6026   3 001    2 162    2.2?0                .73158   .70292   .845.1    .5??5?   .7??1?   7?047
.7?679   [illegible] .60274  61686   .83?51    876??   .89685   .89603
```

END OF DATA REDUCTION

Figure 10b NOVA DATA PRINTOUT FORMAT - RUN DATA (EDITED)



```
                                         DATE:   9/ 2/**     TIME:  19:58: 8

PTAP16  PTAP17  PTAP18  PTAP25  PTAP26  RTAP27  PTAP28  PTAP29  PTAP19  PTAP20  PTAP21  PTAP22  PTAP23  PTAP24  PSWALL
PTAP1   PTAP2   PTAP3   PTAP4   PTAP5   PTAP6   PTAP7   PTAP8   PTAP9   PTAP10  PTAP11  PTAP12  PTAP13  PTAP14  PTAP15

                        FINAL ZERO READINGS     19:58: 8
  -36     -1     -11     -15      2      -2      -10      14     -41     -74     -51      -8    5188     -21     -14
   -5    -19      33       1    -15      -3      -74     -37       9      -6       5     -24     -23     -13    -116

                                         DATE:   9/ 2/**     TIME:  19:58:12

PTAP16  PTAP17  PTAP18  PTAP25  PTAP26  PTAP27  PTAP28  PTAP29  PTAP19  PTAP20  PTAP21  PTAP22  PTAP23  PTAP24  PSWALL
PTAP1   PTAP2   PTAP3   PTAP4   PTAP5   PTAP6   PTAP7   PTAP8   PTAP9   PTAP10  PTAP11  PTAP12  PTAP13  PTAP14  PTAP15

                        FINAL CALIBRATION READINGS      19:58:12
14707   14678   14781   14677   14682   14684   14675   14760   14719   14646   14684   14743    5194   14696   14728
14721   14626   14725   14697   14703   14708   14641   14695   14747   14747   14749   14659   14703   14648   14613
                        FINAL CALIBRATION CORRECTION FACTORS
1.00014 1.00430 1.00029 1.00361 1 00443 1.00607 1.00409  .99998  .99898 1.00170 1.00068  .99959 ******** 1.00190 1 00020
1.00129 1.00745 1.00361 1.00333 1 00149 1.00231 1 00204 1 00088 1.00075  .99946 1.00007 1.00422 1.00129 1 00573 1 00109

                                         DATE:   9/ 2/**     TIME:  19:58:17

                        SRBS WERE DISARMED AT 19:58.17
                                   FINAL TUNNEL READINGS

   PT       PINF     PREF1     PREF2       TT       TINF    MACH NO  DYN. PRES     RE/FT          DENSITY   SPEED SND  VELOCITY
  (PSF)     (PSF)    (PSF)     (PSF)    (DEG F)   (DEG F)              (PSF)                     (LB/FT3)   (FT/SEC)  (FT/SEC)

868 528   430 627   579.961  2122.517   81.918   -16 454    1 053    334 519   .186453E 01    566197E-03  1031.876  1087.091

PTAP16  PTAP17  PTAP18  PTAP25  PTAP26  PTAP27  PTAP28  PTAP29  PTAP19  PTAP20  PTAP21  PTAP22  PTAP23  PTAP24  PSWALL
PTAP1   PTAP2   PTAP3   PTAP4   PTAP5   PTAP6   PTAP7   PTAP8   PTAP9   PTAP10  PTAP11  PTAP12  PTAP13  PTAP14  PTAP15

                        FINAL PRESSURE READINGS IN COUNTS
-3747   -3745   -3855   -11715  -12541  -12434      1      27   -3824   -3793   -3627   -12499   5105   -12471  -2669
-3415   -3183   -3152   -431    -3088   -2814   -2775   -3278   -0501   -3367   -2975   -4328   -3315   -3521   -3258
                        FINAL PRESSURE READINGS IN PSI
 2.149   2.091   2.091   2 974   2.018   2.215  14.693  15 000   2 117   2.135   2.210   2.243  14.740   2.126   2.776
 2.317   2.426   2.447   1 864   2.487   2.616   2.643   2 401   2.276   2.345   2.537   1.753   2 357   2 219   2 396

                        FINAL PRESSURE COEFFICIENTS
-.36222 -.28711 -.38738 -[illegible] -[illegible] -[illegible] 5.01621 5.16981 -.37607 -.36306 -.33606 -.32183 5.03768 -.37194 -[illegible]
-.28780 -.24282 -.23399 -.48506 - 21061 -.16137 -.14973 -.23384 -.39789 -.27799 -.19536 -.53249 -.27288 - 33192 -.25570

