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**THE EFFECT OF GEOMETRIC PARAMETERS ON THE PERFORMANCE
OF SECOND THROAT ANNULAR STEAM EJECTORS**

**A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville**

**Samuel Everett Stephens
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DEDICATION

This thesis is dedicated to my wife, Carolyn, and my parents Earl and Elizabeth for their continuous support of my efforts.

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ABSTRACT

Steam ejectors are simple pumps that, among many possible applications, are used in altitude-simulation rocket motor testing. Of the two main types of ejectors, annular and centerbody, the latter has been the subject of most previous research. Less is known about the operation of annular ejectors. For example, ejector diffusers that contain a contraction, known as a second throat, have been studied widely for centerbody configurations, however, there has been very little prior work conducted on second throat annular ejectors.

An experimental study of second throat annular steam ejectors was conducted with the purpose of determining the effects of specific design variables. The design variables investigated were second throat area ratio, location, and inlet ramp angle.

The experimental results show that second throat area ratio has a strong impact on system operation, as expected. The second throat axial position appears to have a mild impact on the overall pressure recovery of the system over most of the range investigated, but has a strong effect when the second throat ramp is moved forward to the steam nozzle outlet. At this point there is a large degradation in cell pressure. Ramp angle, over the range investigated, does not have a significant effect on cell pressure.

A computational study was also conducted to evaluate the suitability of a single phase Navier-Stokes computational fluid dynamics (CFD) code for prediction of steam ejector flowfields. The results of the computational study concluded that the state of the art (circa 1989) was insufficient for the successful prediction of ejector performance. The inability to model the condensation effects is indicated as a major cause of the deficiency.

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LIST OF SYMBOLS AND ABBREVIATIONS

A_d/A^*	Ratio of diffuser to nozzle throat areas
AEDC	Arnold Engineering Development Center
A_{st}/A_d	Contraction ratio of second throat diffuser, i.e., ratio of final diffuser area to initial area
B	Measurement Bias, percent of reading
BATES	Ballistic Test and Evaluation System
D_d	Ejector diffuser diameter at nozzle exit plane
D_{st}	Ejector diffuser diameter at exit
ETF	Engine Test Facility
GN ₂	Gaseous nitrogen
L_d/D_d	Ratio of length of diffuser constant area section to diameter, upstream of second throat
K_{isen}	Ratio of actual normalized cell pressure for the started ejector to the isentropic static to total pressure ratio for the same area ratio
K_{ns}	Ratio of actual normalized maximum exit pressure to the compressible flow normal shock approximation
$\dot{m}$	Mass flow rate
NIST	National Institute of Standards and Technology, formerly the National Bureau of Standards
$(P/P_t)_{isen}$	Pressure ratio calculated using ideal gas, isentropic, compressible flow equations
$(P_2/P_{t1})_{ns}$	Normal shock downstream static to upstream total pressure ratio
P_{cell}	Test cell pressure, psia
P_{cell-n}	Test cell pressure measurements, psia ($n = 1-3$)
P_{duct-n}	Transition duct static pressure measurement, psia ($n = 1-3$)
P_{ex}	Average of P_{duct1} and P_{duct2} , psia
P_{noz}	Ejector nozzle wall static pressure, psia

P_{seex}	Ejector diffuser exit wall static pressure measurement, psia
P_{tc}	Rocket Motor Chamber Pressure, psia
P_{tex}	Average of ejector diffuser exit pitot pressure probe measurements, psia
P_{tex-n}	Ejector diffuser exit total pressure probe measurement, psia ($n = 1-6$)
P_{tst}	Average of P_{tst1} and P_{tst2} , psia
P_{tst-n}	Steam ejector manifold pressure measurements, psia ($n = 1,2$)
P_{w-n}	Diffuser wall pressure, psia ($n = 1-27$)
R	Gas constant
S	Measurement Precision, percent of reading
t	Time, sec
T	Temperature, deg R
T_{tst}	Steam ejector manifold temperature, deg R
U	Measurement Uncertainty, percent of reading
V	Volume
γ	Ratio of specific heats
θ	Second throat ramp angle, deg

CHAPTER I

INTRODUCTION

An ejector is a simple pump. It uses a high pressure primary flow to pump, by jet mixing, a secondary flow from a low pressure environment to a higher back pressure. One application of an ejector, shown in Fig. 1¹, is in a rocket motor altitude test facility. Here the ejector is used to obtain low test cell pressures to simulate altitude conditions at motor ignition and to help prevent the rocket exhaust flow from blowing back into the test cell at motor burnout. In this application steam is often used for the ejector primary gas.

A steam ejector has two major components, one or more supersonic steam nozzles and a diffuser. The nozzles provide a high pressure, high momentum stream of gas that expands in the diffuser duct. During the expansion, flow is entrained from a secondary source by jet mixing, resulting in a kinetic energy transfer from the primary (steam) flow to the secondary flow [1]². The diffuser slows the mixed flow, converting the kinetic energy into increased static, or recovered, pressure. The net result is the pumping of the low static pressure secondary flow to a higher static pressure.

An ejector can operate at either started or unstarted conditions. At low ratios of back pressure to steam pressure the ejector will operate started. In this case, the flow expands to fill the diffuser duct with supersonic flow across the diameter of duct. Because the flow is supersonic, the pressure at the diffuser inlet is independent of the exit pressure. If there is no net secondary flow, the cell pressure

¹ All figures and tables are located in the appendix.

² Numbers in brackets refer to similarly numbered references.

for a started ejector is a function of the ejector geometry and driving pressure. At higher pressure ratios the diffuser will be unstarted. The flow does not fill the diffuser so there is a subsonic layer to transmit the pressure upstream. Therefore, the cell pressure is also a function of the diffuser exit pressure for an unstarted ejector. The critical ratio of exit to steam pressure that determines whether the system is started or unstarted is referred to as the breakdown pressure.

During the rocket motor firing, the motor and the rocket diffuser can operate together as another ejector. If this 'ejector' is started, the test cell pressure will be a function of the rocket motor and the diffuser geometry. As with the steam ejector, the rocket diffuser exit pressure must be less than its breakdown pressure for it to be started. The steam ejector must be compatible with the rocket diffuser such that it does not prevent starting of, or unstart, the rocket diffuser.

As noted by Lewis and Drabble [2], "Ejectors are normally classified according to the type of primary nozzle used, either annular or central; the annular nozzle being located at the periphery of the mixing tube and the central nozzle along the axis." Lewis and Drabble pointed out that the central nozzle configuration tends to provide better performance than the annular in terms of minimum test cell pressure. However the annular configuration is frequently preferred for rocket altitude testing because the steam ejector body and nozzle are not immersed in the harsh rocket exhaust flow thus reducing the need for elaborate cooling and frequent maintenance.

By varying nozzle and/or diffuser geometry, many ejector configurations are possible. One configuration is shown in Fig. 2. This configuration is an annular ejector where the diffuser contains a contraction, or second throat. Second throat ejectors have an advantage over straight diffusers in that the second throat increases the pressure recovery of the system [3].

Second throat ejectors have been studied in the past [e.g. 3-10] but only to a limited extent. Most of the previous work has focused on second throats for central ejectors. There has only been a little work with annular second throat ejectors [e.g. 9 and 10]. Furthermore, the studies that have been conducted for annular ejectors have been examinations of a few specific geometries, rather than systematic studies. Thus, the effects of individual design parameters on system operation have not been investigated for annular second throat ejectors.

The aim of the research reported herein was to broaden the base of knowledge concerning second throat annular steam ejectors. More specifically, the goal of the thesis study was to evaluate the effects of some individual geometric design variables on ejector operating characteristics, including minimum cell pressure and the pressure rise across the ejector diffuser system.

Because of the range of possible configurations, it is not practical to characterize the parametric effects for all second throat annular configurations. The thesis work focused on one particular ejector design, hereafter referred to as the baseline, and the effects of the individual second throat diffuser design parameters.

The parametric effects were determined by conducting an experimental study. A baseline second throat annular steam ejector was fabricated and tested to establish benchmark performance. Then alternate ejectors that varied from the baseline in one variable were evaluated to determine the contribution of the changed variable. These alternate configurations varied either the location (L_d), the area ratio (A_{st}/A_d), or the ramp angle (θ) of the second throat.

The experimental study is described in Chapters II through IV. Chapter II provides a detailed description of the test apparatus, while Chapter III discusses the methods and procedures used during the testing. The experiment results are discussed in Chapter IV.

To complement the experiments, a computational fluid dynamics study was performed under the author's direction to evaluate the ability of a single phase, ideal gas, Navier-Stokes computational fluid dynamics (CFD) code to predict steam ejector performance. A successfully calibrated computational tool would be valuable for future ejector studies. The current computational study applied a state-of-the-art (circa 1989) Navier-Stokes CFD code to a second throat annular steam ejector configuration. The experimental data reported herein was unavailable at the time of the computational study, therefore a different configuration for which data was available was selected for the study. This configuration is slightly different from the present experimental configuration. The results of this application are presented in Chapter V.

Chapter VI summarizes major results of the current study while chapter VII offers recommendations for future research.

The work reported herein has also been published in a technical report by Stephens and Bates [11]. The current thesis is the sole work of the author.

CHAPTER II

TEST APPARATUS

The testing reported herein was conducted at the Arnold Engineering Development Center (AEDC) in the Engine Test Facility (ETF) Research Test Cell T-6. Figure 3 is a sketch of the test installation. The test hardware consisted of a second throat annular steam ejector along with a model test cell, rocket diffuser, and a transition duct to interface between the test apparatus and the ETF exhaust system. Support systems included a steam supply and a nitrogen purge system. Rocket exhaust products were generated using small solid rocket motors. Additional secondary flow effects were evaluated using air inbleed ports built into the test cell.

Test Facility

The ETF Research Test Cell T-6 is a propulsion development test cell that is designed for the investigation of rocket exhaust plume characteristics. The facility steam supply system is capable of delivering saturated steam to T-6 at pressures up to 200 psia. The test cell is supported by a facility exhaust system capable of providing subatmospheric pressures as low as 0.5 psia. The exhaust system also includes a water spray chamber for cooling and condensing of the combined steam/rocket flow. Because rocket motors typically contain significant quantities of combustible species, the exhaust system also has the ability to add sufficient quantities of nitrogen to inert the flow.

Test Cell & Rocket Diffuser

A test cell was included in the apparatus to house the rocket exhaust gas generator and provide a location for reference cell pressure measurements. Addy

[12] found that the cell geometry does not affect the steady state cell pressure but, as expected, the test cell volume does affect the time required to obtain steady conditions, or response time, after a change in the ejector operating condition. Therefore, the test cell was designed to permit the system to reach equilibrium conditions during the rocket firing, rather than represent a typical rocket altitude test cell.

Two air inbleed ports were built into the test cell to accommodate venturi nozzles for metering the secondary, or bleed, flows into the test cell. The venturi throat diameters were 1.313 and 1.570 inches. Flow through the venturis was controlled in an on/off manner using rubber stoppers. The venturi air flows were used to evaluate secondary flow effects on the operation of the ejector.

The test hardware included a rocket diffuser which was of a second throat design. A rocket diffuser was needed to properly represent the geometry for the interaction of the primary steam flow and the secondary cell flow as in a typical rocket test cell application.

Rocket Exhaust Gas Generator

The Ballistic Test and Evaluation System (BATES) solid rocket motor was selected to generate a rocket exhaust flow. A set of these motors was obtained from the Air Force Astronautics Lab (AFAL).

The BATES motor, shown in Fig. 4, used a propellant cartridge which was replaced after each firing. The motor used a graphite nozzle which was also replaced after each firing. Other major components included the forward and aft closures, case, nozzle retaining ring, and nozzle extension skirt. The extended nozzle had an exit to throat area ratio of 96. All of these components were fabricated out of mild steel and were reusable. The propellant composition consisted of an ammonium perchlorate (AP) oxidizer, a hydroxy-terminated polybutadiene

(HTPB) binder, with aluminum fuel. The propellant aluminum loading was approximately 20% by weight. The motor had a nominal chamber pressure of 2000 psia and a burn time of 2.4 seconds.

Steam Ejector

The annular steam ejector consisted of a nozzle/manifold assembly located around the annulus of, and near the exit of, the rocket diffuser. The steam ejector nozzle/manifold assembly, shown in detail in Fig. 5a, consisted of a steam manifold fed by a supply line with a control valve, and 24 two-dimensional supersonic steam nozzles. The nozzle details are shown in Fig. 5b. This configuration is more accurately referred to as a segmented annular ejector as opposed to a pure annular ejector.

Ejector Diffusers

Seven different ejector configurations were obtained by use of different ejector diffusers. This section discusses the baseline and alternate diffuser configurations that were tested.

Baseline Design

The baseline ejector diffuser employed a second throat configuration with the throat inlet ramp located one diameter downstream of the ejector nozzle exit plane, Table 1. The throat ramp angle was 5 deg and the diffuser throat contracted to an area ratio of 81% relative to the largest diameter section of the diffuser.

The ejector diffuser exited into a larger diameter transition duct as shown in Fig. 3. The transition duct extended 1 diameter downstream and 3/4 diameter upstream from the ejector diffuser exit plane. The assembly was attached to the T-6

exhaust duct and subsequently into the ETF exhaust plant. The transition duct provided the access for a diffuser exit plane pitot pressure rake.

Alternate Configurations

Six alternate ejector diffuser configurations were tested. A summary of the configurations is given in Table 1. The alternate configurations determined the effects of individual design parameters on system performance. The relative results from configurations 2 through 5 ($L_d/D_d = 0.0, 0.333, 0.667$ and 1.333) and the baseline were used to determine the effect of second throat position. Configurations 6 ($A_{st}/A_d = 0.7$) and the baseline were used to define the effect of contraction ratio, and configurations 7 ($\theta = 6.5$ deg) and the baseline were used to determine ramp angle effect.

Instrumentation

Instrumentation locations and parameter names are shown in Fig. 6. The major parameters of interest were test cell pressure, ejector total (manifold) pressure and temperature, ejector diffuser back pressure, and exit pitot pressure profiles. The system exit pressure was measured with three pressure transducers located downstream of the ejector diffuser; two measurements in the transition duct and one in the T-6 exhaust duct. Additionally, 27 pressures were recorded along the walls of the diffusers to help characterize the flow. The ejector diffuser exit pitot pressure was measured with a 6 probe pitot pressure rake. The six probes were set radially from the duct centerline on equal areas.

All pressures were measured using individual bonded, strain-gauge-type pressure transducers, close-coupled to the model. The steam temperature was measured using a Chromel-Alumel thermocouple. Instrument system calibrations

performed during the testing are traceable to the National Institute of Standards and Technology (NIST). Each link in the traceability chain to the NIST is maintained and documented by the AEDC Precision Measurement Equipment Laboratory [13]. Uncertainties for each of the parameters were calculated as described by Thompson and Abernathy [14] and are given in Table 2.

Figure 7 is a schematic of the data acquisition process. The analog signals from the instrumentation were scanned and filtered using a front-end data system. The data were digitized, processed using an SEL 3227 or 3277® computer, and then recorded on digital tape for off-line processing. Final off-Line processing was done using the AEDC Amdahl 5860® Central Computer. The analog signals were also recorded on FM tape as backup and diagnostic tools in the event of a failure. Test conditions including steam driving pressure and temperature, test cell pressure, and transition duct static pressure were monitored on-line in the control room via a display readout from the SEL computer.

CHAPTER III

TEST DESCRIPTION

This chapter discusses the procedures and methodology used during the testing. The same procedures, except as noted, were used for each test to minimize biasing the results of one test relative to another.

Two types of testing were conducted: steam without rocket exhaust and steam with rocket exhaust. For simplicity, these are referred to herein as steam tests and rocket tests, respectively. Many of the test procedures were common to both types of tests. First, all instruments that were in operating range at the ambient conditions were calibrated in situ. Following this, the test apparatus was pumped down using the ETF exhaust plant to approximately 0.5 psia. The remaining low range pressure transducers were then calibrated using a NIST secondary standard.

After the instrumentation calibration discussed above, a facility isolation valve downstream of the test apparatus was closed to perform a leak check. This was accomplished by measuring the static pressure in the test cell as a function of time and relating it to the potential inbleed, or leak, mass flow by the following equation:

$$\dot{m} = \frac{V}{RT} \frac{\delta P_{\text{cell}}}{\delta t} \quad (3.1)$$

where

$\dot{m}$ = Mass flowrate of inleakage,
 V = Volume of the test apparatus upstream of the valve,
 δP_{cell} = Cell pressure variation,
 R = Gas constant for the air,
 T = Ambient air temperature, and
 δt = elapsed time after valve closing.

Equation 3.1 does assume a constant temperature and zero leakage across the isolation valve. The measured leak rates were approximately 2.5% of the

minimum steam flow rates used during the tests. This leak rate is for all of the facility ducting upstream of the isolation valve. The test hardware, especially the test cell which is the most sensitive to leakage, made up only a small fraction of the total ducting surface area. Although it can not be quantified, it is believed that the leakage in the test cell was not large enough to affect the cell pressure during most of the tests. Tests with suspected larger leakages are noted in the presentation of results.

Following the air inleak check, the steam flow was started and set at a driving pressure high enough to ensure that the ejector was started. The steam flow was maintained at this level while the steam system warmed up. Stabilization was monitored by tracking normalized cell pressure, $P_{\text{cell}}/P_{\text{tst}}$, vs. time as shown in Fig. 8. Typical stabilization time for a test was 20 minutes. This procedure was not followed for the first test. The data obtained from the first 20 minutes of the first test was unsteady and deviated from the remainder of the test data. The lack of prior stabilization was identified as the cause. To prevent a recurrence of the problem the above procedure was adopted for the remaining tests. The suspect initial data from the first test is not included in the results reported herein.

The next step was to set the desired back pressure using the plant exhaust machinery. Testing was then conducted with a matrix of various steam ejector driving pressures and diffuser exit pressures. Secondary flow was introduced using the inbleed venturis for several points within the test matrix. Steady-state data points were acquired at each flow condition.

Rocket tests began with a systematic verification of no stray voltages in the motor ignition system to reduce the possibility of inadvertent motor ignition. This was followed by loading of the rocket motor in the test cabin. The calibration and thermal stabilization procedures were then executed as in the steam tests. The next

step in the rocket tests was to initiate a GN_2 purge sequence. This was required to replace as much air (oxygen) as possible with nitrogen to preclude the presence of a combustible mixture within the exhaust system. At 150 seconds before ignition, the steam pressure was increased to the desired level for firing. Also, the exhaust duct pressure was increased at this time to the desired test condition. Recording on the digital data acquisition system was initiated 30 seconds prior to ignition, followed by arming of the rocket motor. Ten seconds before ignition the cell GN_2 was turned off to eliminate secondary flow in the test cabin. The motor was then fired with a nominal burn time of 2.4 seconds. Motor chamber pressure was monitored on the control room oscillograph during the burn. Upon motor burnout, the test cell purge nitrogen flow was resumed. After 260 seconds, the purge flow was stopped and test shutdown procedures were initiated.

CHAPTER IV

TEST RESULTS AND DISCUSSION

The results from the experimental program are presented first for the baseline configuration. These results are subdivided into steam test and rocket test results. Following the baseline results, the effects of individual parameter variation are detailed. As with the baseline, these results are subdivided into steam and rocket test results. A summary of the results is presented in Table 3.

Baseline Configuration

Steam Tests

The results for the baseline ejector were taken from two test periods. The first test was conducted in February of 1990, while the latter test was conducted in September of 1990.

The baseline results with no secondary flows are summarized in Figs. 9 and 10 and also in Table 3. The figures represent two common methods of presenting ejector performance data [15]. Figure 9 shows the ejector performance in terms of diffuser pressure rise ratio, P_{ex}/P_{cell} , versus steam driving pressure normalized by exit pressure, P_{tst}/P_{ex} . A maximum rise ratio of 12 was obtained for the baseline at a normalized total pressure of 28. The diffuser was started, as will be defined below, for normalized total pressures greater than 28.

The two tests show a slight difference in the results. The February data has more scatter and a slightly higher average rise ratio than the September test. A possible explanation for this is the variation of steam quality from season to season. However, this cannot be verified with the current data because steam quality was not measured.

The five data points labelled A-E are reference points to relate Fig. 9 with some of the figures to be discussed below. Table 4 summarizes the conditions associated with each of the points.

Figure 10 is a diffuser breakdown curve that plots cell pressure against exit pressure with both terms normalized by the steam total pressure. The curve shows that, for the baseline, the ejector is started for values of normalized exit pressure (P_{ex}/P_{tst}) below 0.036. As stated in the INTRODUCTION (pg. 1) the diffuser is started when the cell pressure is independent of exit pressure.

Ejector systems sometimes display hysteresis. If hysteresis is present, then the cell pressure at a given P_{ex}/P_{tst} depends on the path taken to that point (i.e., by increasing or decreasing P_{ex}/P_{tst}). The current data did not indicate any hysteresis. For this reason, no attempt will be made to present the data with differentiation based on direction.

The measured normalized cell pressure, P_{cell}/P_{tst} , for started operation was either .0030 or .0032, depending on the test. The former value corresponds to the February test, while the latter value corresponds to the September test. If the hypothesis that the only significant difference between the two tests was delivered steam quality is true, then Fig. 10 indicates that the steam quality has an effect on cell pressure.

Ratios of measured parameters to ideal calculations can be used to evaluate a configuration, or to compare it with other configurations. The one-dimensional, ideal gas, isentropic flow equations are used to calculate the theoretical minimum cell pressure that could be obtained by a given ejector configuration. The theoretical minimum value is defined as the one dimensional isentropic static to total pressure ratio corresponding to the ratio of initial diffuser area to ejector nozzle throat area, A_d/A^* . This pressure is referred to as the isentropic cell pressure ratio,

and is denoted $(P/P_t)_{isen}$. The resulting ratio of normalized cell pressure to isentropic cell pressure is denoted K_{isen} as given in Eq. 4.1.

$$K_{isen} = \frac{P_{cell}/P_{tst}}{(P/P_t)_{isen}} \quad (4.1)$$

A ratio of specific heats, γ , of 1.3 is often used for superheated steam in the ideal gas equations. Using this value and the baseline A_d/A^* of 40.08 yields an isentropic cell pressure of .0014 and a K_{isen} of 2.14 (for $P_{cell}/P_{tst} = .0030$).

As with the cell pressure, a theoretical maximum normalized exit pressure can be calculated and used as a reference. This reference is defined as the ratio of downstream static pressure to upstream total pressure across a normal shock in one dimensional flow at an area ratio equal to the diffuser exit to nozzle throat area ratio and is denoted as $(P_2/P_{t1})_{ns}$. The resulting ratio of actual maximum normalized exit pressure to theoretical normal shock pressure, denoted K_{ns} , is given by Eq. 4.2.

$$K_{ns} = \frac{P_{ex}/P_{tst}}{(P_2/P_{t1})_{ns}} \quad (4.2)$$

Application of the ideal gas normal shock relations to the current baseline configuration with a ratio of specific heats of 1.3 yields a $(P_2/P_{t1})_{ns}$ of .0457 and a K_{ns} of 0.79.

