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TECHNICAL REPORT RD-CR 82-25

AN INVESTIGATION FOR MODELING JET PLUME EFFECTS ON MISSILE AERODYNAMiCS

by:
James H. Henderson
New Technology, Inc.
4811 Bradford Dr.
Huntsville, AL 35805

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U.S. ARMY MISSILE COMMAND
Redstone Arsenal, Alabama 35809

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) Results of an investigation of concepts for modeling jet plume effects on missile aerodynamics tend to confirm the concepts proposed by Korst. Comparisons were made of afterbody pressure distributions influenced by plumes of the same shape but with different plume Mach numbers and with a solid plume. These comparisons indicate that increasing plume Mach number increases the plume effect on afterbody pressures with this effect becoming more pronounced with increasing freestream Mach number. The solid plume has the greatest effect on afterbody pressures with the effect increasing considerably at Mach numbers of 1.25 and higher.

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FOREWORD

The Army is currently engaged in a program to investigate air as a
medium for modeling propulsive jet plume interference effects on missile
aerodynamics. Past research of plume effects on stability characteristics
has indicated the presence of a beneficial effect for free rockets. The
large stable transonic pitching moment usually associated with free rockets
is undesirable because of its effect on free rocket sensitivity to low level
winds during the boost phase of flight (Refs. 1 through 3). Plume interfer-
ence can be utilized to reduce stability (or destabilize the rocket) at
transonic, low supersonic speeds while maintaining stability at the desired
supersonic speeds. Other techniques for tailoring the variation of static
margin with Mach number are discussed in Refs. 1 and 4. Several rocket sys-
tems being developed by the Army would benefit by this scheme of tailoring
the stability characteristics. However, at the present time the estimate of
plume effects on longitudinal stability cannot be made with the required
precision.

Korst (Refs. 5 and 6) has proposed a modeling concept based on match-
ing the plume shape of the rocket (prototype) and the model. He imposes the
additional condition that jet plume surface Mach number be adjusted for the
model to account for the different specific heat ratio of the prototype. A
more detailed description of this modeling concept is presented in Ref. 7.

The purpose of this investigation is to experimentally contribute
to verifying the plume modeling concepts proposed by Korst and thereby improve
prediction of simulated plume effects. The investigation consisted of two
parts: (1) investigate the plume effects of four separate nozzles with
matching plume shapes (when tested at the proper jet total pressure ratio)
but with different plume surface Mach numbers, and (2) test nozzles modeled
to match data obtained from sled tests of a rocket configuration using a
ZAP motor. In addition, a solid plume matching the four air plumes was
tested. A normal jet simulator similar to ones used in longitudinal sta-
bility tests was also tested. Wind tunnel tests were conducted using air

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to supply the jets. The tests were conducted at the Calspan 8-ft transonic wind tunnel at Mach numbers of 0.4 to 1.25 and at the NASA Langley Research Center unitary wind tunnel at Mach numbers of 1.6 to 2.5. All tests were made at an angle of attack of zero with the exception of two configurations where data were obtained at an angle of attack of -5 degrees. Some preliminary results of the transonic tests are discussed in Ref. 8.

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LIST OF SYMBOLS

A_B	Base area
A_j	Nozzle exit area
C_{RT}	Radial thrust coefficient
C_T	Thrust coefficient
D_N/D_B	Nozzle exit to base diameter ratio
M, M_∞	Freestream Mach number
M_F	Plume surface Mach number
M_{F_M}	Model plume surface Mach number
M_{F_p}	Prototype plume surface Mach number
M_j	Nozzle exit Mach number
P_∞	Freestream static pressure
P_j	Nozzle exit static pressure
P_b/P_∞	Base pressure ratio
P_C/P_b, PC/PB	Jet total pressure ratio
P_C/p	Jet total to local nozzle static pressure ratio
PL/P	Local to freestream static pressure ratio
q_∞	Freestream dynamic pressure
R/R_B	Local to base radius ratio
R_R	Radius of plume curvature in nozzle exit radii
γ_m	Specific heat ratio, model plume
γ_p	Specific heat ratio, prototype plume
γ_j	Specific heat ratio, jet exit
γ_∞	Specific heat ratio, freestream
θ_i	Initial plume angle
θ_n	Nozzle exit angle

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1.0 BACKGROUND

The Army has been interested in jet plume effects on missile aerodynamics for the past 15 years. The primary interest has been the adverse effects on longitudinal stability and control effectiveness. These effects can significantly influence the flight behavior of free rockets and missiles having simplified guidance and control systems.

A research program (Ref. 9) was started for the purpose of obtaining an understanding which would enable the avoidance or alleviation of adverse effects. The general objectives of the program were: (1) prediction of flight conditions where plume effects would occur, (2) development of wind tunnel test techniques which would adequately simulate plume effects on longitudinal stability, and (3) development of d sign techniques for avoiding problem areas and where not possible, find means of alleviating undesirable aerodynamic effects.

During this program a strut-mounted model with an axial jet and a sting-mounted force model with a normal jet plume simulator were used. Effects of nozzle geometry, afterbody geometry, body length, fin shape and size, and the longitudinal distance of the fins from the base of the model were investigated. The sting-supported model was tested at Mach numbers of 0.2 to 2.3 (Refs. 10 through 14) and the strut-supported model was tested at Mach numbers of 0.4 to 2.87 (Refs 15 through 18). Results of these tests showed base pressure to be a good indicator of the degree of plume effects present. Comparisons of base and body pressure distributions with the axial jet and the normal jet simulator were made to determine the level of plume effects that each was simulating. It was apparent from stability tests on various configurations that normal force and pitching moment coefficients varied smoothly with increased normal jet simulator chamber pressure (increased simulated plume effects) and that these characteristics were repeatable. It became apparent that design control of the variation of pitching moment with Mach number could be used to advantage in reducing the highly stable transonic pitching moments in a manner which would reduce the wind sensitivity of free rockets.

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The severity of plume effects vary with missile acceleration. Plume effects are first noticed at subsonic-transonic speeds for moderate accelerations and extend to higher Mach numbers as acceleration is increased. For a constant acceleration the region of plume influence on the missile recedes with increasing Mach number with only a small region at the base influenced at the highest Mach number. By placing fins forward of the base (on the order of 0.5 to 2.0 missile diameters) it is possible for the fins to become fully effective at the desired supersonic Mach number while the body surface near the base is still under the influence of the plume. By proper sizing and location of the fins it is possible to have some design control over the pitching moment characteristics.

In addition to wind tunnel tests, a series of sled tests were made with a ZAP rocket firing during the sled run in an attempt to verify plume effects during flight (Refs. 19 and 20). It was planned to make both force and pressure measurements during the tests. The force tests were unsuccessful but sufficient pressure data were obtained to verify the presence of jet plume effects. Most of the pressure data were influenced by sled interference but some interference free data were obtained for Mach numbers of about 1.4 to 1.6.

At the present time, tailoring the pitching moment for free rockets cannot be done as precisely as required for the optimum reduction in wind errors during boost. For improved tailoring it is necessary to know how well the actual rocket plume is being simulated in the wind tunnel. A comparison can be made between the normal jet simulator and various cold air nozzle axial jets. The remaining problem is knowing the difference between the effects of cold air axial jet (or other unheated fluid) and the actual rocket plume.

2.0 ANALYTICAL BACKGROUND

The analysis of axially symmetric supersonic flow near the center of expansion as developed by Johannesen and Meyer (Ref. 21) has been used by Korst (Refs. 5 and 6) to form the basis for plume modeling involving gases with dissimilar specific heat ratios. This analysis allows the rapid calculation of plume shapes which are approximated by a circular arc defined by the initial slope of the jet boundary (θ_i) and the radius of curvature (R_R). The first requirement of Korst's modeling technique is the geometric matching of the plume to be modeled (prototype) with the model plume. The assumption of locally conical source flow near the exit of the nozzle leads to a direct correspondence of nozzle shapes producing the same plume geometry. Thus, modeling requirements are reduced to determining the nozzle exit Mach number (M_j) and nozzle exit angle (θ_n).

Korst sets another condition in addition to the geometric matching of the plumes: the proper modeling of the closure condition for the wake is necessary. Korst suggests for consideration a choice of four specifying conditions for the wake closure of the modeling law in Ref. 5. These conditions are matching the wake recompression of the Chapman-Korst flow model, matching momentum at the corresponding plume boundaries, matching mass flux at the corresponding plume boundaries, and matching the supersonic inviscid streamline deflection-pressure rise relation on the basis of local linearization. In Ref. 7, Korst and Deep recommend the final specifying condition which requires that

$$\frac{\gamma_M \, M_{F_M}^2}{(M_{F_M}^2 - 1)^{1/2}} = \frac{\gamma_P \, M_{F_P}^2}{(M_{F_P}^2 - 1)^{1/2}} \tag{1}$$

where γ is specific heat ratio, M_F is the plume surface Mach number, and the subscripts M and P represent the model and prototype, respectively.

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Although the circular arc approximation starts to diverge from the actual plume shape after about one nozzle radius, the analysis of Ref. 21 provides the second-order initial conditions necessary for the calculation of the plume boundary by the method of characteristics (Ref. 22). Thus, it is possible to obtain accurate plume matching well beyond the validity of the circular arc approximation. (See the plume comparisons of Ref. 5.)

3.0 TEST CONCEPT

The purpose of the tests was to verify the plume modeling concepts proposed by Korst. By using the simplified method for rapid determination of plume shape, it was possible to determine families of nozzles which produce identical plume shapes when operating at the proper jet total pressure (P_c/P_b). Since the plume surface Mach number (M_F) would differ for each nozzle, the validity of wake closure conditions could be investigated with the use of only one jet gas. With the specific heat ratio constant, the direct effect of plume surface Mach number on afterbody flow could be investigated. An investigation to verify the plume modeling concept using dissimilar propellant gases is now in progress in Sweden (Ref. 23).

The exit geometry of four nozzles were determined which would give matching plume shapes at the desired (design) pressure ratio. An initial plume angle of 42 deg was selected to insure a plume having characteristics which would cause flow interference. The matching plume geometry and the characteristics of the four nozzles are given in Table 1.

Table 1 Plume Geometry and Nozzle Characteristics

M_J	θ_n	DESIGN P_c/P_b	M_F	R_R
1.7	9.1	39.6	3.05	3.734
2.0	13.6	55.14	3.274	3.739
2.4	19.35	82.44	3.555	3.739
2.7	23.3	108.2	3.750	3.734

The plumes of the four nozzles match only at the proper value of chamber to base pressure ratio. With a change of chamber pressure from the "design point," the radius of curvature changes slightly for matching values of initial plume angle (Fig. 1). Comparisons of plumes with matching initial angles several degrees off of the design value should be valid.
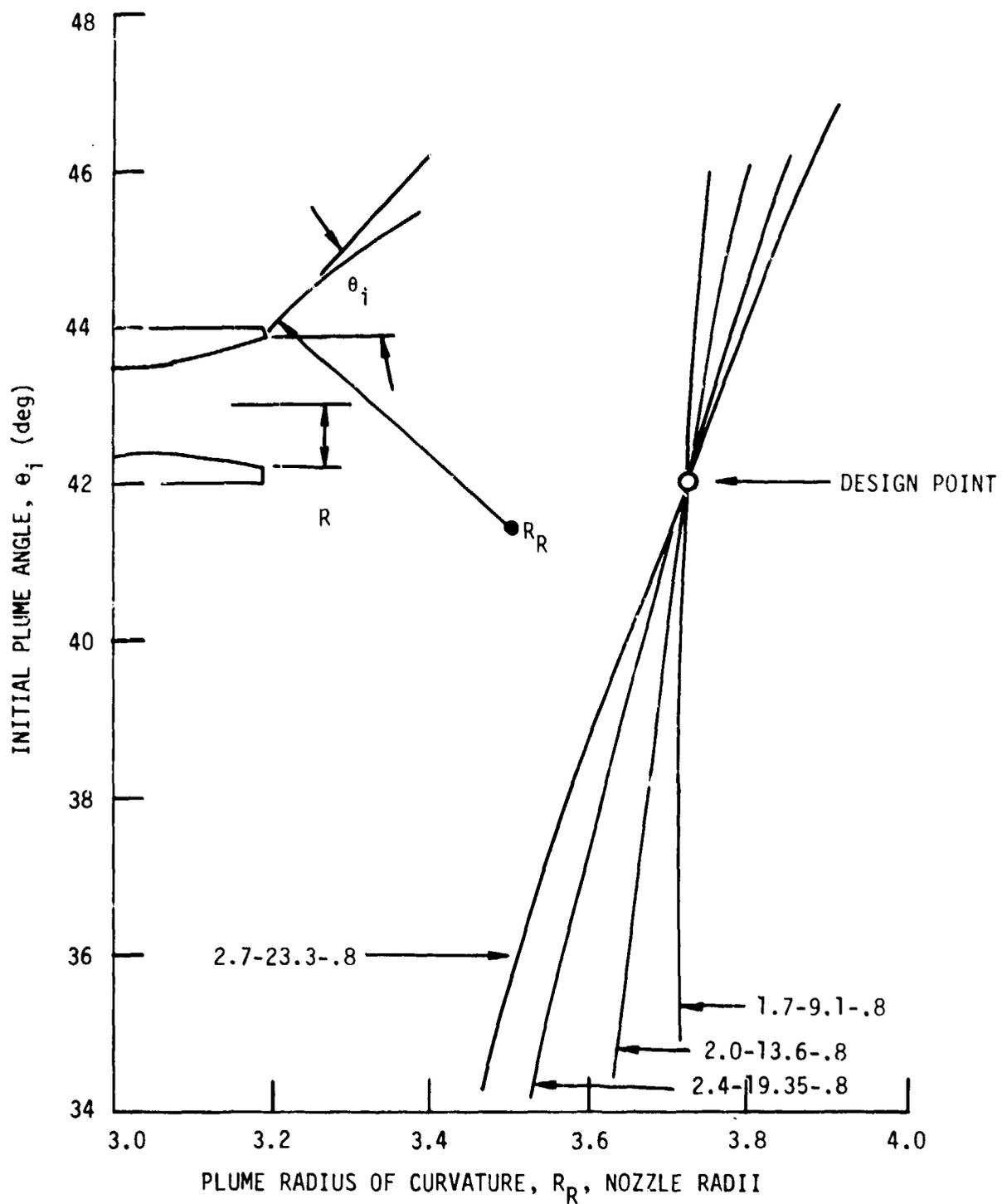
Fig. 1 Effect of Being Off Design Point on Initial Plume Geometry

In addition to the four nozzles a solid plume was investigated. The plume shape was determined by the method of characteristics and matched the plume shape produced by the four nozzles at the "design point." By comparing the effects of the solid plume on afterbody pressures with the effects of the four nozzles, a measure of plume flexibility may be determined. The solid plume represents a plume with infinite stiffness (Ref. 8).

The second part of the investigation of plume modeling techniques consisted of an attempt to model the plume effects of the ZAP rocket motor. The Army Missile Command has recently been involved in sled tests where ZAP motors were fired. The sled was accelerated to low supersonic Mach numbers with the rocket being ignited at various sled velocities. The sled test configuration had an ogive nose and was strut mounted on the sled with a boundary layer plate between the sled and the model. The first series of tests used the same rocket diameter as the ZAP vehicle (6.13 in). The second series of tests had diameters of 7 in. Both afterbody and base pressure measurements were made. An unsuccessful attempt was made to also measure aerodynamic forces on the 7-in model. A complete description of the sled test is given in Refs. 19 and 20.

In order to model the ZAP plume effects it was necessary to determine nozzle exit conditions. The Solid Propellant Equilibrium Chemistry Program utilized for this purpose gave an exit Mach number of 2.53 and a ratio of specific heats at a nozzle exit of 1.235. ZAP nozzle has an exit cone angle of 10.36 deg. The measurable thrust obtained during the sled tests varied between about 10,000 to 27,000 lb. For plume modeling purposes a thrust of about 19,000 lb was chosen. At this thrust the ZAP (prototype) has a plume Mach number (M_E) of 3.35, an initial plume angle of 32.31 deg, an initial plume radius of curvature of 5.427, and a chamber to base pressure ratio of 83.1. Using the streamline deflection closure condition [Eq. (1)], a plume Mach number for the ZAP model was determined to be 2.906. It was determined that the model (air) nozzle would have an exit Mach number of 1.76 and an exit angle of 3.95 deg, and would match the prototype plume when the chamber to base pressure ratio was 39.1. Model nozzles were fabricated to match both the 6.13-in and 7.0-in diameter sled vehicles having nozzle to base diameter ratios (D_N/D_B) of 0.8 and 0.93, respectively.

Since the nozzles of this investigation have short divergent sections, the supersonic flow can be significantly affected by throat geometry. A program was written by Korst (Ref. 24) where throat curvature could be determined which would give flow conditions approaching the nozzle lip that were close to ideal conical source flow. This program uses transonic flow field solutions near the throat, suggested by a combination of the Oswattitch-Rothstein (Ref. 25) and Sauer (Ref. 26) analysis followed by the method of characteristics.