PET1/P  PET2/P  PET3/P  PET4/P  PET5/P  PET6/P  PET7/P  PET8/P  PET9/P  PET10/P PET11/P PET12/P PET13/P PET14/P PET15/P

 .77188  .51137  .61833  .62319  .83173  .87465   88369  .89282  .76122  .78407  .84824  .58633  .78802  .74216   80137
```

Figure 10c NOVA DATA PRINTOUT FORMAT - POST-RUN REFERENCE DATA

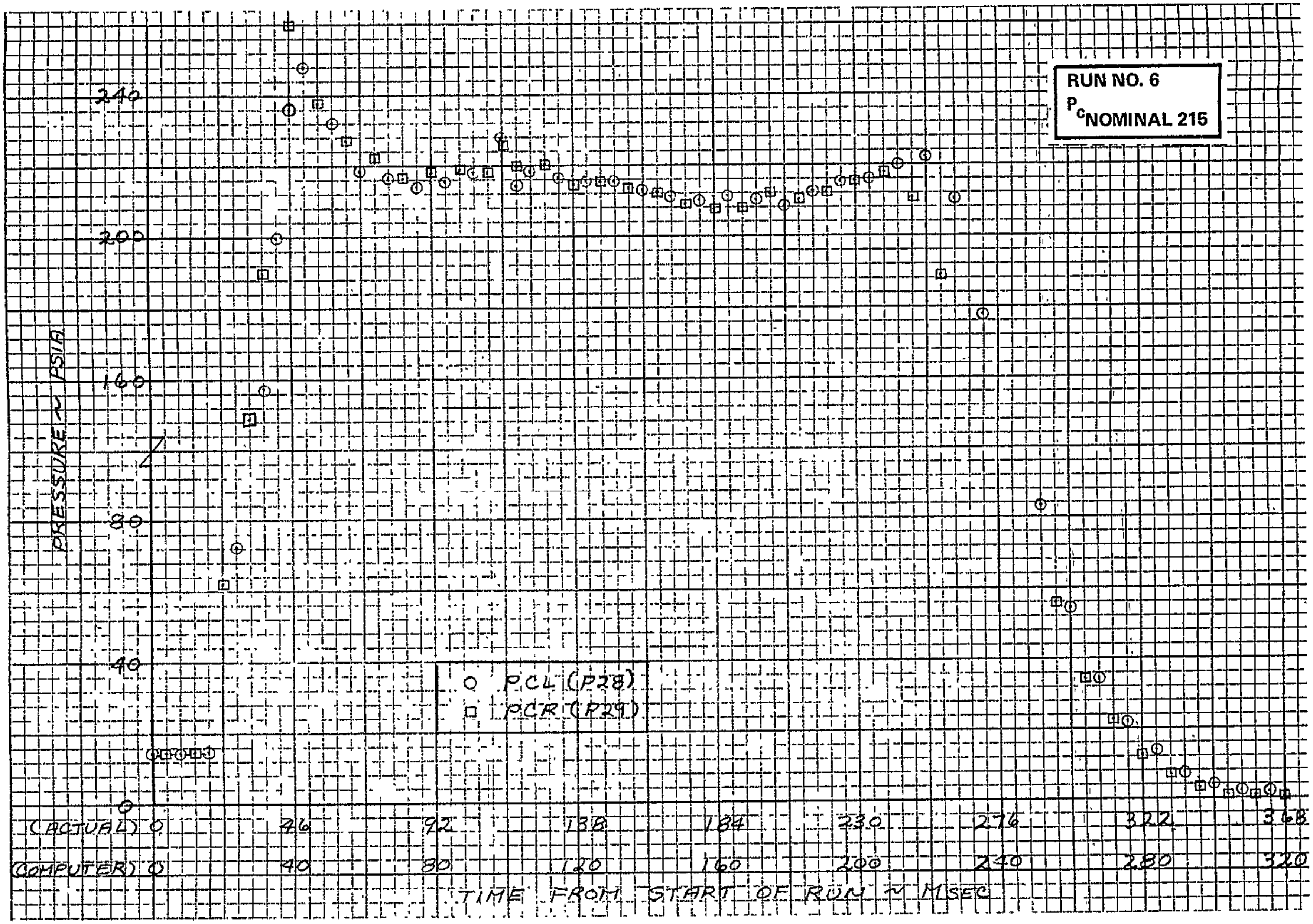


Figure 11 SRB COMBUSTION CHAMBER PRESSURES

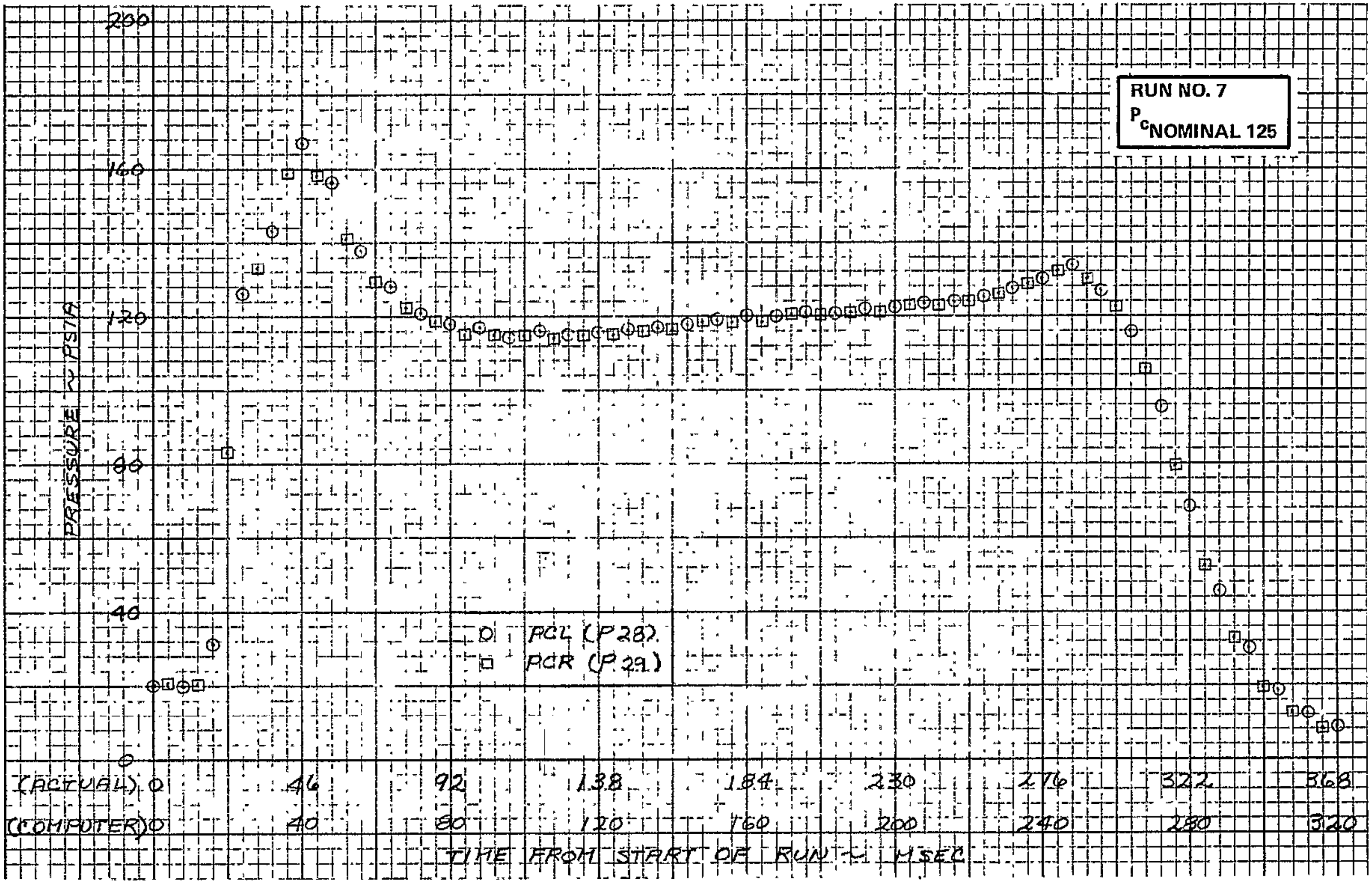