A comparison of the baseline ejector system is made with a second throat annular steam ejector tested by Hale and Gobbell [9], shown in Fig. 11 as configuration 11a. Hale and Gobbell also tested a straight diffuser version of the same ejector, configuration 11 in Fig. 11. The current baseline is compared to both of these configurations in Fig. 12. Figure 12a shows the started cell pressure as a function of diffuser to ejector throat area ratio, A_d/A^* . The isentropic cell pressure line for $\gamma = 1.3$ is also shown as a reference. Both of the Hale and Gobbell configurations had the same cell pressure, indicating that as expected, the diffuser geometry

downstream of the initial steam plume expansion had little to no impact on the cell pressure. The current baseline and Hale's data are different in that, the baseline has a K_{isen} that is 21% higher (i.e., the normalized cell pressure is 21% further above the isentropic line) than the Hale data. This indicates that other parameters that were different between the two Hale and Gobbell configurations and the baseline have a significant effect. Two significant differences between the two designs, as shown in Figs. 5 and 11, were the nozzle exit to throat area ratios which were 27 and 11 for the Hale and Gobbell and baseline configurations, respectively, and the segmented versus annular nozzle. Sufficient information is not available to separate the effects of these differences.

The normalized exit pressure at breakdown for the baseline and the Hale and Gobbell configurations are shown in Fig. 12b as a function of the diffuser exit to nozzle throat area ratio. Hale and Gobbell's straight diffuser started at a normalized exit pressure of .0224, which is 62% of the normal shock pressure ratio for that area ratio. Hale and Gobbell reduced the diffuser exit to throat area ratio by 62% which increased the starting exit pressure ratio by 52% to .034. However, the ideal normal shock recovery also increased. The net result was the second throat achieved 60% of the normal shock recovery, nearly the same as the straight diffuser version.

The current baseline second throat had a starting exit pressure ratio of .036, or 79% of its corresponding normal shock value. This is a significantly higher percentage than either of the Hale and Gobbell configurations. The difference is most likely due to the fact that the baseline diffuser was more than 60% longer, in terms of exit diameters, than Hale and Gobbell's second throat diffuser, and twice as long as the straight diffuser.

A pressure rake at the diffuser exit provided profiles of pitot pressure measurements. The profiles for five data points are shown in Fig. 13 with the pitot

pressure normalized by the ejector exit static pressure $P_{\text{tex-n}}/P_{\text{seex}}$. Also, shown in Fig. 13 is a line at $P_{\text{tex-n}}/P_{\text{seex}}$ of 1.83 that represents the $\gamma = 1.3$ one-dimensional ideal gas pitot pressure for sonic velocity (Mach = 1) flow. Values of $P_{\text{tex-n}}/P_{\text{tst}}$ to the left of this line represent subsonic flow while values to the right represent supersonic flow. The profiles of Fig. 13 show that when the diffuser is unstarted, the exit pitot profiles are subsonic and flat, lines D and E. When the diffuser starts, the profiles become highly nonuniform, with a supersonic core, lines A, B, and C, Fig. 13. Observations during testing showed that the pitot pressures were very unsteady when the diffuser was started. The steam pitot pressure measurements shown are instantaneous measurements, not time averaged. At low values of $P_{\text{ex}}/P_{\text{tst}}$ (< 0.03), core region pressures varied by as much as ± 1 psia from moment to moment.

The rake pressures were area-averaged, normalized by steam driving pressure, and plotted against the normalized cell pressure. The resulting data are shown in Fig. 14. Comparison with the breakdown curve of Fig. 10 shows that the unstarted leg of the curve is similar for both figures. This is expected since the exit pitot and wall static pressures are nearly the same in the unstarted regime. However, for the started diffuser, the exit pitot pressure increases faster than the driving pressure and the curve moves to higher values of $P_{\text{tex}}/P_{\text{tst}}$. The curve shows that the normalized cell pressure is a double-valued function of the pitot pressure ratio.

In addition to the exit rake measurements, several wall pressure measurements were also taken. Profiles of wall pressure versus distance are shown in Fig. 15 for the baseline configuration. The wall pressures in Fig. 15 are normalized by the steam driving pressure. The figure shows that for the case of the $P_{\text{ex}}/P_{\text{tst}} = .011$, the wall pressure does not change much with distance except over the last diameter of diffuser length. As $P_{\text{ex}}/P_{\text{tst}}$ increases the length of diffuser over which the pressure rise takes place increases. For $P_{\text{ex}}/P_{\text{tst}} = .038$, which is slightly above the

critical starting value of .036, the pressure rise is distributed throughout the diffuser length. In the region of pressure rise, the rate at which the pressure increases as a function of distance is nearly constant. As the normalized exit pressure is increased further, the region of pressure rise becomes shorter.

Figures 9, 10, 13, 14, and 15 show five data points, labelled A through E. Table 4 describes the conditions for each of the 5 points. These figures can be used together to relate different parameters at similar conditions. For example, it can be seen from Fig. 10 that points A, B, and C all have the same value for normalized cell pressure. However, Fig. 9 shows that at point C the diffuser pumps at a much higher diffuser rise ratio. From Fig. 13 it can be seen that points A and B have much larger exit total to static pressure ratios, and therefore higher velocities, than point C. Therefore, it can be concluded that the reason the diffuser pumps better at point C is because more of the available kinetic energy is being recovered into pressure in the diffuser.

The effect of secondary flow on the baseline ejector performance is shown in Fig. 16. The data were obtained using the air inbleed venturis at various steam driving pressures and different diffuser exit pressures. The figure presents the data as the ratio of cell pressure to minimum (no secondary flow) cell pressure versus secondary to primary mass flow ratio. The data indicate that for a secondary flow ratio of 0.04 the cell pressure for the started diffuser has increased by approximately 40% and at a secondary flow ratio of 0.13 the cell pressure is doubled. The data in the figure contains approximately 20% scatter. Observations of fluctuations in cell pressure readings on the control room display indicated that the flow inside the test cell was unsteady. The discrete measurement of unsteady flow conditions could be the source of the scatter shown in Fig. 16.

Rocket Tests

Three rocket tests were conducted with the baseline configuration. The first test evaluated system operation with the steam ejector started and operating at low levels of steam and back pressure. The second test was conducted with an unstarted ejector at high steam and back pressures. The last of the baseline configuration rocket tests was conducted with a started ejector at a high steam pressure and moderate back pressure.

Figure 17 shows the results of the first rocket test. The exit pressure, P_{ex} , was set at 2.0 psia and the steam pressure, P_{tst} , was held constant at 63 psia. The steam ejector was initially started with a normalized exit pressure of 0.032. The motor burn was nominally 2.4 seconds long with a maximum chamber pressure just below 2000 psia. After ignition, the test cell pressure, P_{cell} , immediately dropped, then followed the contour of the rocket motor chamber pressure trace (i.e., P_{cell}/P_{tc} is constant). This indicates that the rocket diffuser was started. The rocket diffuser unstarted when the rocket motor chamber pressure decreased during rocket motor tailoff. The excursion in P_{ex} is likely because the diffuser and transition duct acted like another ejector during the firing with the diffuser flow expanding and reducing the pressure in the transition duct.

The second rocket test evaluated operation with higher steam and exit pressures and an initially unstarted diffuser. The results are shown in Fig. 18. The exit and steam driving pressures were 8.0 and 190 psia, respectively. After ignition, the rocket diffuser started and pumped the cell down to approximately 0.3 psia. The rocket diffuser unstarted at 22% of maximum chamber pressure.

The cell pressure at tailoff was higher for the second firing (0.3 psia) as compared to the previous firing (0.2). The data indicates that this was because the system did not reach equilibrium. The baseline steam only data showed that the

normalized exit pressure for this test was insufficient to start the ejector prior to ignition. Because the ejector was initially unstated, the cell pressure prior to ignition was substantially higher than would have been encountered if the ejector was started. As a result the started rocket diffuser had a larger mass of gas to pump out before the test cell pressure would come to equilibrium with the rocket chamber pressure. Figure 18 shows that cell pressure was decreasing throughout the burn. However, the motor burn time was too short to allow the system to reach equilibrium at these conditions.

The last rocket test of the baseline configuration evaluated operation at a high steam driving pressure and a back pressure reduced to permit started operation of the ejector prior to ignition. The results are presented in Fig. 19. Since the ejector was started, the cell pressure at ignition was substantially lower than the previous case, 0.6 vs. 2.5 psia, respectively. Upon ignition the rocket diffuser again started and pumped the cell down to near 0.2 psia. The rocket diffuser unstated at 14% of maximum chamber pressure.

The rocket diffuser started and operated for three different steam ejector operating conditions. Therefore, there is no indication that the steam ejector is incompatible with the tested rocket motor/diffuser combination.

Effect of Throat Location

Steam Tests

The effect of diffuser second throat location relative to the ejector nozzles was evaluated by testing alternate configurations 2, 3, 4, and 5, listed in Table 1. The results of these tests, summarized in Table 3, were compared to the baseline results.

The breakdown curve for the baseline and alternate throat location configurations is shown in Fig. 20. The data indicate that as the throat is moved forward, the

cell pressure decreases slightly until the throat is located at the nozzle exit plane. At this location, there is a strong degradation in cell pressure. The normalized exit pressure at which breakdown occurs does not vary significantly. The effect of throat location on maximum diffuser pressure rise is shown in Fig. 21. The rise ratio increases slightly as the throat is moved forward from $4/3$ to $1/3$ diffuser diameters due to the decrease in cell pressure. The correspondence of rise ratio to throat location over this region is nearly linear. However, when the throat is located at the nozzle exit plane there is a significant decrease in rise ratio.

Based on Bauer and German's previous experimental work with central ejectors [3], there is a limit on the distance of the second throat contraction from the nozzle exit beyond which it is not possible to start the diffuser. This type of limit was not encountered in the current research. However, this does not imply that such a limit does not exist. The central nozzle tests showed a limit on the order of 4 diameters. This is far outside the range of locations that were investigated in this study. It should also be noted that the central nozzle tests used air for the primary gas. It is not known what effect the nozzle geometry and gas composition have on the limiting value of throat location.

The wall pressure measurements from the nozzle exit plane through the throat ramp are shown in Fig. 22 for the 5 throat location configurations. The wall pressure at the nozzle exit plane was measured on the rearward facing step below the nozzle in what is expected to be a recirculation zone for the flow. Configuration 2, with the throat inlet located at the nozzle exit, had increased wall pressures below the nozzle exit and at the first measurement station on the ramp. The other configurations show a trend of decreased wall pressure with distance, except for the case with the throat located furthest downstream, where there is a strong pressure rise on the throat ramp that is not present for the other configurations.

Rocket Tests

Two rocket firings were conducted with the ejector diffuser second throat located $4/3$ diameters downstream of the ejector nozzle exit plane, configuration 5. One firing was conducted at the low steam and back pressures and one firing was conducted at a higher steam pressure. Both tests were conducted in such a manner that the steam ejector was started.

The results of the low steam pressure test are shown in Fig. 23. As evidenced by the test cell pressure data, the rocket diffuser started and remained started throughout the firing. As with the baseline configuration rocket test at the same conditions, the rocket chamber at diffuser unstart was too low to be measured reliably. The high steam pressure test results are presented in Fig. 24. In this case, the rocket diffuser started and remained started until 17% of maximum chamber pressure. The increase in cell pressure noted at approximately 0.8 seconds is believed to be due to rocket exhaust gas leaking into the test cell from a crack in the graphite nozzle insert. This crack was discovered during a post-test examination of the motor. Such a crack would degrade the rocket thrust and therefore the stream thrust at diffuser unstart may have actually been closer to the baseline configuration result that the chamber pressure data indicates.

One motor firing was conducted with the ejector diffuser second throat positioned $2/3$ diameter downstream of the ejector nozzle exit plane, configuration 5. This firing was conducted with a high steam pressure and an initially started diffuser. The results of this test, shown in Fig. 25, indicate that the rocket diffuser started and remained started until the motor chamber pressure decreased to 15% of its maximum value. Note also that the cell pressure exhibits an increase during the motor firing similar to that seen in Fig. 24. Again, post-test inspection revealed a crack in the graphite nozzle insert.

Effect of Throat Contraction

Steam Tests

The effect of throat contraction was evaluated by comparing the results from the baseline and configuration 6, both of which are shown in Table 3. The breakdown curve for both configurations is shown in Fig. 26. The data indicates that as the throat diameter is decreased the maximum started normalized exit pressure increases, as expected from central nozzle tests, [3]. The data also indicate an increase in cell pressure. However, this increase may be due to a slight test cell air inleakage. The effect of throat contraction on maximum diffuser pressure rise is shown in Fig. 27. For the two configurations evaluated, the trend is increased rise ratio for decreased area ratio.

Wall pressure measurements for the two throat contractions are shown in Fig. 28. Two sets of four data points, taken at similar conditions, are shown for both diffuser configurations. The first pair of data points are for an underdriven ejector, where the normalized exit pressure is higher than the value required for starting. One line (+ 's) is a data point for the underdriven baseline ejector, while the other symbol ($\square$'s) is for the smaller diffuser at a similar underdriven condition. The two lines lie nearly on top of each other. Similarly, data points for an underdriven ejector show nearly identical profiles for both ejectors. One pair of data points is for the two ejectors at an intermediate condition where the normalized exit pressure is near the critical value required for starting. The intermediate points shown in Fig. 28 are for started diffusers. The two lines for the intermediate condition are slightly separated, with the larger diffuser having slightly larger wall pressures. The difference is believed to be due to the difference in set exit and driving pressures.

Rocket Tests

Two rocket firings were conducted with the smaller second throat contraction of 0.7, configuration 6. Firings were conducted at the low and high steam pressures, nominally the same conditions tested with the baseline and configuration 5.

The results of the low steam pressure test are shown in Fig. 29. The rocket diffuser started and remained started throughout the firing. The post-fire regime test results are presented in Fig. 30. These data indicate that the rocket diffuser started and remained started until 18% of maximum chamber pressure. This level is higher than was recorded for the baseline possibly due to the smaller throat, however the increase is so small that it may only be due to uncertainty of the data.

Effect of Ramp Angle

Steam Tests

The effect of second throat ramp angle was examined by comparing the results from the baseline and configuration 7, shown in Table 3. The breakdown curve for both configurations is shown in Fig. 31. The data indicates that as the ramp angle is increased there is a slight degradation in the cell pressure. As with the effect of contraction ratio, some of this increase may be due to the presence of secondary flow from inleakage. Essentially no change is seen in the maximum normalized exit pressure. The increase in cell pressure reduces the overall rise ratio as shown in Fig. 32. As can be seen from the figure, the effect of ramp angle on rise ratio is not very strong. Further, the actual effect may be weaker if the data are corrected for the cell inleakage for the configuration 7 test. The results agree with previous centerbody work by Bauer and German [13] in that the effect of second throat ramp angle on overall ejector performance is small.

The wall pressure measurements for the two diffusers are shown in Fig. 33. The two sets of data points were taken at similar operating conditions and show little difference in the wall pressure profiles. Since there were no significant overall system differences at the steeper ramp angle, no major differences were expected in the wall profiles.

Rocket Tests

One motor firing was conducted with the ejector diffuser second throat ramp angle increased from 5 degrees to 6.5 degrees, configuration 7. This firing was conducted with a high steam pressure and a started diffuser. The results of this test, shown in Fig. 34, indicate that the rocket diffuser started and remained started until chamber pressure decreased to 20% of its maximum value. This is 6% higher than the baseline. The measured increase might be due to the increased effective blockage of the steam plume. The steam is entering the diffuser at a steeper angle but the same initial momentum as the baseline. As a result the steam penetrates further into the rocket exhaust stream. However, it must be remembered that the increase relative to the baseline is the same order of magnitude as the uncertainty, so the actual change, if any, due to physics cannot be quantified accurately.

CHAPTER V

APPLICATION OF COMPUTATIONAL TECHNIQUES TO EJECTOR PERFORMANCE PREDICTION

An effort was made to determine if a typical current computational fluid dynamics (CFD) code could be applied to an ejector configuration and predict major aspects of the flow. This process is referred to as CFD program calibration based on the definitions given by Bradley [16], as reported by Garrard and Phares [17]. If the calibration was successful, the program would then be applied to the subscale test configuration reported in the previous sections to verify the ability of the program to accurately model the critical physics of the flow. As per Bradley, this second step is referred to as program validation. Upon successful validation, the program could be applied to other ejector designs to investigate parametric effects.

The PARC code [17] was selected for application because it has been used extensively and lends itself well to problems involving multiple stream mixing and complex geometries. The PARC code is a general purpose CFD program that provides aerodynamic flow-field simulation using the Reynold's-averaged Navier-Stokes equations for a single phase, single species ideal gas. The thesis study used Version 5.0 of the code which is the latest version documented in the reference.

The code calibration effort was begun before the experimental data was taken, therefore an alternate data set was required. The existing Hale and Gobbell data [9] for a second throat annular ejector were utilized. The geometry for this case, configuration 11a in Fig. 11, was considered to be sufficiently similar to the baseline configuration to provide a basis for code calibration. Because the geometry was axisymmetric, the 2-dimensional/axisymmetric version of the PARC code was used.

A comparison of computed to measured cell pressure as a function of nozzle total and diffuser exit pressures was selected as the primary metric for evaluating code performance. The PARC code was to be calibrated by computing the flowfield for the specified geometry at a set nozzle total pressure and diffuser exit pressure. Then the numerical values for the coefficient of turbulent mixing in the algebraic turbulence model would be adjusted until the computed and measured cell pressure matched. Upon successful completion of this step, the code would be evaluated by computing solutions for other nozzle total and diffuser exit pressures and comparing the results to the experimental breakdown curve.

The calibration was initiated by modelling the second throat geometry, shown in Fig. 11, and applying boundary conditions such that P_{ex}/P_{tst} had a value of 0.03. The code also required a specification of the ratio of specific heats for the gas. A value of 1.3 was input for the specific heat ratio. The initial solution for the cell pressure is shown in Fig. 35, labelled ' $\gamma = 1.3$ (PARC)', along with the experimental data. The code prediction of cell pressure was too low by a factor of 3.

Next, the coefficient of turbulent mixing was varied in an attempt to match the cell pressure to the data. However, for the current ejector, variation of the coefficient had virtually no effect on the cell pressure. Because the same process of manipulating the viscous effects had been successfully performed by Garrard and Phares [17], other aspects of the code were called into question for this application.

It was hypothesized that for the ejector flowfield, condensation effects are more significant than viscous effects. Because the PARC code does not have a mechanism to model the physics of condensation the use of the PARC as a stand alone code was discarded and a new computational methodology was formulated.

The new approach was to first account for condensation in the steam ejector nozzle and then, using these new nozzle exit conditions, compute the diffuser flow

field with PARC neglecting the condensed water phase. Condensation effects in the ejector nozzle were assessed using FIRACON [18], a NASA Langley code for 1-dimensional finite rate water condensation. This code was adapted and applied to the steam nozzle ejector problem. The new nozzle exit conditions included a higher static pressure and a ratio of specific heats of 1.19. Cell pressure was predicted using the PARC code with the steam nozzle exit plane fixed to the gas property values computed by FIRACON. Results of this computation are shown in Fig. 35 and are labelled ' $\gamma = 1.19$ (FIRACON/PARC)'. While this approach was an improvement, the computed cell pressure was still low by 30%.

The sensitivity of the diffuser flow field to γ was further investigated through a variation of γ from 1.19 to 1.08 to account for condensation beyond the nozzle exit (with the latter γ value chosen arbitrarily). These results are also shown in Fig. 35. In this case, the computed cell pressure was high by approximately 10%.

At this point the calibration effort was terminated. Theoretically, the code could have been 'calibrated' by varying γ until the cell pressures matched. However, changing a flowfield γ to account for condensation within the flowfield does not accurately represent the physics of the flow. The PARC code would still be unable to account for the change in the gas mass flowrate as the steam condenses and it is the mass flow balance of gas entrainment and recirculation that determines cell pressure.

The calibration effort concluded that the PARC code (as used) was insufficient to predict ejector flows. It is judged that a phase change model and a two phase conservation equation needs to be incorporated into PARC before the code can be successfully calibrated. At that point, an effort can be made to validate the code for a specific geometry.

CHAPTER VI

SUMMARY OF RESULTS

A baseline configuration second throat annular steam ejector was tested with steam only, steam with inbleed air, and combined steam and rocket exhaust flows. Six alternate configurations were tested to investigate the effects of geometric variables on the baseline design. The alternate configurations varied the second throat location from 0 to $4/3$ duct diameters aft of the steam nozzle exit (baseline = 1.0). One alternate configuration reduced the throat contraction ratio from .81 (baseline) to .70. The last configuration increased the throat ramp angle from 5 (baseline) to 6.5 degrees. The results of the tests are summarized below.

1. The baseline ejector started and operated with a maximum pressure ratio across the system of 12.
2. Test cell atmospheric inbleeds had a strong effect on the cell pressure. A secondary flow of 4% of the steam flow increased cell pressure by 40%.
3. The rocket diffuser flow was started for the baseline and all alternate configurations tested with rocket exhaust flows.
4. Six alternate configurations were tested in addition to the baseline design to investigate the effects of geometric variables on the baseline design.
5. Second throat location affected operation by decreasing the cell pressure, and therefore increasing the pressure rise, as the throat was moved forward from the baseline design. When the throat was moved to the plane of the ejector nozzle exit, the cell pressure increased significantly. There was no discernable effect on rocket diffuser unstart.
6. A smaller contraction ratio second throat diffuser increased the maximum exit pressure, and therefore pressure rise, of the system. The contraction ratio

effect on rocket diffuser unstart pressure was very small; smaller than the measurement uncertainty.

7. Variation of the ramp angle did not have a significant effect on the ejector operating characteristics. A small increase in the rocket diffuser unstart pressure was observed.
8. The computational study indicates that condensation effects appear to be much more significant than viscous effects in the diffuser/ejector flowfield.
9. Use of version 5.0 of the PARC code as a stand alone predictive tool is inadequate for ejector flows because it is limited to single phase flow with an ideal gas equation of state.

CHAPTER VII

RECOMMENDATIONS

1. Additional geometries should be tested to determine the starting limits for throat location and throat contraction for second throat annular ejectors.
2. Tests should be conducted to determine the interaction effects between variables, e.g. comparing the results of a test with a smaller throat moved forward versus the separate results reported herein for the size and movement effects.
3. The PARC code should be modified to include the ability to model two-phase steam flow with finite rate nucleation and condensation.

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APPENDIX

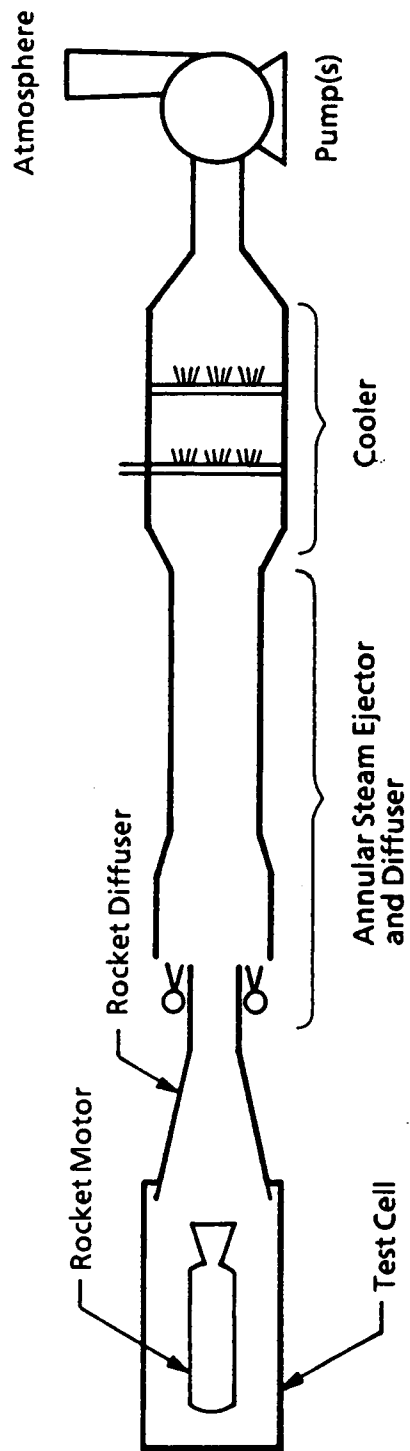


Figure 1. Rocket motor altitude test facility.