A normal jet plume effects simulator has been utilized by the Army Missile Command to obtain stability characteristics on several missile and free rocket configurations (e.g., Refs. 10 through 14). The normal jet simulator is advantageous because of the comparatively low mass flow required to simulate jet effects and because of the absence of unintended interference with the model flow field. A normal jet simulator was tested so that its relationship with the modeled plumes could be investigated.

4.0 APPARATUS AND TESTS

4.1 WIND TUNNELS

Tests were conducted in the Calspan Corporation 8-ft transonic wind tunnel and the NASA Langley Research Center unitary plan facility.

The Calspan 8-ft transonic wind tunnel is a continuous flow, variable density facility. The maximum clear tunnel Mach number is 1.30. The tunnel may be operated at stagnation pressures from 0.10 to 3.25 atmospheres to provide a variation of Reynolds number independent of Mach number. A detailed description of the tunnel is presented in Ref. 27.

The supersonic tests were conducted in the low-speed circuit of the unitary plan wind tunnel. This facility is a continuous circuit wind tunnel with a 4 x 4 ft test section capable of operating at stagnation pressures up to 60 psia and at Mach numbers of 1.50 to 2.87. A detailed description of the facility is given in Ref. 28.

4.2 MODEL

The model was a 2.5-in diameter body of revolution having a four-caliber tangent ogive nose followed by a cylinder. The model was 32.5-in long with the aft 8.55 in of the cylinder consisting of interchangeable afterbodies. A strut support was used to mount the model to the wind tunnel support system. The strut was ducted internally to supply high pressure air to the model chamber. Pressure instrumentation was also routed through the strut.

A drawing of the model installed in the Calspan 8-ft transonic wind tunnel is shown in Fig. 2. A photograph of the model in the Langley Research Center unitary plan facility is shown in Fig. 3. In the Langley facility the model was arranged in the test section so that the support strut was 30 deg above the horizontal. The sting support system was offset to the right side of the model center line.
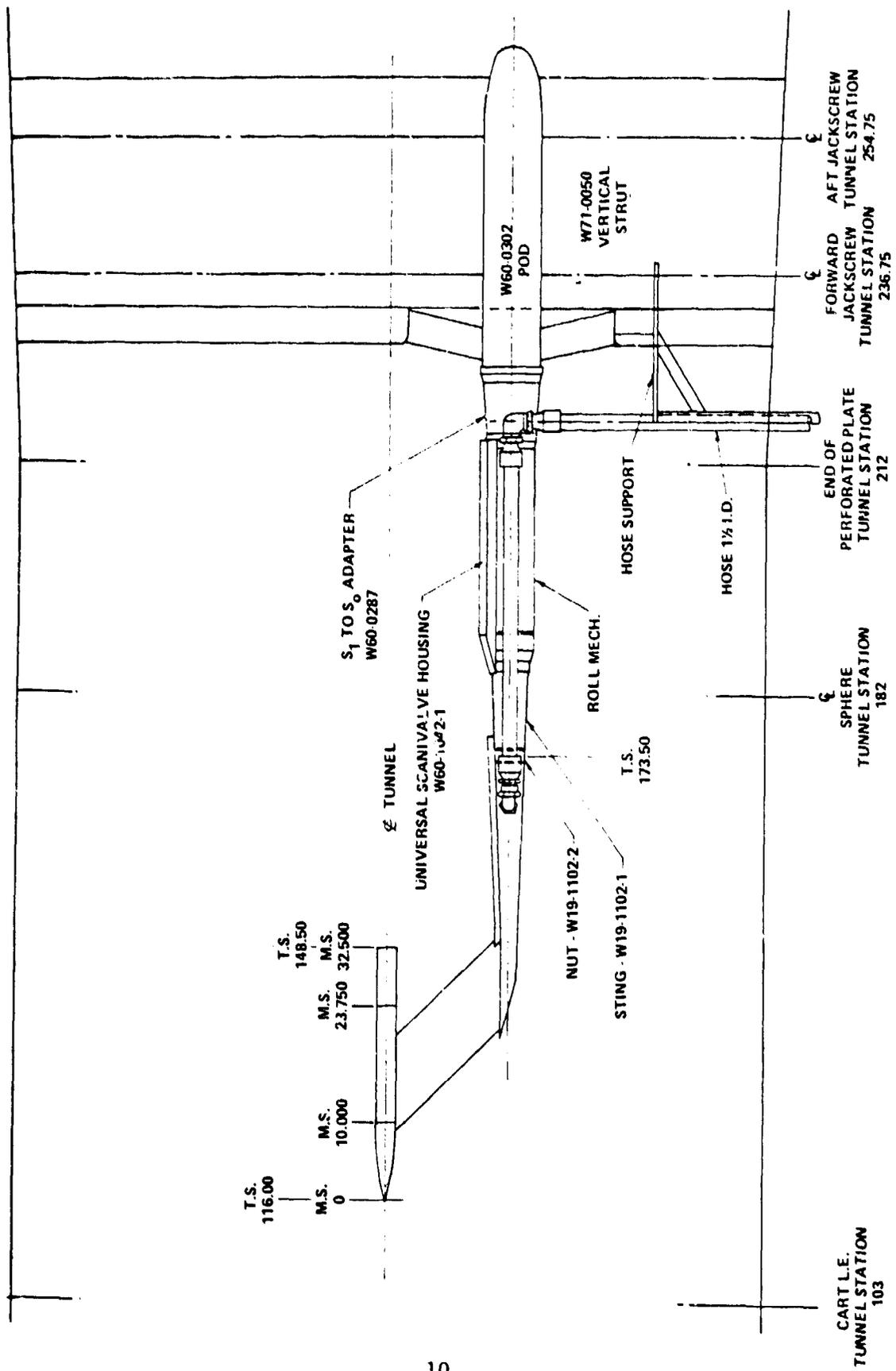
Fig. 2 Installation Drawing of Model in The Calspan 8-ft Transonic Wind Tunnel
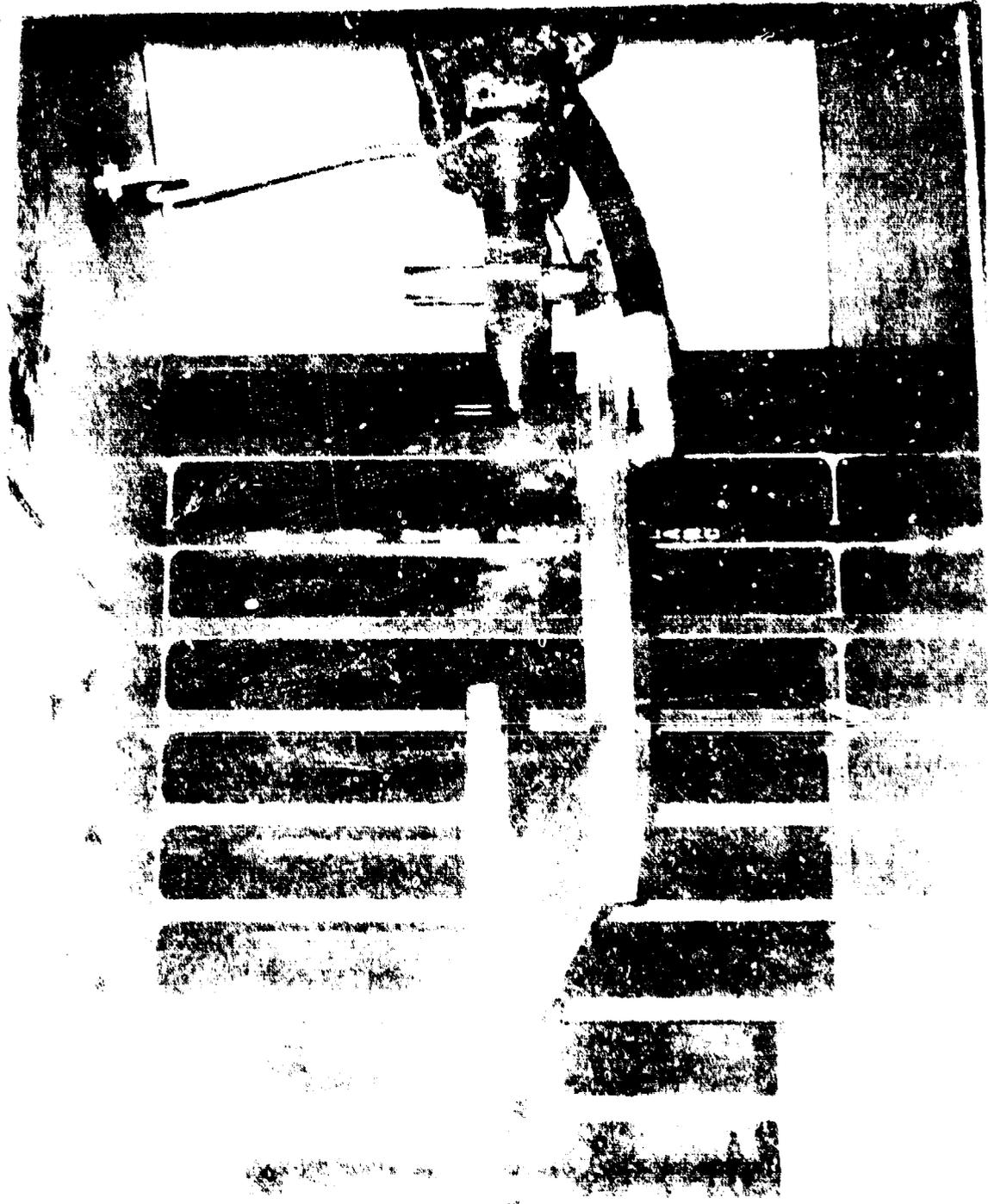
Fig. 3 Photograph of the Model in the NASA Langley Research Center Unitary Plan Wind Tunnel

Seven afterbodies were built by Calspan for the present tests. On each afterbody 10 external static pressure orifices were installed in a single row 180 deg from the strut. A manifold of three base pressure orifices was installed in the upper quadrant of each afterbody.

Four of the afterbodies incorporated nozzles designed to produce congruent plumes when operating at the proper jet pressure ratio (Fig. 1). Two additional afterbodies contained nozzles designed to model the plume effects of the ZAP rocket on both the 6.12- and 7.0-in diameter sled configurations. The afterbodies had nozzle exit to base diameter ratios (D_N/D_B) of 0.8 except the nozzle modeling the 7.0-in diameter sled configurations. This afterbody had a base diameter ratio of 0.93. Each nozzle had four static pressure orifices on the nozzle wall opposite the support strut.

The final afterbody was built to hold the solid plume and the normal jet simulator. This afterbody had the same distribution of external pressure orifices as the nozzle afterbodies. The solid plume was designed to match the size and shape of the plumes of the four nozzles previously mentioned. The normal jet simulator consists of 24 sonic nozzles arranged circumferentially in two rows with a common air chamber. Air is supplied to the chamber through the model. The combined exit area of the 24 nozzles represented 6% of the model base area. (The geometry of the normal jet simulator is proportional to the normal jet simulators used on sting supported model tests. In these tests the simulator was mounted on the sting and air was supplied from the rear.)

Details of the various afterbodies are presented in Fig. 4. Orifice locations in terms of model diameters from the base are presented in Table 2. Due to the lack of test time, the internal orifices on the two ZAP model nozzles were not connected.

4.3 TESTS

The model was tested at zero angle of attack except for a few runs at transonic speeds where the model was pitched to -5 deg angle of attack. During a run Mach number was held constant and jet chamber total pressure was varied up to about 600 psia. Where matching plumes were desired, the P_c/P_b value was set on or near the "design point" with additional data points close to the design point. No transition grit was applied to the model.

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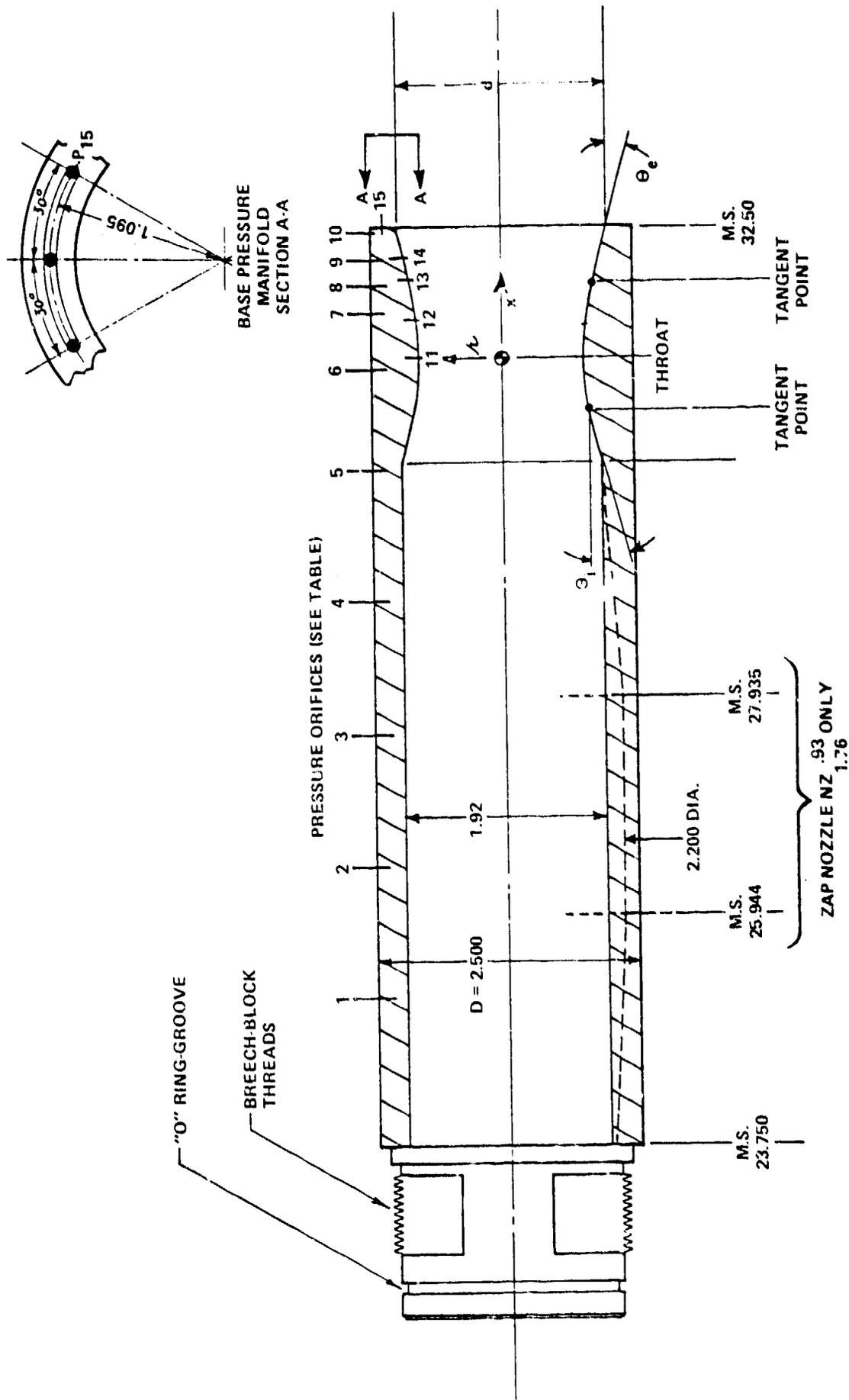
a. TYPICAL NOZZLE CONFIGURATION

Fig. 4 Configuration Description

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AFTERBODY EXTERNAL ORIFICES (ALL NOZZLES)

ORIFICE NO.:	1	2	3	4	5
MODEL STA.:	25.188	26.458	27.638	28.938	30.188
ORIFICE NO.:	6	7	8	9	10
MODEL STA.:	31.128	31.688	31.938	32.188	32.438
ORIFICE NO.:	15 ^{b}				
MODEL STA.:	32.500 (BASE MANIFOLD)				

NOZZLE INTERNAL ORIFICES

M = 1.7 CONICAL NOZZLE $NC^{.8}_{1.7}$

ORIFICE NO.:	11	12	13	14
NOZZLE STA.:	0	0.25	0.75	1.00
MODEL STA.:	31.3611	31.6111	32.1111	32.3611

M = 2.0 CONICAL NOZZLE $NC^{.8}_{2.0}$

ORIFICE NO.:	11	12	13	14
NOZZLE STA.:	0	0.375	0.750	1.125
MODEL STA.:	31.245	31.620	31.995	32.370

M = 2.4 CONICAL NOZZLE $NC^{.8}_{2.4}$

ORIFICE NO.:	11	12	13	14
NOZZLE STA.:	0	0.375	0.75	1.125
MODEL STA.:	31.1668	31.5418	31.9168	32.2918

M = 2.7 CONICAL NOZZLE $NC^{.8}_{2.7}$

ORIFICE NO.:	11	12	13	14
NOZZLE STA.:	0	0.500	1.000	1.250
MODEL STA.:	31.0509	31.5509	32.0509	32.3009

SMALL ZAP NOZZLE $NZ^{.8}_{1.76}$

ORIFICE NO.:	11	12	13	14
NOZZLE STA.:	0	0.500	1.375	2.375
MODEL STA.:	29.9978	30.4978	31.3728	32.3728

LARGE ZAP NOZZLE $NZ^{.93}_{1.76}$

ORIFICE NO.:	11	12	13	14
NOZZLE STA.:	0	0.75	1.75	2.75
MODEL STA.:	29.5014	30.3514	31.3514	32.3514

b. PRESSURE ORIFICE LOCATIONS

Fig. 4 Configuration Description (Continued)