Figure 11 SRB COMBUSTION CHAMBER PRESSURES (Cont.)

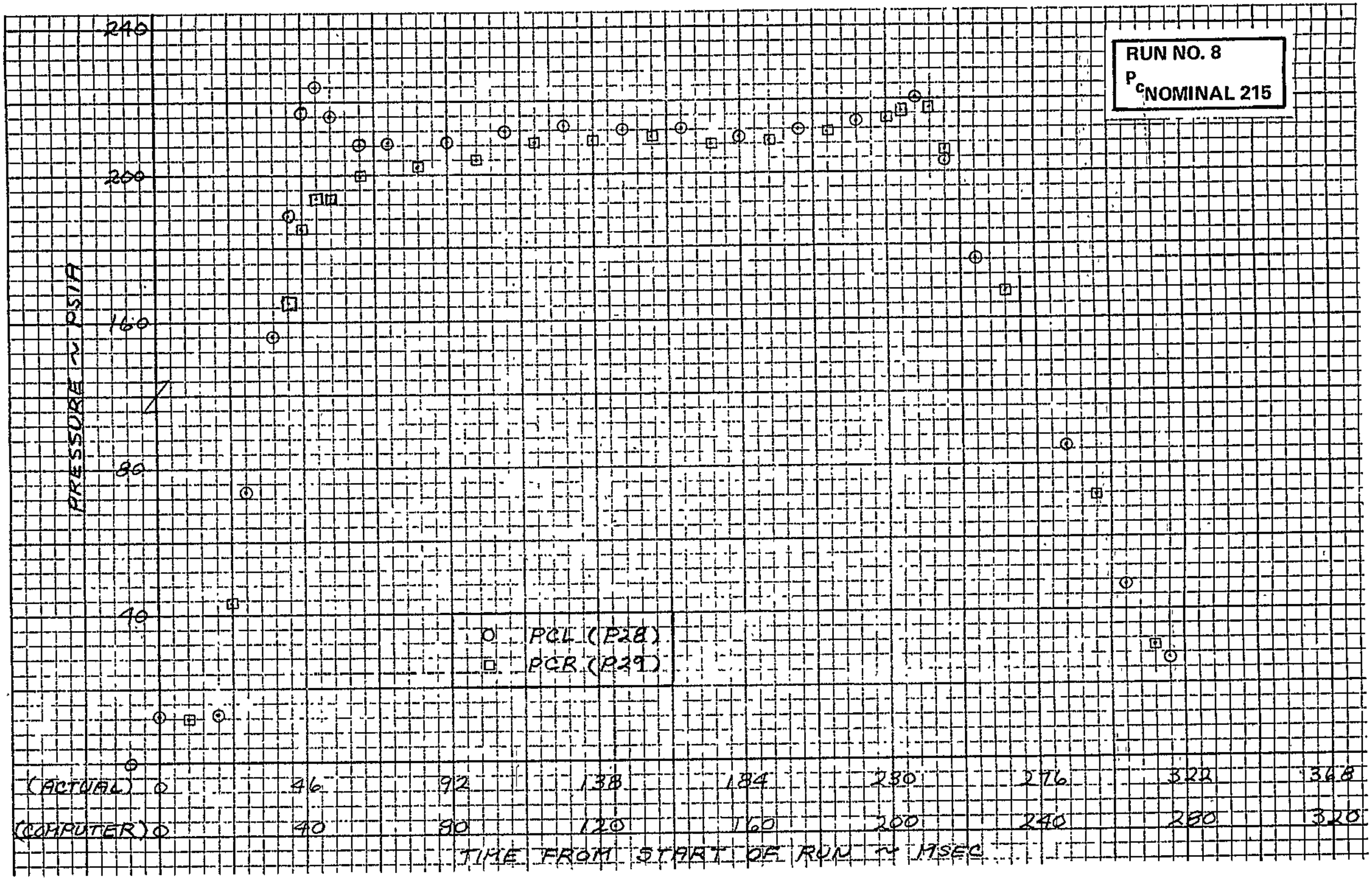


Figure 11 SRB COMBUSTION CHAMBER PRESSURES (Cont.)

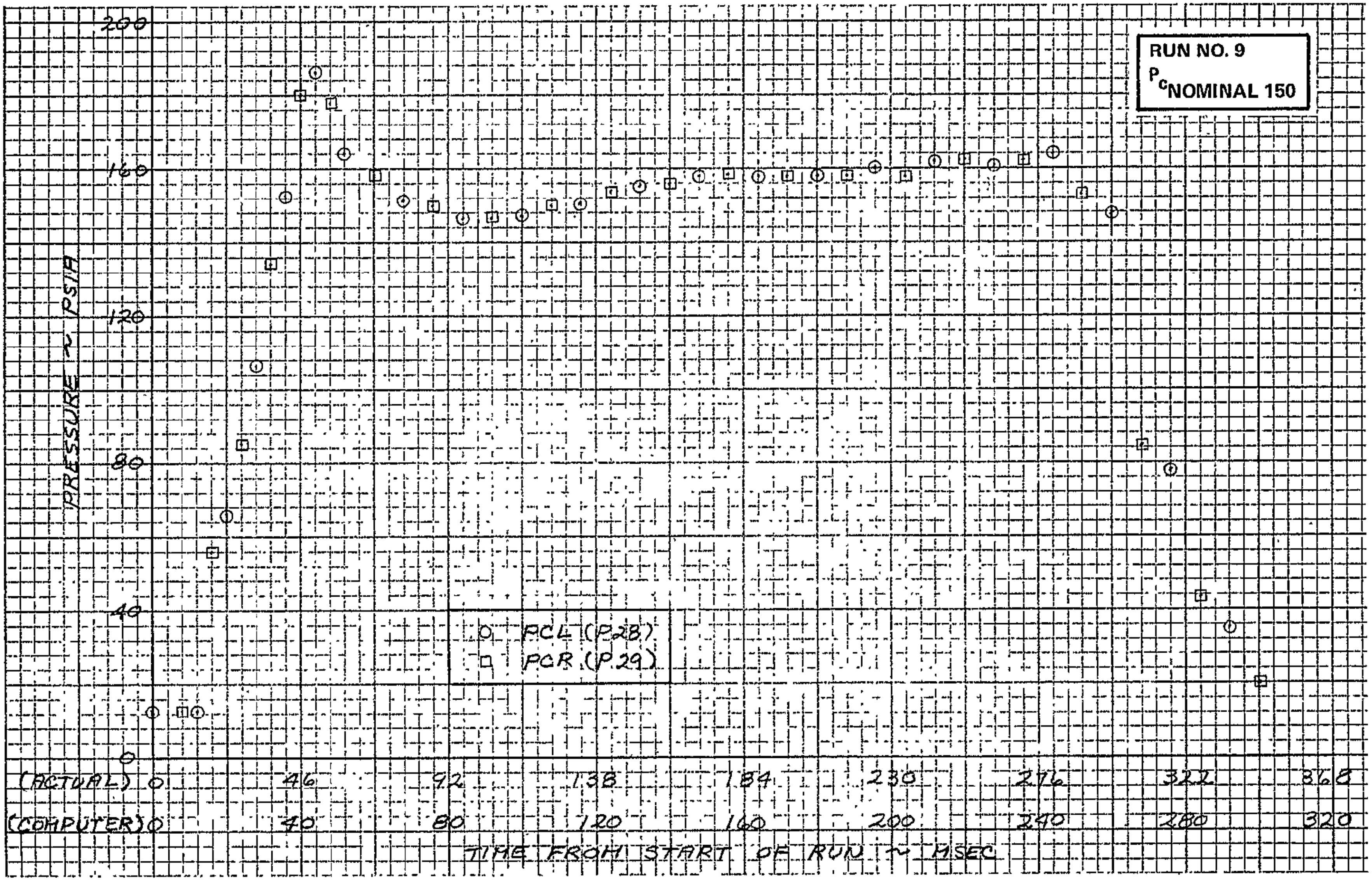


Figure 11 SRB COMBUSTION CHAMBER PRESSURES (Cont.)

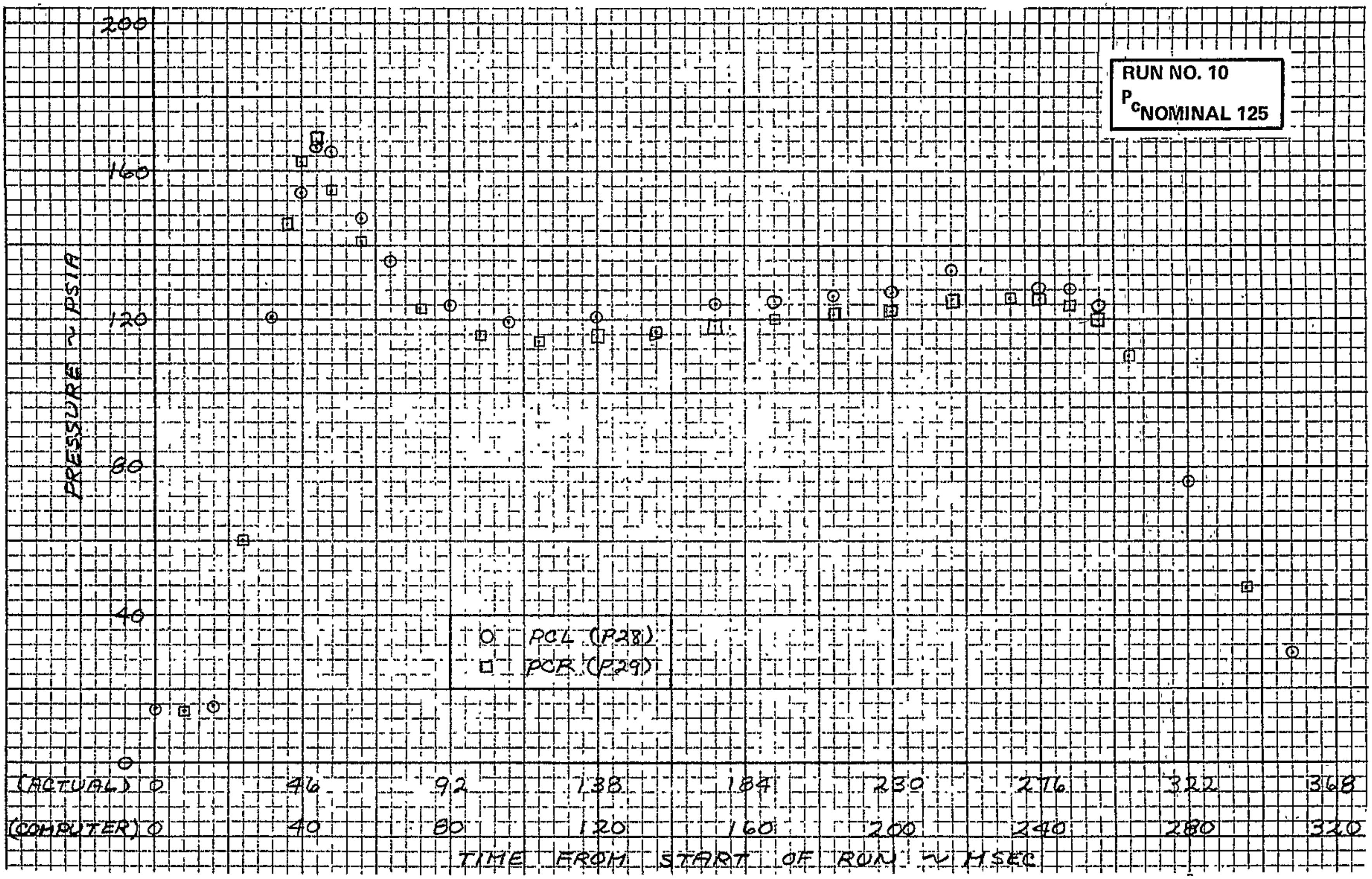


Figure 11 SRB COMBUSTION CHAMBER PRESSURES (Cont.)

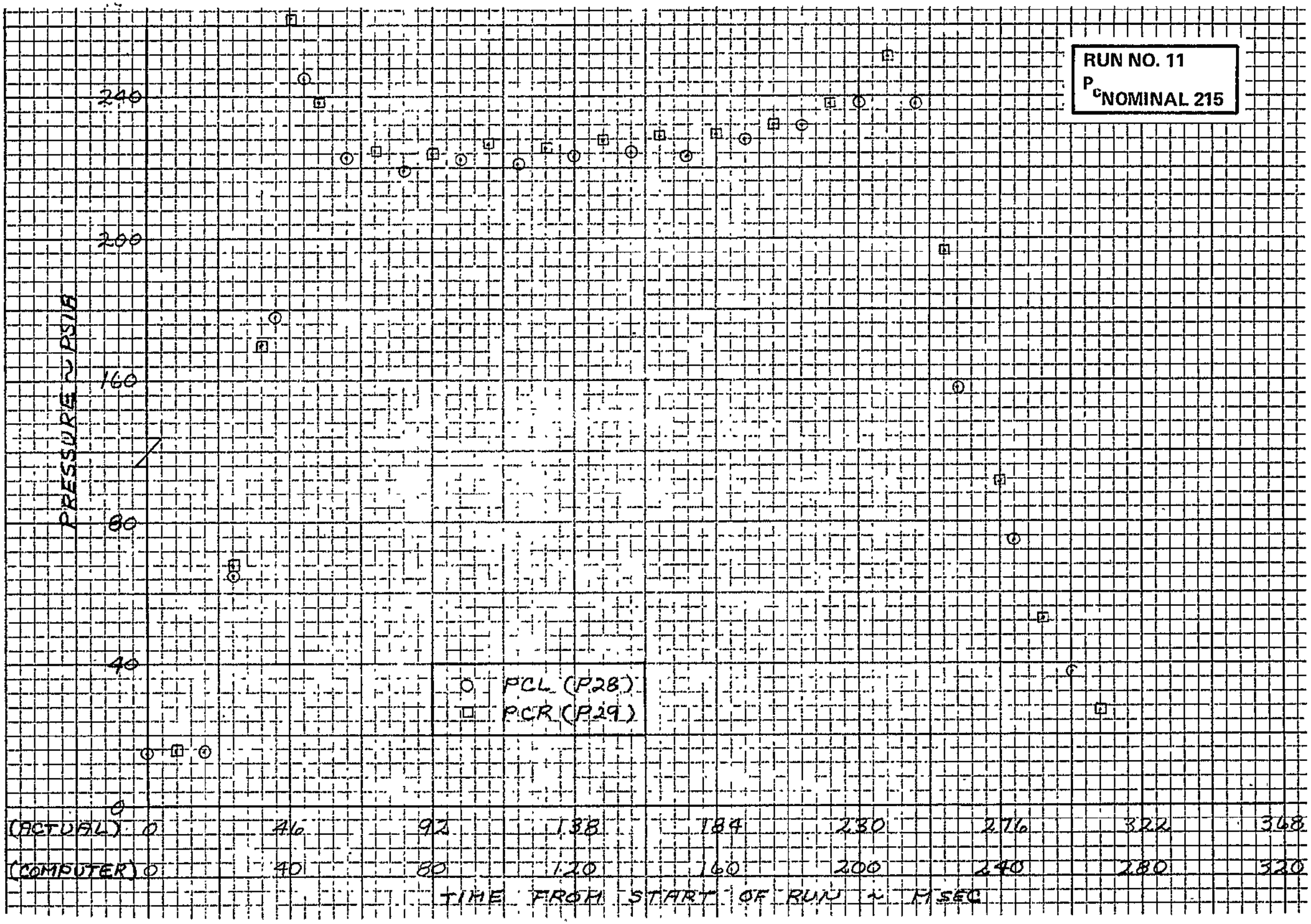


Figure 11 SRB COMBUSTION CHAMBER PRESSURES (Cont.)

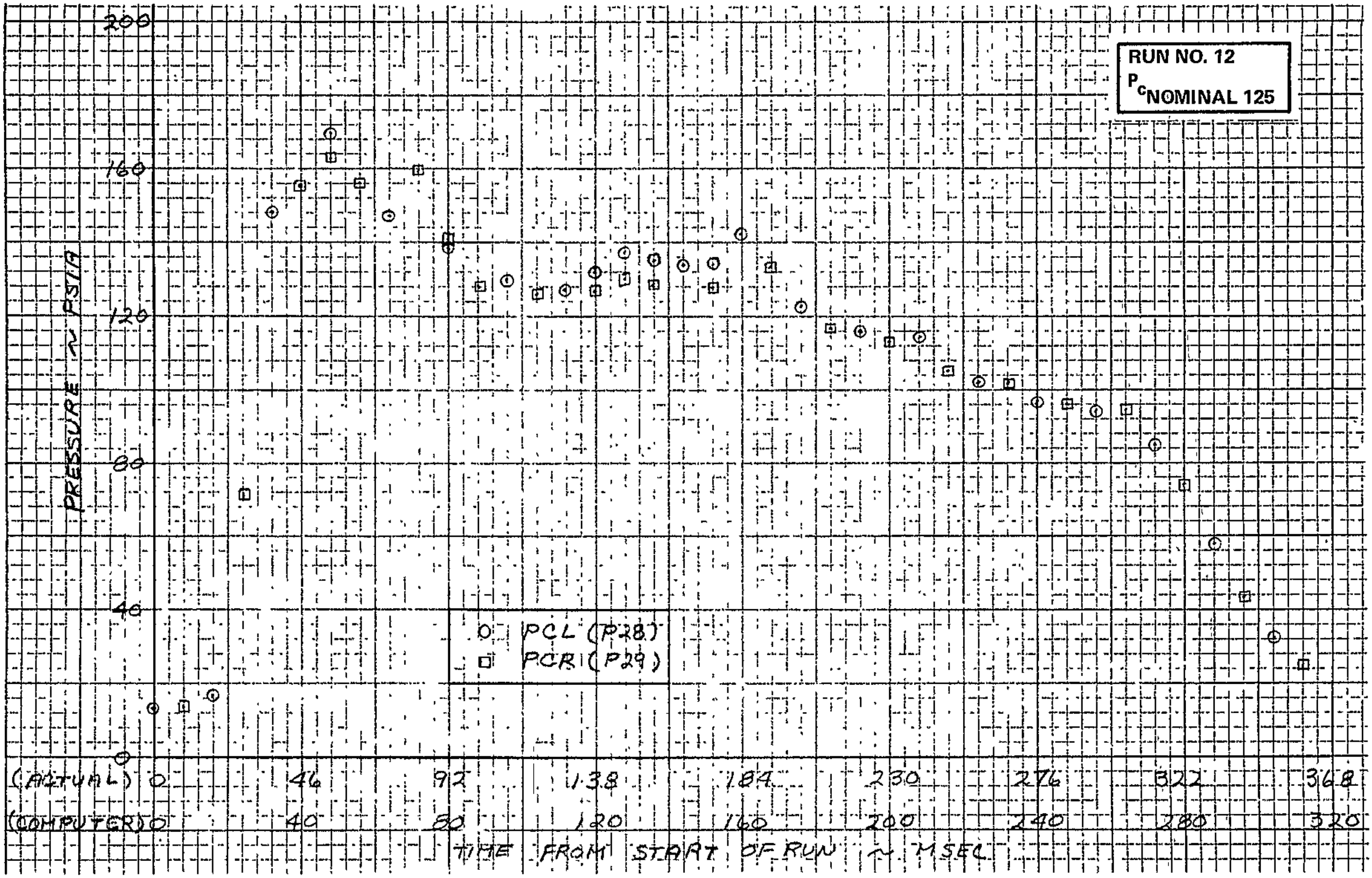