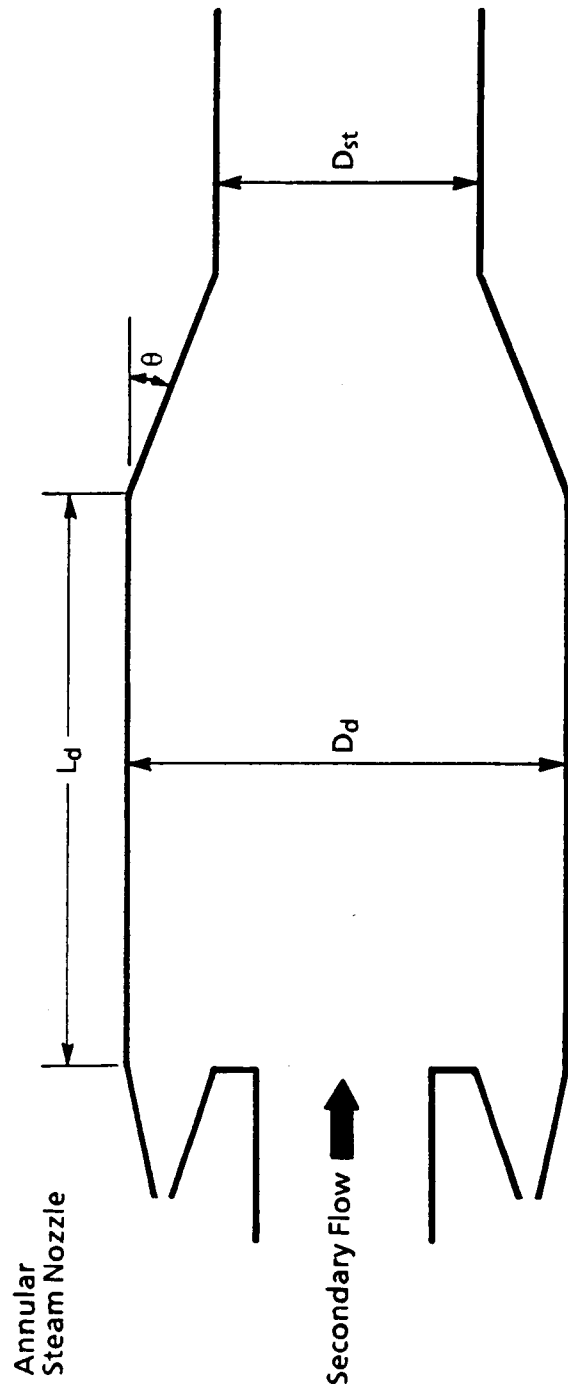


Figure 2. Second throat annular steam ejector.

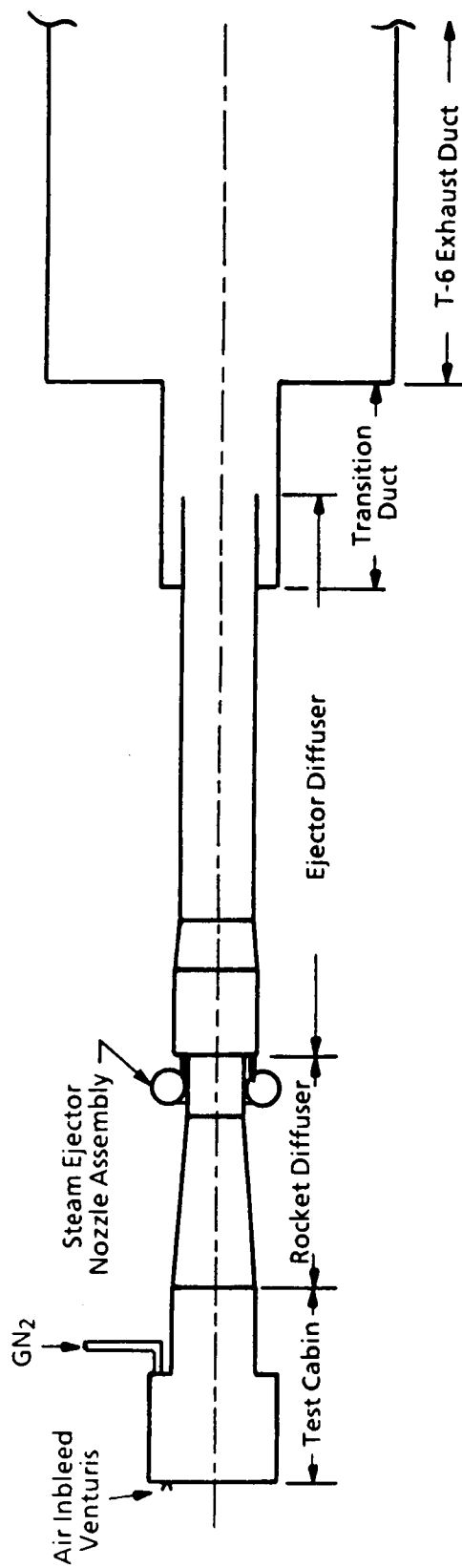
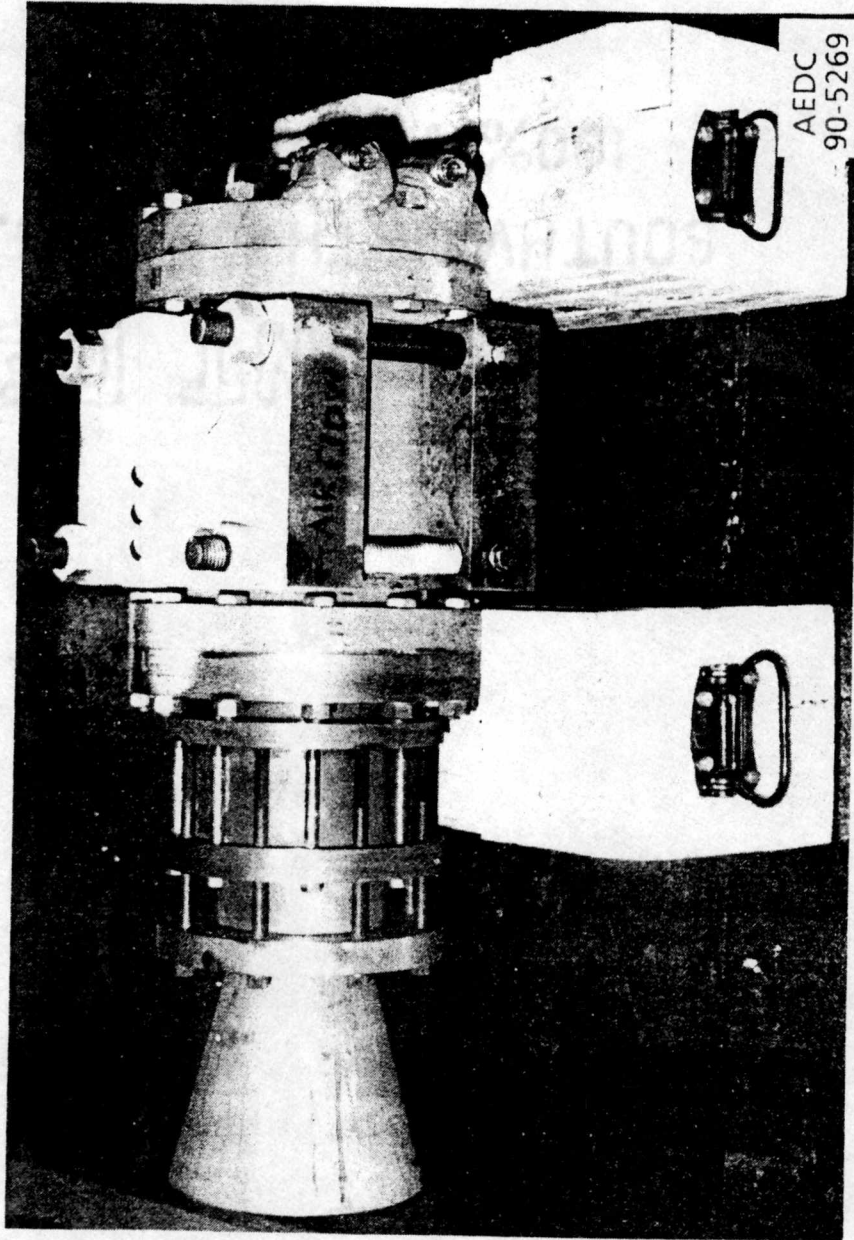
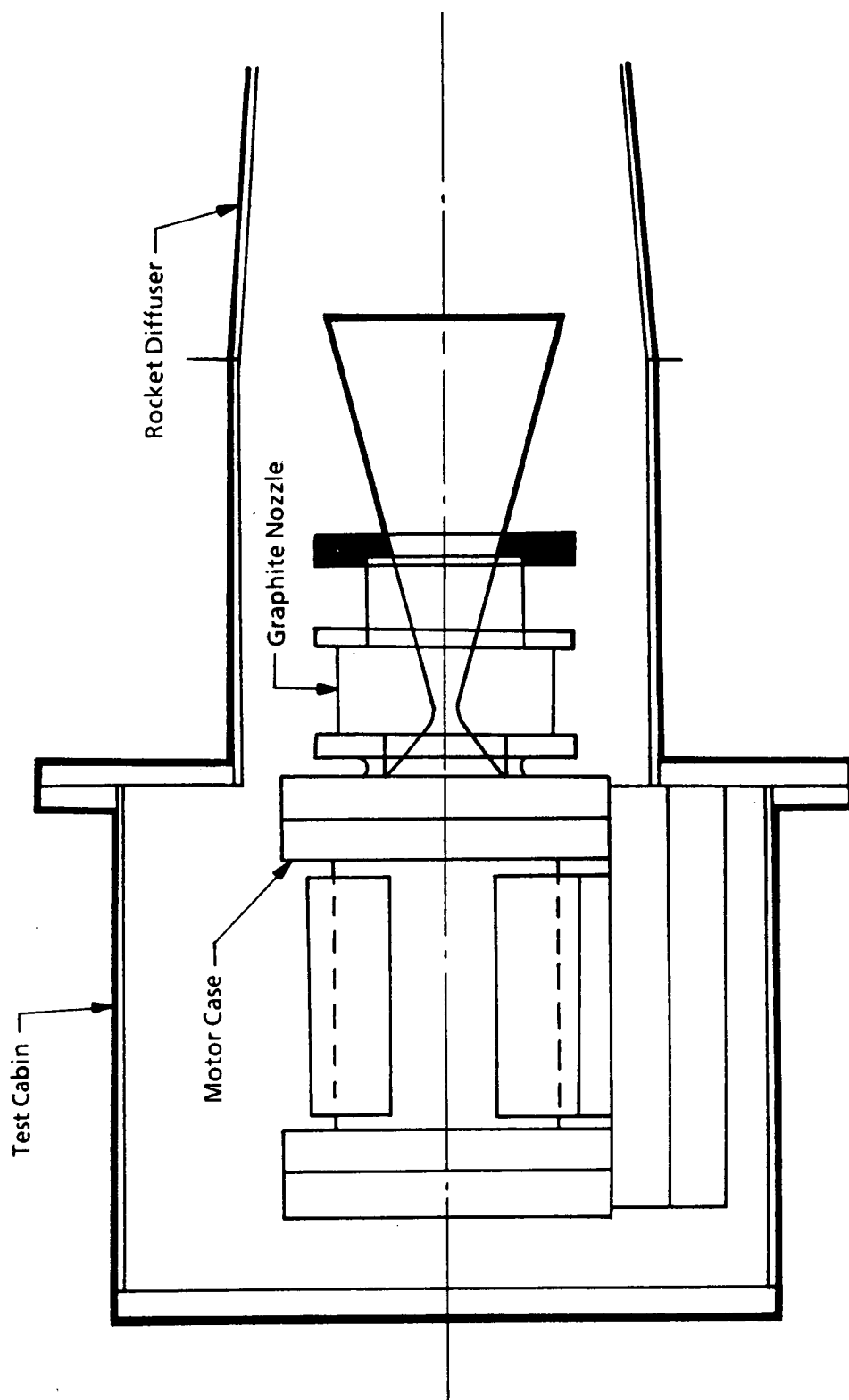


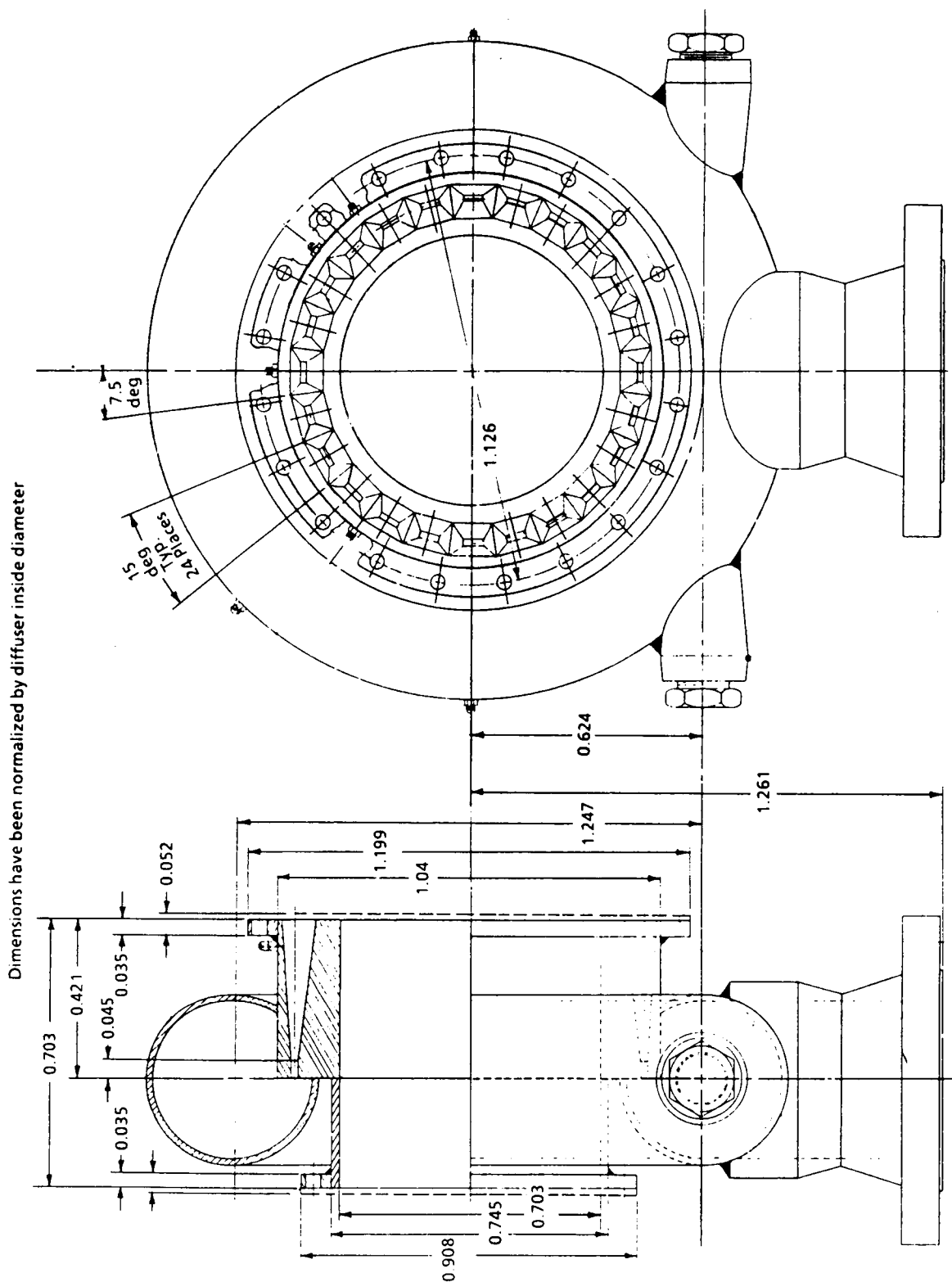
Figure 3. Test configuration.



a. Photograph
Figure 4. BATES solid-propellant rocket motor.

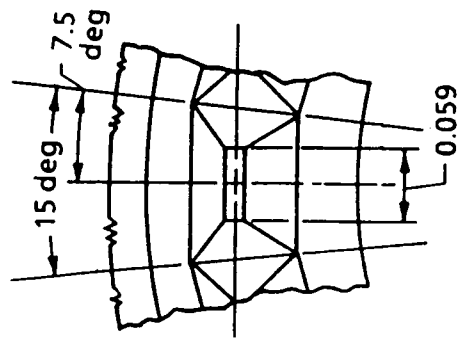


b. Motor installed in test cell
Figure 4. Concluded.



a. Manifold/nozzle ejector assembly
Figure 5. Steam ejector geometry.

Technical drawing of a pressure tap assembly showing a cross-section of a pipe with a pressure tap and a pressure tap assembly. The drawing includes dimensions: 0.070, 0.045, 0.014, 3.75 deg, 6.50 deg, 0.947 Diam, and 0.421. A label "Pressure Tap" points to the assembly.



b. Nozzle details

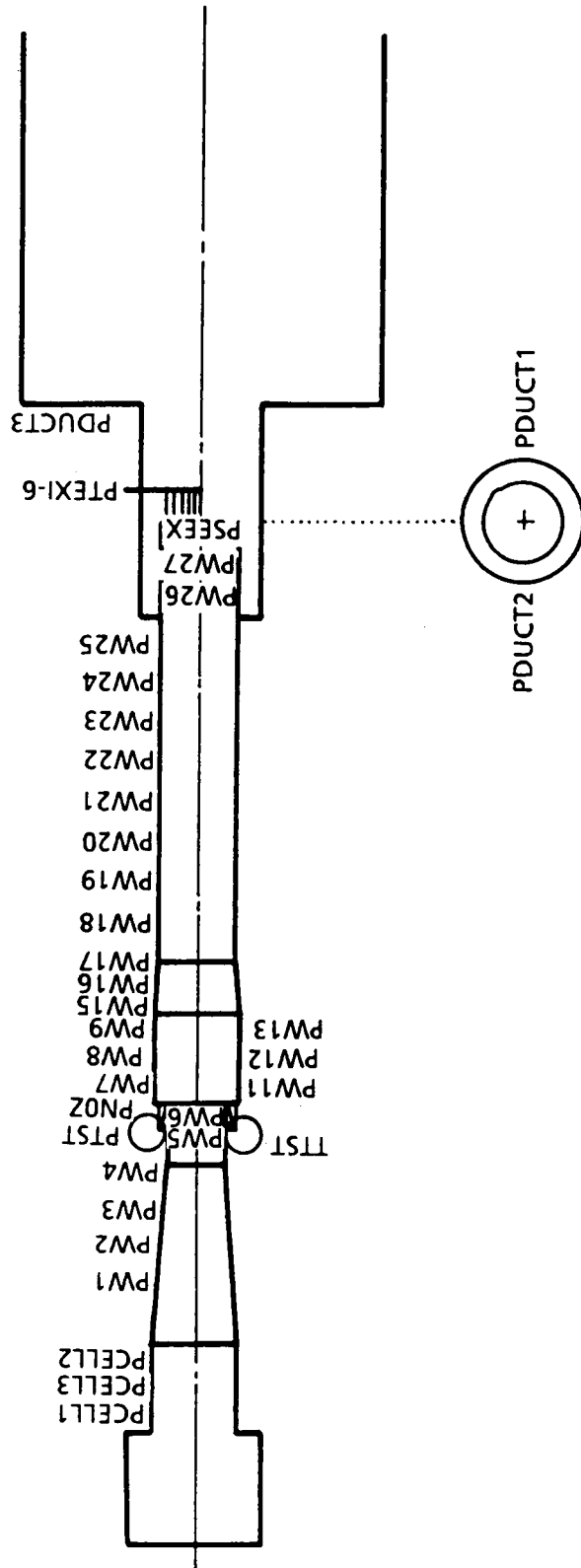


Figure 6. Test instrumentation locations.

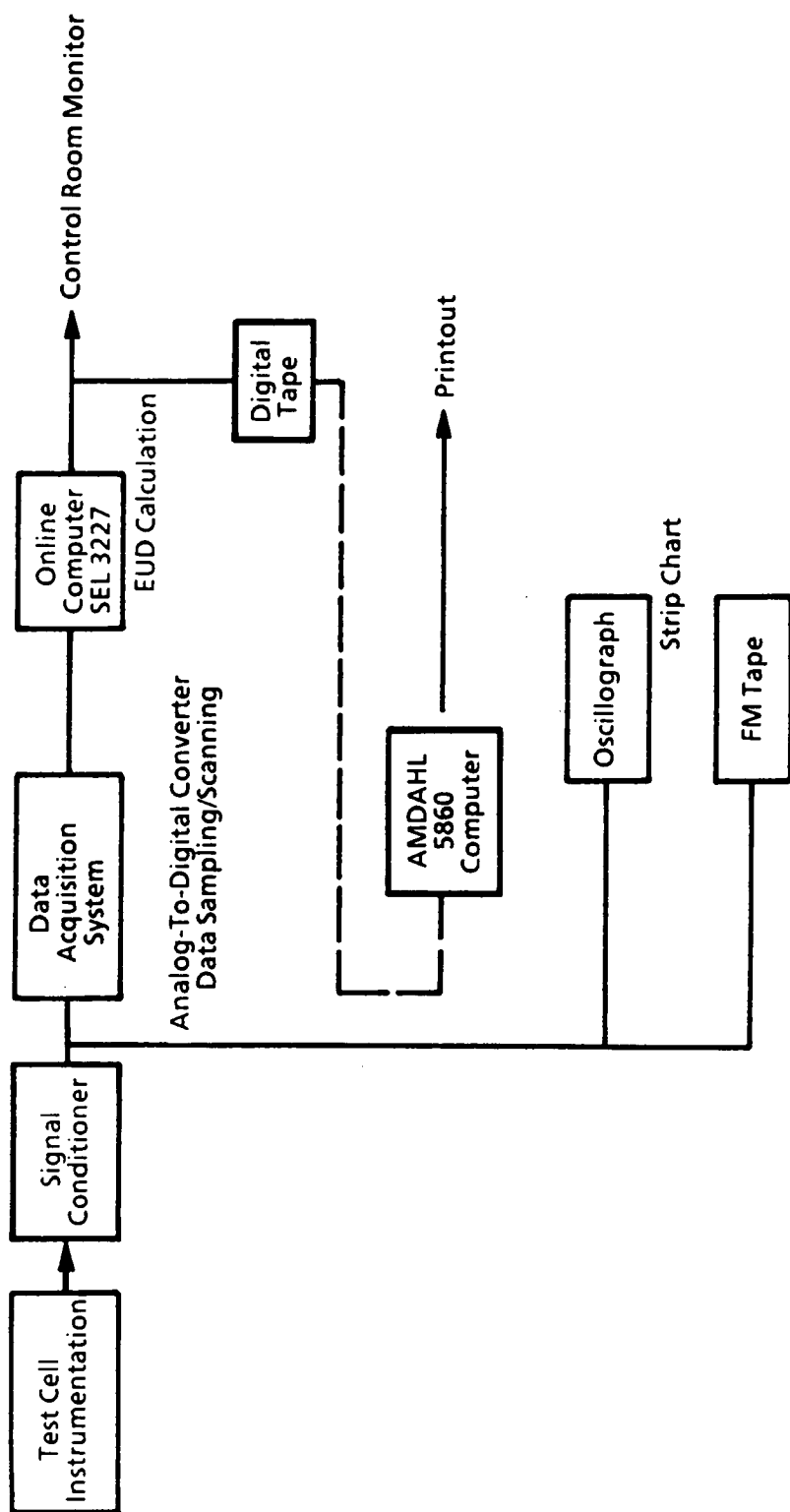


Figure 7. Instrumentation system schematic.