NC .3 / 1.7		NC .8 / 2.0		NC .8 / 2.4		NC .8 / 2.7	
d = 2.0000		d = 2.0000		d = 2.000		d = 2.000	
d/D = 0.80		d/D = 0.80		d/D = 0.80		d/D = 0.80	
θ_i = 7.5°		θ_i = 15°		θ_i = 15°		θ_i = 15°	
θ_e = 9.10°		θ_e = 13.60°		θ_e = 19.35°		θ_e = 23.30°	
x	r	x	r	x	r	x	r
-.9560	.9600①			-1.3681	.9600①		
-.4889	.8985②	-1.0061	.9600①	-.4914	.7251②		
-.4510	.8939	-.4944	.8229②	-.4537	.7169		
-.4137	.8898	-.4535	.8159	-.4177	.7093		
-.3768	.8860	-.4133	.8096	-.3823	.7025		
-.3401	.8826	-.3736	.8039	-.3476	.6963	-1.5954	.9600①
-.3035	.8795	-.3341	.7987	-.3129	.6907	-.5210	.6721②
-.2666	.8767	-.2943	.7941	-.2785	.6857	-.4361	.6537
-.2299	.8743	-.2547	.7901	-.2435	.6812	-.3596	.6396
-.1922	.8722	-.2138	.7865	-.2089	.6773	-.2867	.6284
-.1282	.8695	-.1425	.7817	-.1724	.6738	-.2158	.6199
-.0641	.8679	-.0713	.7788	-.0862	.6681	-.1414	.6134
0	.8674③	0	.7778③	0	.6562③	0	.6085③
.0641	.8679	.0713	.7788	.0862	.6681	.1414	6134
.1282	.8695	.1425	.7817	.1724	.6738	.2158	.6199
.1922	.8722	.2138	.7865	.2089	.6773	.2867	.6284
.2299	.8743	.2547	.7901	.2435	.6812	.3596	.6396
.2660	.8767	.2943	.7941	.2785	.6857	.4361	.6537
.3035	.8795	.3341	.7987	.3129	.6907	.5210	.6721
.3401	.8826	.3736	.8039	.3476	.6963	.6201	.6968
.3768	.8860	.4133	.8096	.3823	.7025	.7445	.7325
.4137	.8898	.4535	.8159	.4177	.7093	.9118	.7872
.4510	.8939	4944	.8229	.4527	.7169	1.1533	.8771
.4889	.8985	.5615	.8355	.4914	.7251	1.4138	.9848④
.5276	.9035	.6596	.8564	.5252	.7342	1.4491	1.0000⑤
.5673	.9090	.7125	.8688④	.5696	.7444		
.6084	.9152	1.2550	1.0000⑤	.6121	.7558		
.6408	.9202④			.6577	.7687		
1.1389	1.0000⑤			.7071	.7835		
				.7608	.8004		
				.8194	.8199		
				8620	.8346④		
				1.3332	1.0000⑤		

① NOZZLE ENTRANCE
② UPSTREAM TANGENT POINT
③ THROAT
④ DOWNSTREAM TANGENT POINT
⑤ NOZZLE EXIT

NOZZLE IS CONICAL BETWEEN ① AND ② , AND BETWEEN ④ AND ⑤ , AT HALF ANGLES OF θ_i AND θ_e, RESPECTIVELY.

c. CONICAL NOZZLE COORDINATES

Fig. 4 Configuration Description (Continued)

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NZ $\frac{.8}{1.76}$		NZ $\frac{.93}{1.76}$	
d = 2.0000		d = 2.3168	
d/D = .80		d/D = .9267	
Θ_i = 5°		Θ_i = 5°	
Θ_e = 3.95°		Θ_e = 3 95	
x	r	x	r
-1.6018	.9600①		
- .4588	.8600②		
- .4088	.8575	-1.2483	1.1000①
- .3609	.8553	- .4181	.9908②
- .3145	.8535	- .3643	.9887
- .2690	.8519	- .3116	.9868
- .2243	.8506	- .2598	.9854
- .1800	.8496	- .2085	.9842
0	.8478③	0	.9819③
.1800	.8496	.2085	.9842
.2243	.8506	.2598	.9854
.2690	.8519	.3116	.9868
.3145	.8535	.3643	.9887
.2609	.8553	.4181	.9908
.4088	.8575	.4736	.9933
.4588	.8600	.5315	.9962
.5115	.8629	.5925	.9996
.5678	.8665	.6577	1.0037
.5998	.8686④	.6948	1.0062④
2.5022	1.0000⑤	2.8986	1.1584⑤

① NOZZLE ENTRANCE

② UPSTREAM TANGENT POINT

③ THROAT

④ DOWNSTREAM TANGENT POINT

⑤ NOZZLE EXIT

NOTE: INLET SECTION AHEAD OF NZ $\frac{.93}{1.76}$ NOZZLE IS EXPANDED TO 2.200 IN. DIA. — SEE SKETCH

d. ZAP NOZZLE COORDINATES

Fig. 4 Configuration Description (Continued)

SOLID PLUME SIMULATOR
COORDINATES

x	r
.000	1.009
.235	1.200
.364	1.300
.501	1.400
.806	1.600
1.160	1.800
1.565	2.000
1.790	2.100
2.302	2.300
2.588	2.400
2.902	2.500
3.249	2.600
3.640	2.700
4.081	2.800
4.585	2.900
5.189	3.000
5.591	3.100
7.028	3.190
8.535	3.216

6.432R

2.90

9.535
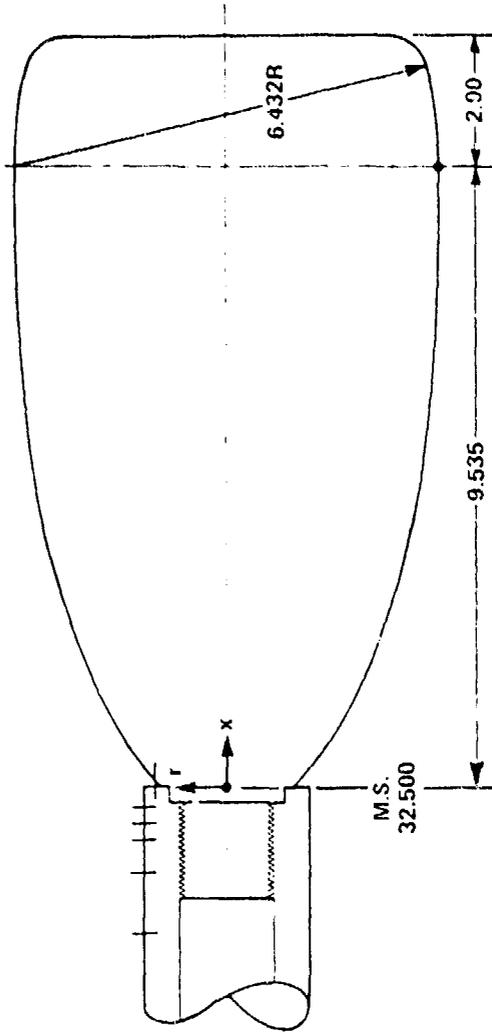
S₂ SOLID PLUME SIMULATOR

M.S.
32.500
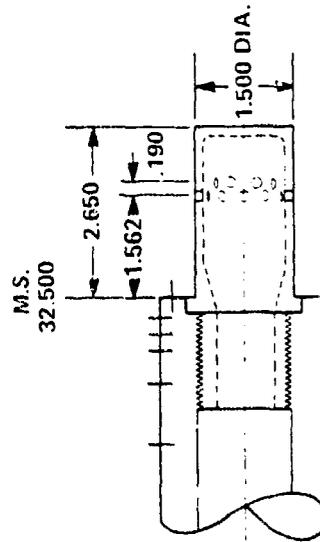
NOTE: SAME AFTERBODY USED TO ATTACH
BOTH PLUME SIMULATORS.

EXTERNAL PRESSURE ORIFICE PATTERN
SAME AS ON NOZZLE AFTERBODIES.

M.S.
32.500

2.650

1.562

.190

1.500 DIA.

S₁ NORMAL JET PLUME SIMULATOR

e. PLUME SIMULATORS

Fig. 4 Configuration Description (Continued)

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Table 2   Orifice Locations (X/D Forward of Base)

BASE AND AFTERBODY ORIFICE LOCATIONS

ORIFICE NO.	X/D (CALIBERS FORWARD OF BASE)
15	0.000 (BASE)
10	0.025
9	0.125
8	0.225
7	0.325
6	0.551
5	0.925
4	1.425
3	1.945
2	2.417
1	2.925

NOZZLE ORIFICE LOCATIONS

TAP	1.76-3.95-.8 X/D	R/R_B	1.76-3.95-.8 X/D	R/R_B	1.7-9.1-.8 X/D	R/R_B
14	0.051	0.7955	0.059	0.9279	0.056	0.7827
13	0.451	0.7417	0.459	0.8822	0.156	0.7501
12	0.801	0.6898	0.859	0.8081	0.356	0.7005
11	1.001	0.6782	1.159	0.7855	0.456	0.6939
TAP	2.0-13.6-.8		2.4-19.35-.8		2.7-23.3-.8	
14	0.052	0.7780	0.083	0.7436	0.080	0.7328
13	0.202	0.7024	0.233	0.6375	0.180	0.6550
12	0.352	0.6433	0.383	0.5610	0.380	0.5338
11	0.502	0.6222	0.533	0.5330	0.580	0.4868

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The transonic test was run at constant mass operating conditions of 1/3 atmosphere wind-off pressure. Mach number varied between 0.4 and 1.25 and Reynolds number varied between about 0.8 to 2.0 million/ft. Several data points were obtained with zero tunnel velocity. A complete description of the transonic tests is given in Ref. 29. Mr. C.F. Reid was the Project Manager for tests in the Calspan Corporation Transonic Wind Tunnel.

The supersonic tests were performed over a Mach number range from 1.6 to 2.5. Only one run was made at a Mach number of 1.6 due to the plume choking the tunnel flow. A Mach number of 1.65 was subsequently tested as the minimum Mach number. The tunnel stagnation pressure varied from about 1080 lb/ft^2 to about 1600 lb/ft^2. The Reynolds number was held constant at 2.0 million/ft. The dewpoint was maintained sufficiently low to insure negligible condensation effects. Mr. Peter F. Covell was the Project Manager for the tests in the Langley Research Center unitary plan facility.

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5.0 MODEL NOMENCLATURE

Where data from nozzle configurations are compared the more descriptive
nomenclature used in previous Army Missile Command reports will be used. This
nomenclature is designated by $M_J-\theta_N-D_N/D_B$ where M_J represents jet exit Mach
number, θ_N represents nozzle exit angle and D_N/D_B represents the nozzle exit
to model base diameter ratio. For example, the large ZAP nozzle is designated
as 1.76-3.95-.93. Results of the present tests have been stored in the Army
Missile Command Aerodynamic Analyzer System data base. This system was used
to make plots of the basic data. A 5- or 6-character designation was used to
identify configurations and are used on the plots of the basic data in
Appendix A. A different model designation was used by Calspan. Figures 2
through 4 were reprinted from Ref. 29 and the Calspan designation is used.
A comparison of the three designations are given in Table 3.

Table 3 Model Nomenclature

PRESENT REPORT $M_J-\theta_N-D_N/D_B$	MICOM AAS DATA BASE	CALSPAN (REF. 28)
1.7-9.1-.8	B1AZ43	NC $\frac{.8}{1.7}$
2.0-13.6-.8	B1AZ44	NC $\frac{.8}{2.0}$
2.4-19.35-.8	B1AZ45	NC $\frac{.8}{2.4}$
2.7-23.3-.8	B1AZ46	NC $\frac{.8}{2.7}$
1.76-3.95-.8	B1AZ41	NZ $\frac{.8}{1.76}$
1.76-3.95-.93	B1AZ42	NZ $\frac{.93}{1.76}$
NORMAL JET	B1AJ2	S1
SOLID PLUME	B1AS3	S2

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6.0   RESULTS AND DISCUSSION

The basic results of this investigation are presented in Appendix A.
Typical distributions of base and afterbody pressures are shown for various
jet total pressure ratios (P_c/P_b) for each test configuration at both transonic
and supersonic speeds.

As previously mentioned, four nozzle were built which were designed
to give the same plume shape when operating at the proper jet total pressure
ratio. The design jet total pressure ratio and the resulting plume Mach
number for these nozzles are as follows:

NOZZLE	P_c/P_b	M_F
1.7-9.1-.8	39.6	3.05
2.0-13.6-.8	55.14	3.274
2.4-19.35-.8	82.44	3..55
2.7-23.3-.8	108.2	3.75

Pressure distributions of the four nozzles at the "design" pressure
ratio are compared to the solid plume (with the same shape) in Fig. 5.
Generally at Mach numbers of one or less, there is little effect of plume
surface Mach number on afterbody pressures. However, there is a tendency
for the plumes with higher surface Mach numbers to cause higher pressures,
and plumes with lower surface Mach numbers to cause lower pressures. The
solid plume generally results in the highest pressures. With increasing
Mach number the effect of plume Mach number increases and solid plume
distribution diverges more from the air nozzle data. At the supersonic Mach
numbers there is a significant difference between the various nozzles and the
solid plume. In general, plume surface Mach number can be related to plume
flexibility (or stiffness) with the solid plume representing zero flexibility
(Ref. 8).
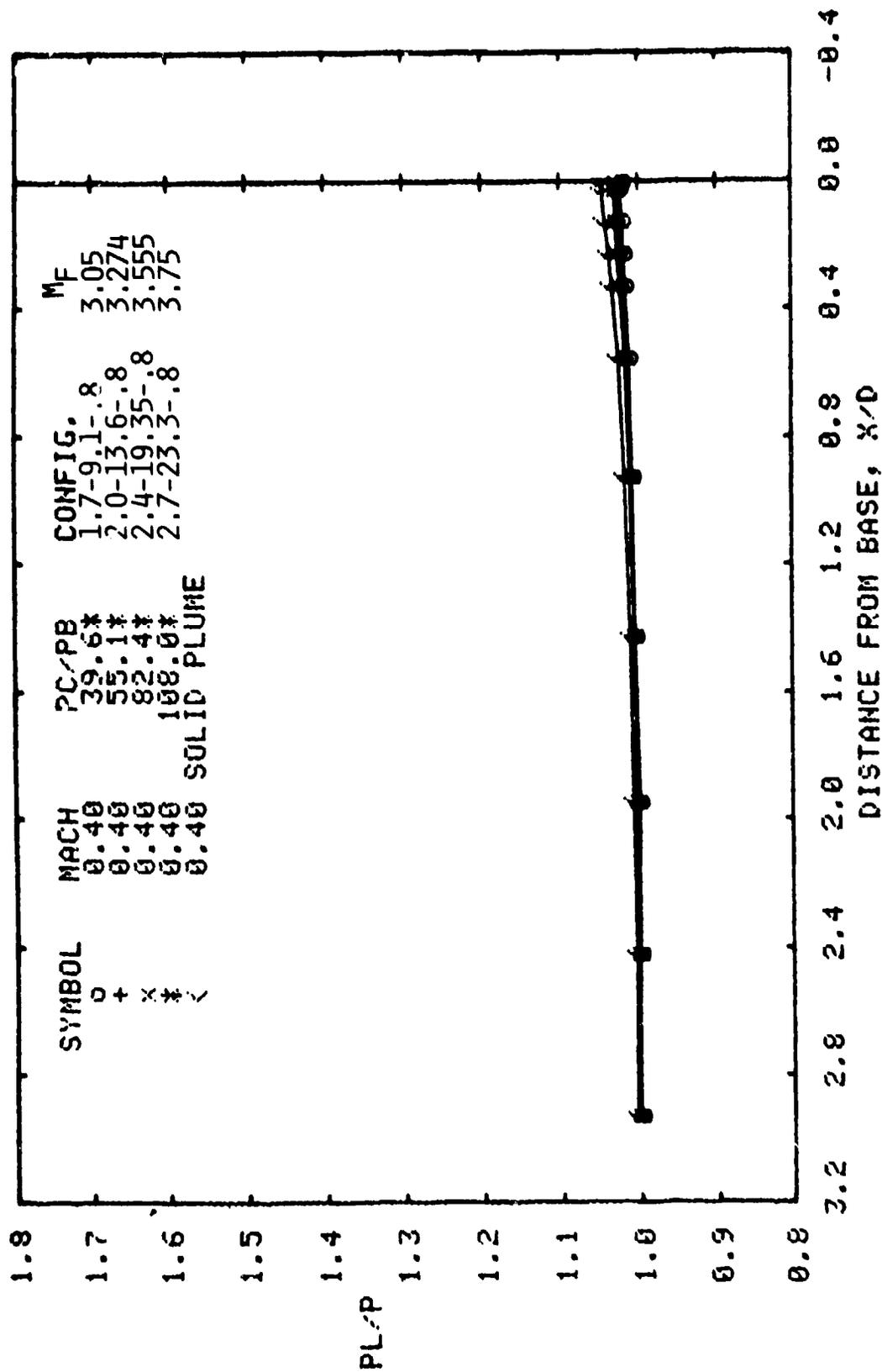
23