Figure 11 SRB COMBUSTION CHAMBER PRESSURES (Cont.)

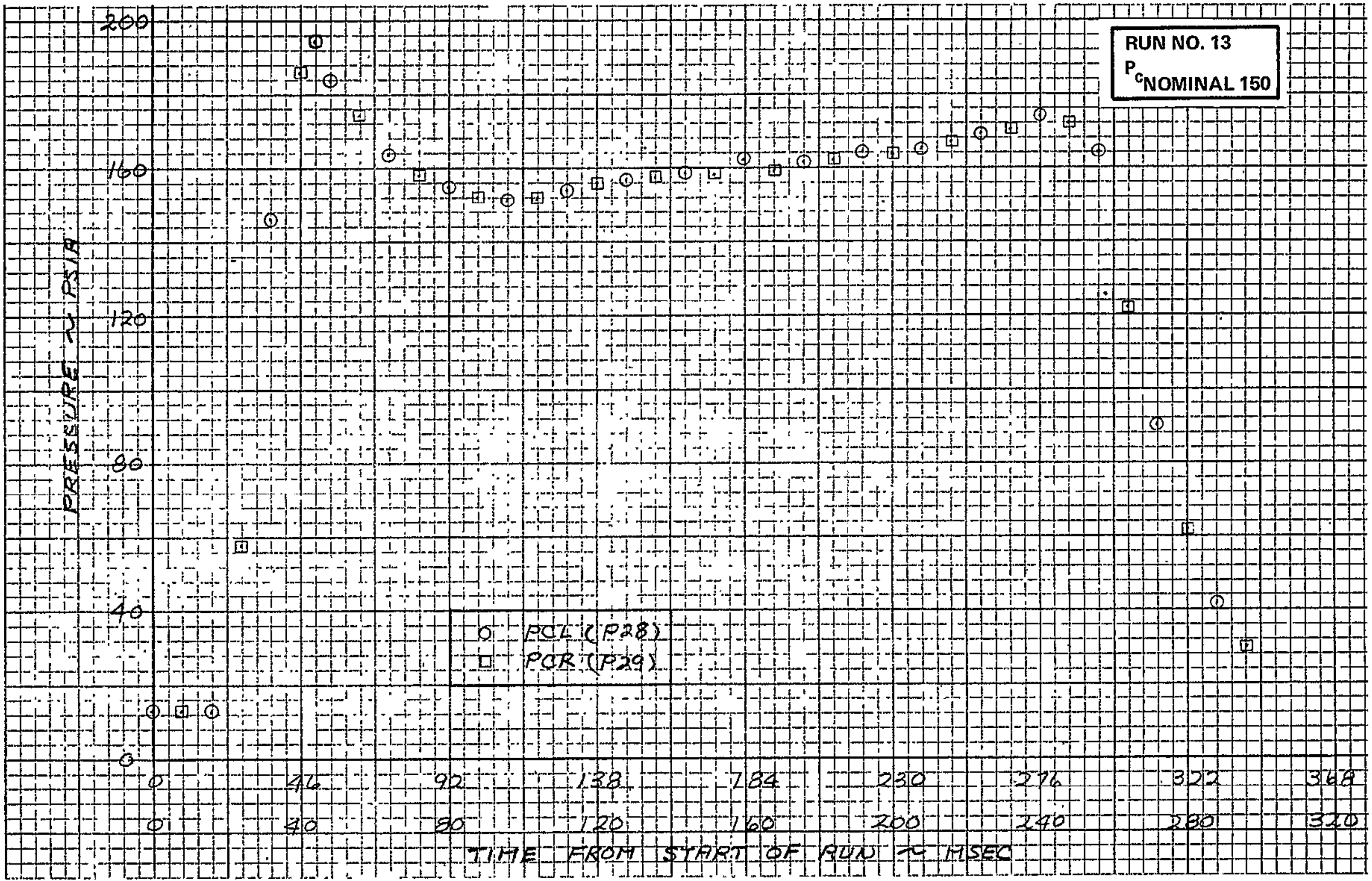


Figure 11 SRB COMBUSTION CHAMBER PRESSURES (Cont.)

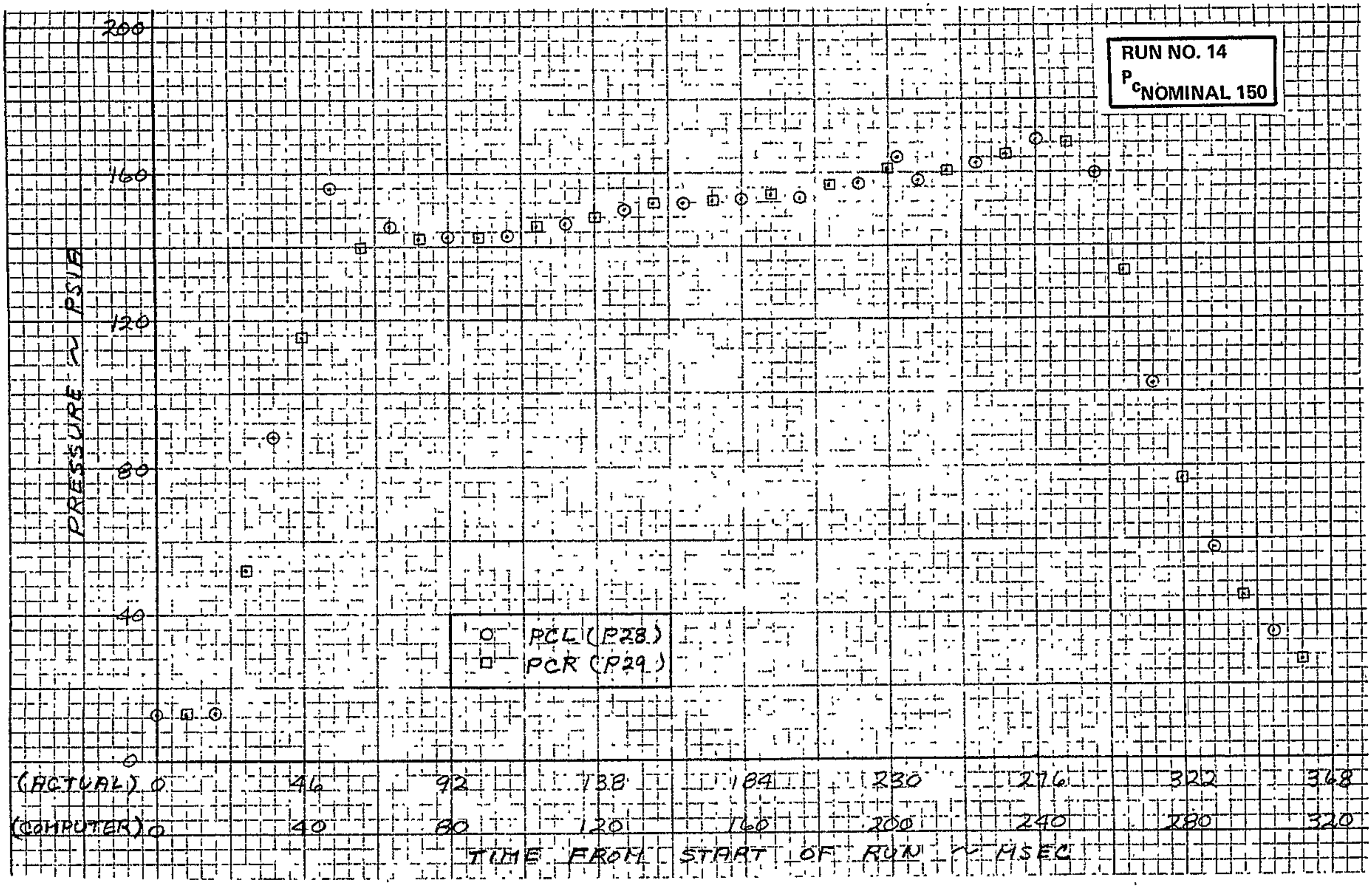


Figure 11 SRB COMBUSTION CHAMBER PRESSURES (Cont.)

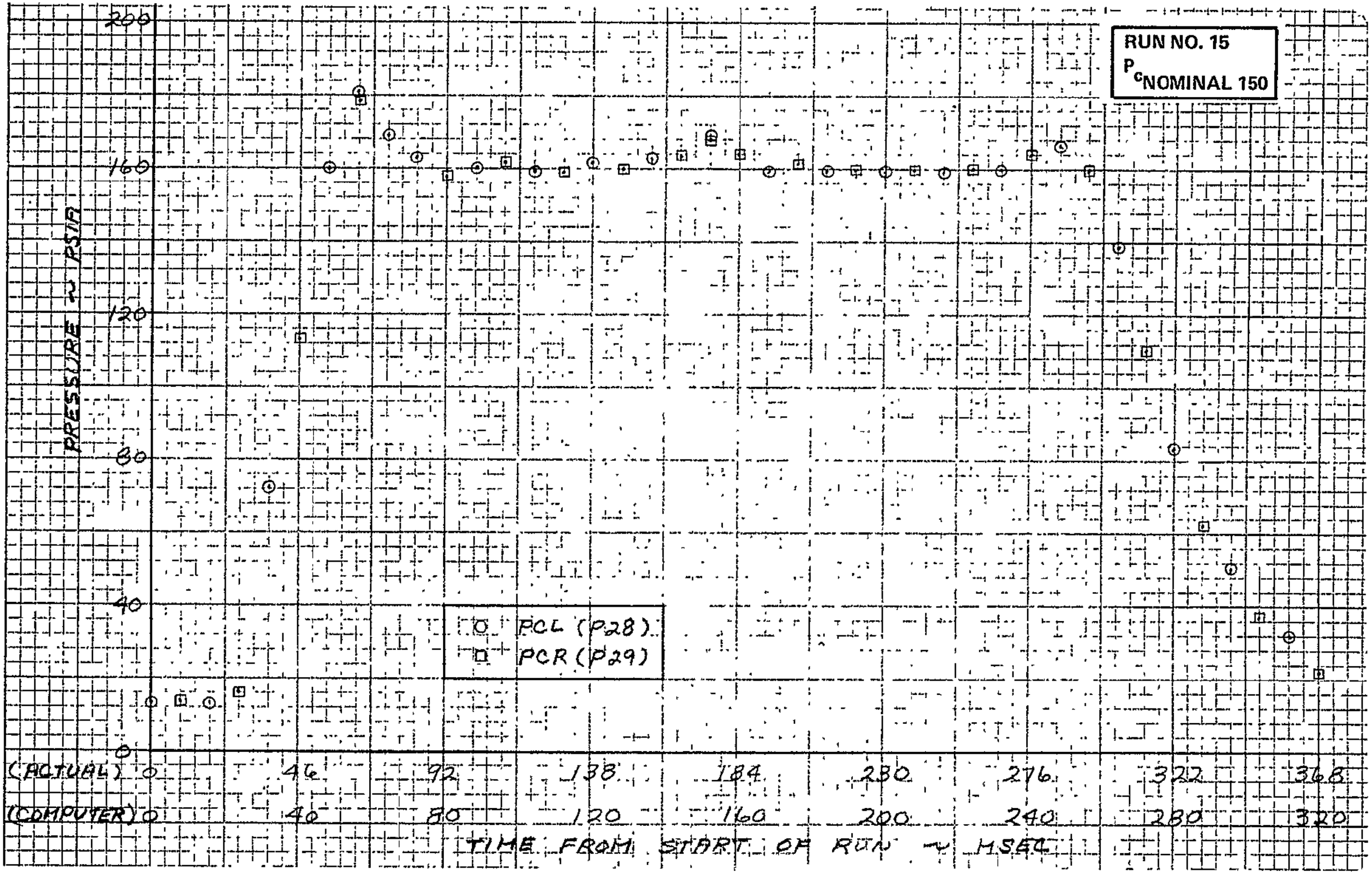


Figure 11 SRB COMBUSTION CHAMBER PRESSURES (Cont.)

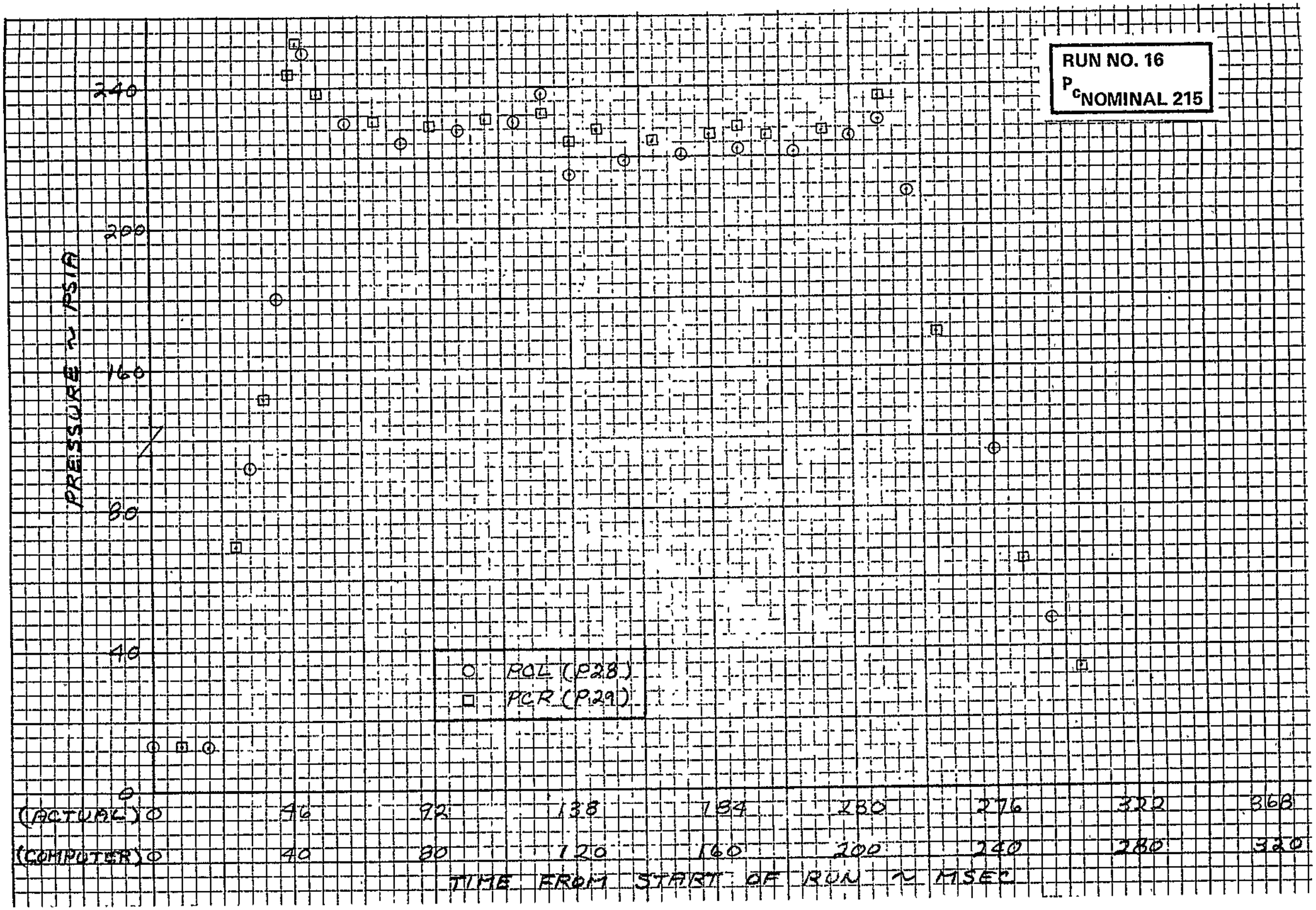


Figure 11 SRB COMBUSTION CHAMBER PRESSURES (Cont.)

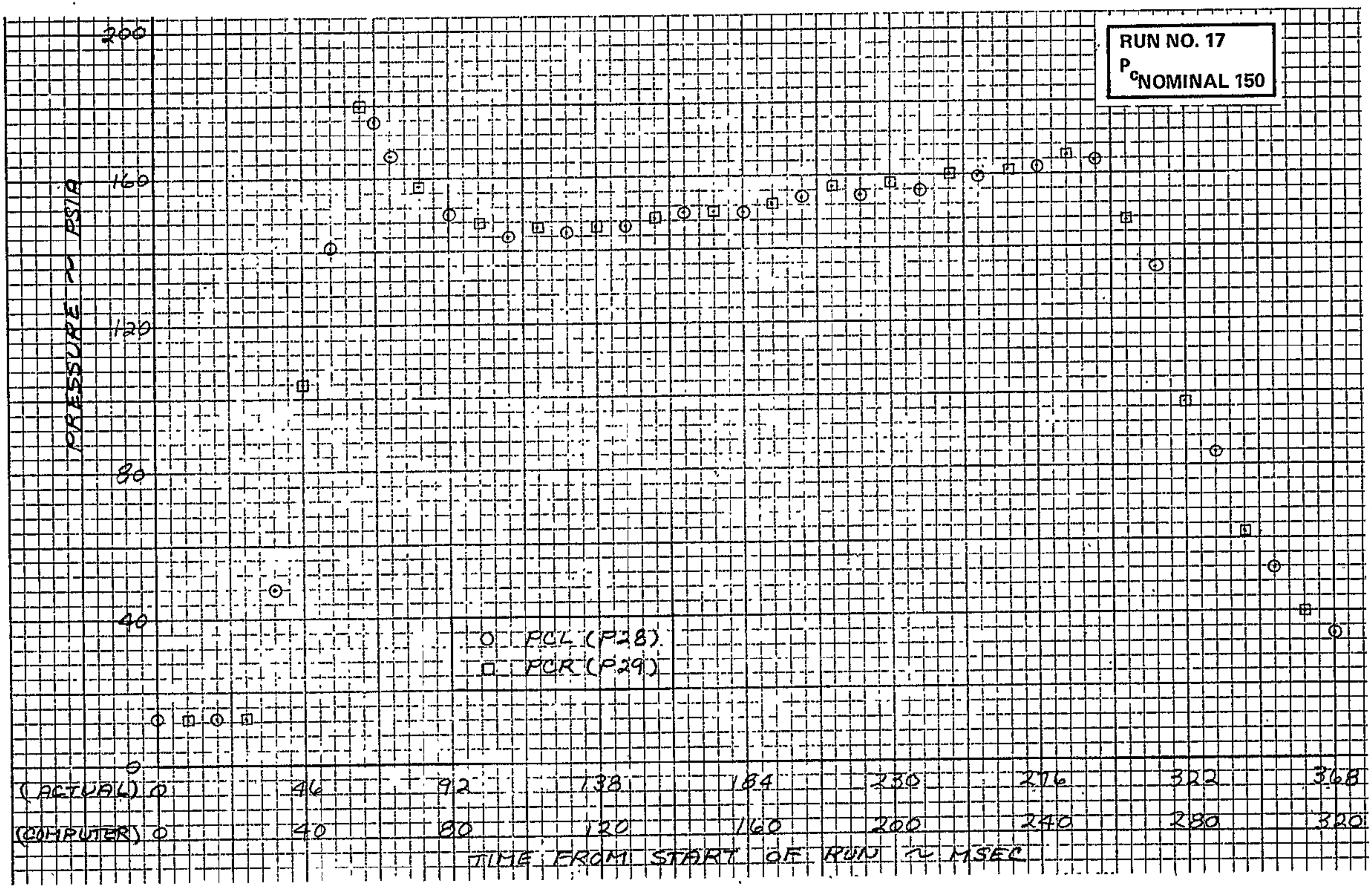