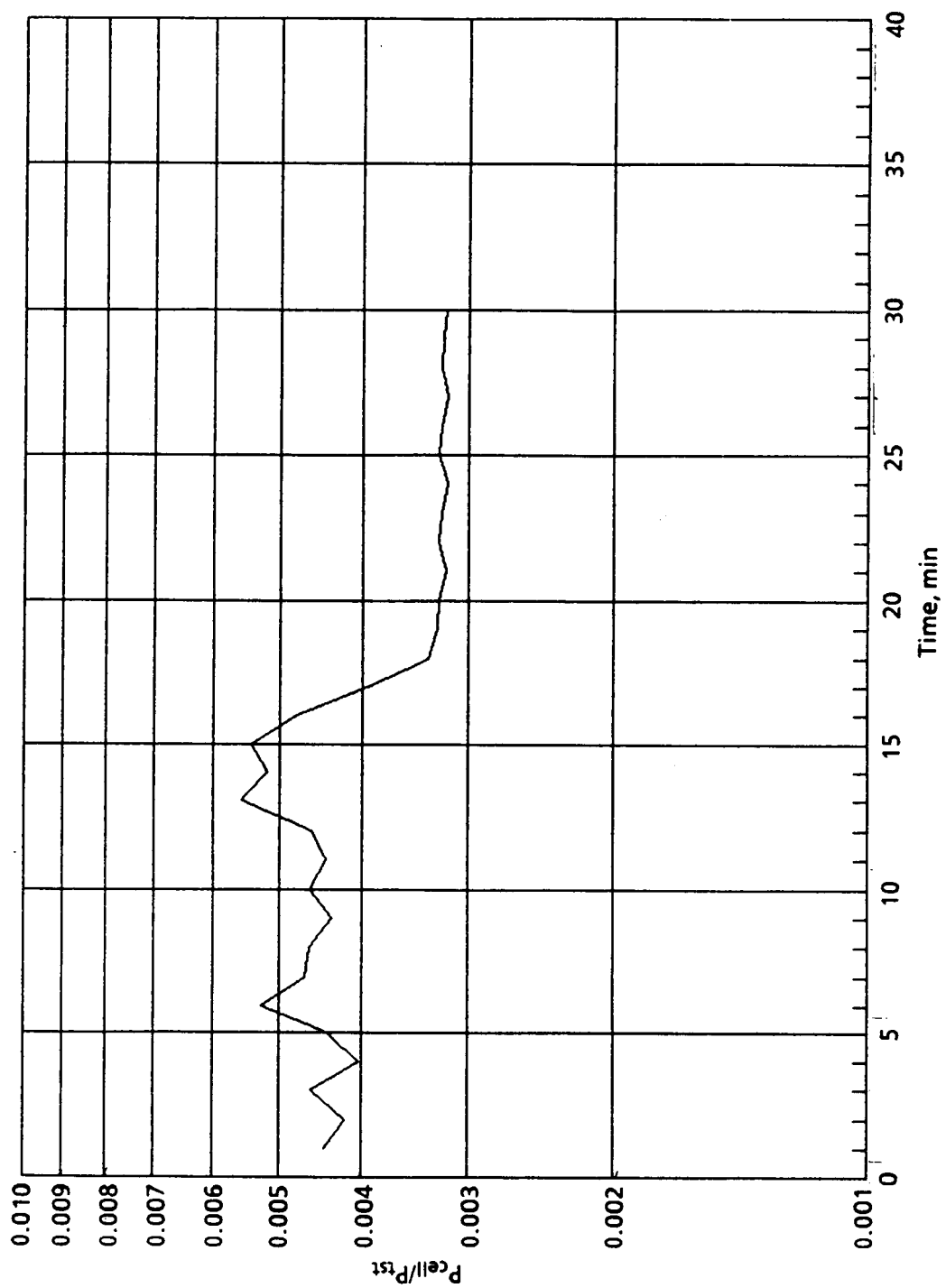


Figure 8. Typical time trace for steam system stabilization.

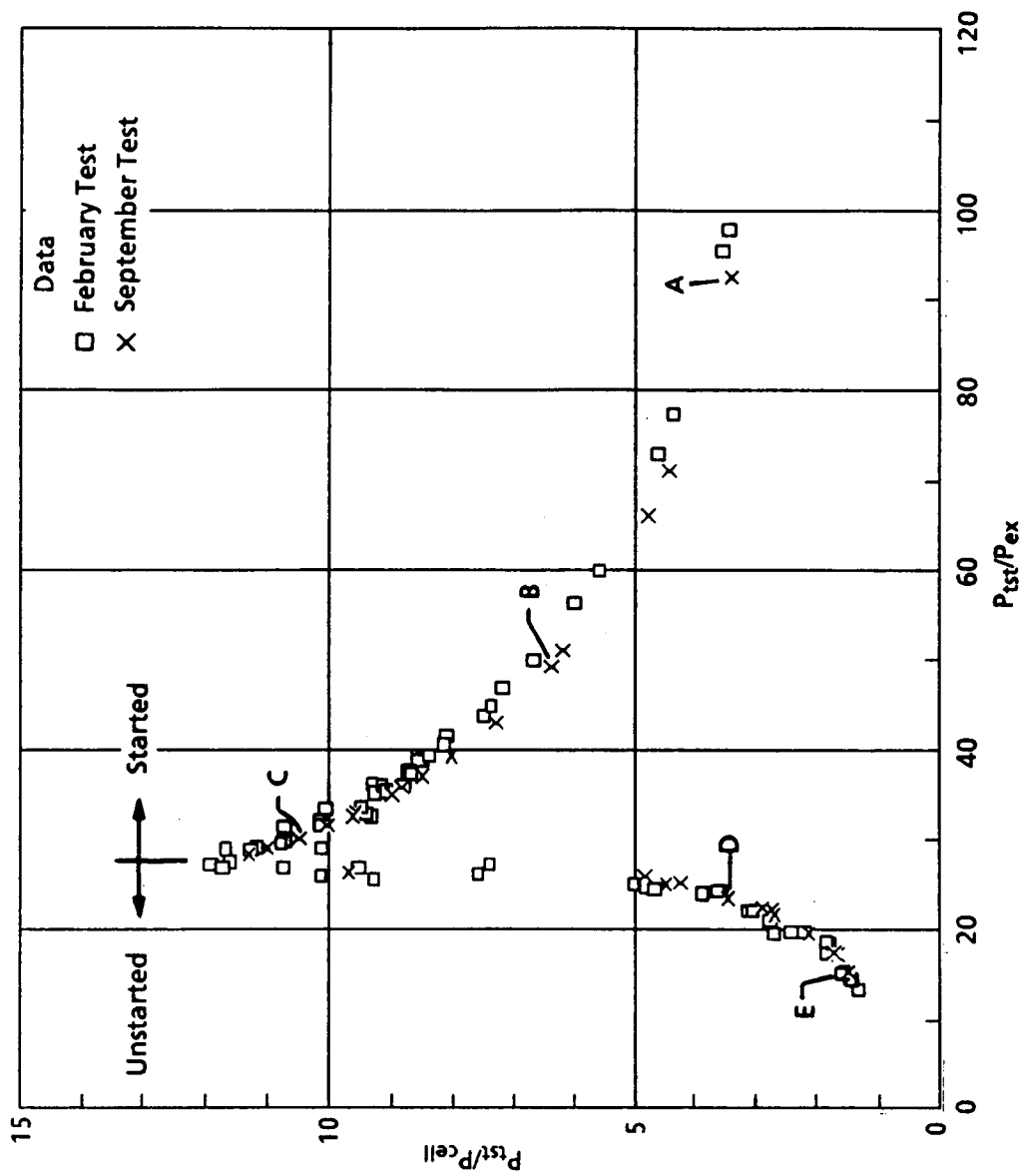


Figure 9. Steam ejector rise ratio versus normalized total pressure for baseline design.

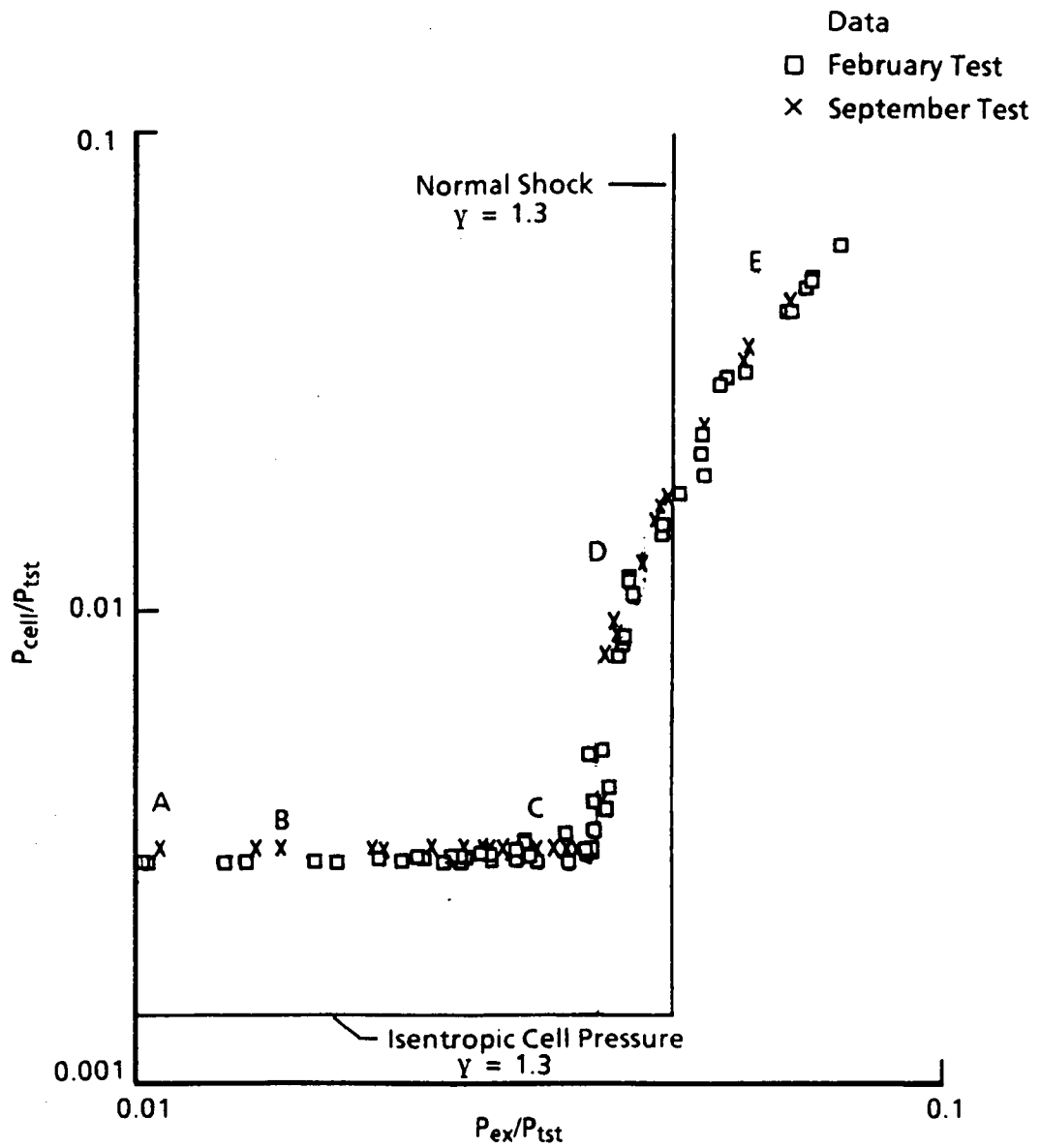
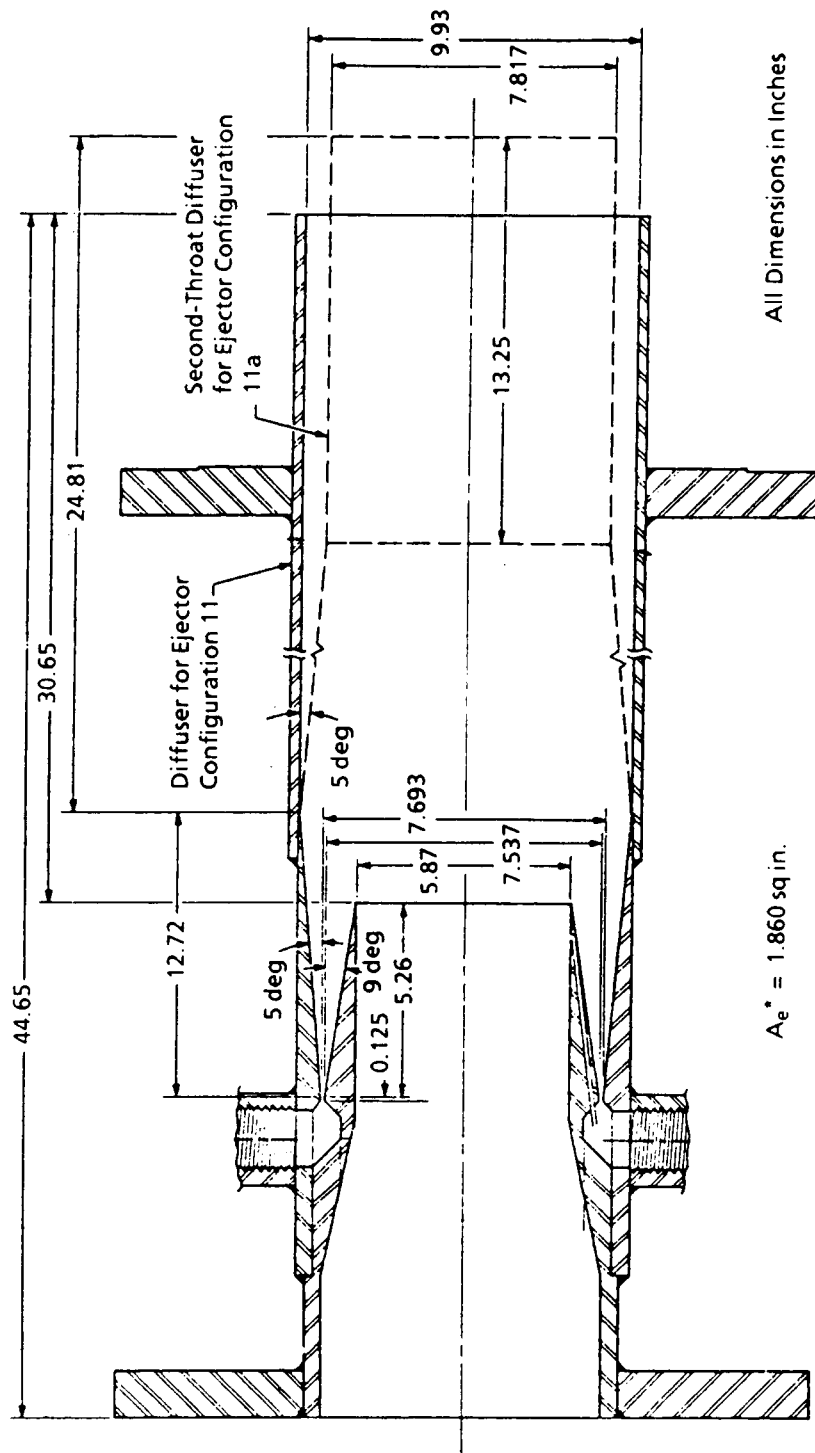


Figure 10. Steam ejector breakdown curve for baseline design.

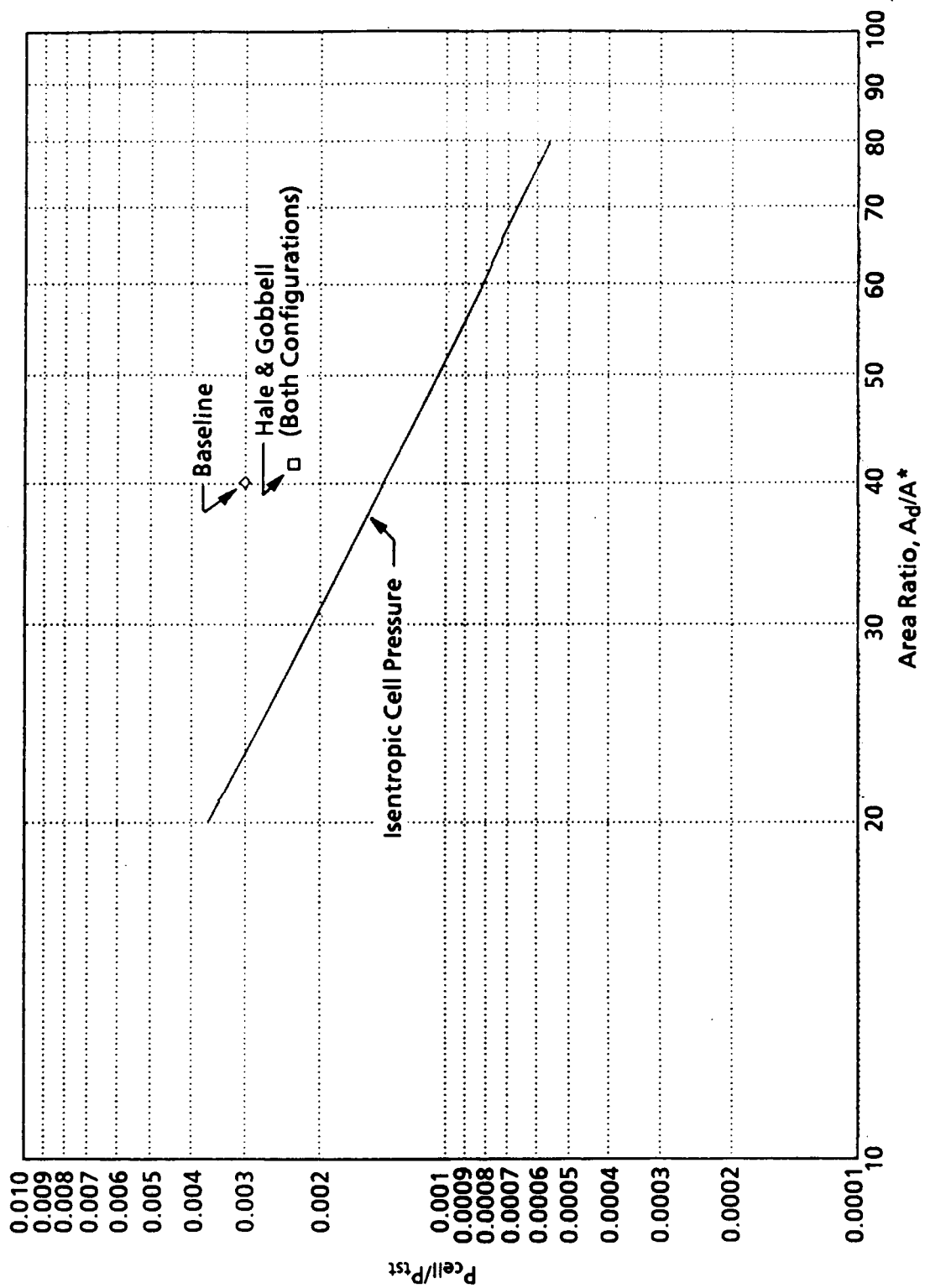


$$A_e^* = 1.860 \text{ sq in.}$$

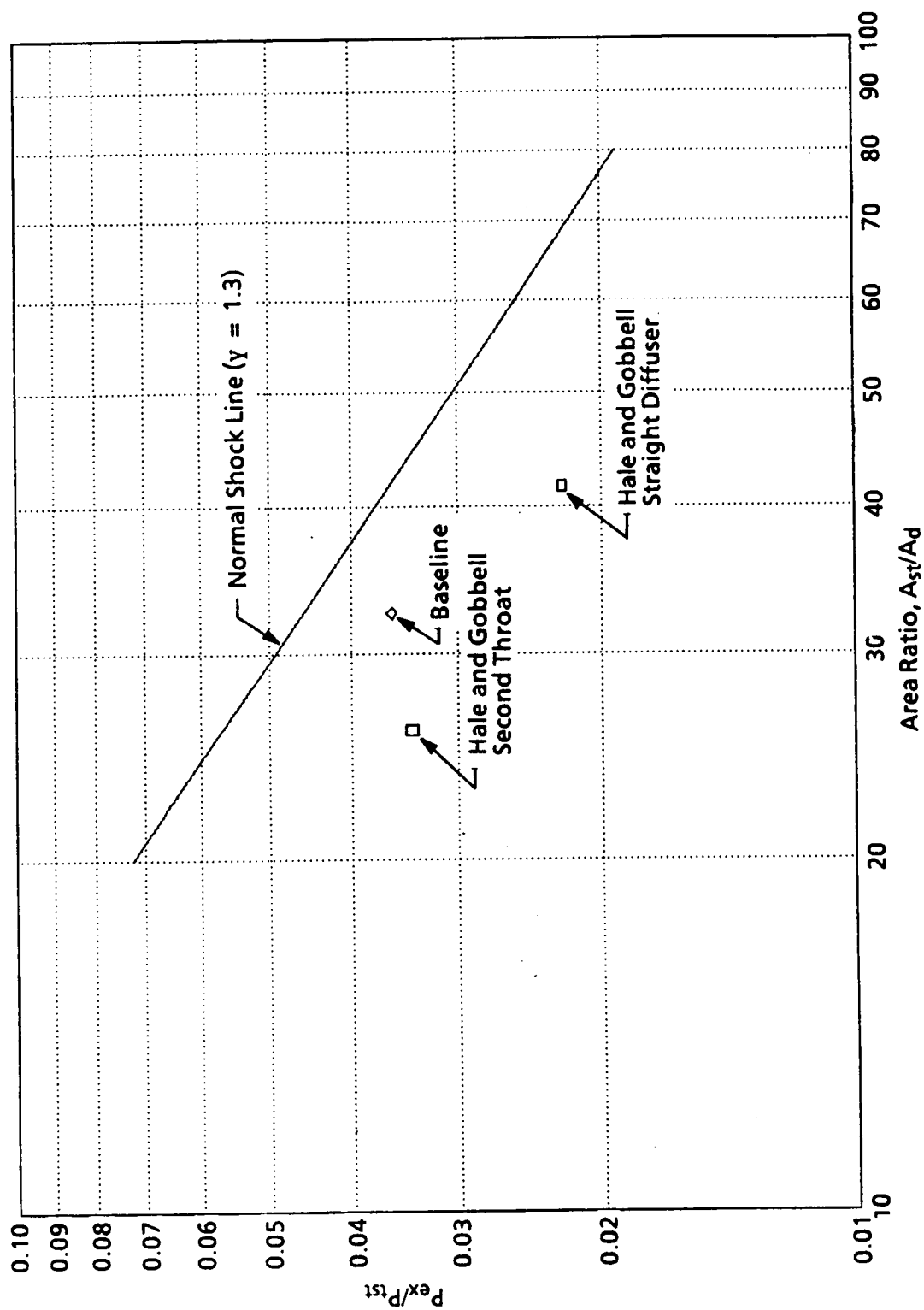
$$(A_{ne}/A^*)_e = 16.62$$

All Dimensions in Inches

Figure 11. Hale and Gobbell's annular ejector configurations (Ref. 9).



a. Minimum cell pressure
 Figure 12. Comparison of baseline to data of Hale and Gobbell (Ref. 9).



b. Exit pressure
Figure 12. Concluded.