PL/P

1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8

3.2 2.8 2.4 2.0 1.6 1.2 0.8 0.4 0.0 -0.4

DISTANCE FROM BASE, X/D

SYMBOL	MACH	PC/PB	CONFIG.	M_F
O	0.40	39.6*	1.7-9.1-.8	3.05
+	0.40	55.1*	2.0-13.6-.8	3.274
x	0.40	82.4*	2.4-19.35-.8	3.555
*	0.40	108.0*	2.7-23.3-.8	3.75
⌄	0.40	SOLID PLUME		

Fig. 5   Comparison of Pressure Distributions of the Four Nozzles at the
Design Pressure Ratio and a Solid Plume

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Fig. 5 Comparison of Pressure Distributions of the Four Nozzles at the
Design Pressure Ratio and a Solid Plume (Continued)

Fig. 5 Comparison of Pressure Distributions of the Four Nozzles at the Design Pressure Ratio and a Solid Plume (Continued)

Fig. 5 Comparison of Pressure Distributions of the Four Nozzles at the Design Pressure Ratio and a Solid Plume (Continued)

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Fig. 5 Comparison of Pressure Distributions of the Four Nozzles at the Design Pressure Ratio and a Solid Plume (Continued)

27

Fig. 5 Comparison of Pressure Distributions of the Four Nozzles at the Design Pressure Ratio and a Solid Plume (Continued)

Fig. 5 Comparison of Pressure Distributions of the Four Nozzles at the
Design Pressure Ratio and a Solid Plume (Continued)

Fig. 5 Comparison of Pressure Distributions of the Four Nozzles at the Design Pressure Ratio and a Solid Plume (Continued)

Fig. 5 Comparison of Pressure Distributions of the Four Nozzles at the Design Pressure Ratio and a Solid Plume (Continued)

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Fig. 5 Comparison of Pressure Distributions of the Four Nozzles at the Design Pressure Ratio and a Solid Plume (Continued)

There is some doubt of the precision of plume geometry at the "design" conditions. The nozzle wall pressure distributions are compared to computed distributions in Fig. 6. From extrapolation of the measured values it appears that the nozzle designed for an exit Mach number of 2.7 has an exit Mach number nearer to 2.6 and the nozzle designed for an exit Mach number of 1.7 is nearer to 1.8. The other two nozzles appear to be close to the design value. Even with the reduced precision, it is expected that the general conclusions stated will remain valid. An analysis of the transonic data by Nenni (Ref. 30) indicates that the "design" plume shapes from schlieren photographs compare well with computed plume shapes.

A review of the sled data was made for possible comparisons with the wind tunnel results. It appears that the sled data at conditions matching transonic tunnel measurements was affected by interference from the sled to such an extent as to make it questionable. When tests were run at the unitary tunnel, blockage resulting from the plume size voided planned tests at a Mach number of 1.5. A run was made with the smaller ZAP model nozzle (1.76-3.95-.8) at a Mach number of 1.6 and blockage occurred at values of $P_c/P_b > 40$. The remaining ZAP configuration (1.76-3.95-.93) was tested at a minimum Mach number for the test of 1.65.

No exact comparisons were available between the sled data and wind tunnel data. However some off-design comparison can be made where the two Mach numbers are slightly different. For thrust levels where the prototype (ZAP) is not exactly modeled, the comparison should still be valid (Ref. 7). Where initial plume angles are matched there is only a small discrepancy in initial plume radius of curvature. The variation of P_c/P_b with initial plume angle for both the prototype ($\gamma=1.235$) and the model ($\gamma=1.4$) is shown in Fig. 7. Comparison between the 6.12-in sled data (M=1.56, $P_c/P_b=105$) and the model (M=1.6, $P_c/P_b=40$) is shown in Fig. 8. From the preceding figure it is apparent the plumes nearly match. The data in Fig. 8 compare both the jet-on and jet-off pressure distributions. For this case the sled plume effects are greater than the model plume effects.
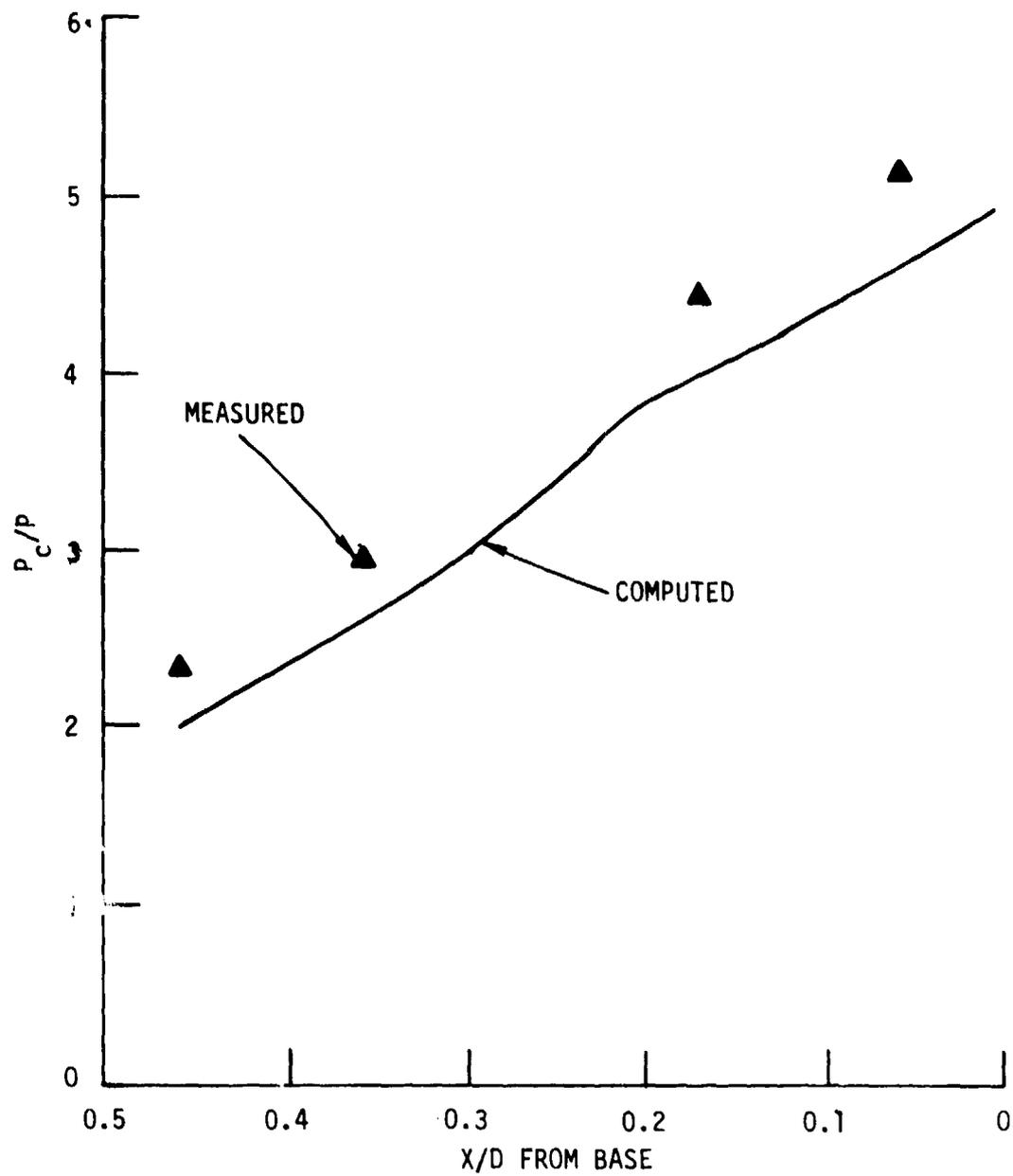
a.   NOZZLE 1.7-9.1-.8

Fig. 6 Comparison of Measured Nozzle Pressures with
Computed Distribution
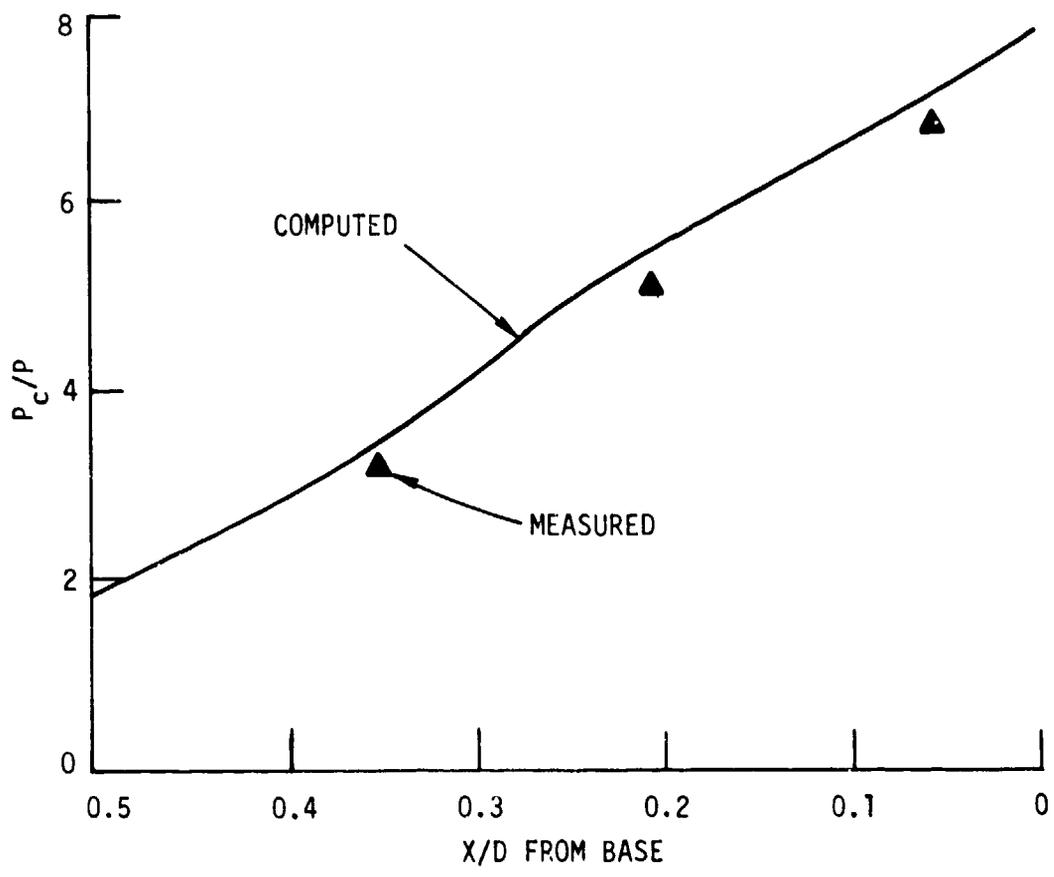
b. NOZZLE 2.0-13.6-.8

Fig. 6 Comparison of Measured Nozzle Pressures with
Computed Distribution (Continued)
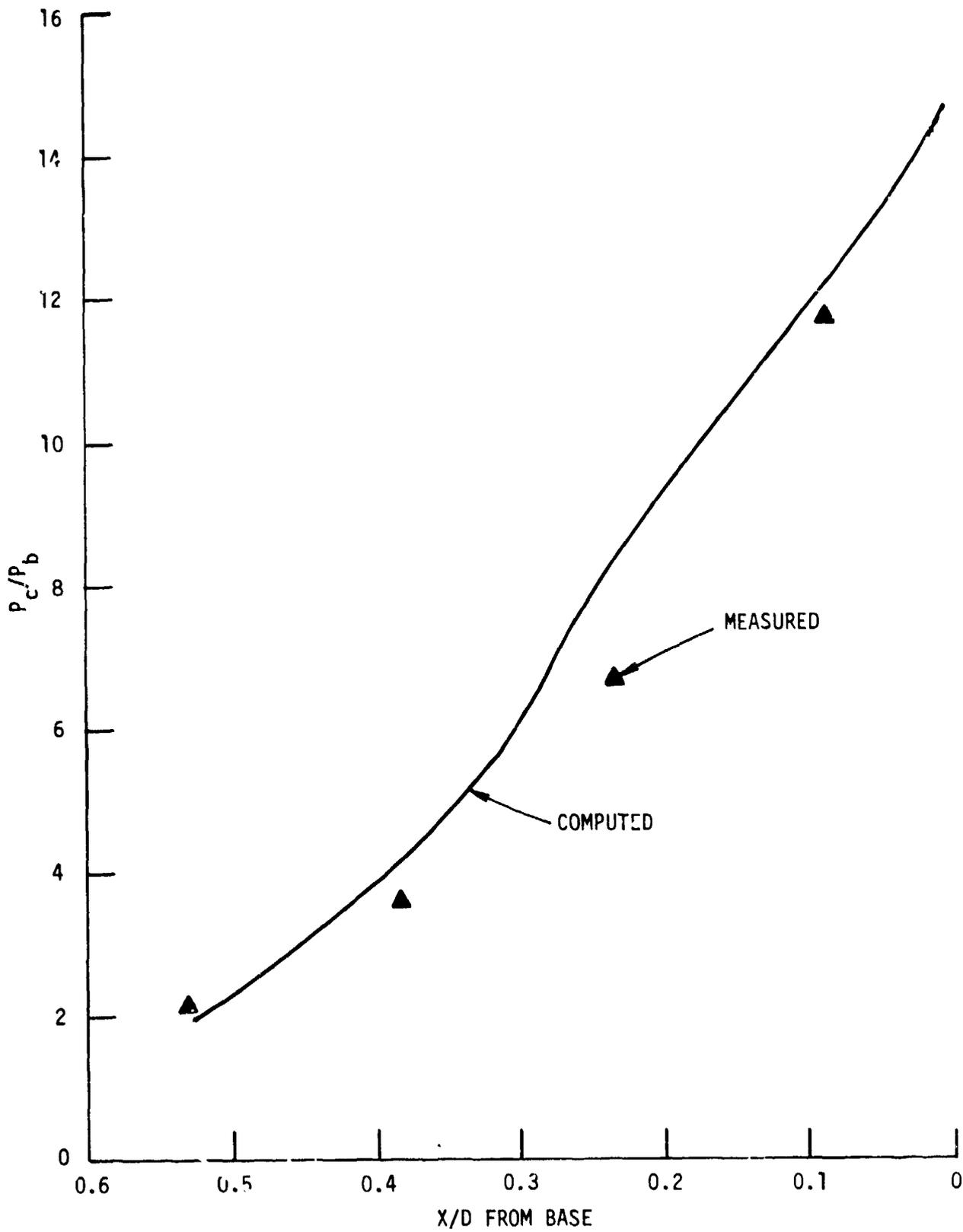
c. NOZZLE 2.4-19.35-.8

Fig. 6 Comparison of Measured Nozzle Pressures with
Computed Distribution (Continued)
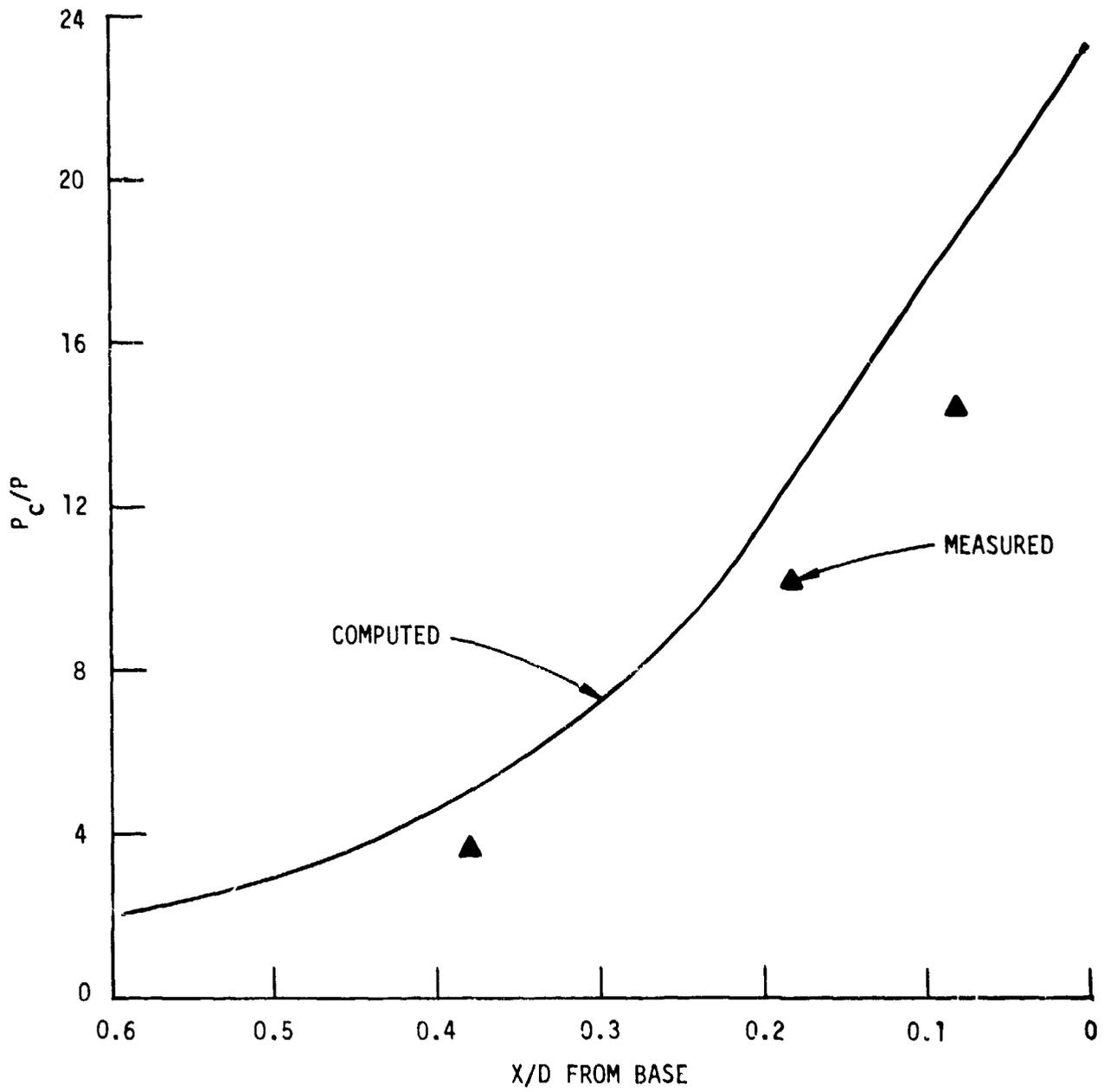
d. NOZZLE 2.7-23.3-.8