Figure 11 SRB COMBUSTION CHAMBER PRESSURES (Cont.)

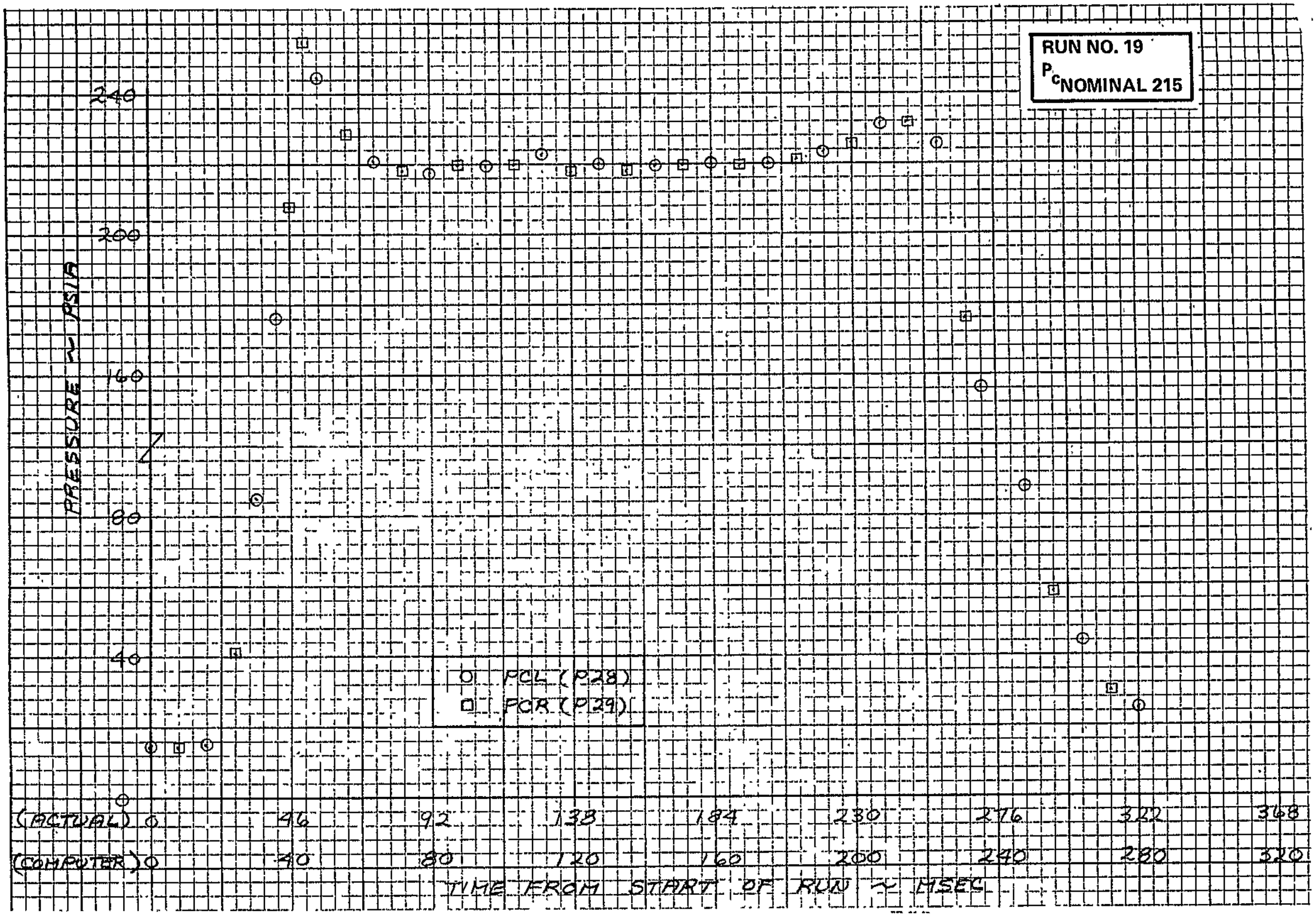


Figure 11 SRB COMBUSTION CHAMBER PRESSURES (Cont.)

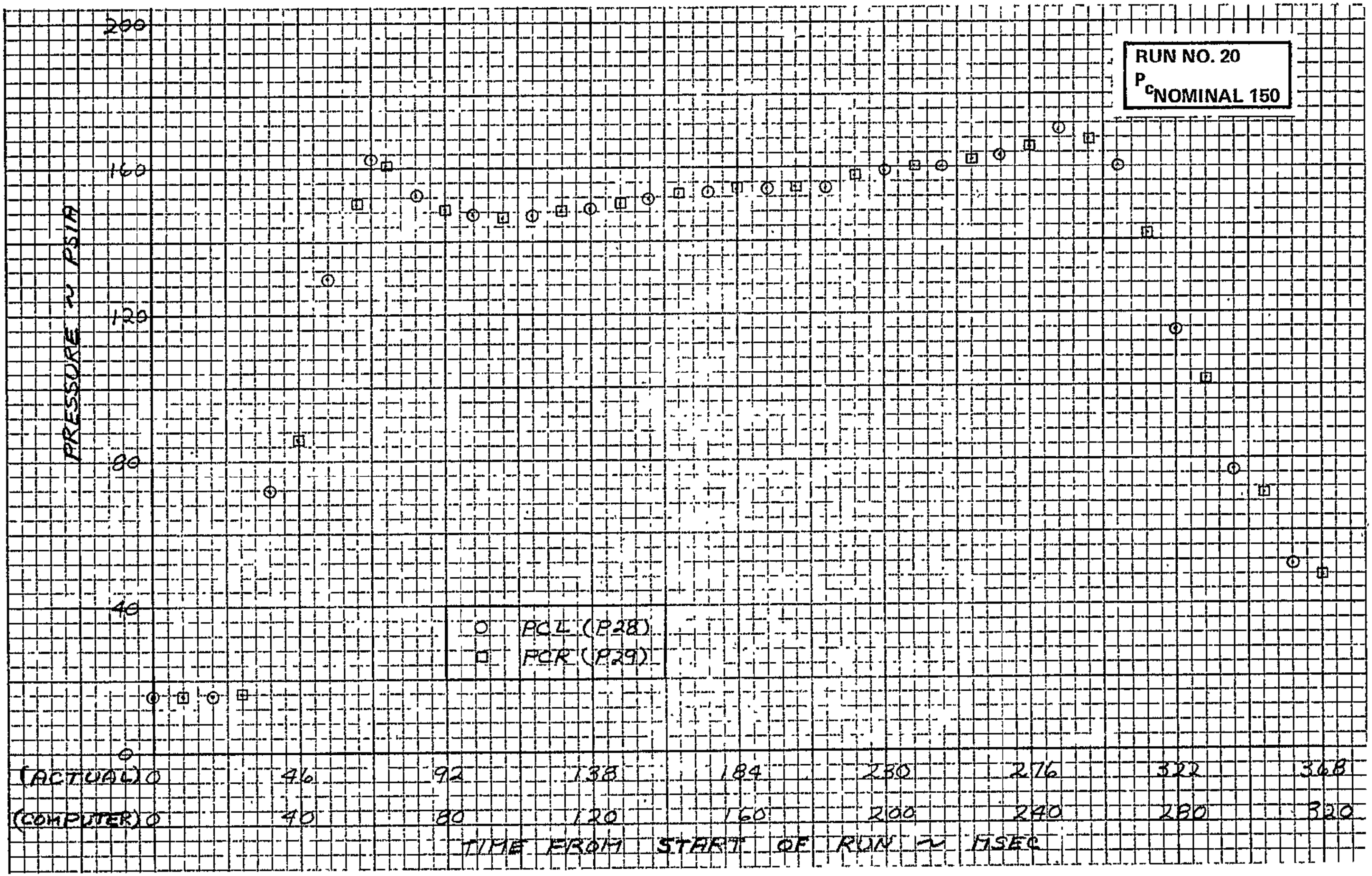


Figure 11 SRB COMBUSTION CHAMBER PRESSURES (Cont.)

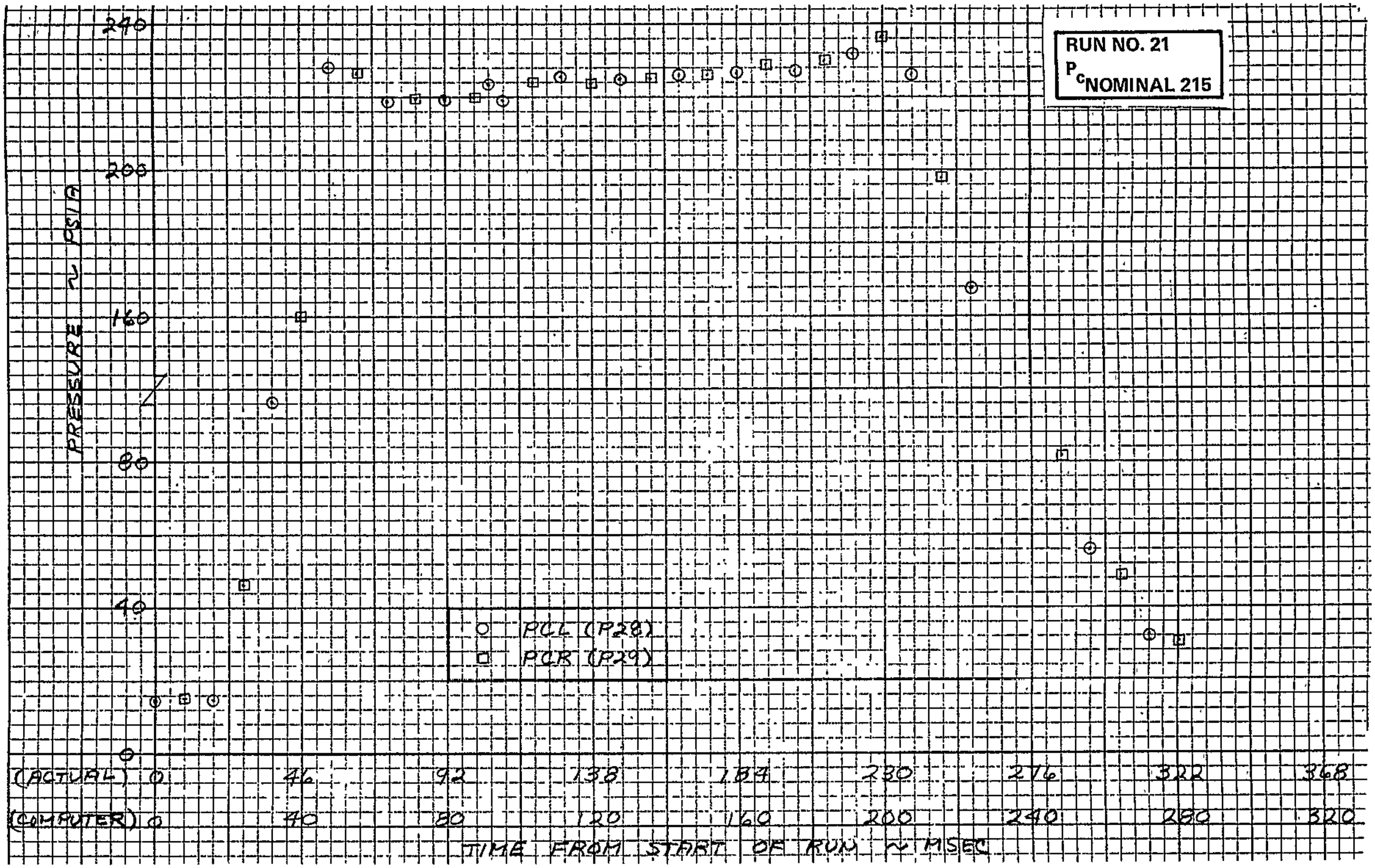


Figure 11 SRB COMBUSTION CHAMBER PRESSURES (Cont.)

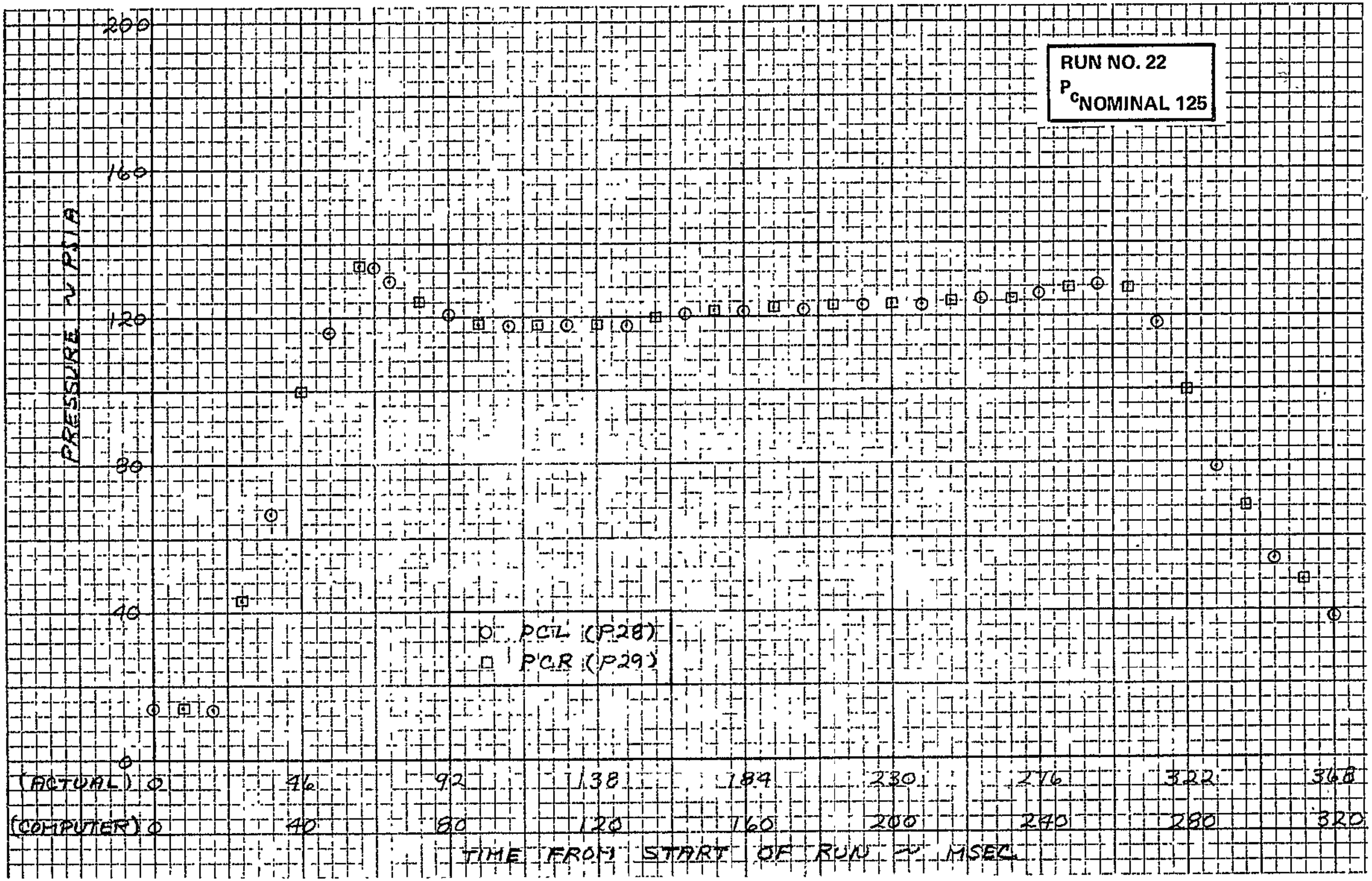


Figure 11 SRB COMBUSTION CHAMBER PRESSURES (Cont.)