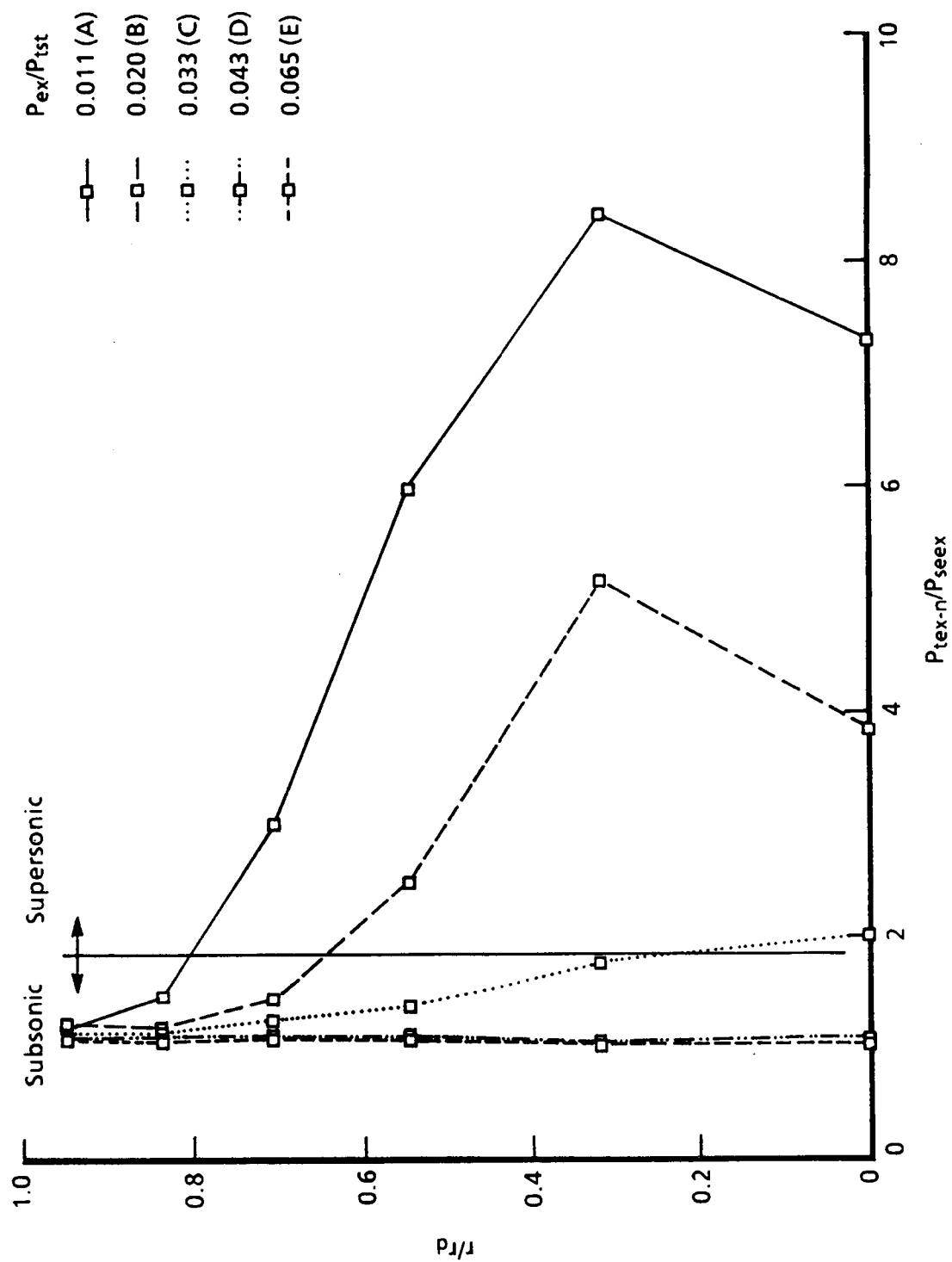


Figure 13. Ejector diffuser exit pitot pressure profiles.

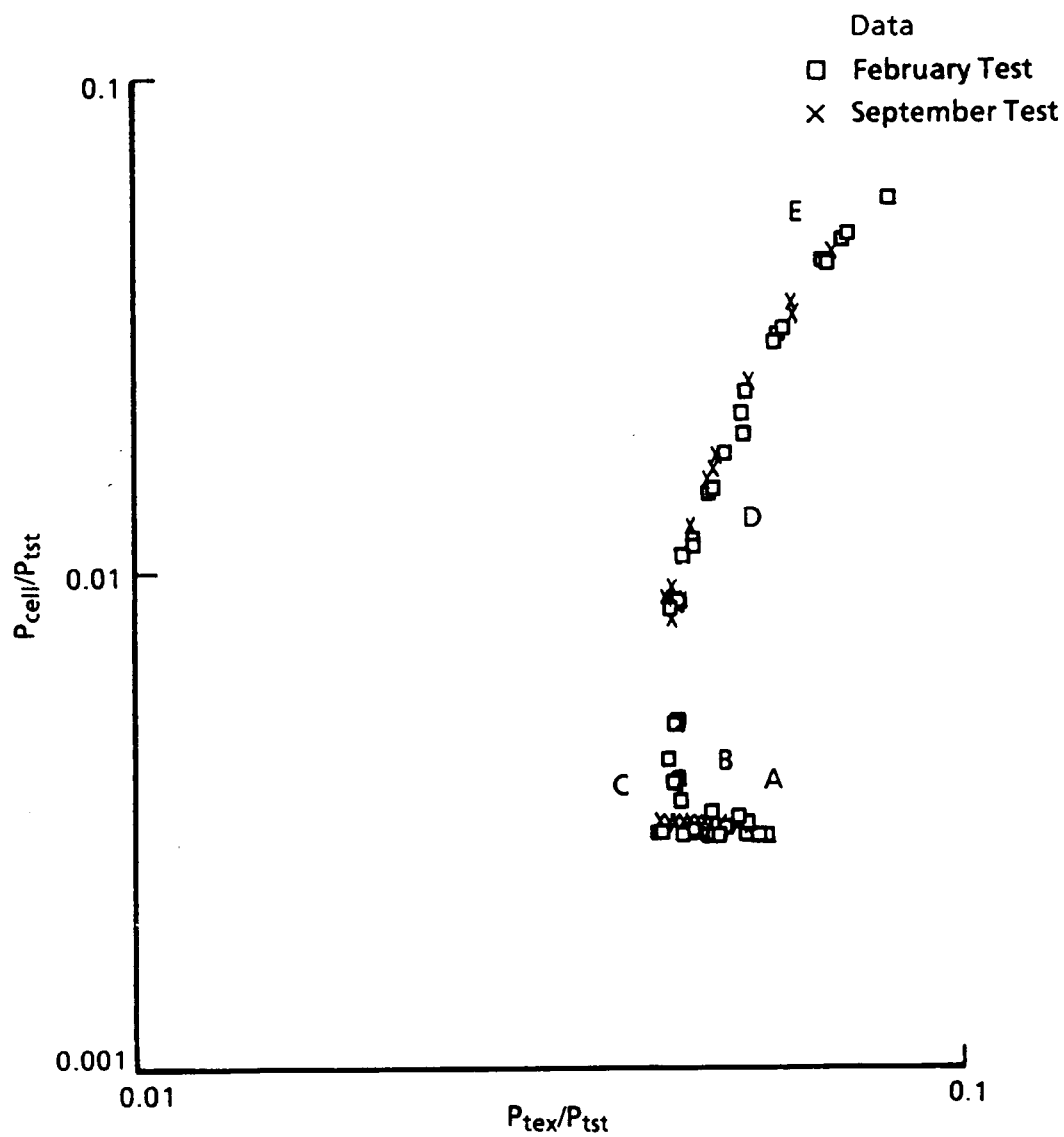


Figure 14. Normalized cell pressure versus rake average exit pitot pressure.

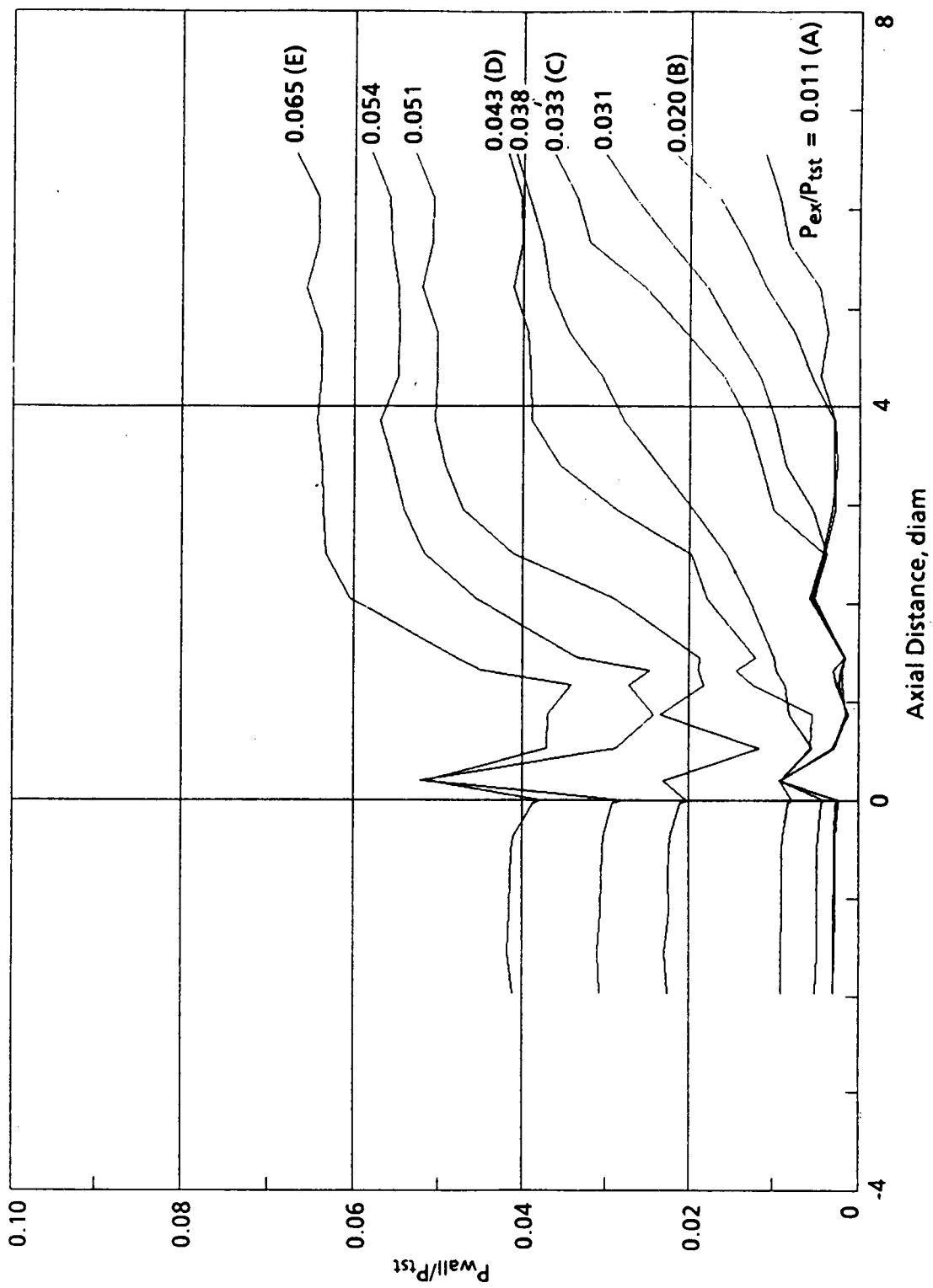


Figure 15. Baseline wall pressure profiles.

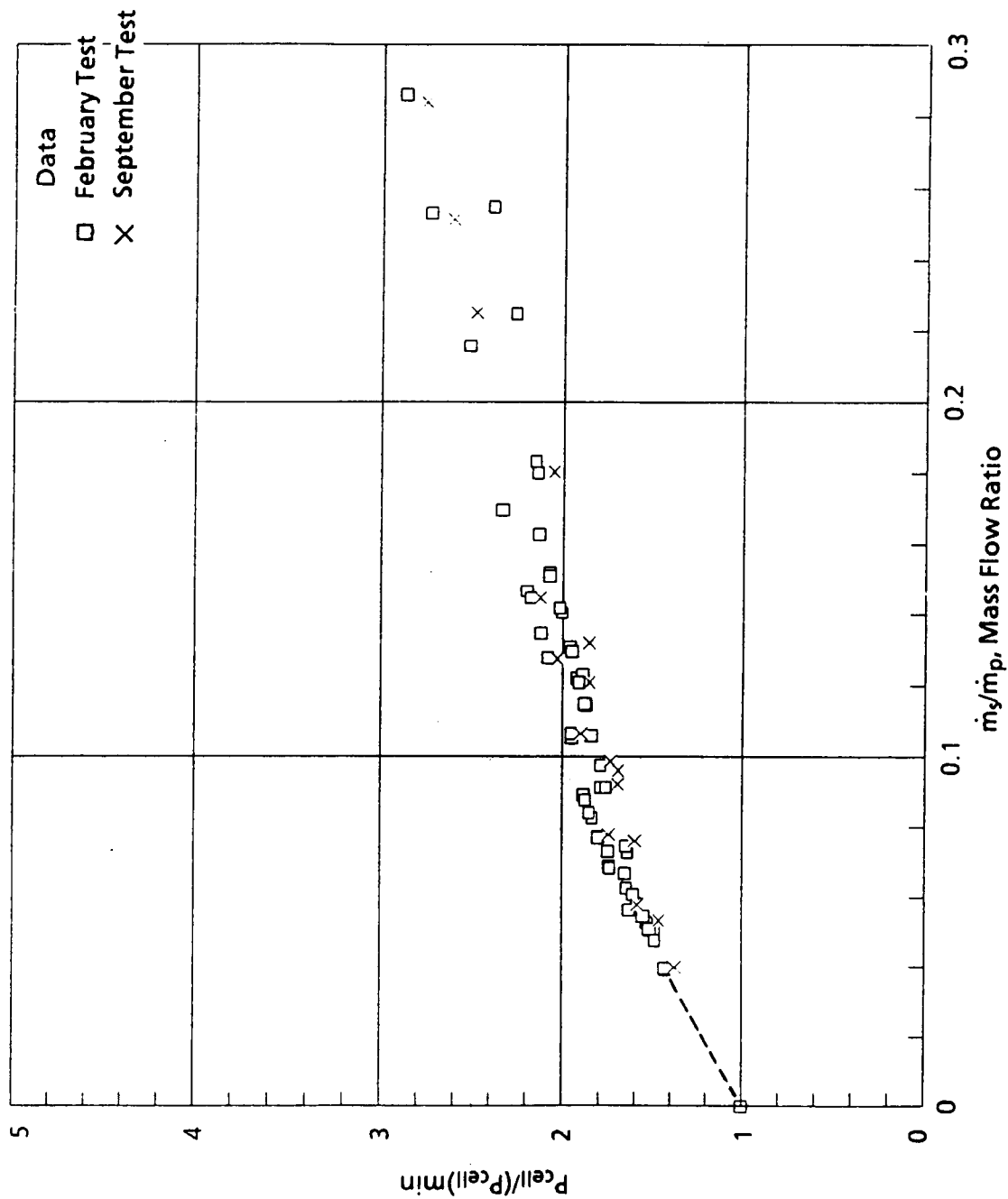


Figure 16. Effect of secondary flow on minimum cell pressure.

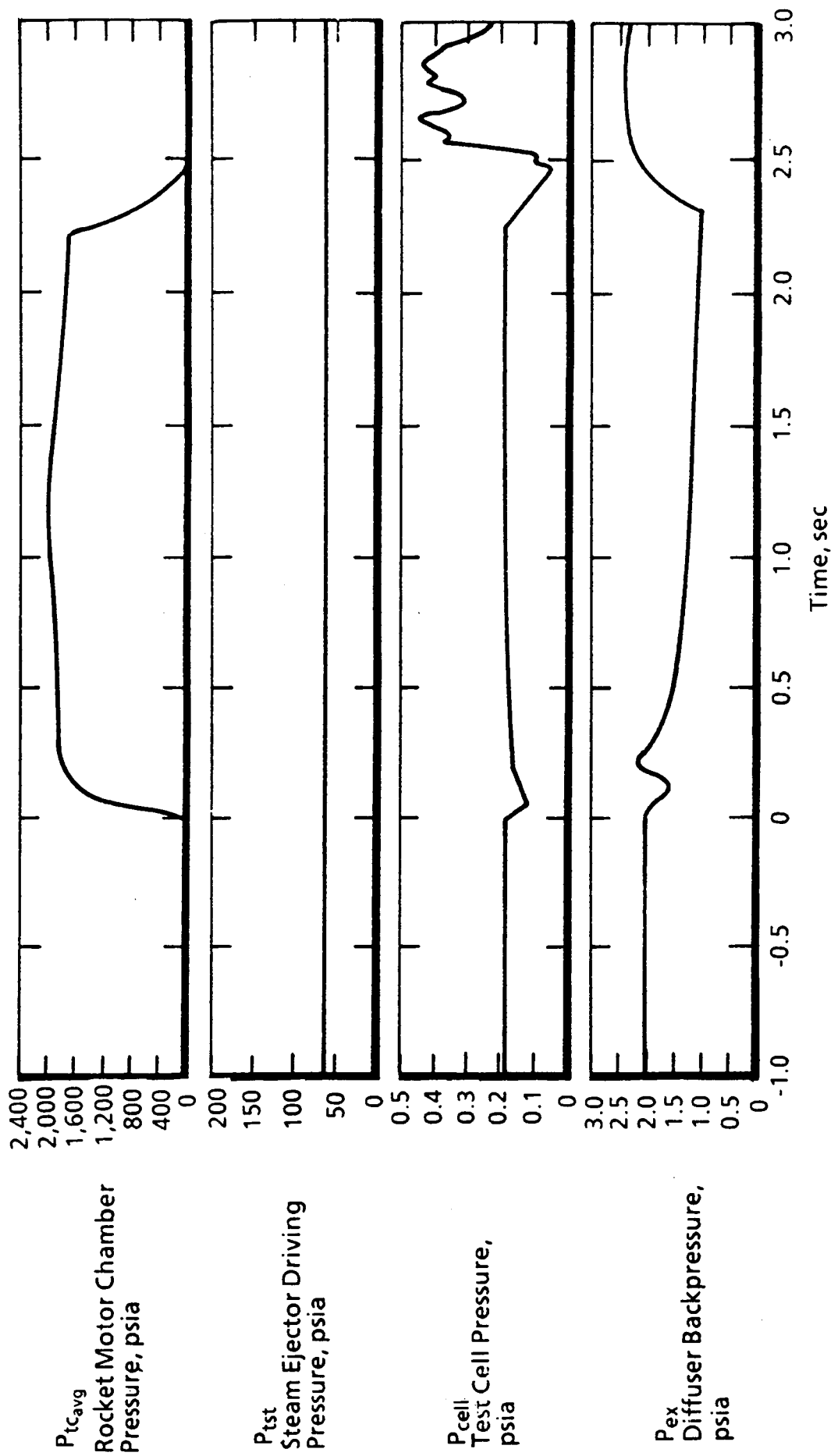


Figure 17. Rocket test results for baseline at low steam and exit pressures - started diffuser.

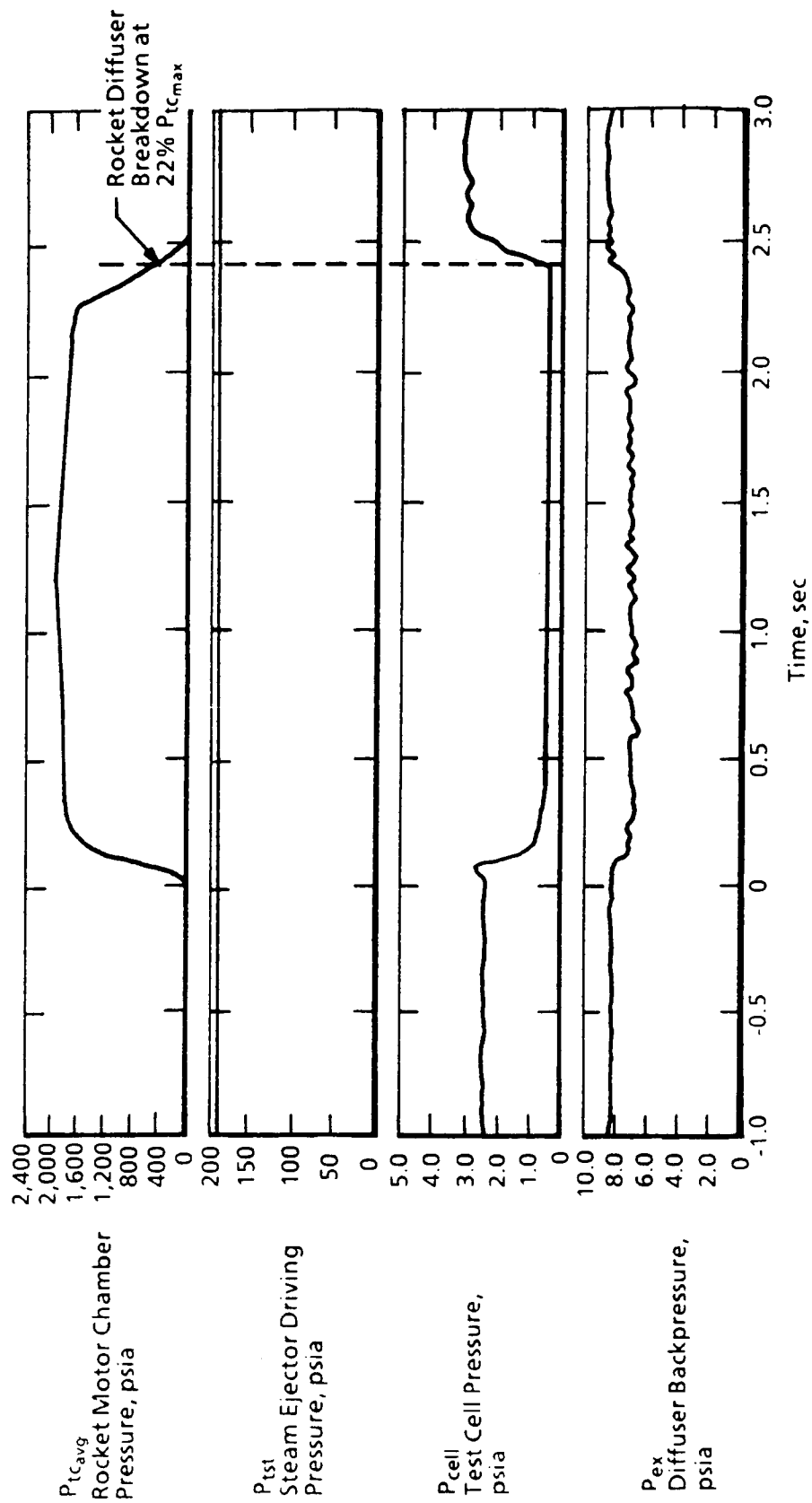


Figure 18. Rocket test results for baseline at high steam and exit pressures—unstarted diffuser.