Fig. 6 Comparison of Measured Nozzle Pressures with
Computed Distribution (Continued)

37
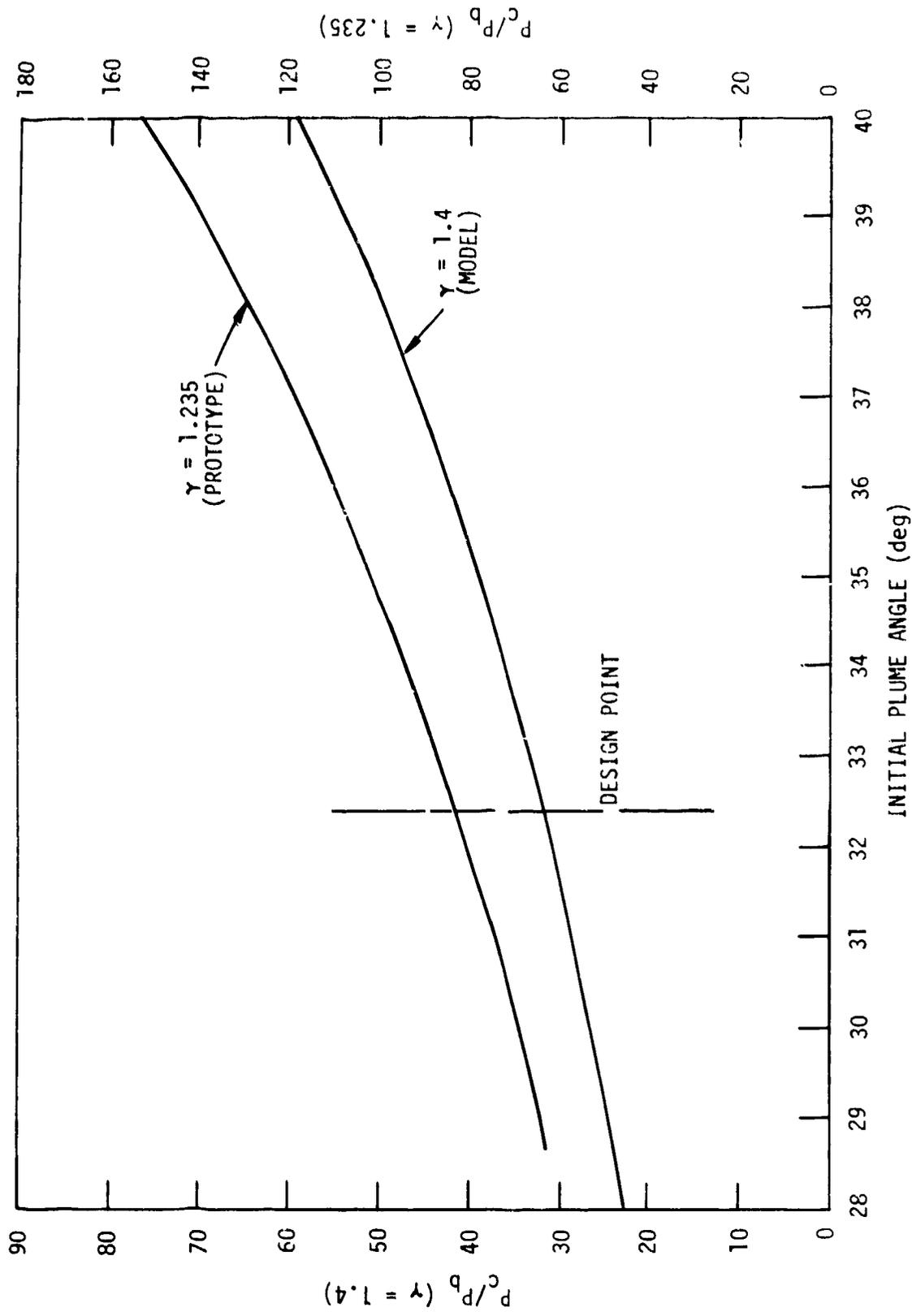
Fig. 7 Variation of Initial Plume Angle with Jet Total Pressure Ratio for ZAP Nozzle and ZAP Model Nozzle
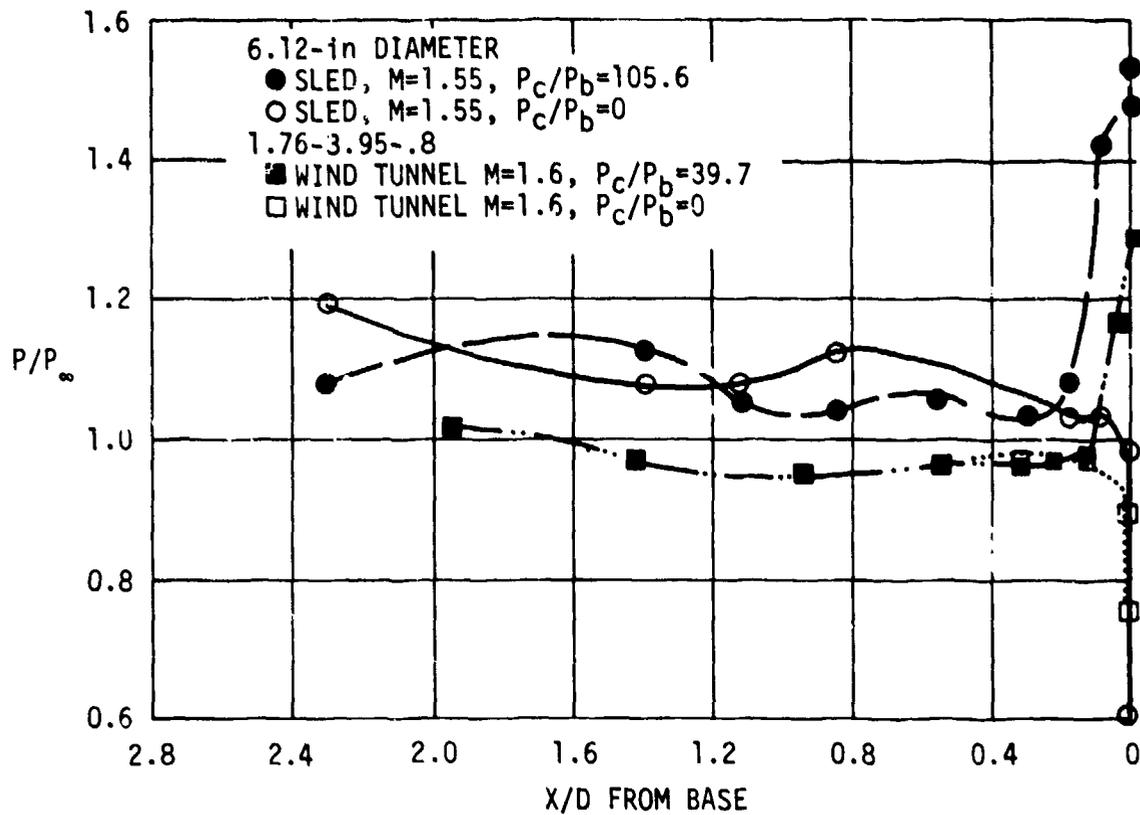
Fig. 8   Comparison of Jet-On and Jet-Off Base and Afterbody Pressures
Between the 6.12-in Sled Configuration and Wind Tunnel
Configuration (1.76-3.95-.8)

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There appears to be more matching conditions for the earlier 6-in ZAP configuration and the modeled nozzle (1.76-3.95-.8). Unfortunately, the orifice distribution on the sled was designed to measure pressures at transonic speeds and consequently few orifices are located near the base of the model where the plume effects are restricted to a small area at supersonic speeds. The variation of base and afterbody pressures on the wind tunnel configuration (1.76-3.95-.8) with sled jet total pressure ratio at a Mach number of 1.65 is shown in Fig. 9. The wind tunnel P_c/P_b was related to the sled P_c/P_b by using Fig. 7. Also shown in Fig. 9 is the variation of base pressure on the 7-in sled at a Mach number of 1.63. The base pressure was the only usable data during this sled run. The only other orifice in the area influenced by the plume appeared to be plugged. However, there appears to be a fairly good match between sled and wind tunnel base pressures.

Brazzel (Ref. 31) used thrust coefficient (C_T) as a parameter for correlating sustainer level jet effects on base pressure. Although jet-on base pressure is influenced by many variables, the use of C_T allowed the analysis of experimental data in a manner where adequate design information could be obtained. Thrust coefficient is given by

$$C_T = \frac{\gamma_j p_j A_j M_j^2 + A_j (p_j - p_\infty)}{1/2 \gamma_\infty p_\infty A_B M_\infty^2} = \frac{\text{Thrust}}{q_\infty A_B} \qquad (2)$$

where the subscripts j and ∞ represent the jet and freestream, respectively.

For simulated sustainer thrust levels where the base is aspirated by the jet, the use of C_T appears to account for all the variables except jet Mach number (assuming the use of air or similar gas for the jet). At the thrust levels high enough for the plume to influence the afterbody, there is the added effect of nozzle exit angle and nozzle exit to base diameter ratio.

Since four of the nozzles of the present tests were built to give the same "design" plume shape, it appeared reasonable that C_T should be a good parameter to correlate base pressure. Shown in Fig. 10 is a comparison of the variation of P_b/p_∞ with C_T for these nozzles for Mach numbers of 0.9 to 2.5.

40
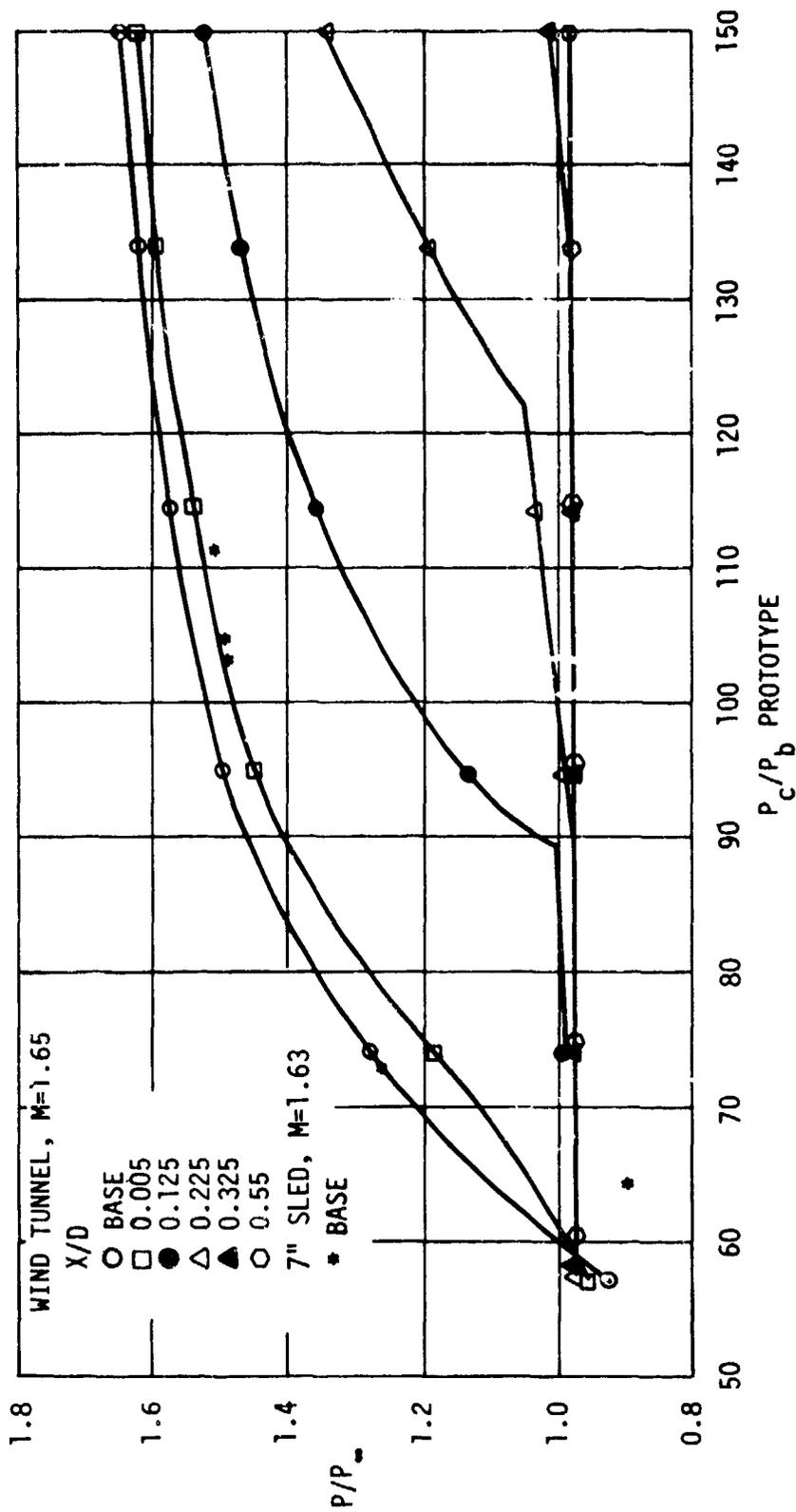
Fig. 9 Comparison of Wind Tunnel Model (1.76-3.95-.93) Pressures Related to Sled P_c/P_b at M=1.65 to 7-in Diameter Sled Base Pressures at M=1.63
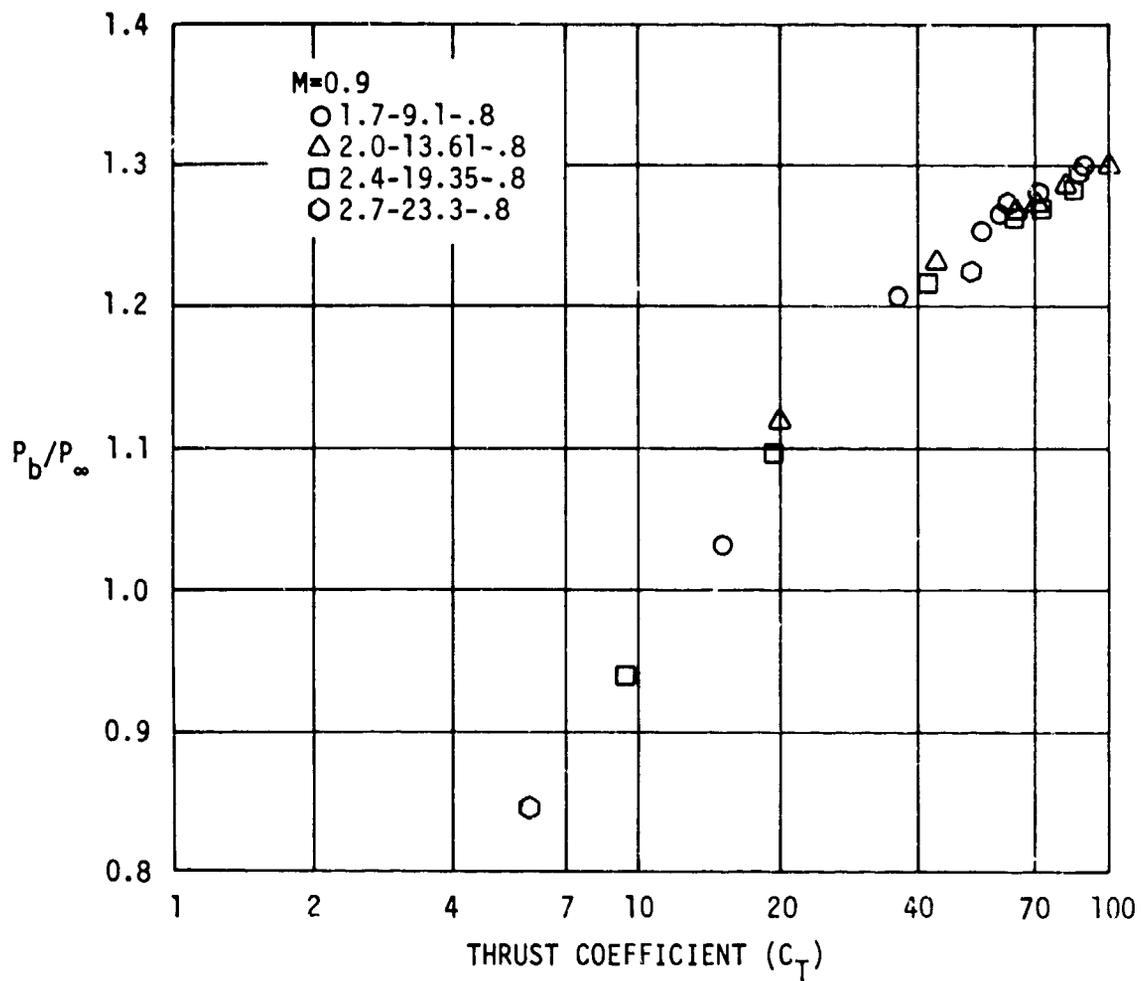
41