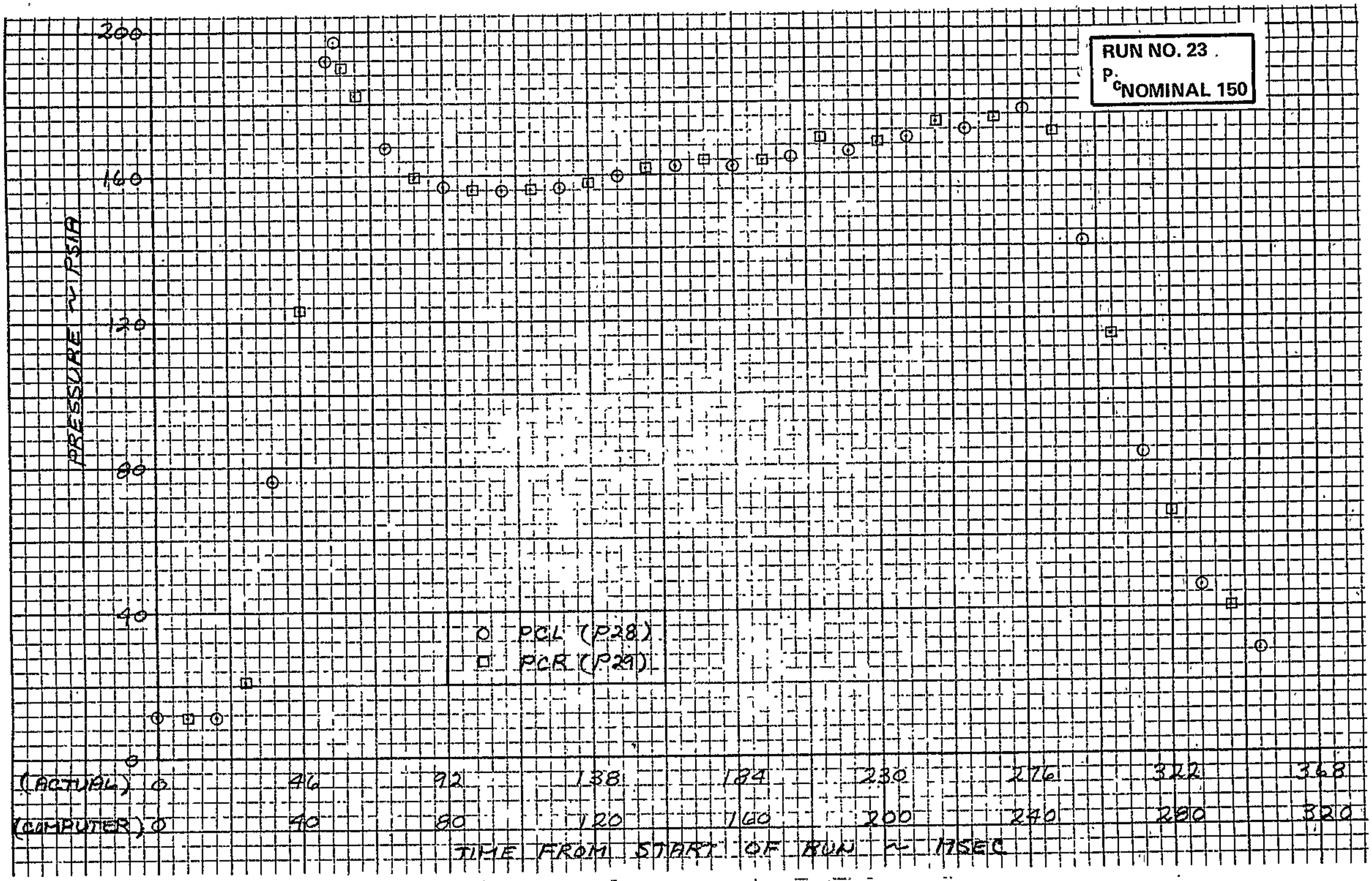


Figure 11 SRB COMBUSTION CHAMBER PRESSURES (Cont.)

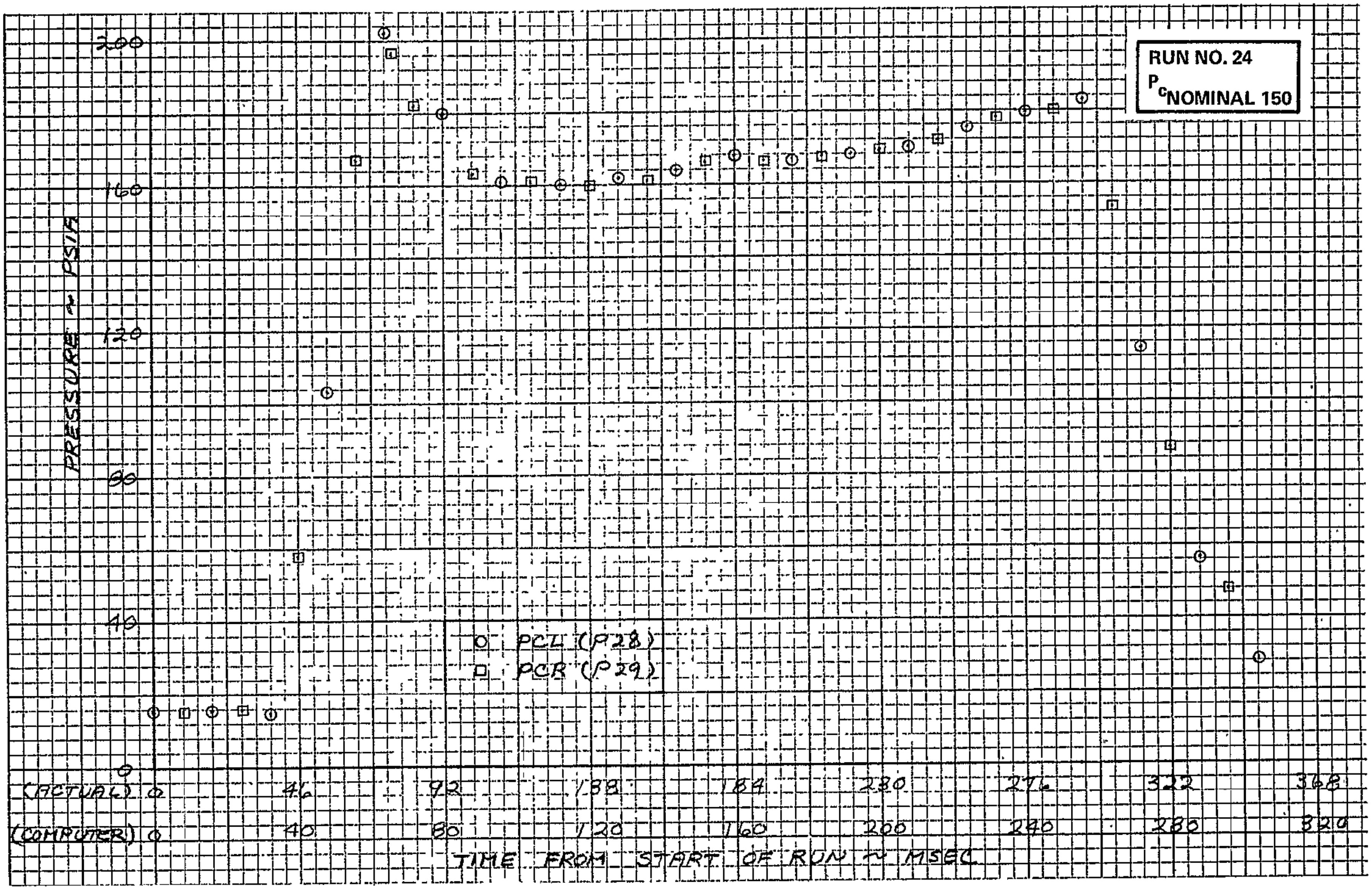


Figure 11 SRB COMBUSTION CHAMBER PRESSURES (Cont.)

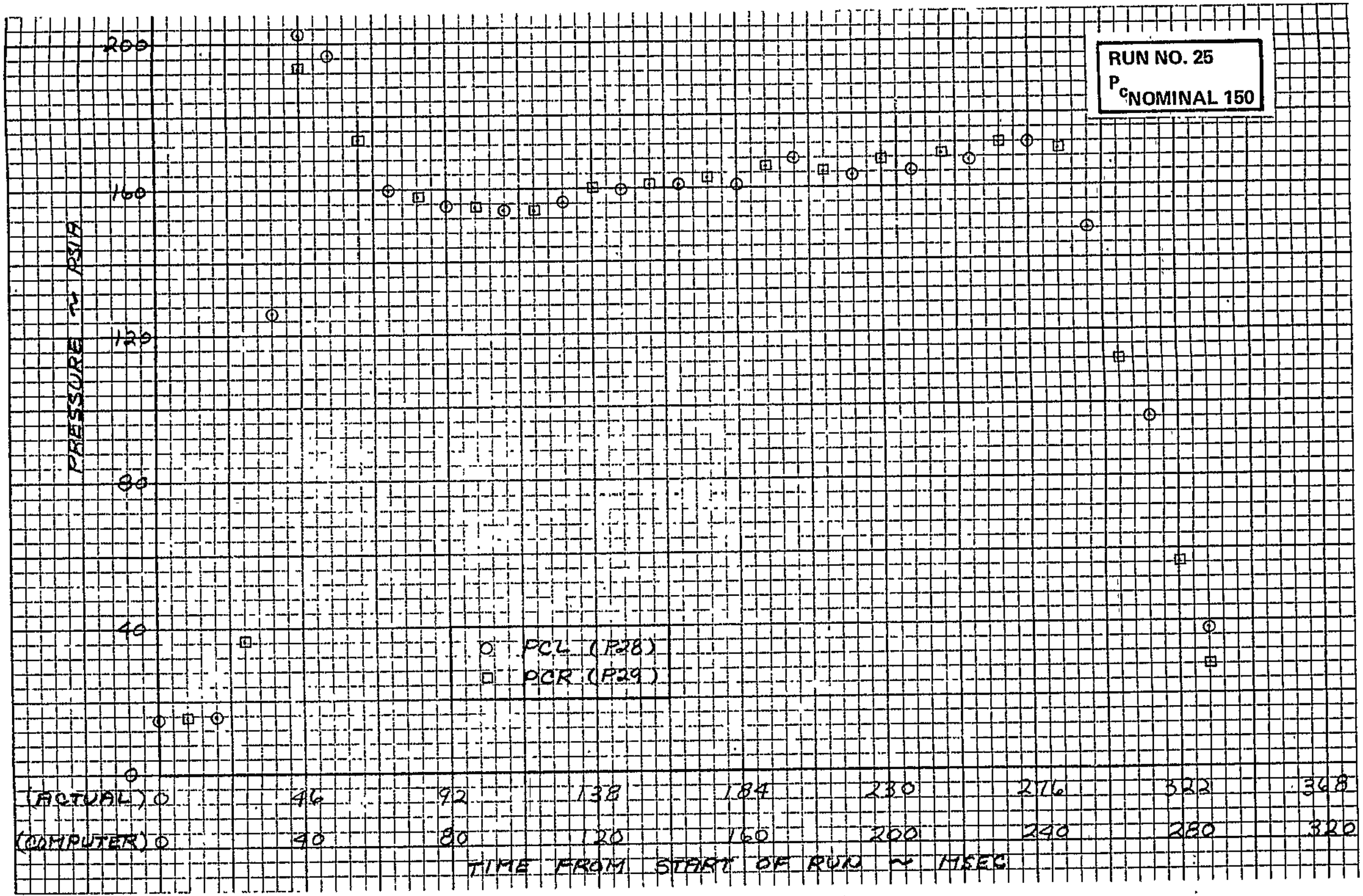


Figure 11 SRB COMBUSTION CHAMBER PRESSURES (Cont.)

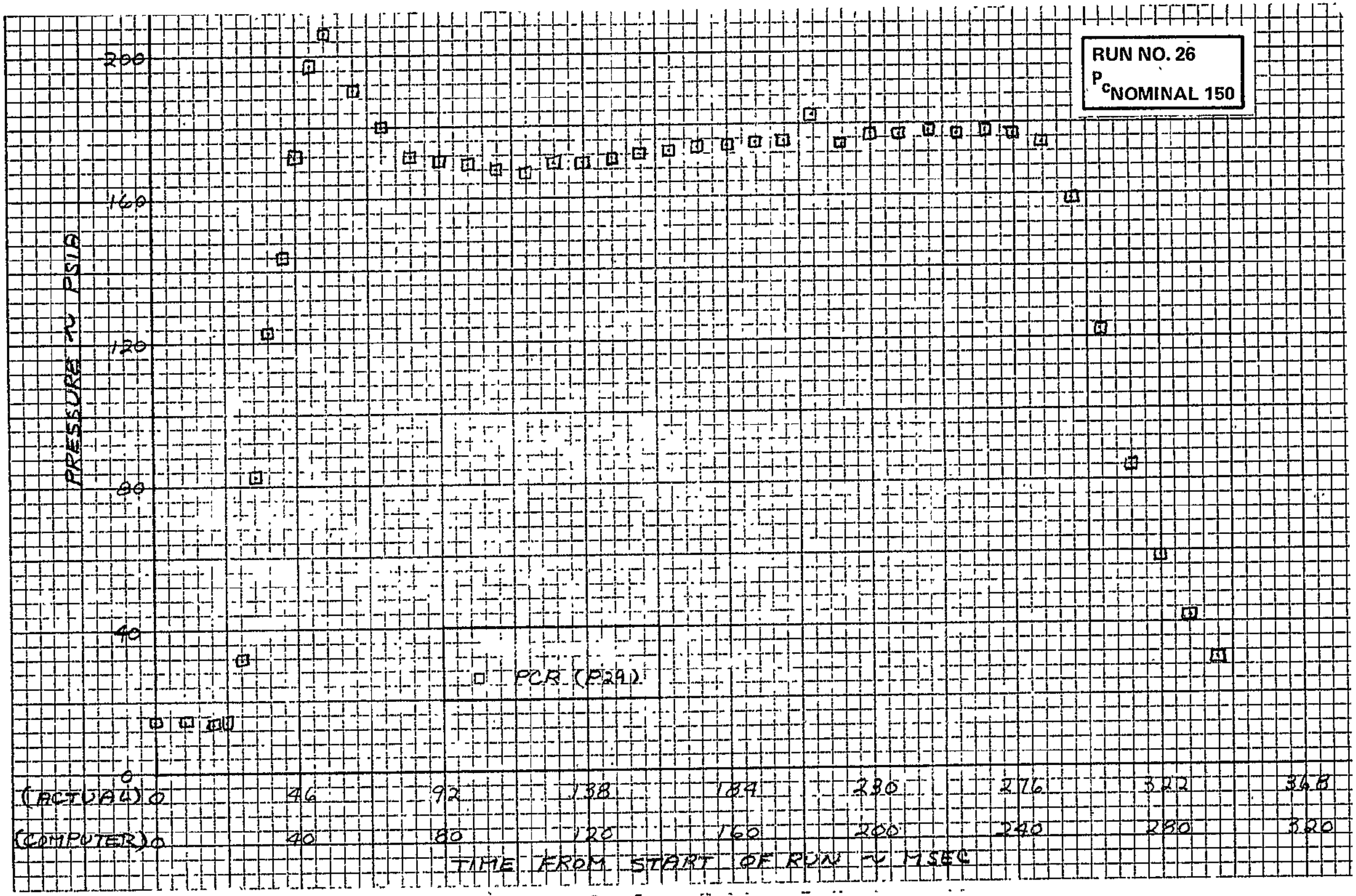


Figure 11 SRB COMBUSTION CHAMBER PRESSURES (Cont.)

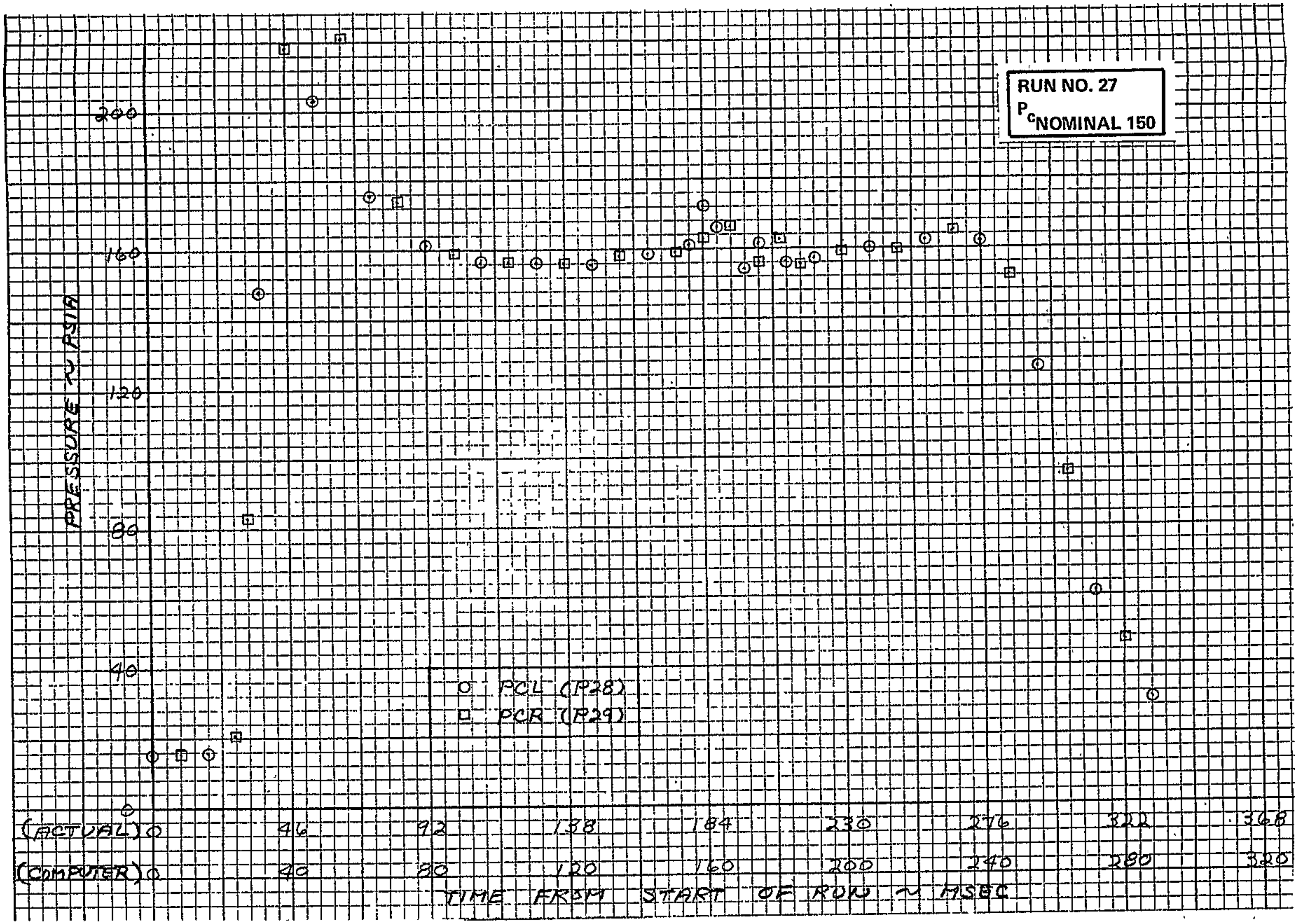


Figure 11 SRB COMBUSTION CHAMBER PRESSURES (Cont.)