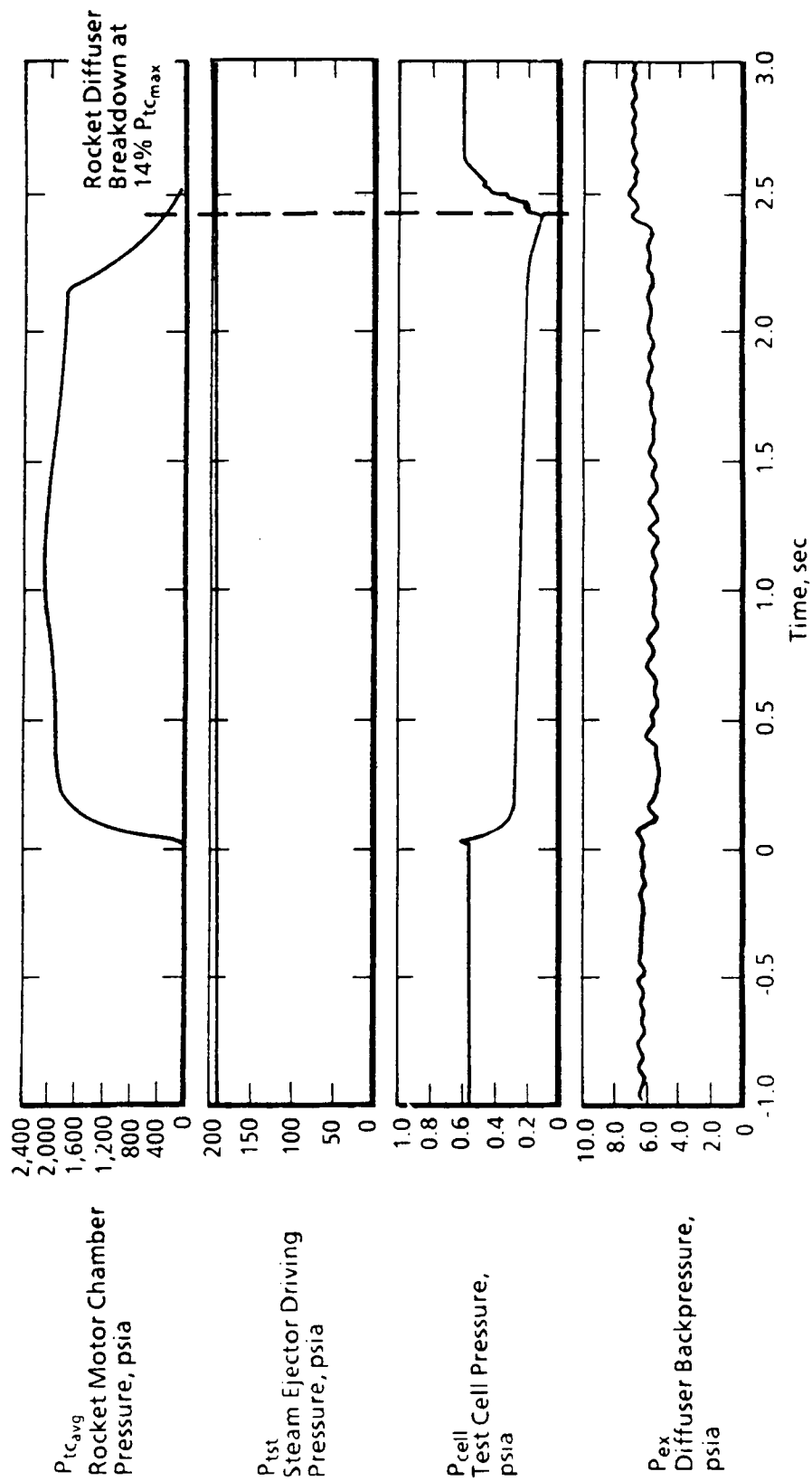


Figure 19. Rocket test results for baseline at high steam pressure and started diffuser.

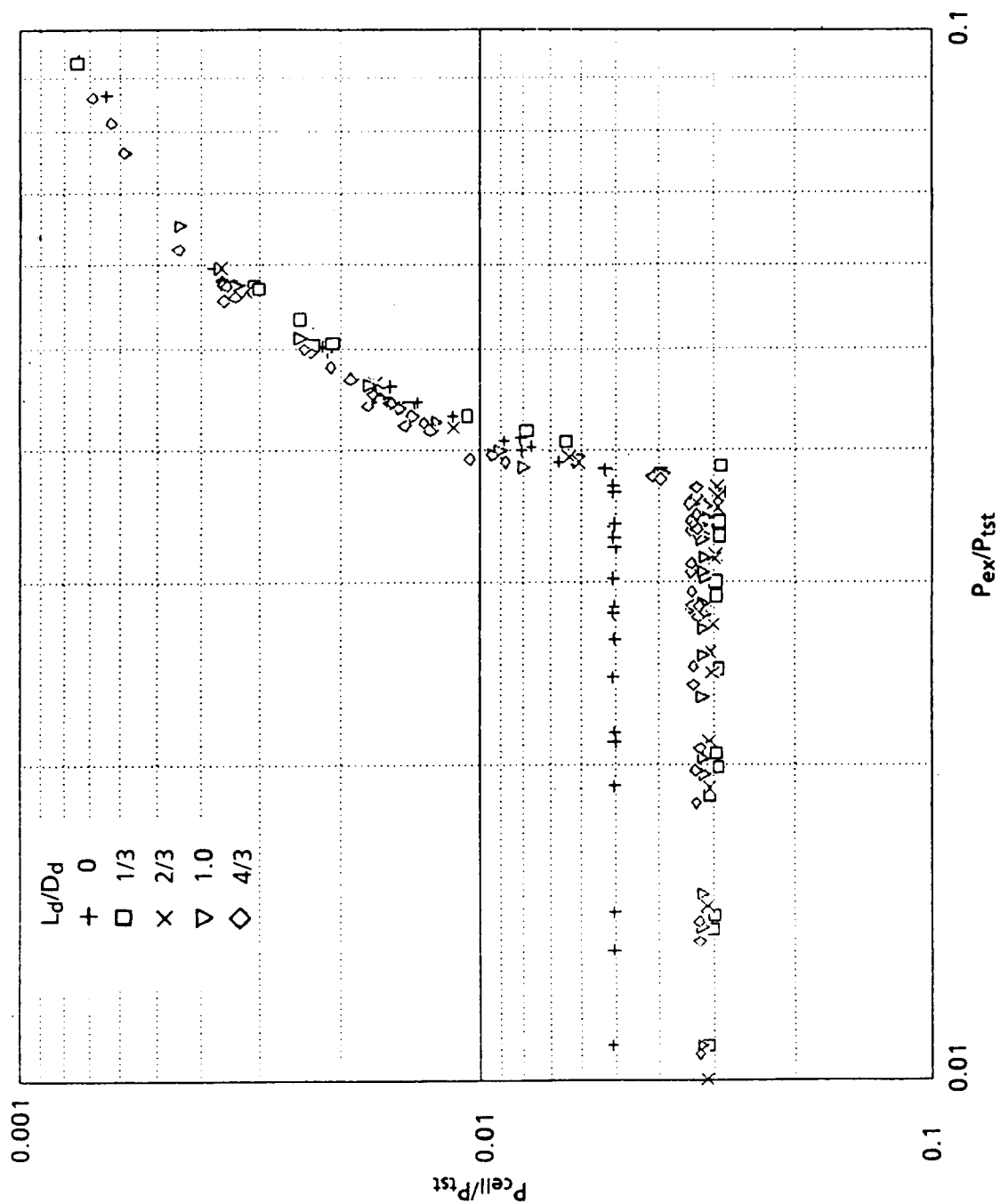


Figure 20. Effect of throat location on ejector breakdown curve.

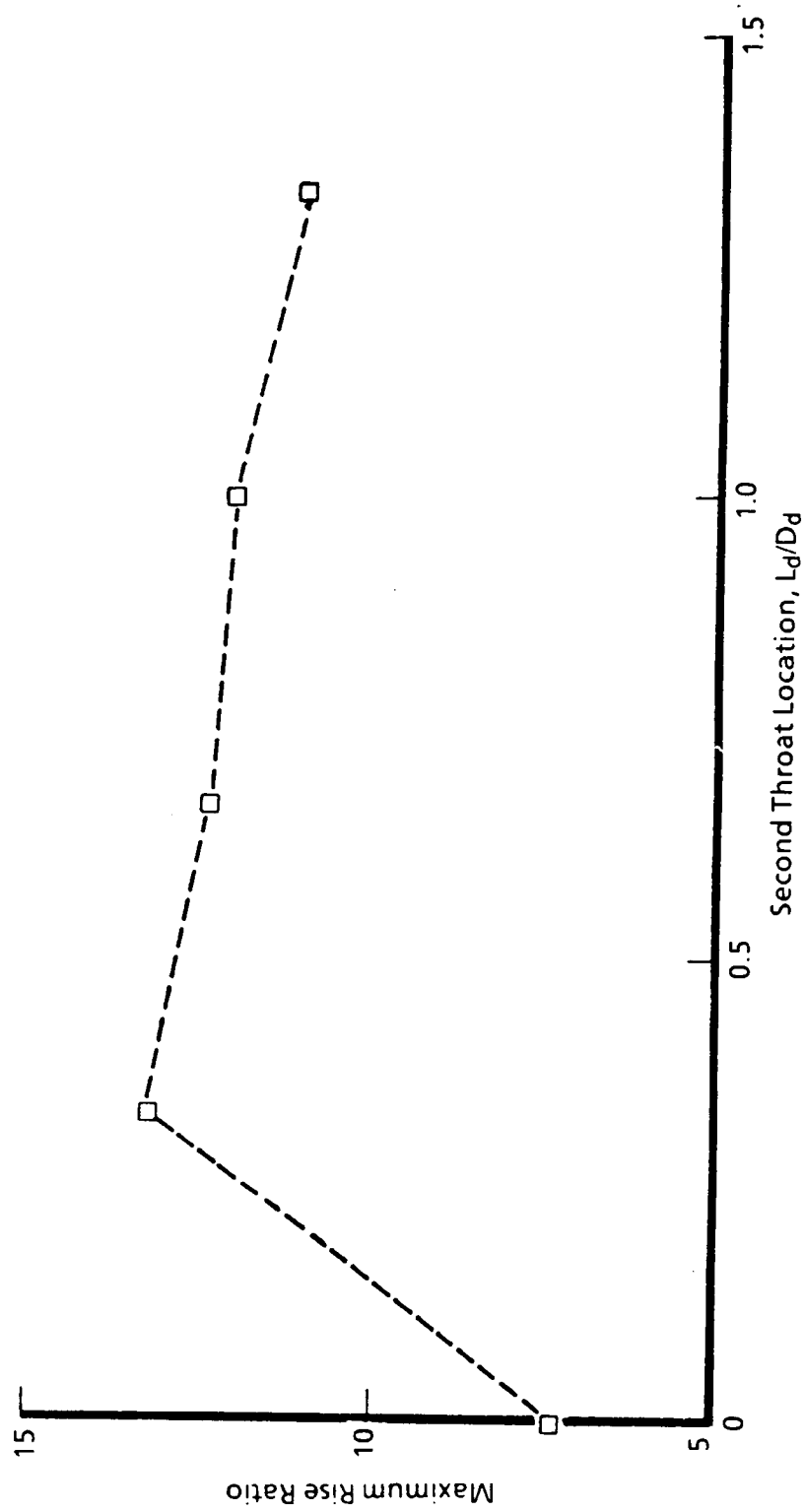
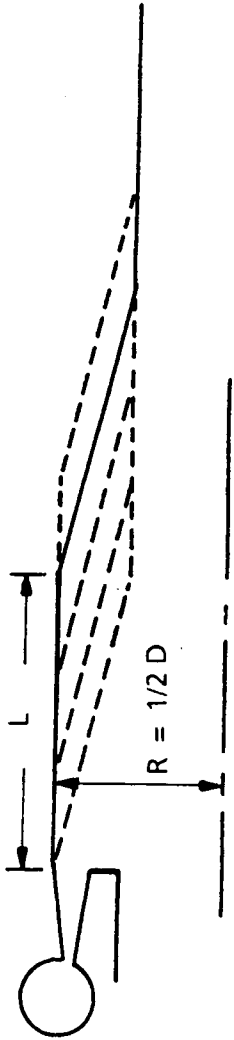


Figure 21. Effect of throat location on maximum rise ratio.

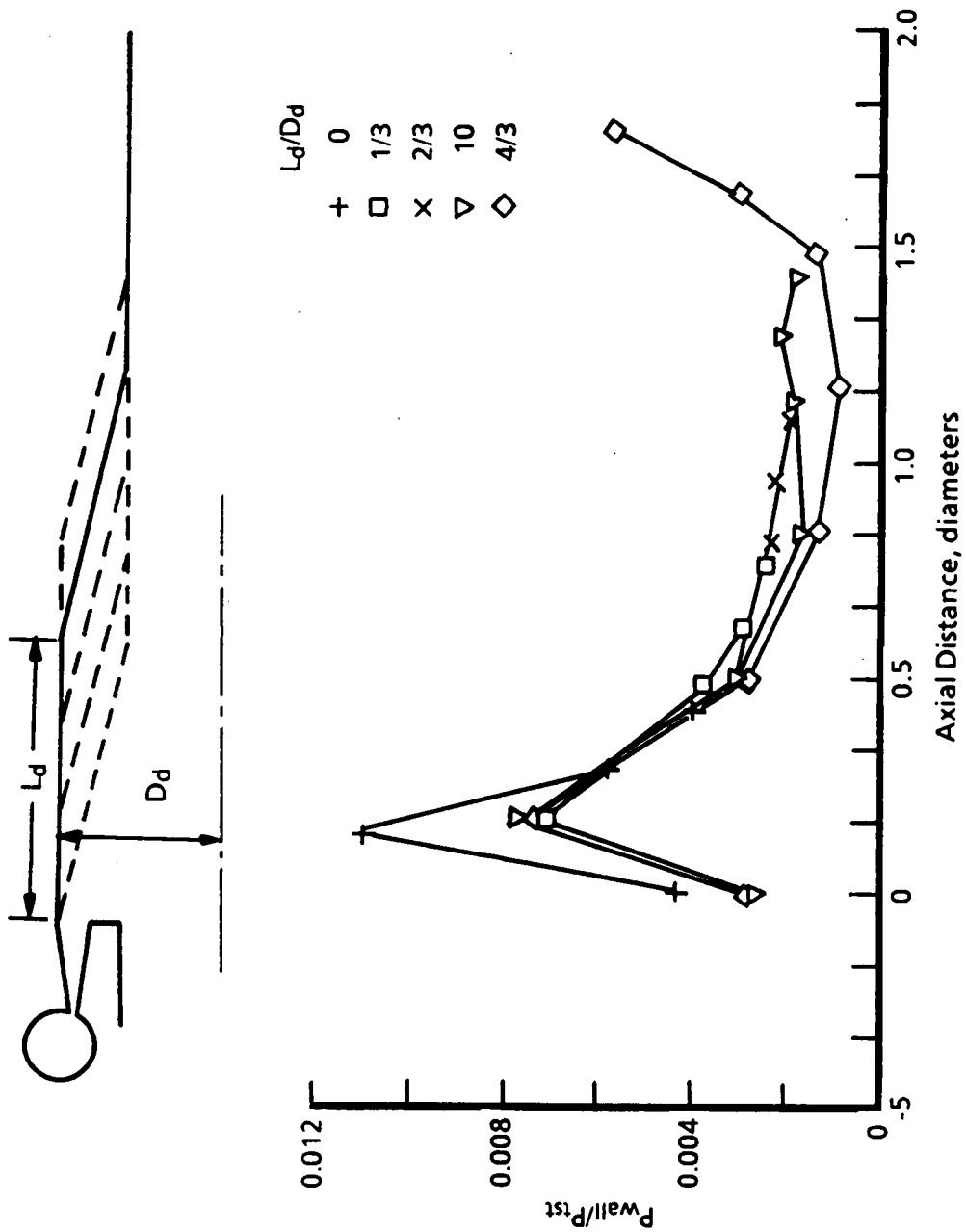


Figure 22. Effect of throat location on wall pressure profile.

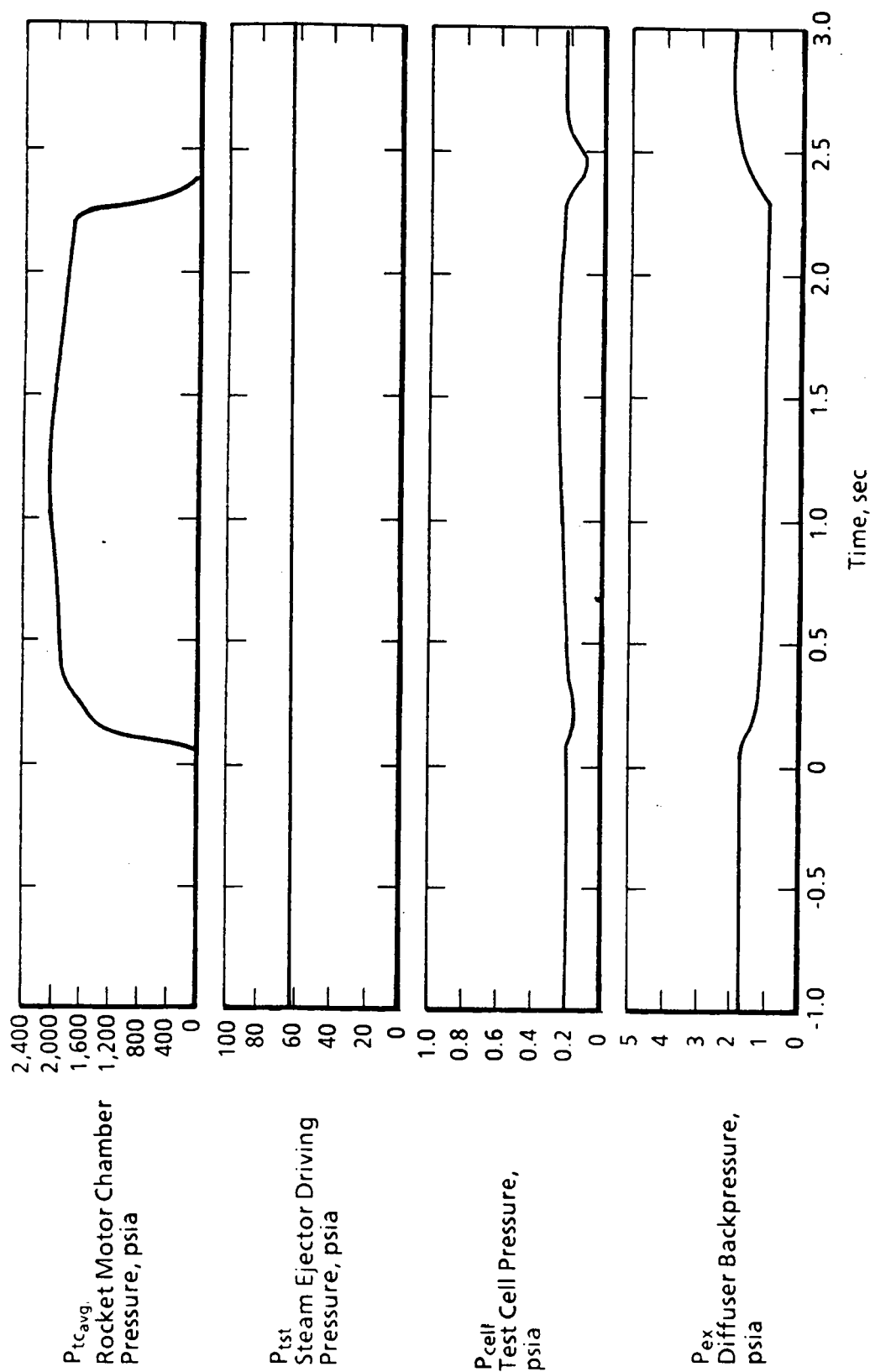


Figure 23. Rocket test results for Configuration 5 at low steam and exit pressures—started diffuser.

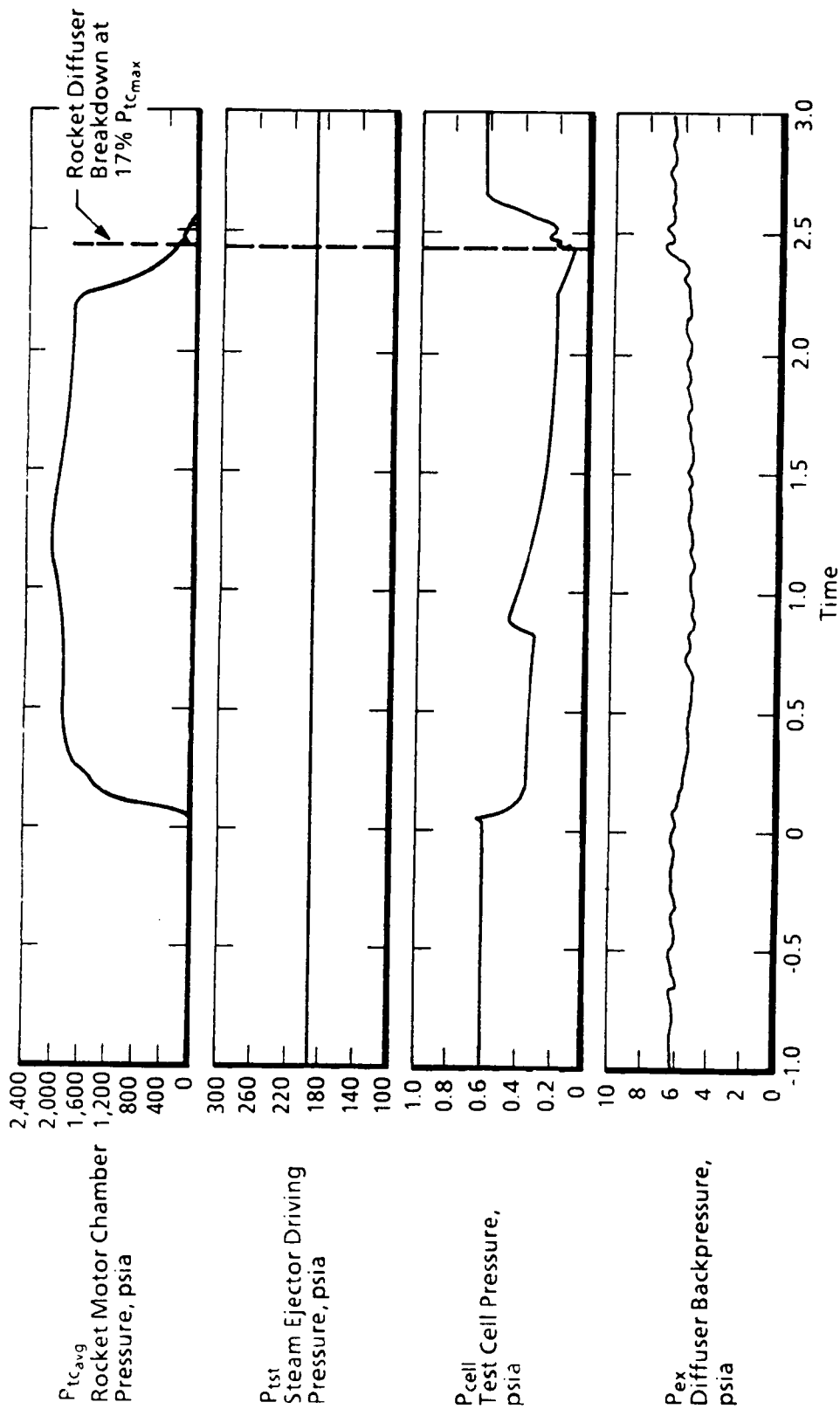


Figure 24. Rocket test results for Configuration 5 at high steam pressure and started diffuser.