Fig. 10 Variation of Base Pressure with Thrust Coefficient for the Four Nozzles with Same "Design" Plume Shape

Fig. 10   Variation of Base Pressure with Thrust Coefficient for the
Four Nozzles with Same "Design" Plume Shape (Continued)

43

Fig. 10   Variation of Base Pressure with Thrust Coefficient for the
Four Nozzles with Same "Design" Plume Shape (Continued)

44
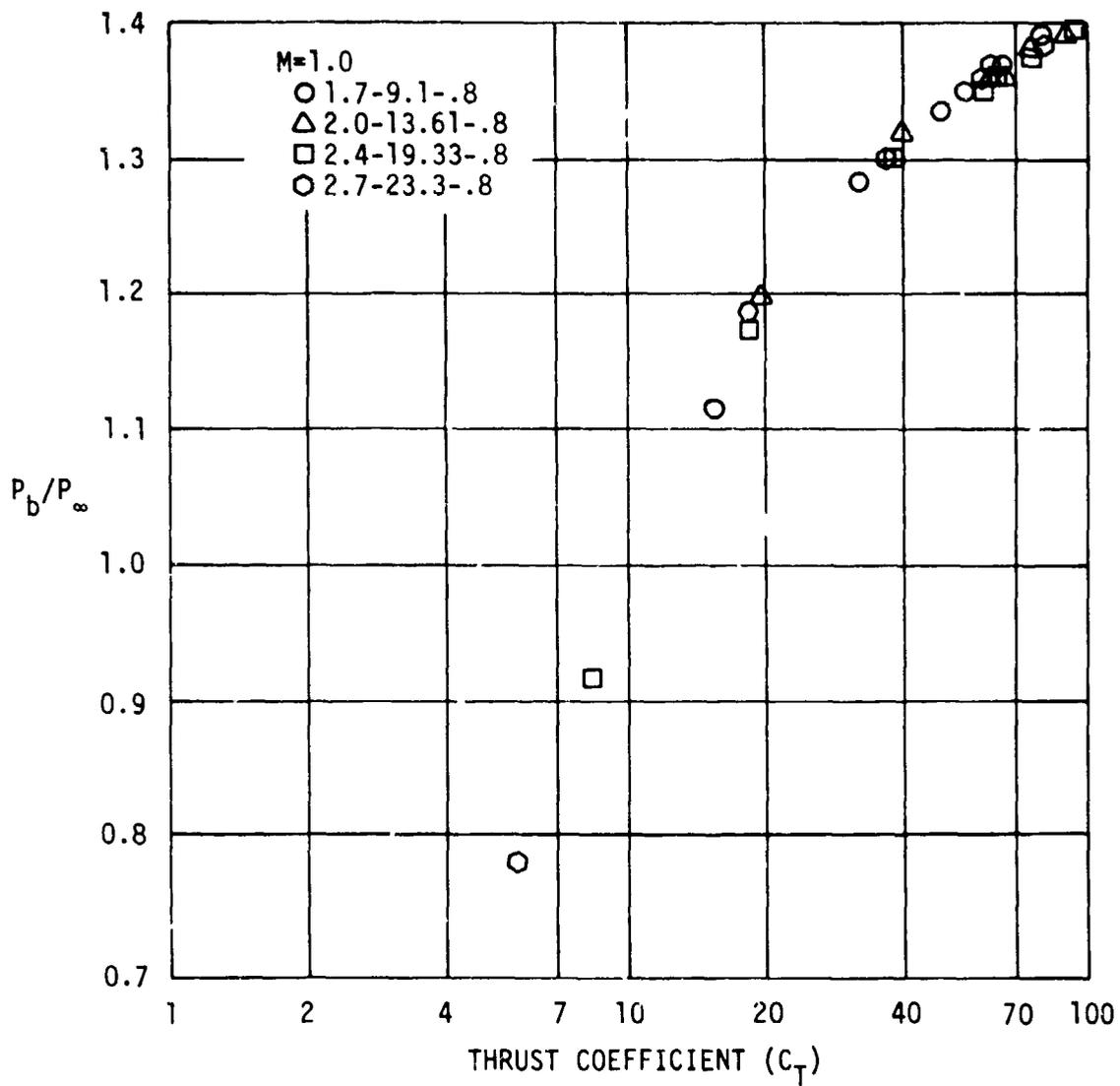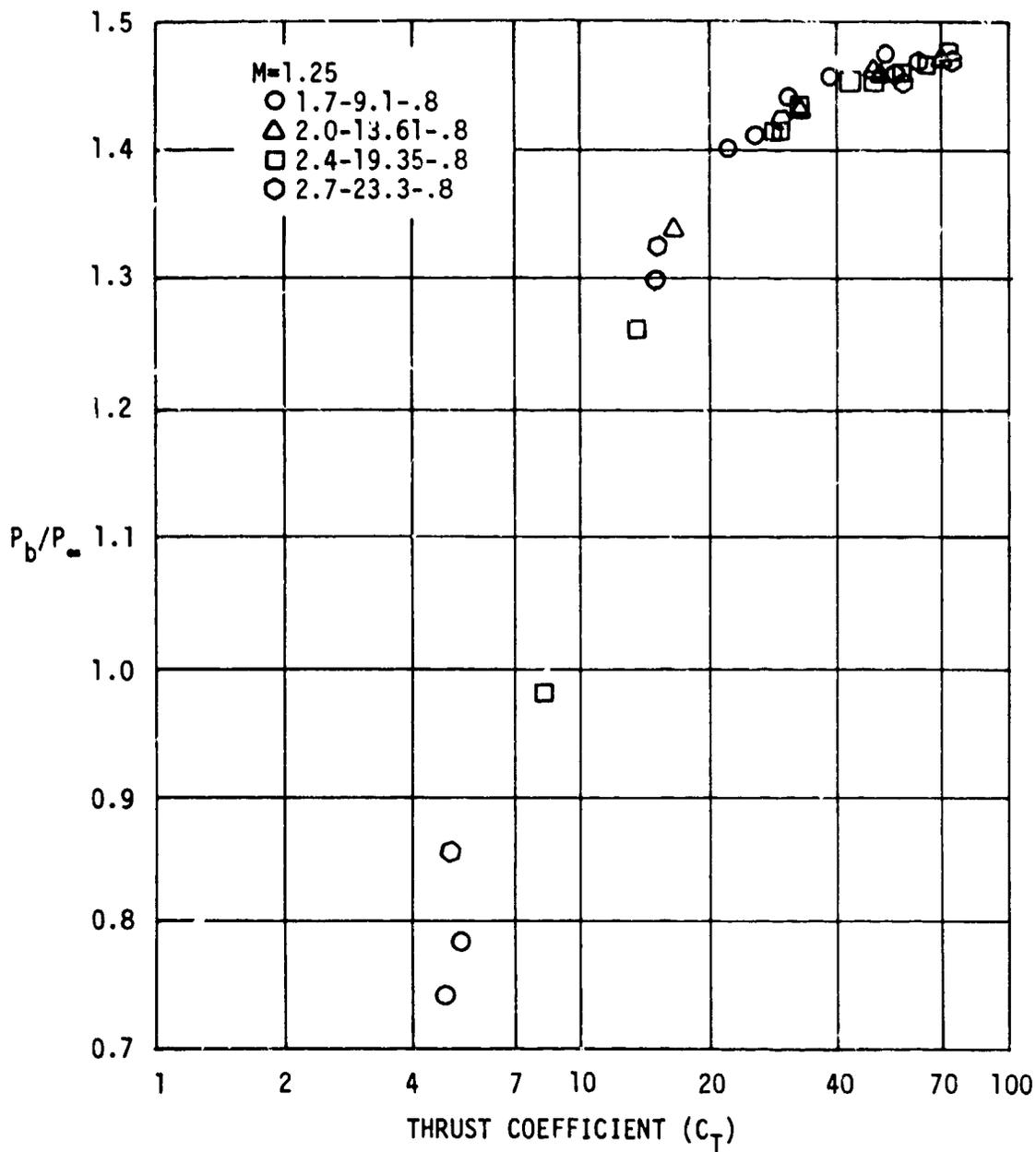
Fig. 10   Variation of Base Pressure with Thrust Coefficient for the
Four Nozzles with Same "Design" Plume Shape (Continued)
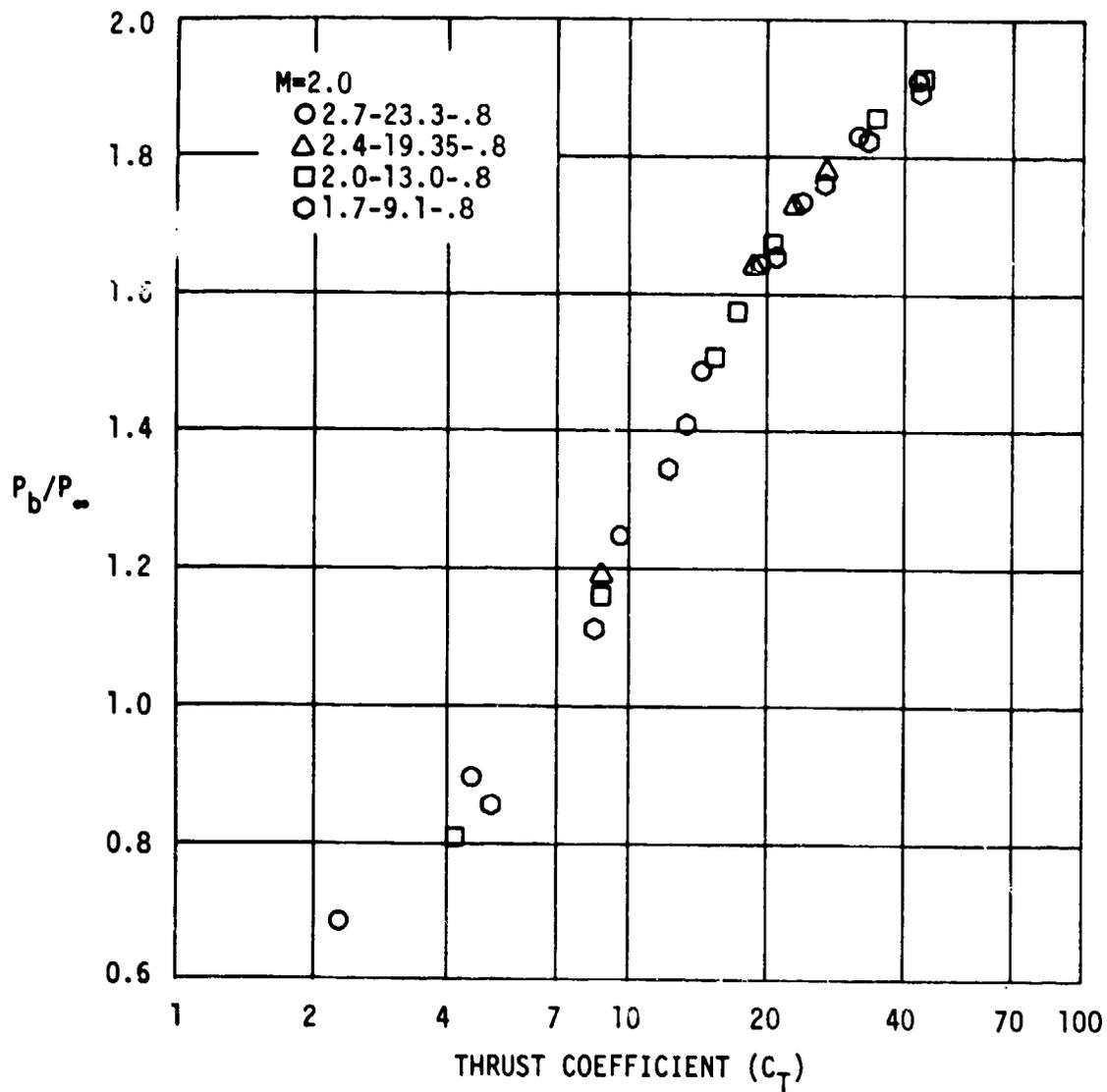
Fig. 10 Variation of Base Pressure with Thrust Coefficient for the Four Nozzles with Same "Design" Plume Shape (Continue.)

Fig. 10   Variation of Base Pressure with Thrust Coefficient for the
Four Nozzles with Same "Design" Plume Shape (Continued)

47
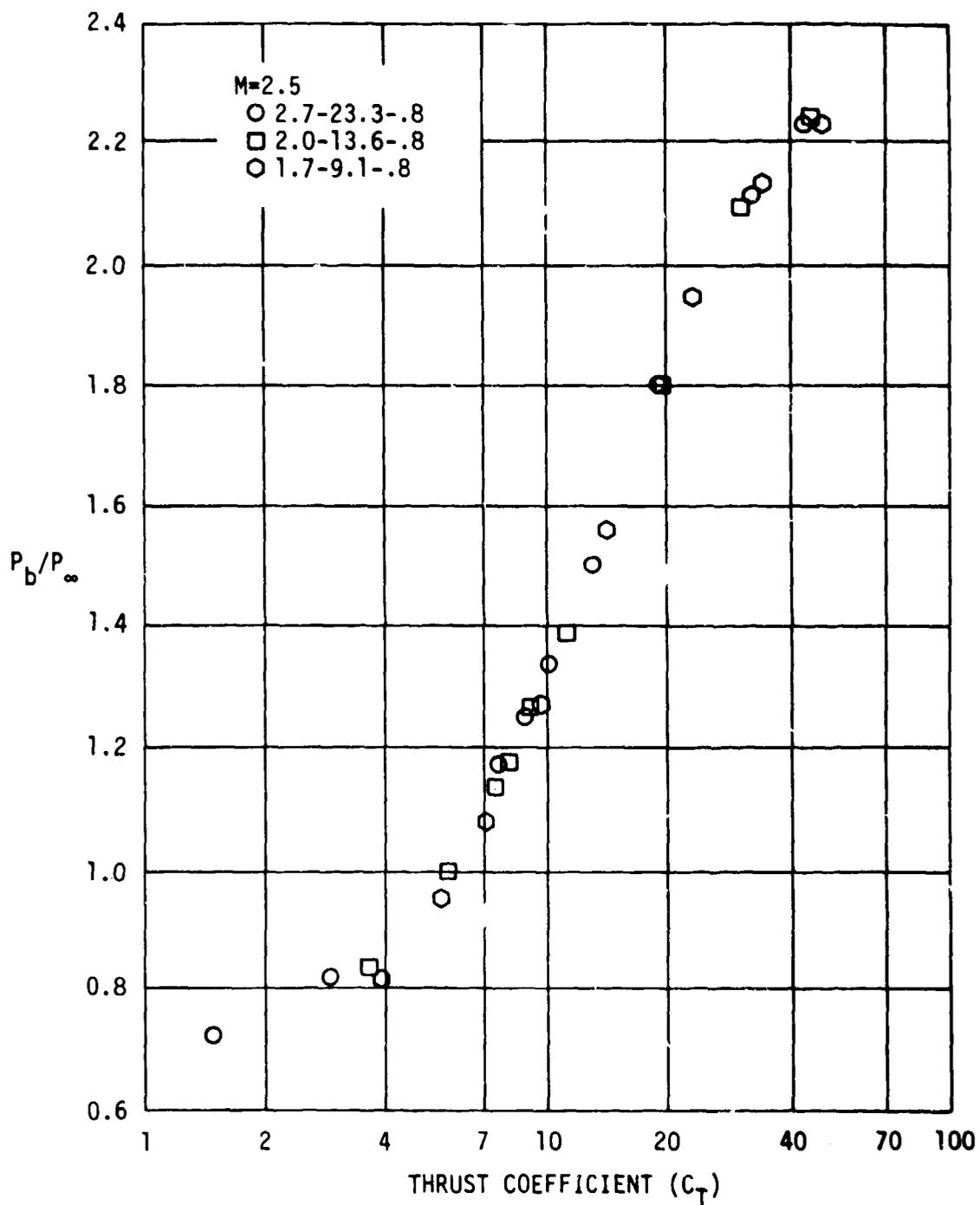
It appears that a fairly good correlation is obtained for all of the freestream Mach numbers shown. The approximate value of P_b/p_∞ for the "design" plumes may be obtained from Fig. 5.