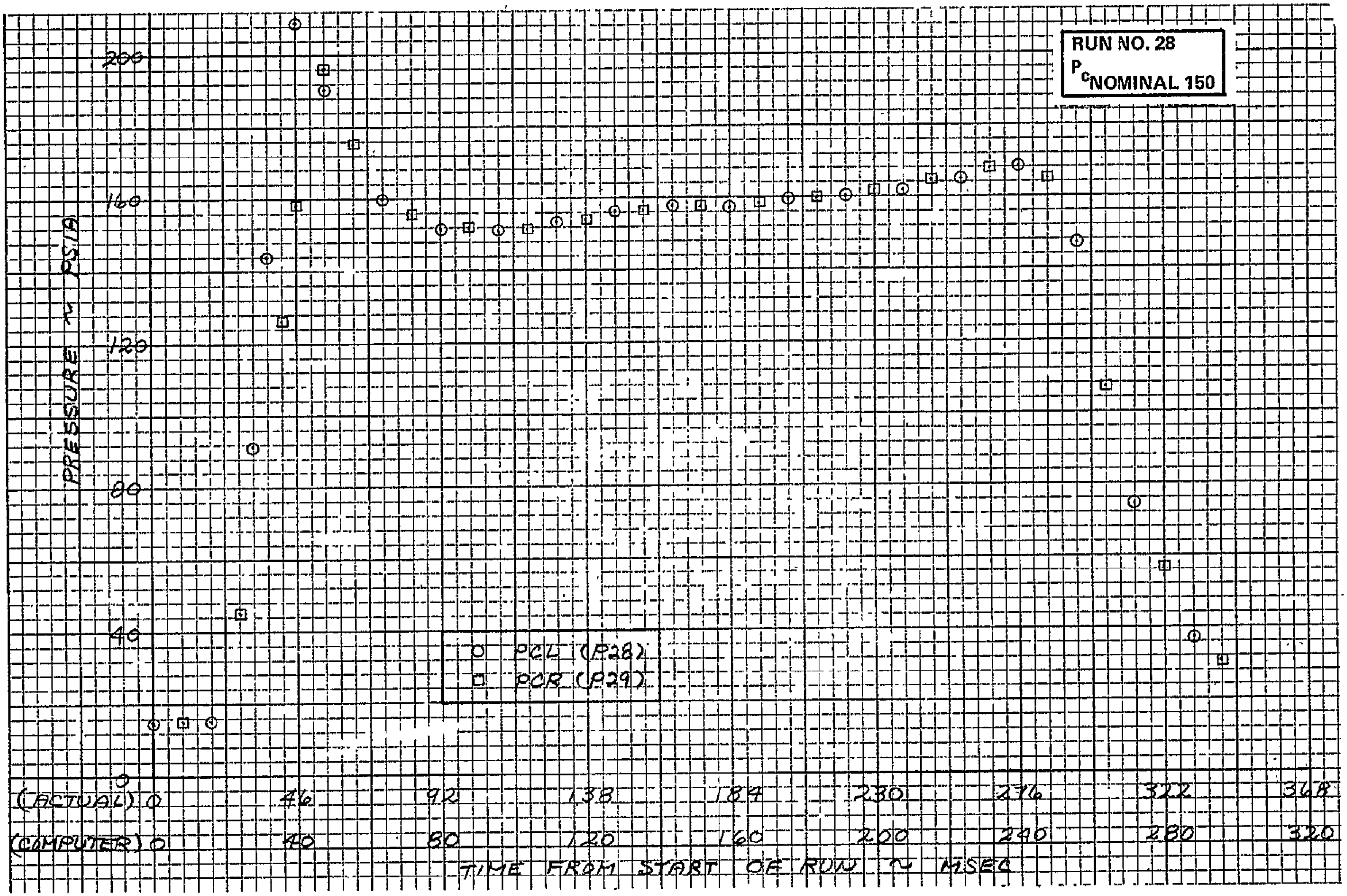


Figure 11 SRB COMBUSTION CHAMBER PRESSURES (Cont.)

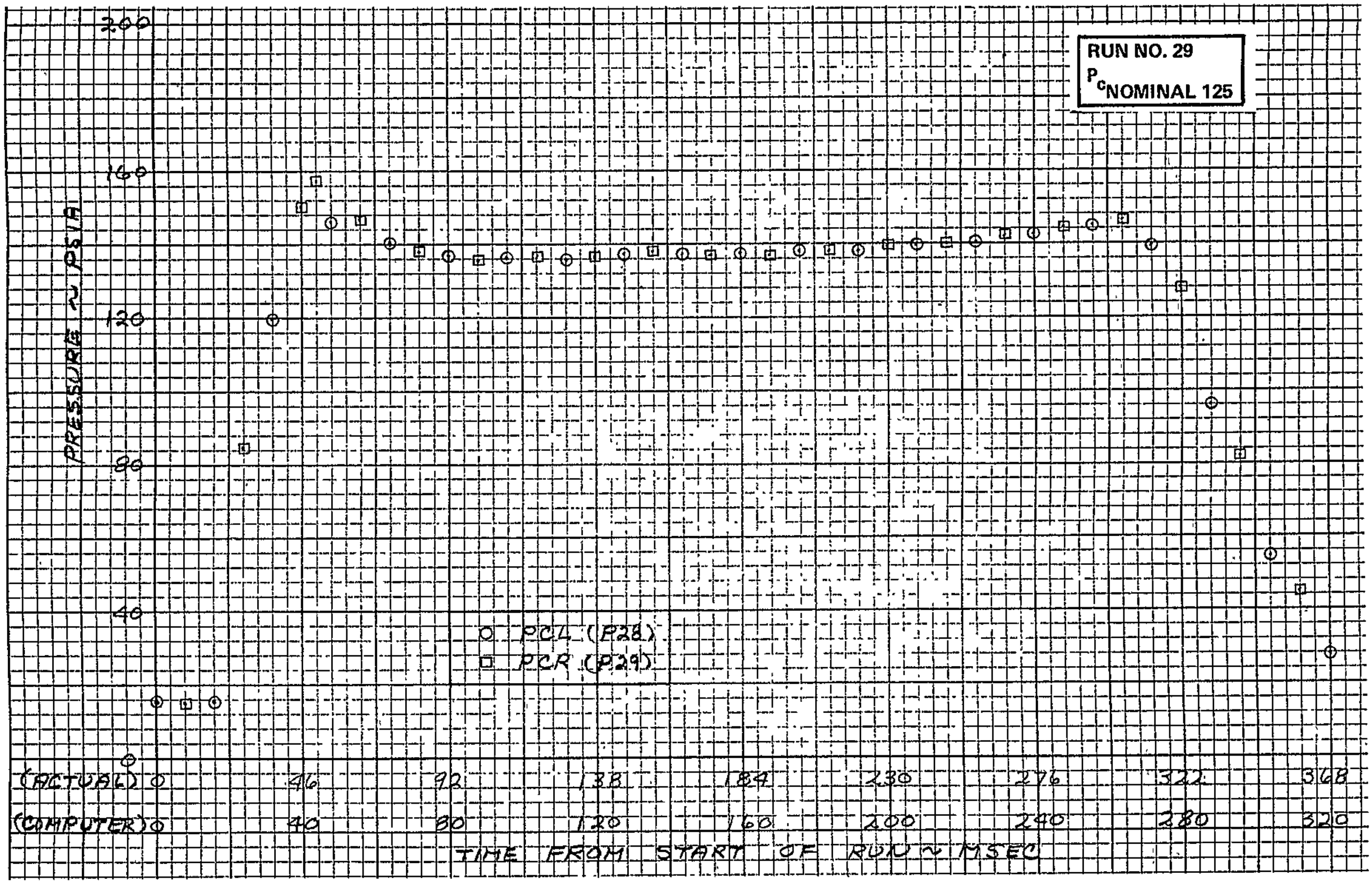


Figure 11 SRB COMBUSTION CHAMBER PRESSURES (Cont.)

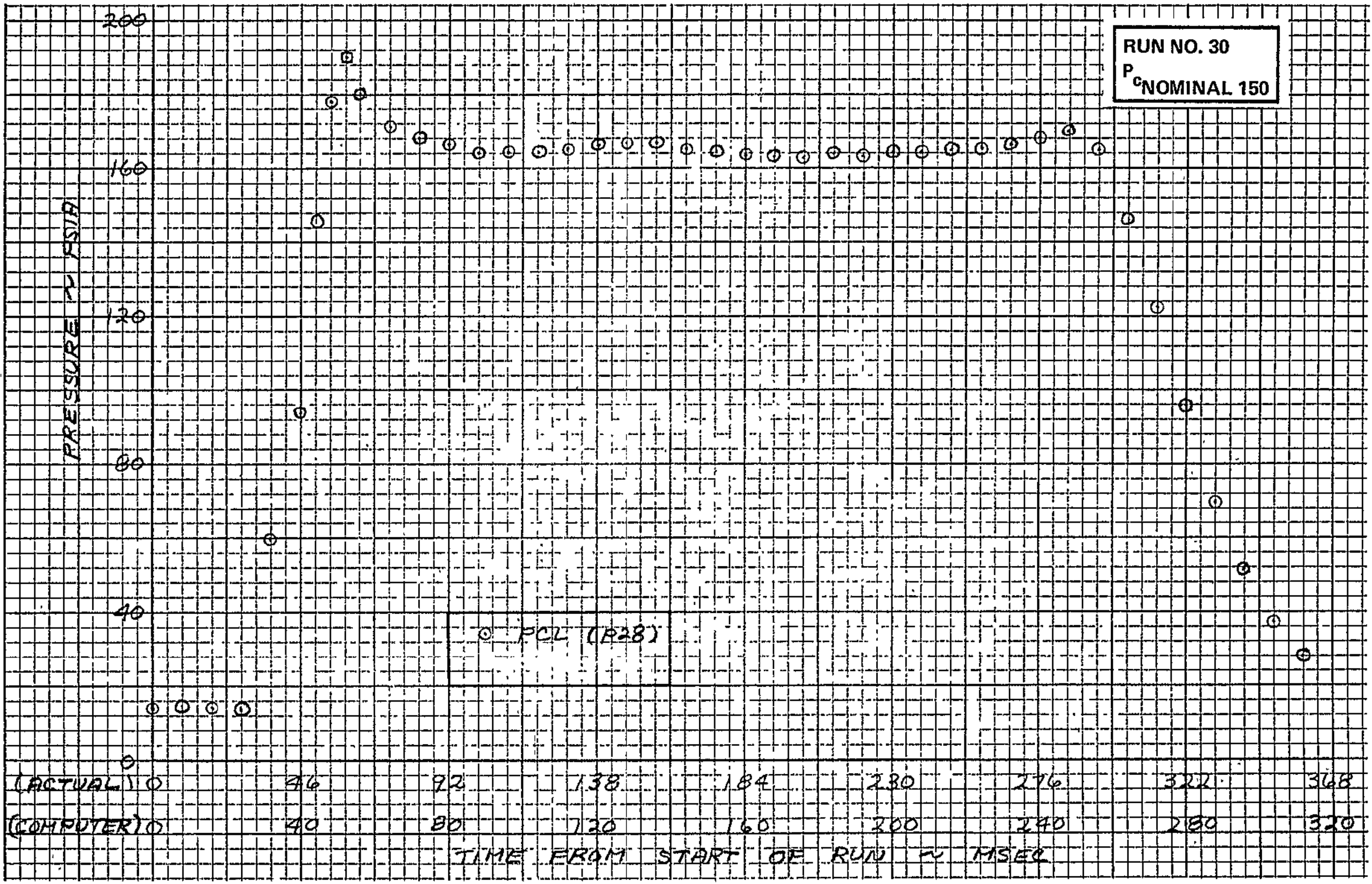


Figure 11 SRB COMBUSTION CHAMBER PRESSURES (Cont.)

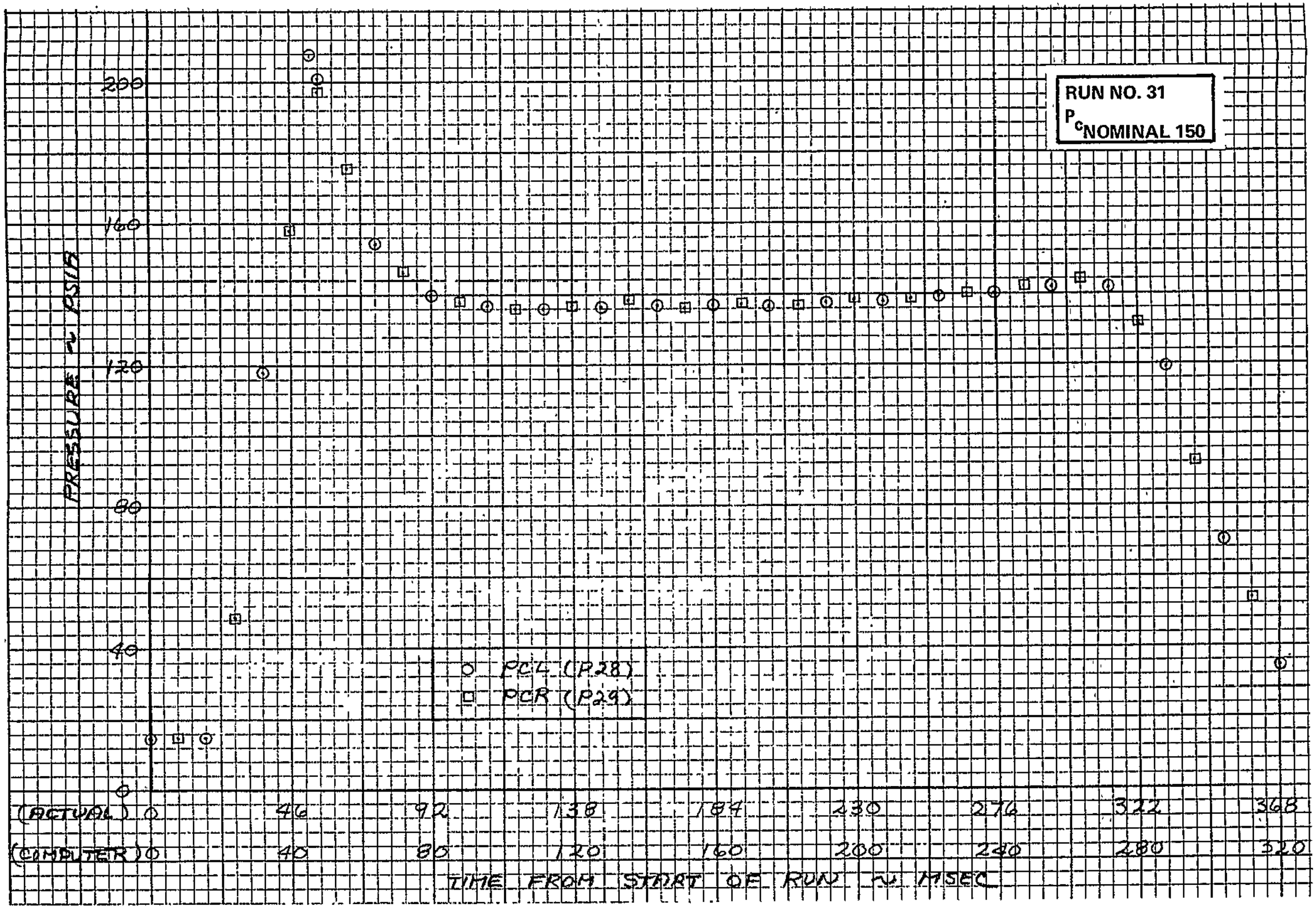


Figure 11 SRB COMBUSTION CHAMBER PRESSURES (Cont.)

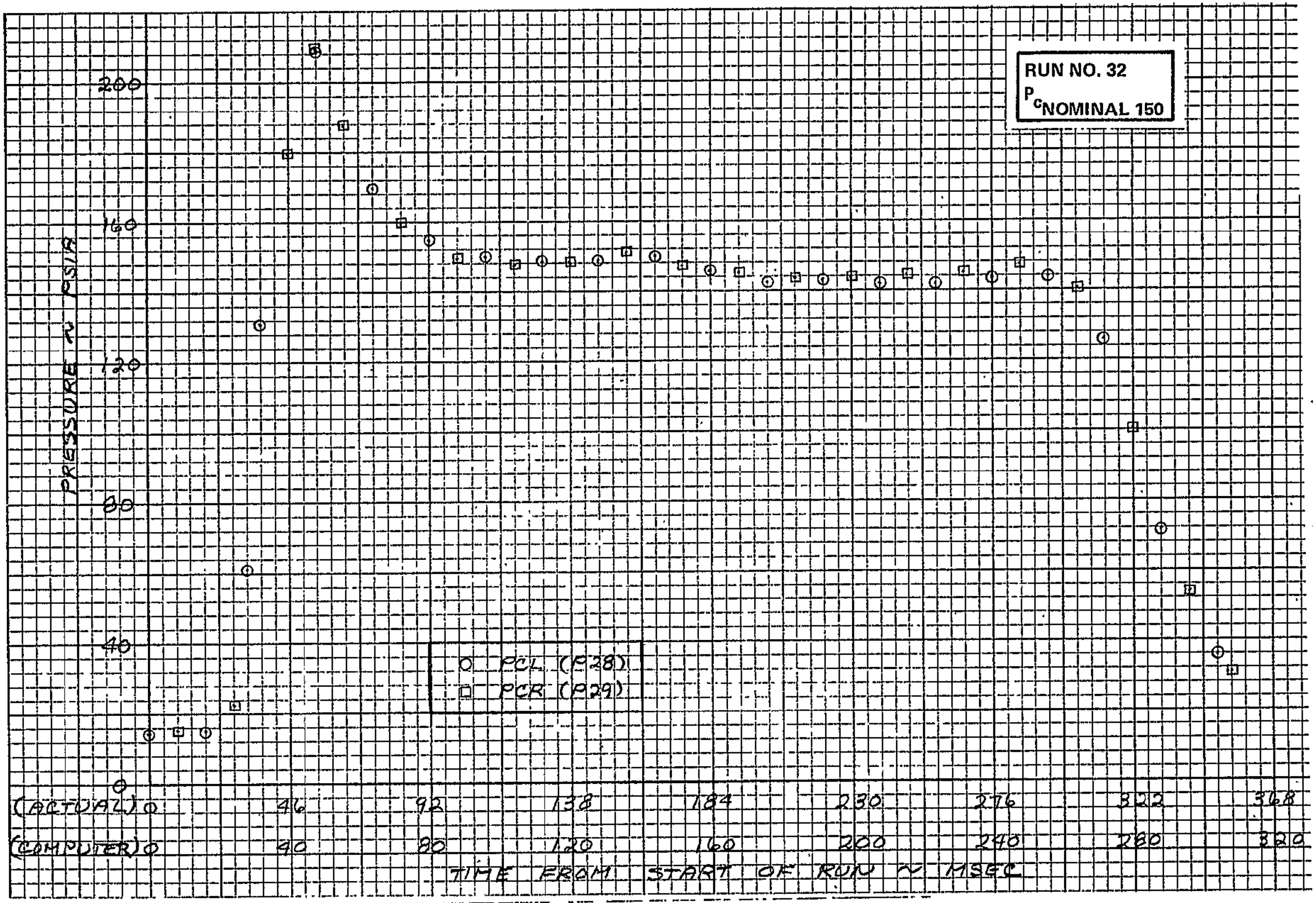