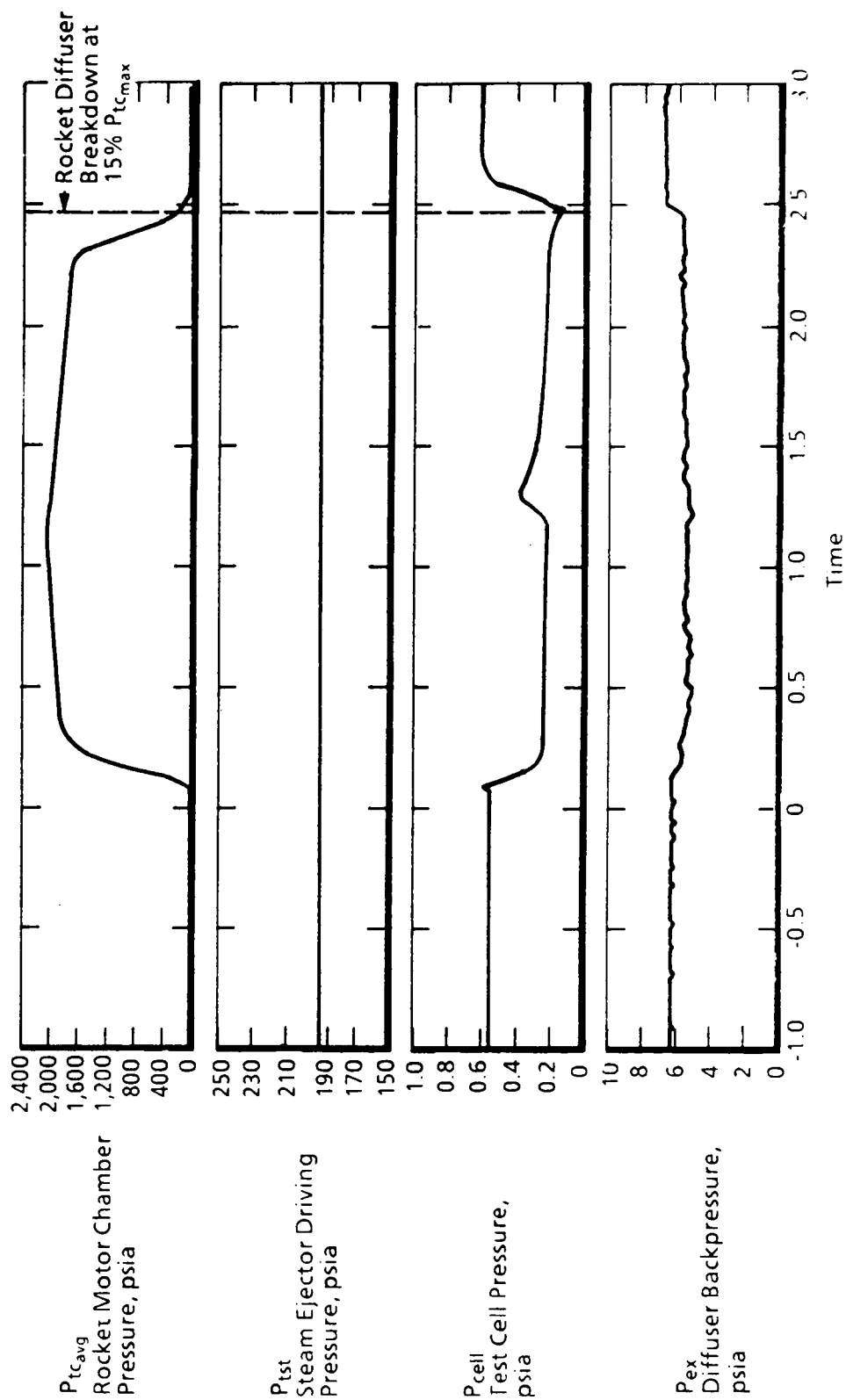


Figure 25. Rocket test results for Configuration 4 at high steam pressure and started diffuser.

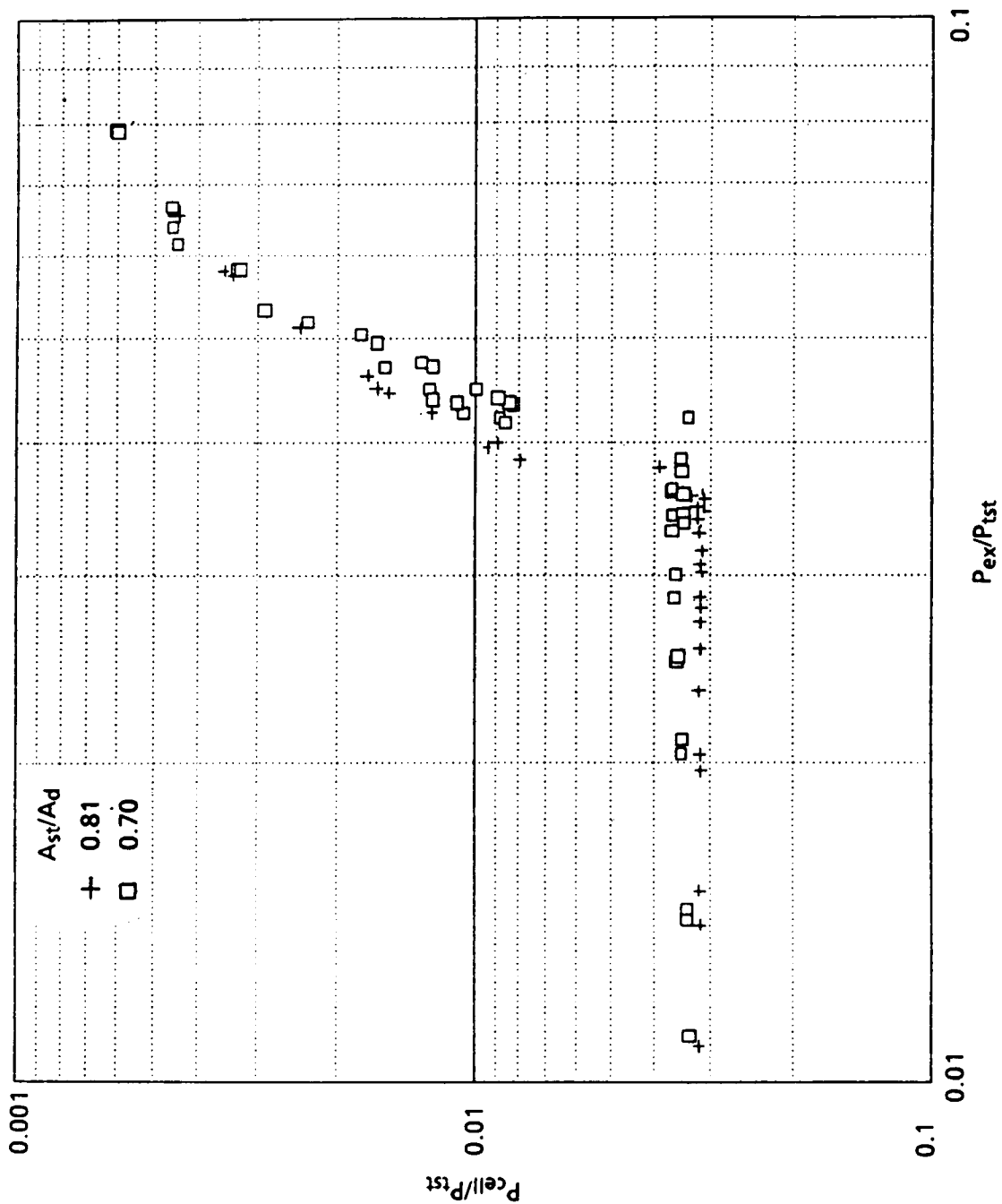


Figure 26. Effect of contraction ratio on ejector breakdown curve.

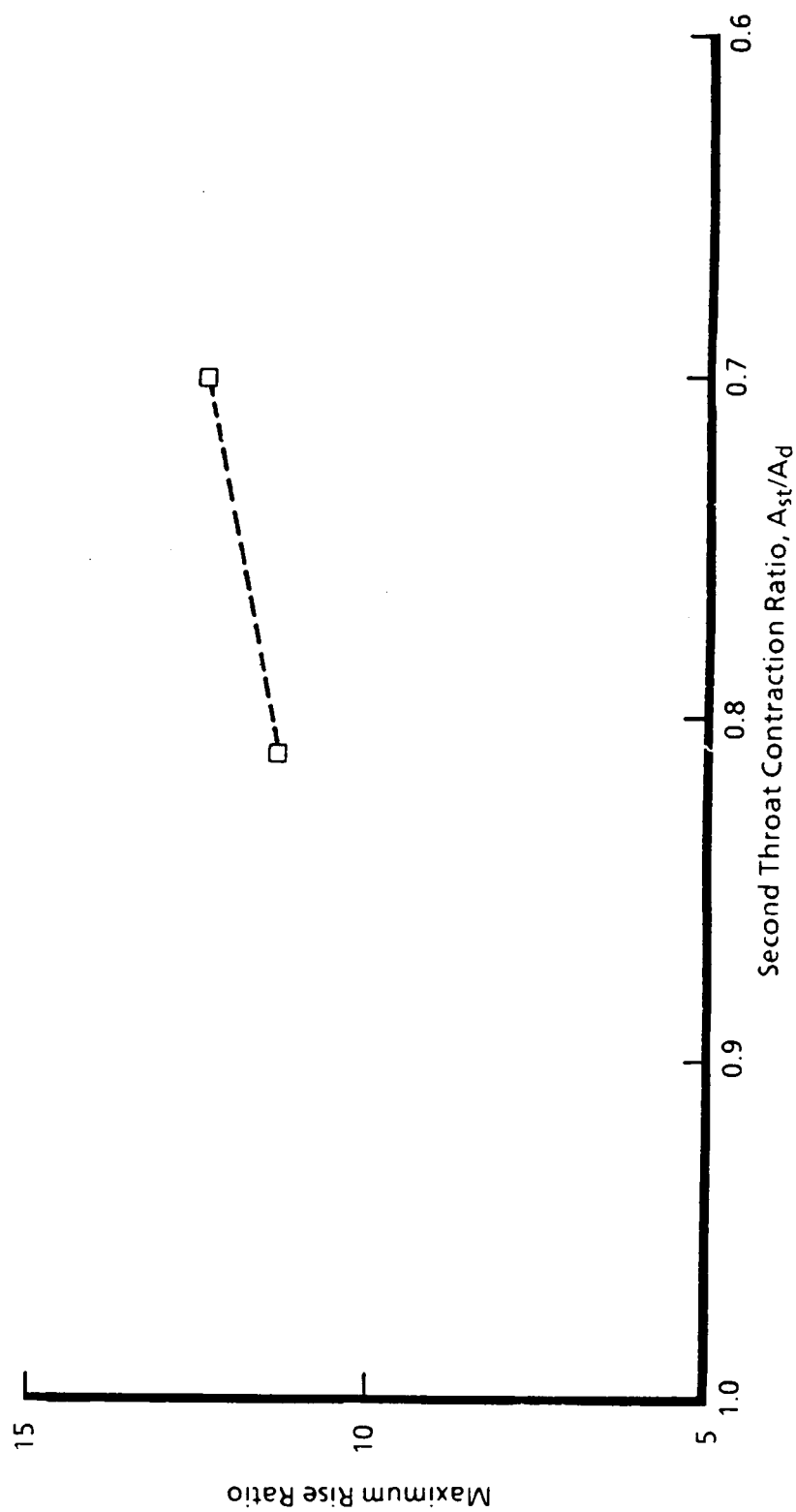
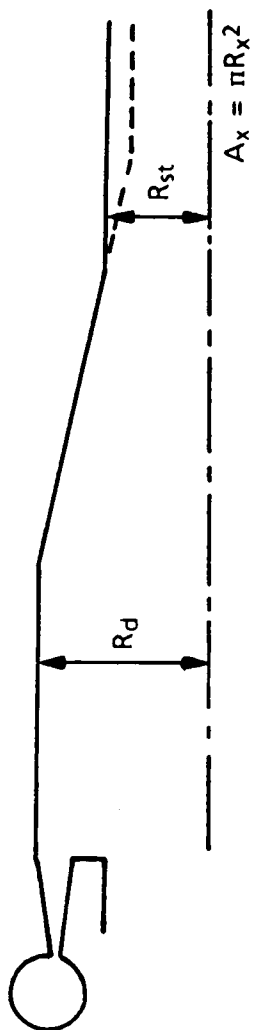


Figure 27. Effect of contraction ratio on maximum rise ratio.

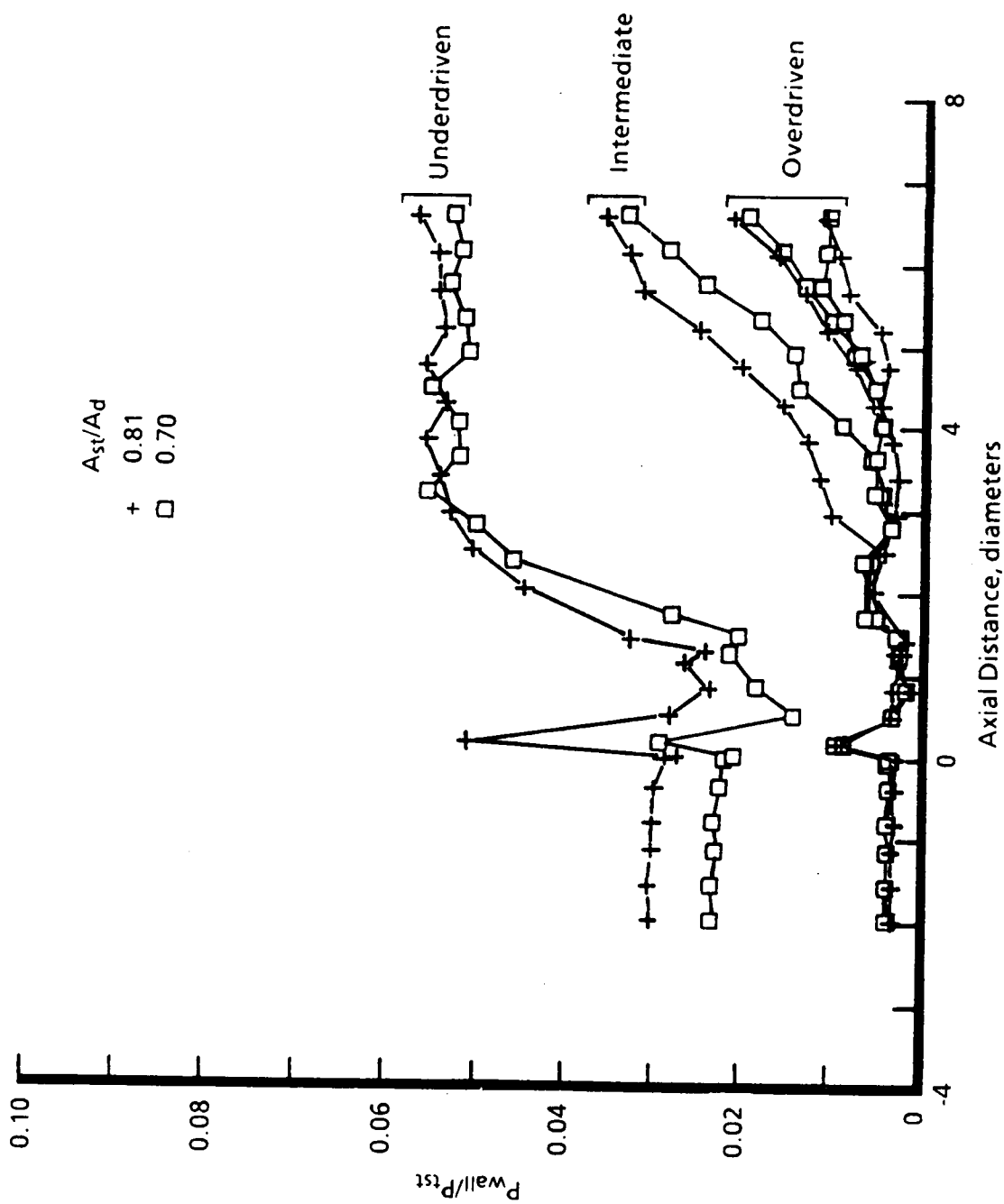


Figure 28. Effect of contraction ratio on wall pressure profile.

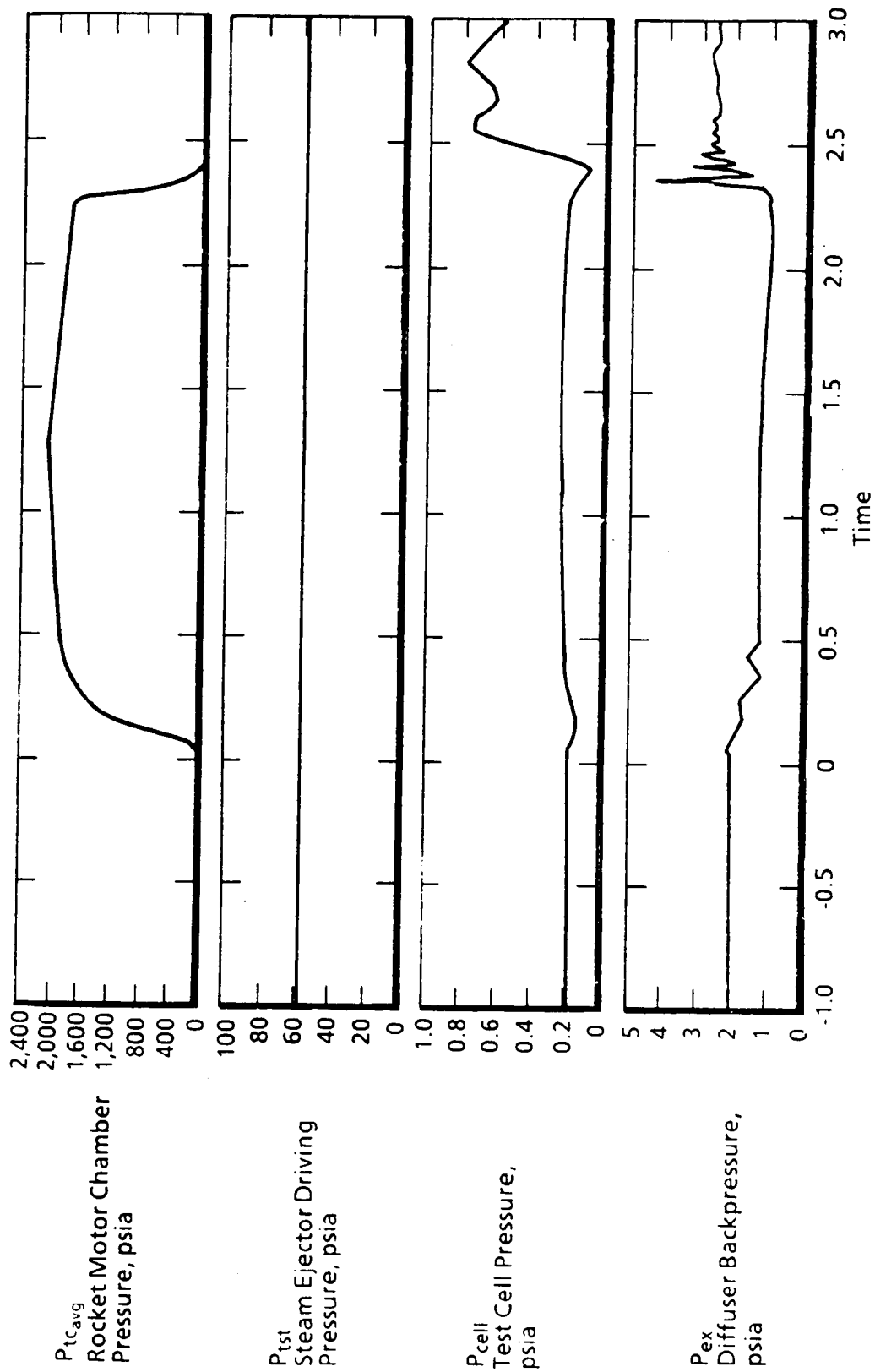


Figure 29. Rocket test results for Configuration 6 at low steam and exit pressures—started diffuser.

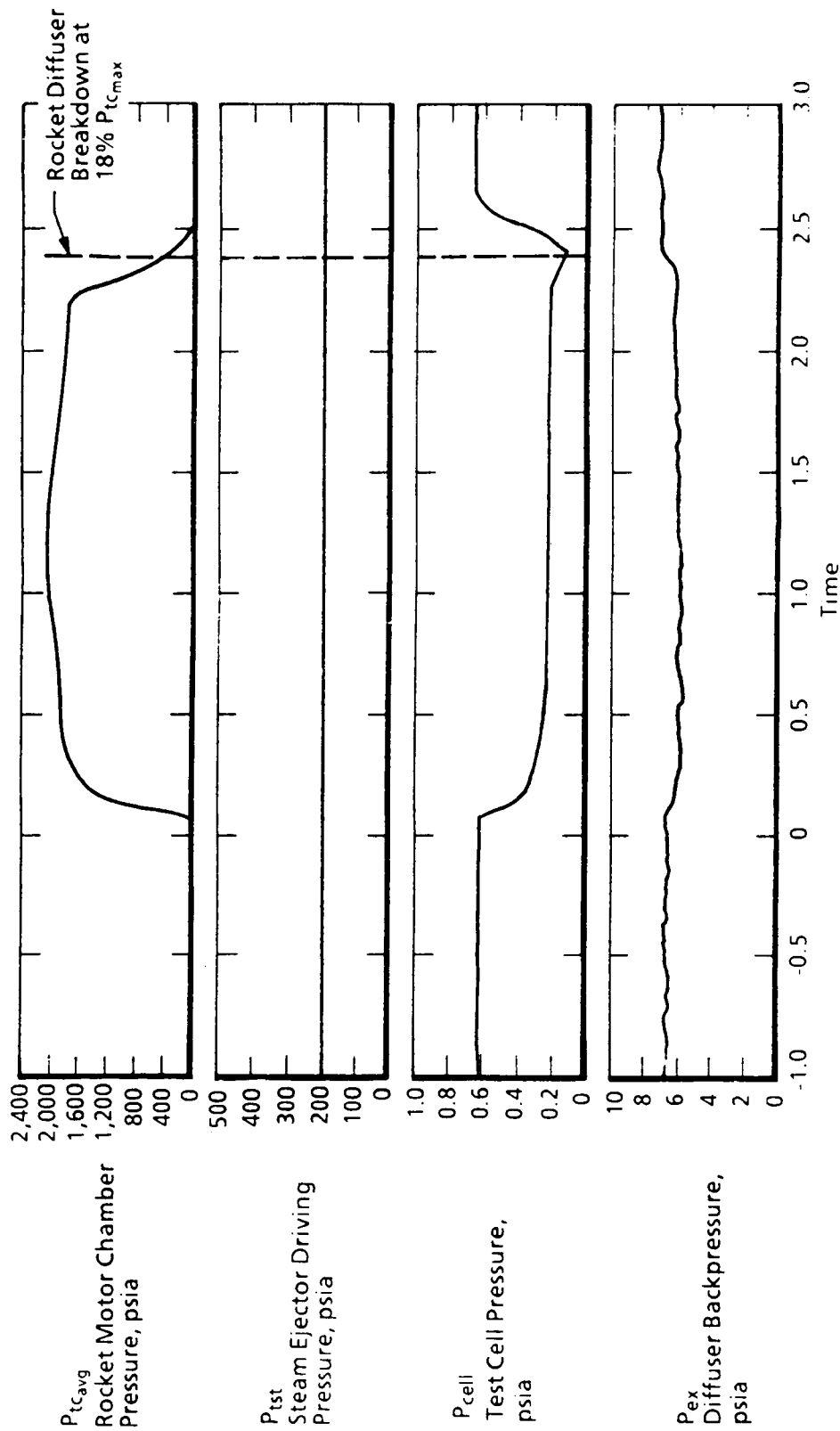


Figure 30. Rocket test results for Configuration 6 at high steam pressure and started diffuser.