The correlation obtained in Fig. 10 suggests a slight change in approach of modeling plume effects on aerodynamics. For high acceleration tactical missiles and free rockets, the exit Mach number is usually between about 2.3 to 2.7. Using the Korst modeling technique the model nozzle exit Mach number will vary from less than two to nearly sonic. When the exit Mach number is close to sonic, the nozzle will be difficult to fabricate with precision required to give an accurate exit Mach number. However, a higher exit Mach number and higher exit angle nozzle designed to match the plume shape of the model nozzle could be utilized. For example, a model nozzle having an exit Mach number of 1.7 and an exit angle of 4 deg could be replaced by a nozzle having an exit Mach number of 2.5 and an exit angle of 15 deg. The plume Mach number for the $M_j = 2.5$ nozzle would be higher than that of the model nozzle resulting in plume with a higher stiffness factor, but this fact would tend to account for the effects of afterburning (Ref. 32).

The variation of base pressure with C_T for the two ZAP configurations is shown in Fig. 11. Base pressure is not correlated by C_T as well as for the nozzles in Fig. 10.

The variation of base pressure with radial thrust coefficient (C_{RT}) for the normal jet plume effects simulator is presented in Fig. 12. Radial thrust coefficient is given by

$$C_{RT} = \frac{\text{radial thrust}}{q_\infty A_{ref}}$$

where radial thrust is the total thrust from the 24 nozzles on the simulator. The normal jet simulator, which is used on sting-mounted force models, tends to simulate the radial component of momentum of an axial plume. By comparing the variation of base pressure with C_T from Figs. 10 and 11, and variation of base pressure with C_{RT} in Fig. 12, an indication can be obtained of the amount of radial thrust required to simulate the same plume effect as the axial jet.

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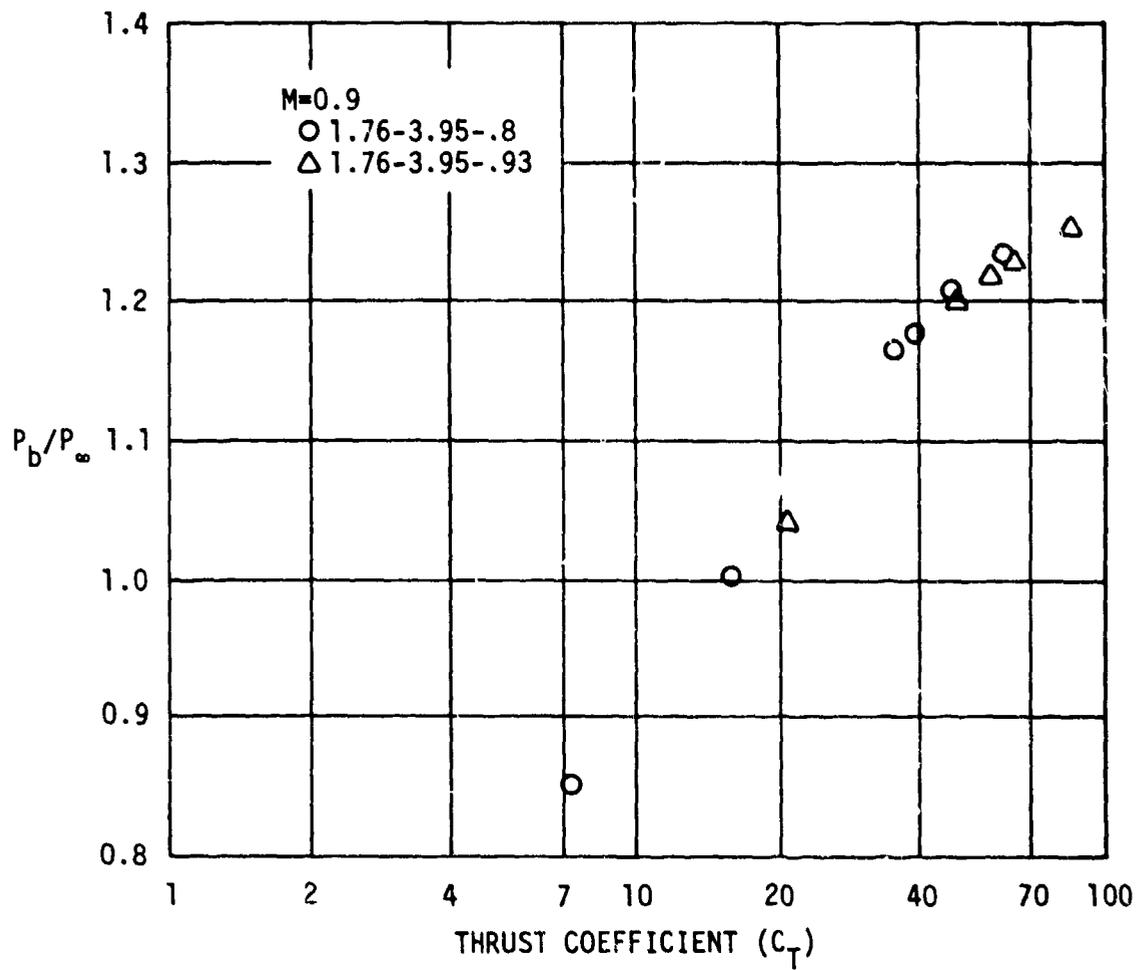
Fig. 11 Effect of D_N/D_B on Variation of Base Pressure with Thrust Coefficient
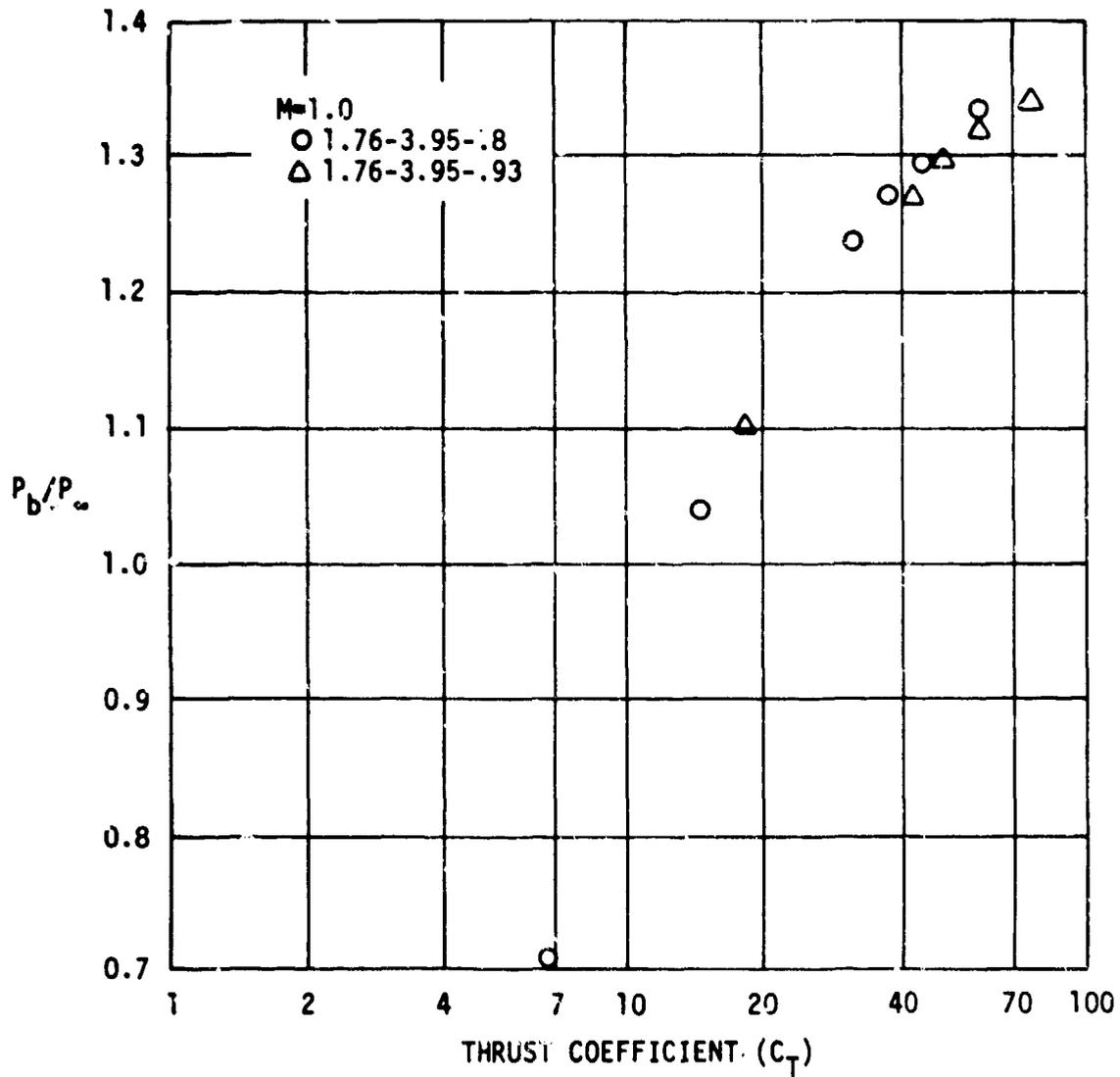
Fig. 11 Effect of D_N/D_B on Variation of Base Pressure with Thrust Coefficient (Continued)
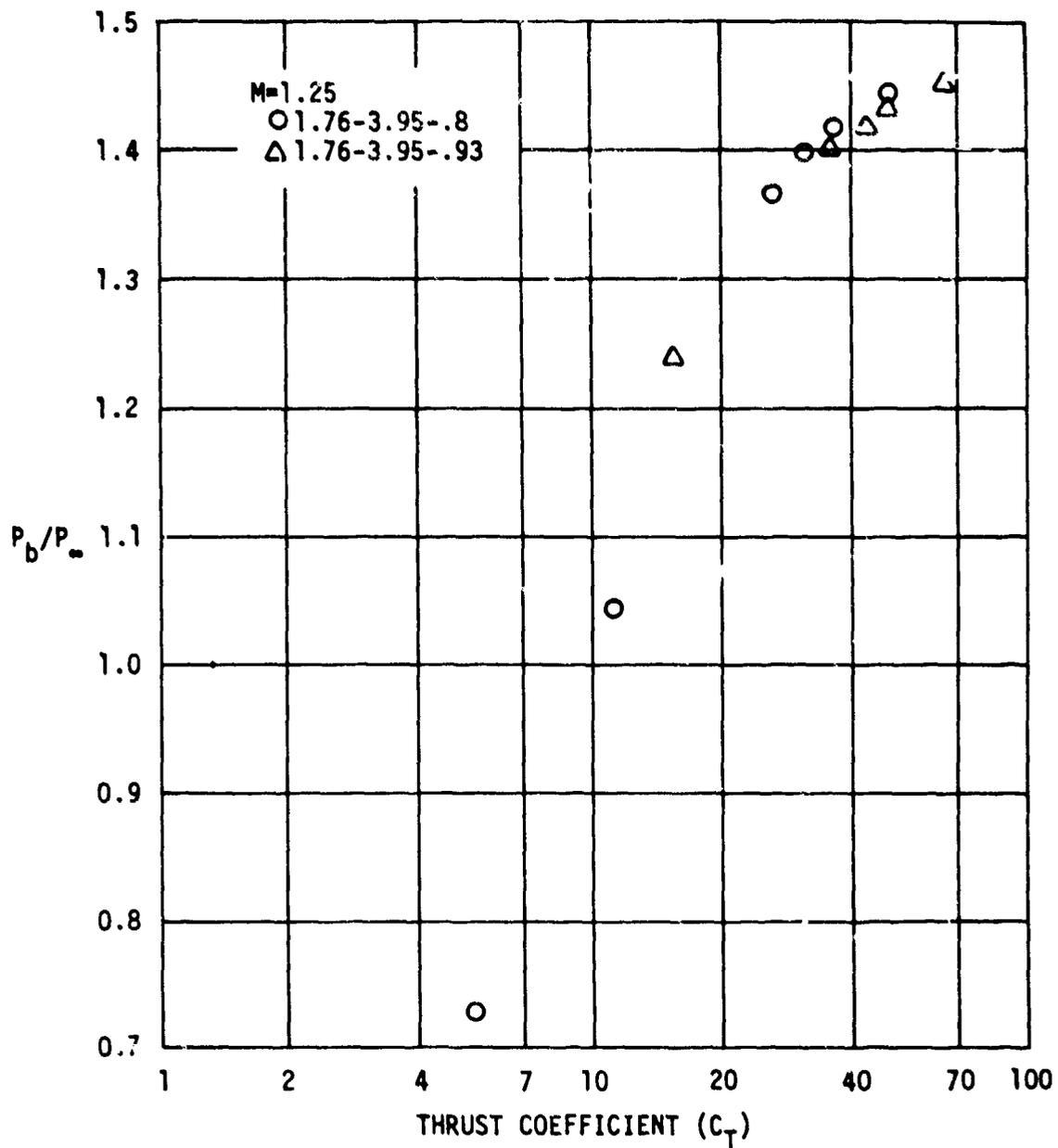
Fig. 11   Effect of D_N/D_B on Variation of Base Pressure with
Thrust Coefficient (Continued)
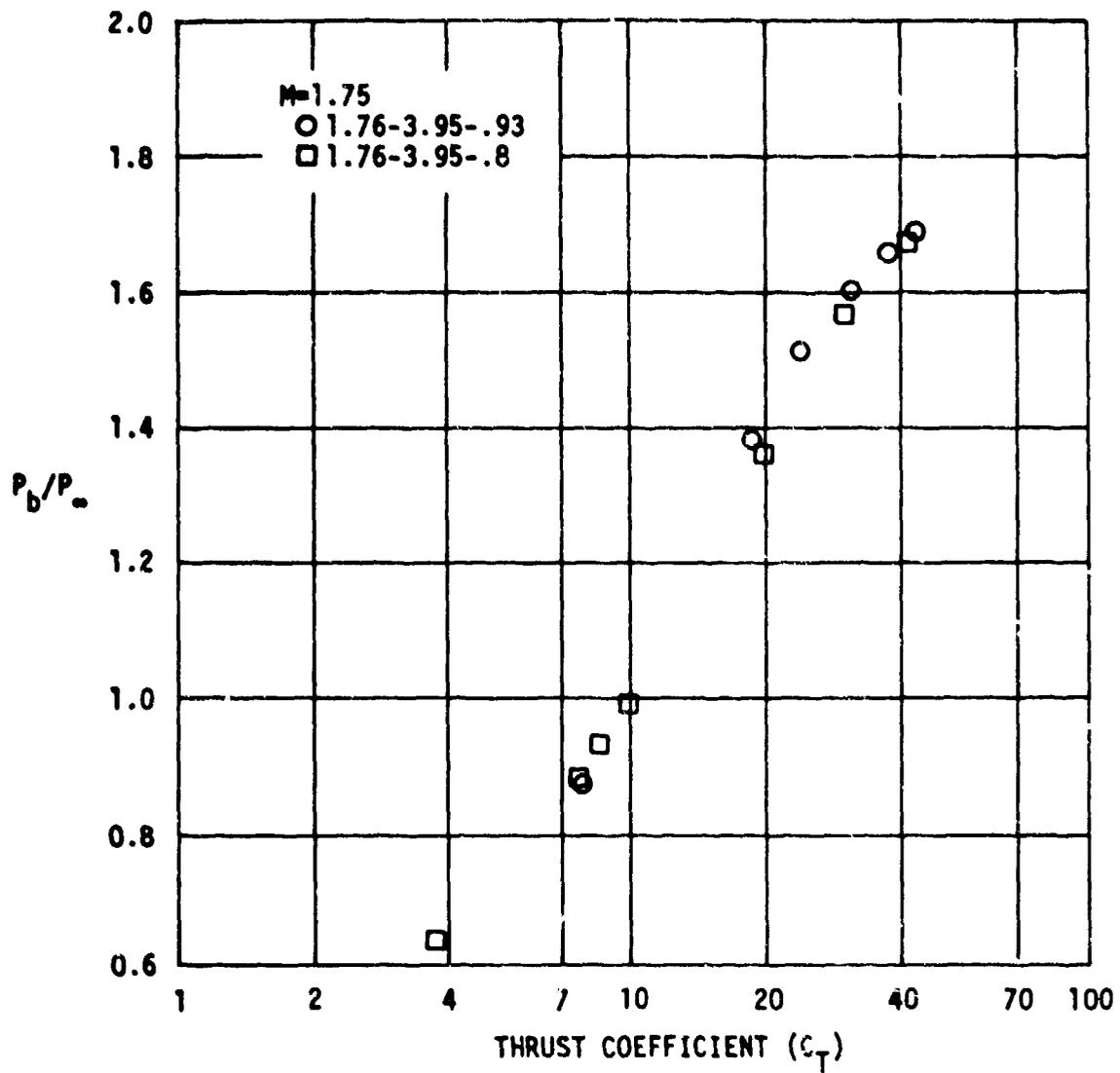
Fig. 11 Effect of D_N/D_B on Variation of Base Pressure with Thrust Coefficient (Continued)
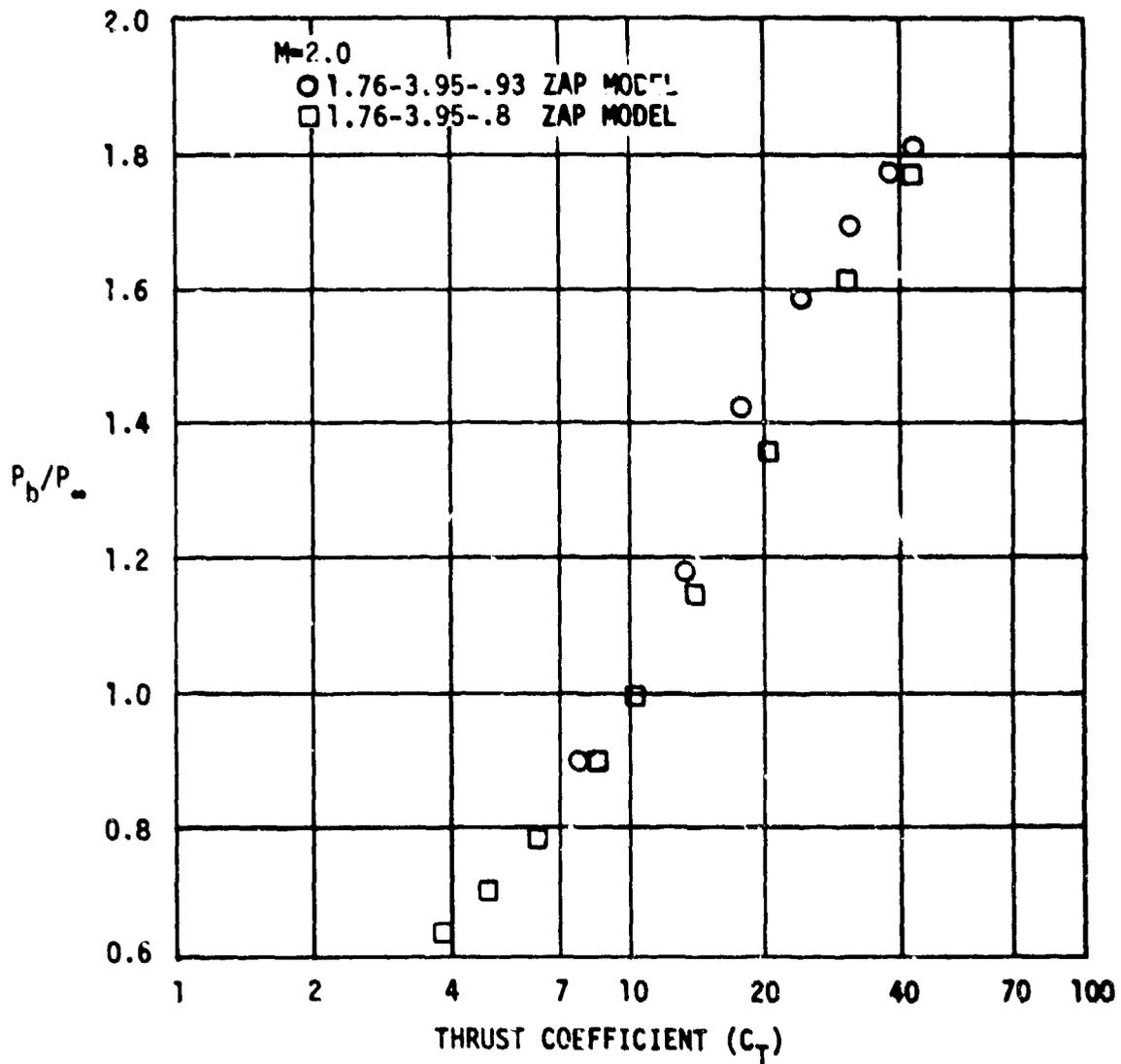
Fig. 11   Effect of D_N/D_B on Variation of Base Pressure with
Thrust Coefficient (Continued)
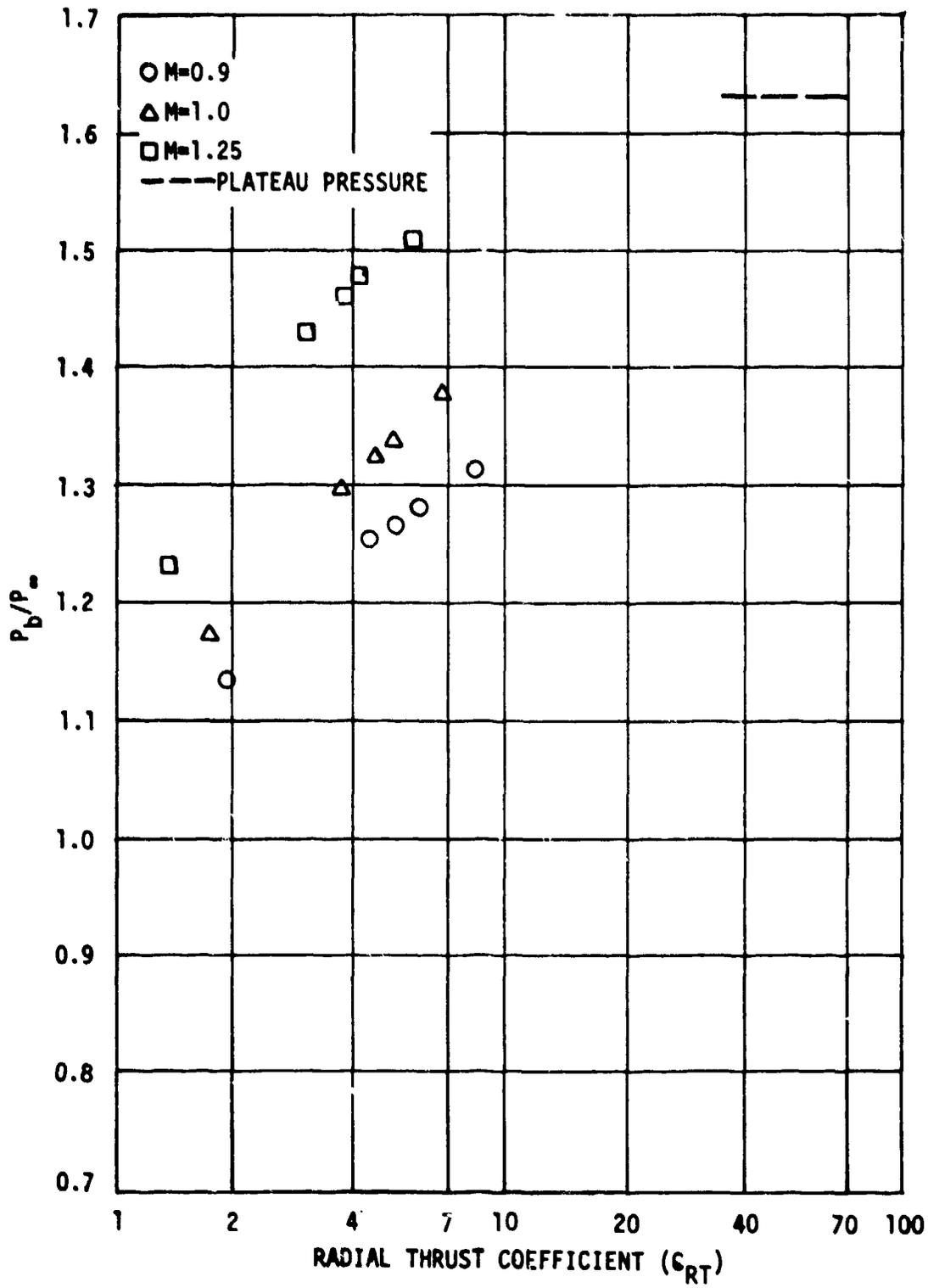
Fig. 12 Variation of Base Pressure with Radial Thrust Coefficient
for the Normal Jet Plume Effects
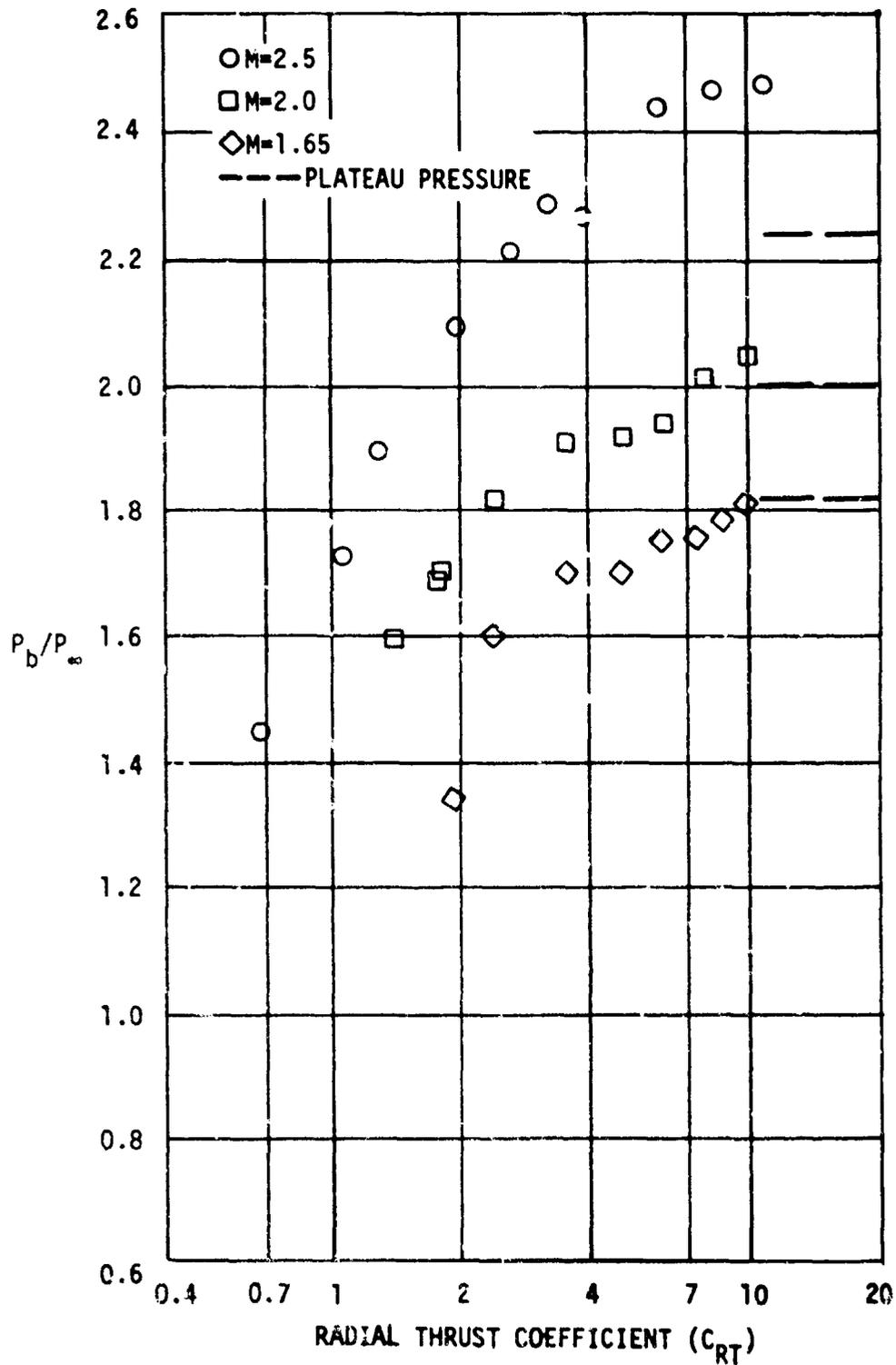
Fig. 12 Variation of Base Pressure with Radial Thrust Coefficient
for the Normal Jet Plume Effects (Continued)