Figure 11 SRB COMBUSTION CHAMBER PRESSURES (Cont.)

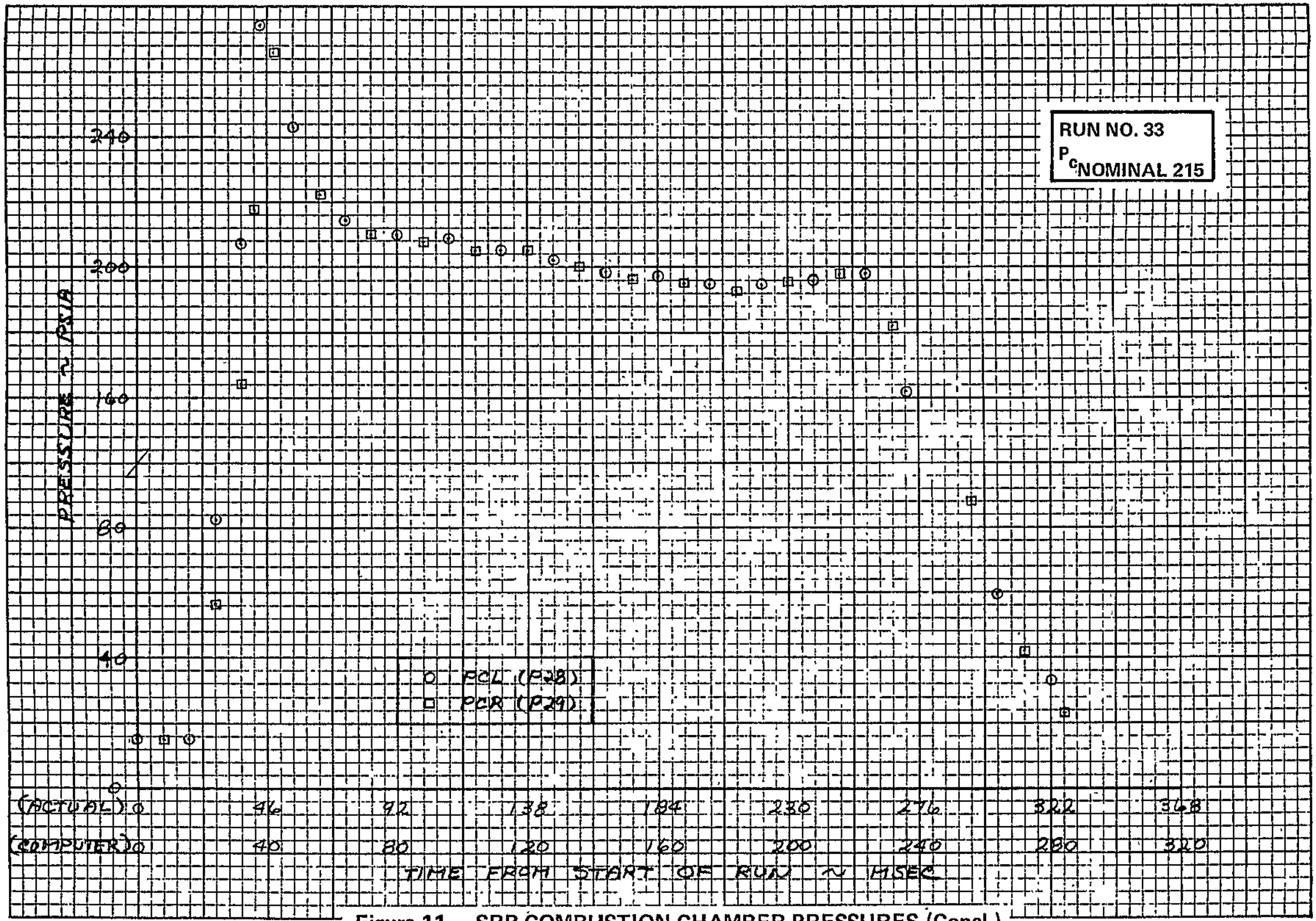


Figure 11 SRB COMBUSTION CHAMBER PRESSURES (Concl.)

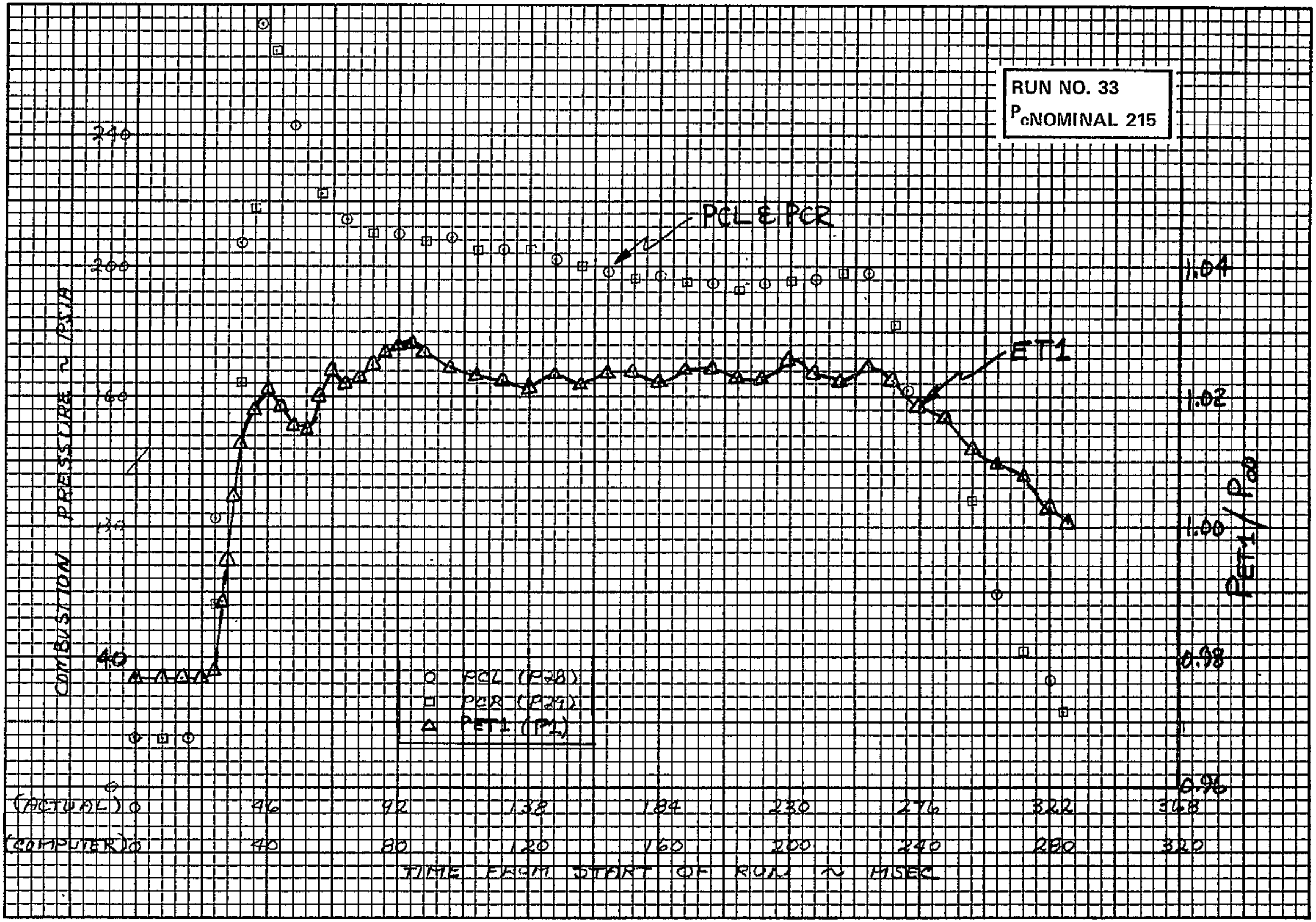


Figure 12 TIME CORRELATION OF SRB COMBUSTOR & ET PRESSURES

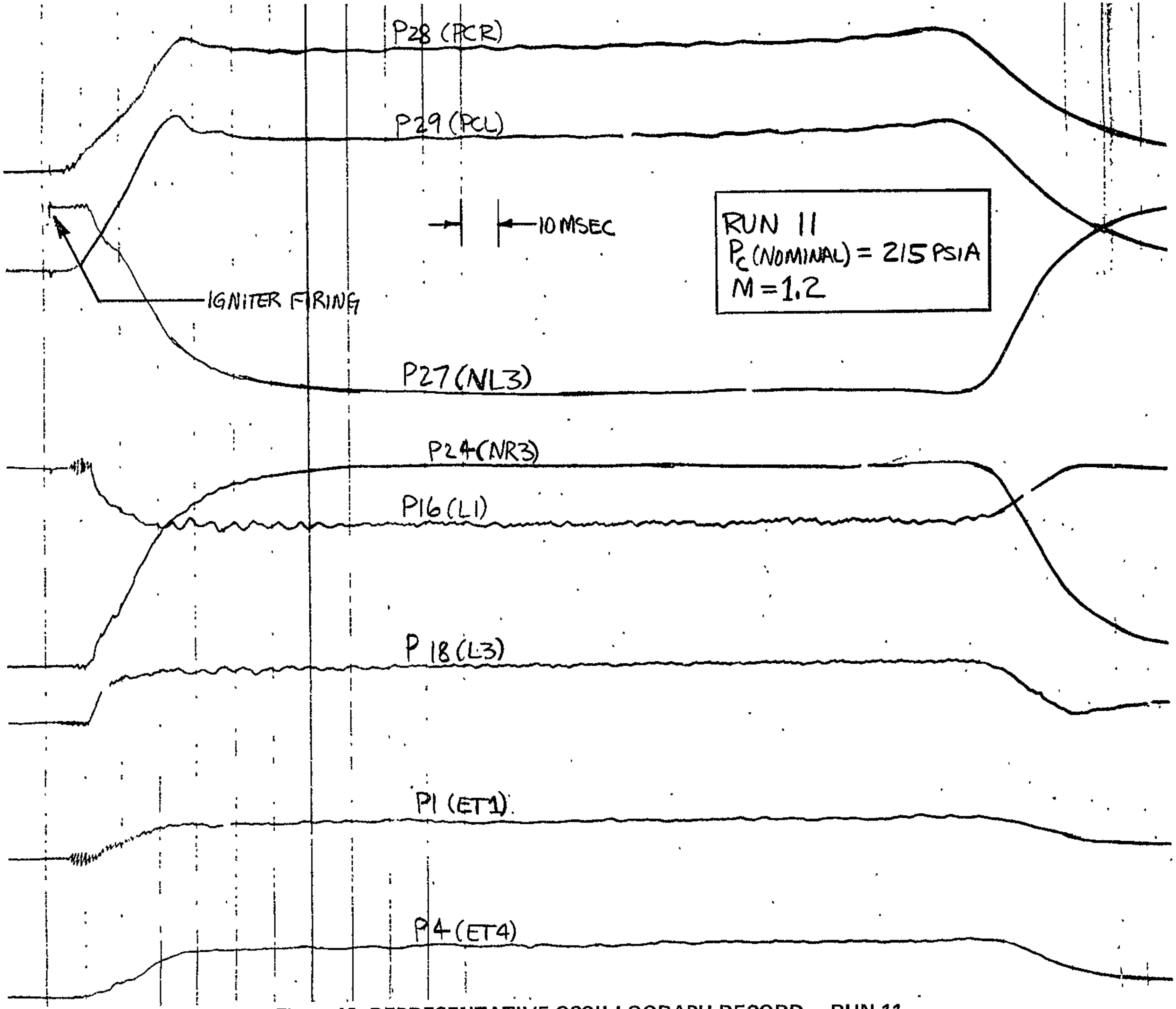


Figure 13 REPRESENTATIVE OSCILLOGRAPH RECORD – RUN 11

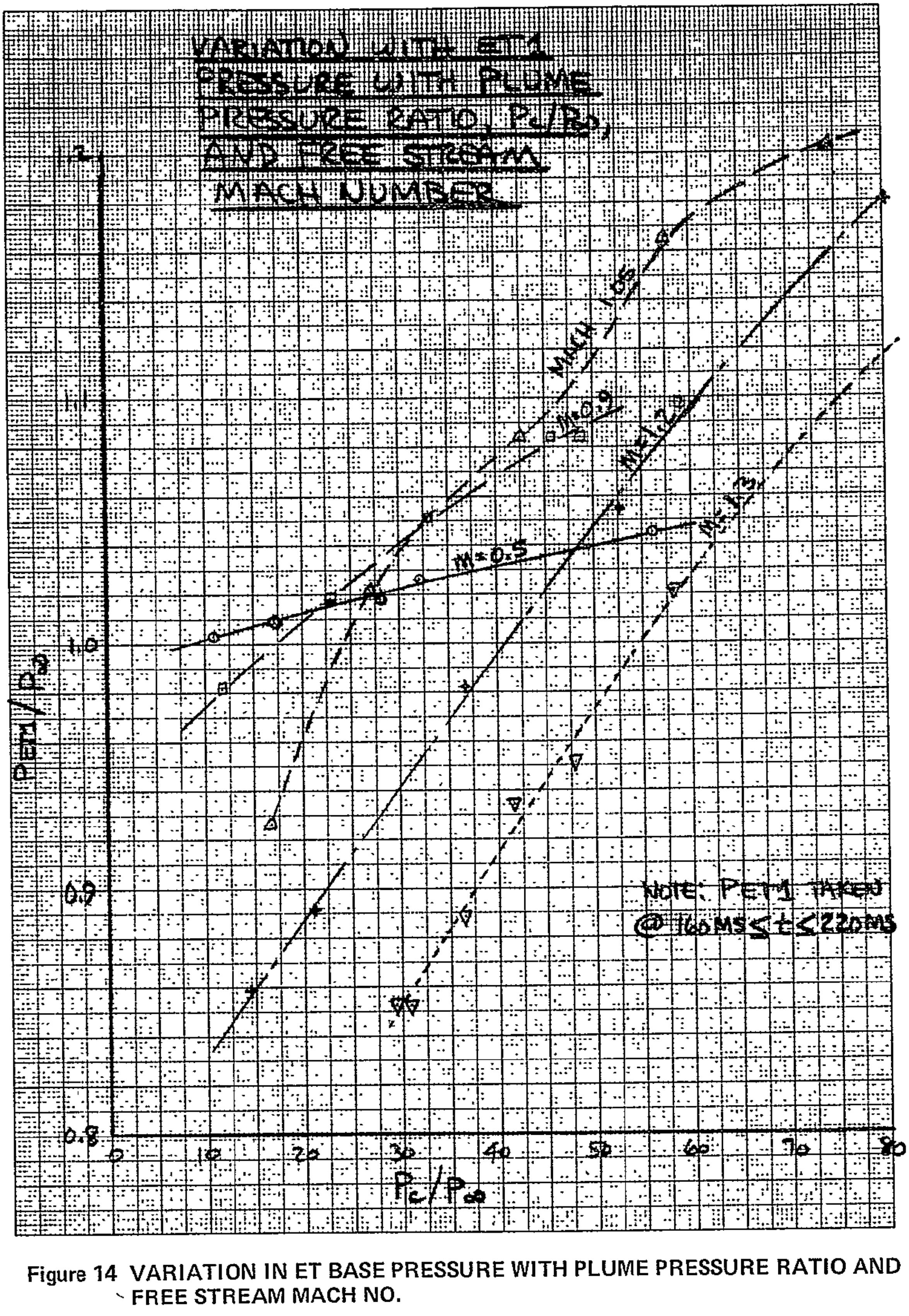


Figure 14 VARIATION IN ET BASE PRESSURE WITH PLUME PRESSURE RATIO AND FREE STREAM MACH NO.