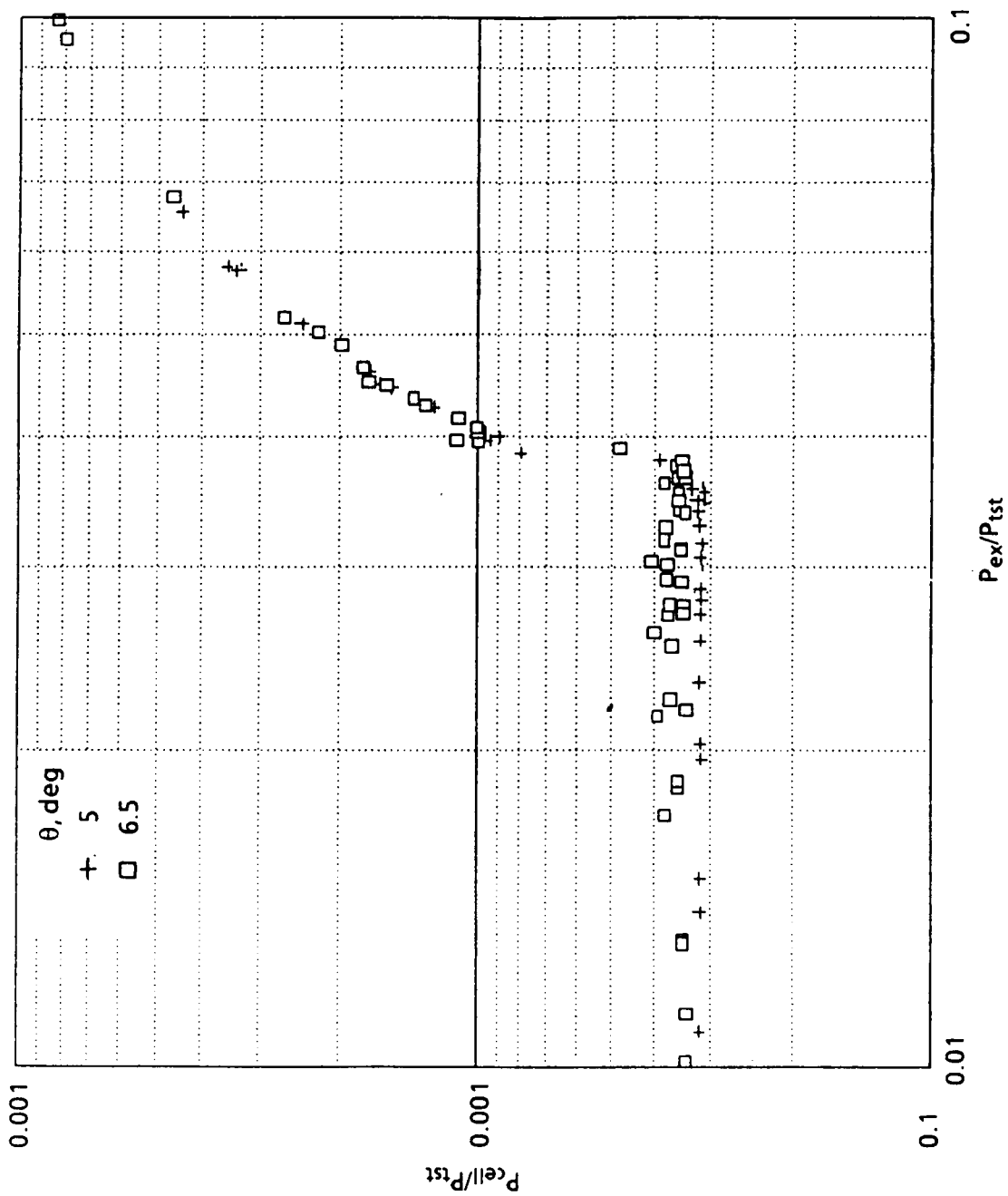


Figure 31. Effect of ramp angle on ejector breakdown curve.

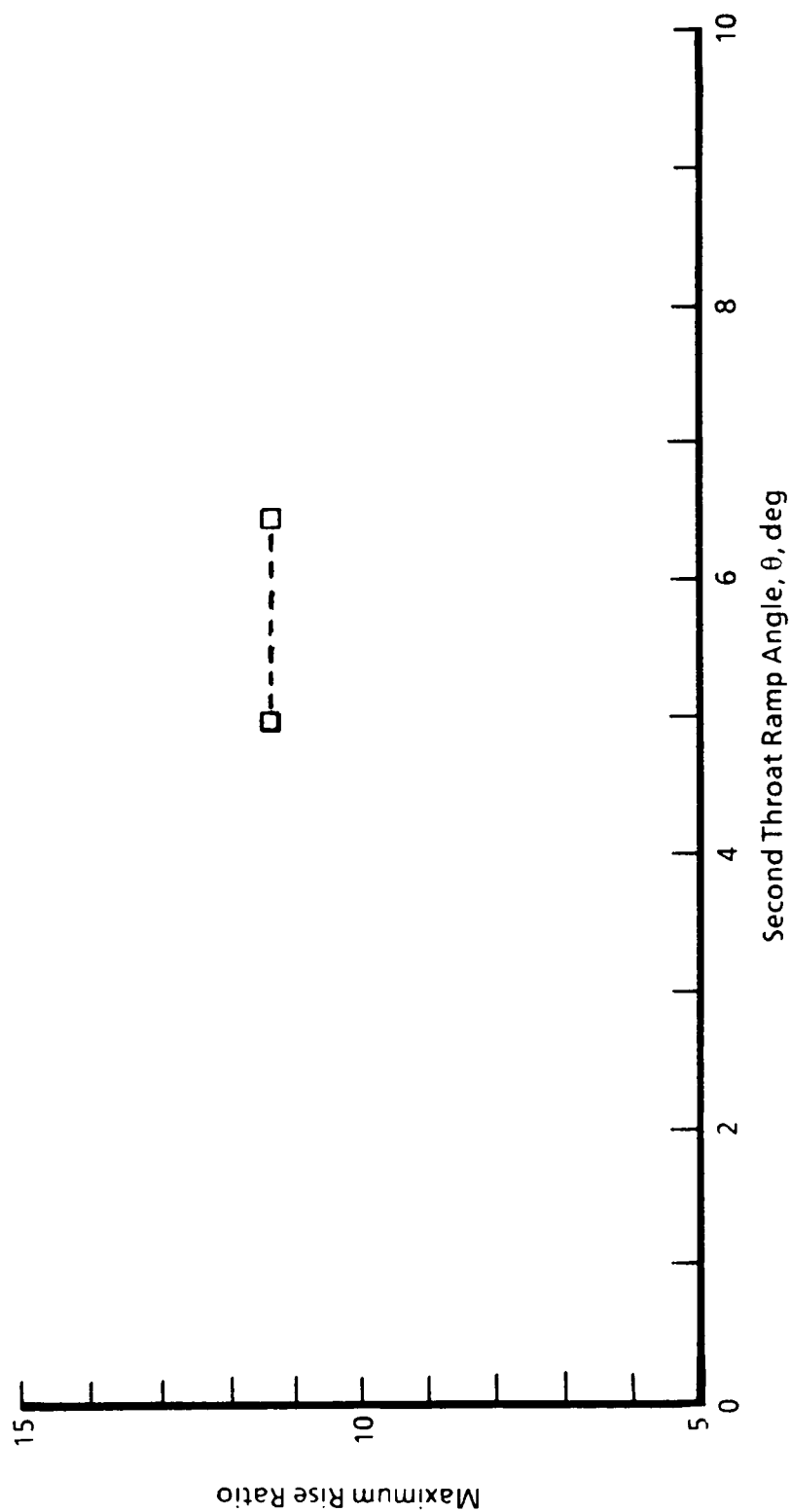


Figure 32. Effect of ramp angle on maximum rise ratio.

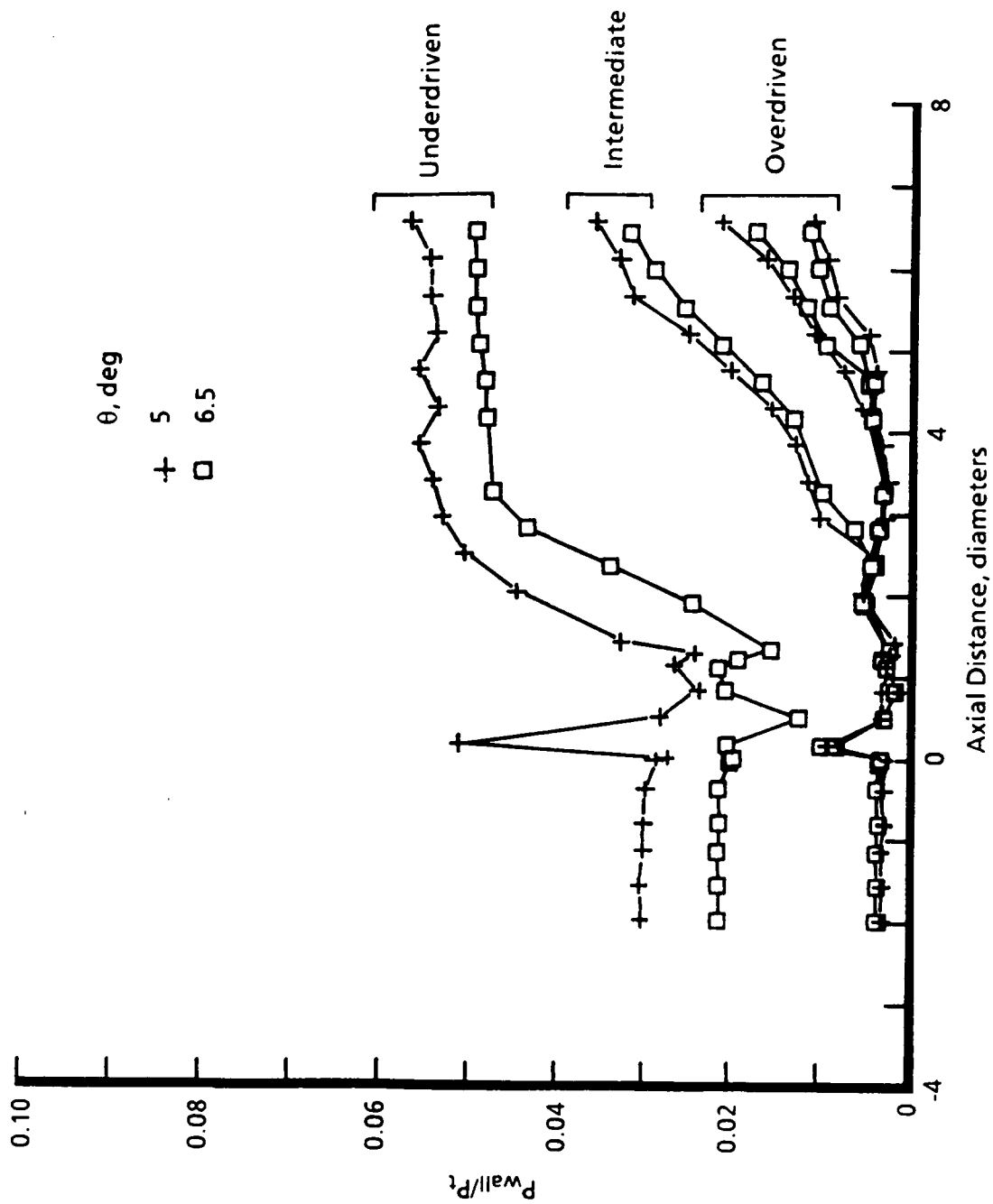


Figure 33. Effect of ramp angle on wall pressure profile.

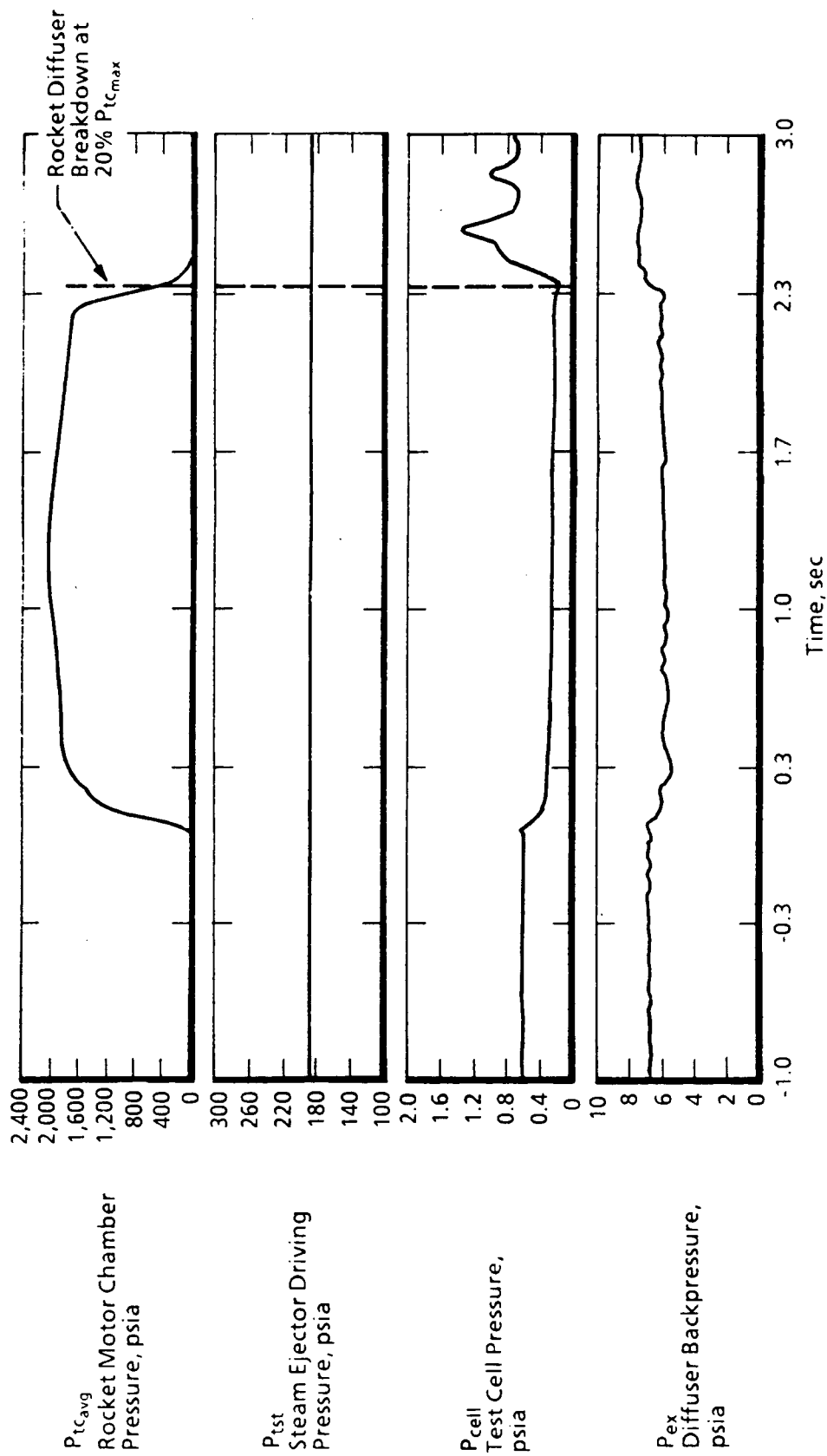


Figure 34. Rocket test results for Configuration 7 at high steam pressure and started diffuser.

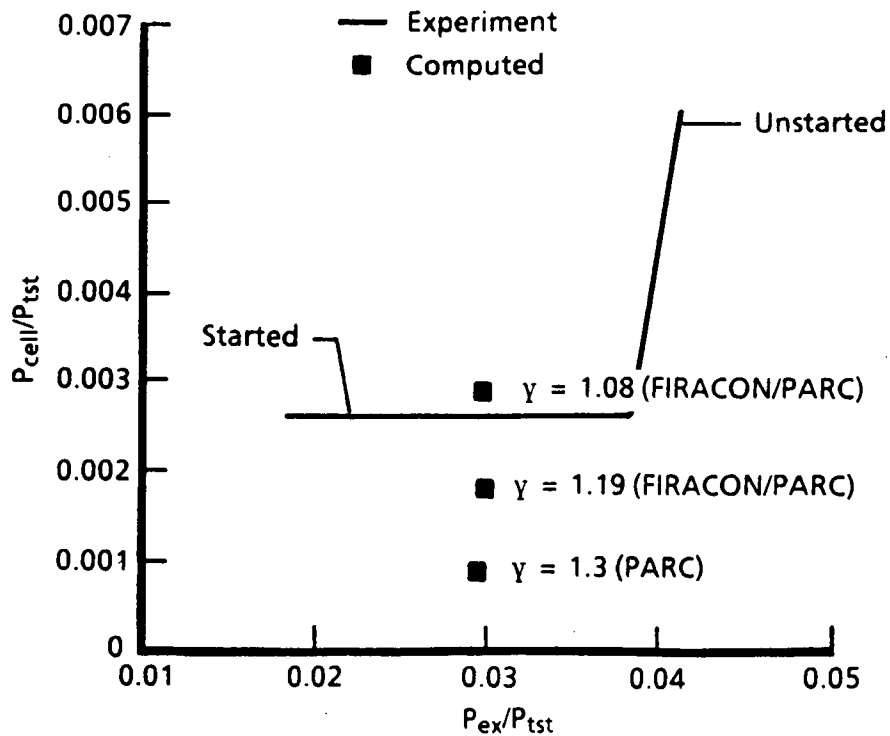
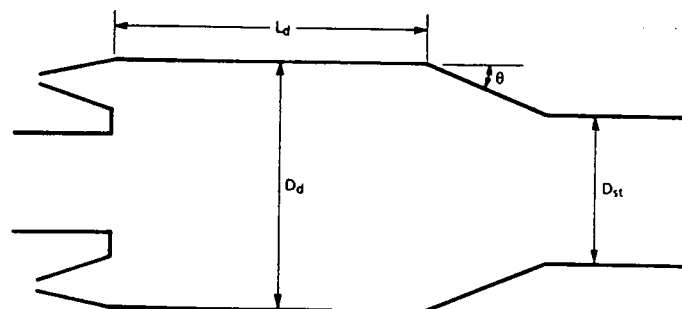


Figure 35. Analytical code calibration results.

Table 1. Ejector Configurations



Configuration Designation	L_d/D_d	A_{st}/A_d^*	Θ , deg
Baseline	1.000	0.812	5.0
2	0	0.812	5.0
3	0.333	0.812	5.0
4	0.667	0.812	5.0
5	1.333	0.812	5.0
6	1.000	0.700	5.0
7	1.000	0.812	6.5

* $A_{st}/A_d = (D_{st}/D_d)^2$

Table 2. Measurement Uncertainties*

Parameter	Description	Bias (B)	Precision (S)	Uncertainty† (U)	Range
Pcell1	Test cell pressure	±0.036 psia	±0.0017 psia	±0.007 psia	0.15 to 1.5 psia
Pcell2	Test cell pressure	±2.0	±1.0	±4.0	0.5 to 3.0 psia
Pcell3	Test cell pressure	±1.4	±0.3	±2.0	2 to 15 psia
Pwall1 - Pwall6	Rocket diffuser wall static pressure	±0.035 psia	±0.0075 psia	±0.05 psia	0.5 to 3.0 psia
Pwall7 - Pwall13	Ejector diffuser wall static pressure	±2.0	±1.0	±4.0	0.5 to 3.0 psia
Pwall14 - Pwall17	Ejector diffuser wall static pressure	±2.0	±1.0	±4.0	1 to 5 psia
Pwall18 - Pwall27	Ejector diffuser wall static pressure	±1.4	±0.3	±2.0	2 to 15 psia
Pseex	Ejector diffuser exit wall static pressure	±1.4	±0.3	±2.0	2 to 15 psia
Ptex1 - Ptex6	Ejector diffuser exit pitot pressure	±1.4	±0.3	±2.0	2 to 15 psia
Pduct1 - Pduct2	Transition duct wall static pressure	±1.4	±0.3	±2.0	2 to 15 psia
Pduct3	Exhaust duct static pressure	±1.4	±0.3	±2.0	2 to 15 psia
Ptst1 - Ptst2	Steam manifold pressure	±1.4	±0.3	±2.0	50 to 210 psia
Ptc1, Ptc2	Rocket motor chamber pressure	±2.0 ±10 psia	±1.0 ±5 psia	±4.0 ±20 psia	500 to 2,000 psia <500 psia
Ttst	Steam manifold temperature	±(0.8°F + 0.38 percent Reading)	±0.6°F	±(2.0°F + 0.38 percent Reading)	240 to 400°F

* Bias, precision, and uncertainty are all percent of reading unless otherwise noted.

† $U = (B + t_{95}S)$

Table 3. Ejector Performance Summary

Configuration Designation	$\frac{P_{ex}}{P_{cell}} \Big]_{\max}$	$\frac{P_{cell}}{P_{tst}} \Big]_{\min}$	$\frac{P_{ex}}{P_{tst}} \Big]_{bd}$	K_{isen}	K_{ns}
Baseline					
-February	12.0	0.0030	0.036	2.14	0.79
-September	11.3	0.0032	0.036	2.29	0.79
2	7.2	0.0050	0.036	3.57	0.79
3	12.7	0.0031	0.037	2.07	0.81
4	11.9	0.0031	0.037	2.21	0.81
5	10.9	0.0034	0.037	2.43	0.81
6	12.7	0.0033	0.042	2.36	0.80
7	11.9	0.0032	0.038	2.29	0.83

bd = at breakdown

Table 4. Point Correlation for Figures 9-10, 13-15

Point Label	P_{ex}	P_{tst}	P_{ex}/P_{tst}
A	2.04	189	0.011
B	2.10	103	0.020
C	2.00	60.2	0.033
D	4.22	99.1	0.043
E	4.17	63.8	0.065

VITA

Samuel Everett Stephens was born in Parkersburg, West Virginia on December 25, 1960. He attended public schools in that city, graduating from Parkersburg High School in June of 1979. He continued his education at the University of Cincinnati, Cincinnati, Ohio where in June of 1984 he received his Bachelor of Science degree in Aerospace Engineering. In September of 1985 he enrolled at the University of Tennessee Space Institute in Tullahoma, Tennessee. He received his Master of Science Degree in Aerospace Engineering from this institution in December of 1991.

During his undergraduate studies, the author accepted a co-op work study position with Sverdrup Technology, Inc., at the United States Air Force Arnold Engineering Development Center in Tullahoma, Tennessee. Following graduation, he accepted a position as an Engineer with Sverdrup in the Propulsion Test Technology Section where the work reported herein was conducted. The author currently works for Sverdrup Technology at the NASA Stennis Space Center near Bay Saint Louis, Mississippi in the Technology Development Section.

The author is a member of the American Institute of Aeronautics and Astronautics and the American Society of Mechanical Engineers.