The fraction of radial to axial thrust required to simulate about the same plume effects is shown in Fig. 13 for the two families of nozzles in the present investigation.

At high values of C_{RT} and for the supersonic Mach numbers in Fig. 12(b), the base pressures induced by the normal jet simulator exceed the plateau pressure established by Zukoski (Ref. 33). If thrusts at this level are to be simulated, better results would probably be obtained with the simulator moved further aft.
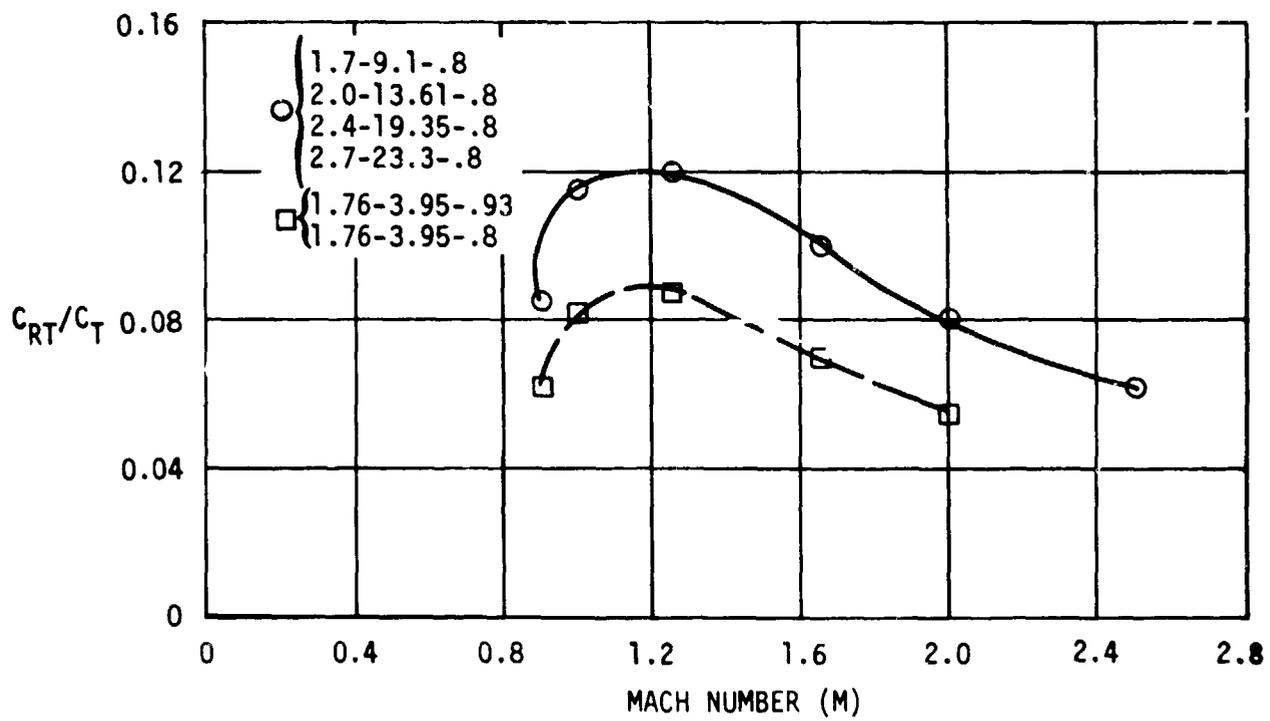
Fig. 13   Ratio of Radial Thrust to Axial Thrust Required for the
Same Plume Effect

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7.0 CONCLUDING REMARKS

An investigation of concepts for modeling jet plume effects on missile aerodynamics has been made. The experimental results tend to verify the modeling concepts proposed by Korst. Comparisons were made of afterbody pressure distributions under the influence of different air plumes having the same shape but with different surface Mach numbers. The comparisons indicate that increasing plume Mach number generally increases the plume effect on afterbody pressures with this effect becoming more pronounced with increasing Mach number. A solid plume with the same shape as the air plumes has the greatest effect on afterbody pressures with the effect increasing considerably at freestream Mach numbers of 1.25 and higher.

The shape of afterbody pressure distributions under the influence of plume effects simulated by the normal jet simulator compared favorably with the distributions under the influence of axial jets. The ratio of normal to axial thrusts, C_{RT}/C_T, required to simulate the same level of effects varies with both freestream Mach number and axial jet nozzle geometry.

An attempt was made to compare sled tests of the ZAP rocket with an air nozzle modeled by Korst's concept. No exact match of test conditions was available, but the few cases where comparisons were possible tended to confirm the validity of the modeling concept.

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9. Deep, R.A., J.H. Henderson, and C.E. Brazzel, "Thrust Effects on Missile Aerodynamics," U.S. Army Missile Command, Redstone Arsenal, Alabama, Report No. RD-TR-71-9, May 1971.

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APPENDIX A

DATA BASE

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DISTANCE FROM BASE, X/D

PL/P

| SYMBOL	MACH	PC/PB	CONFIG.
o	0.40	13.7	B1AZ43
+	0.40	21.6	B1AZ43
x	0.40	35.1	B1AZ43
*	0.40	39.2	B1AZ43
v	0.40	44.9	B1AZ43
>	0.40	62.4	B1AZ43
c	0.40	76.4	B1AZ43
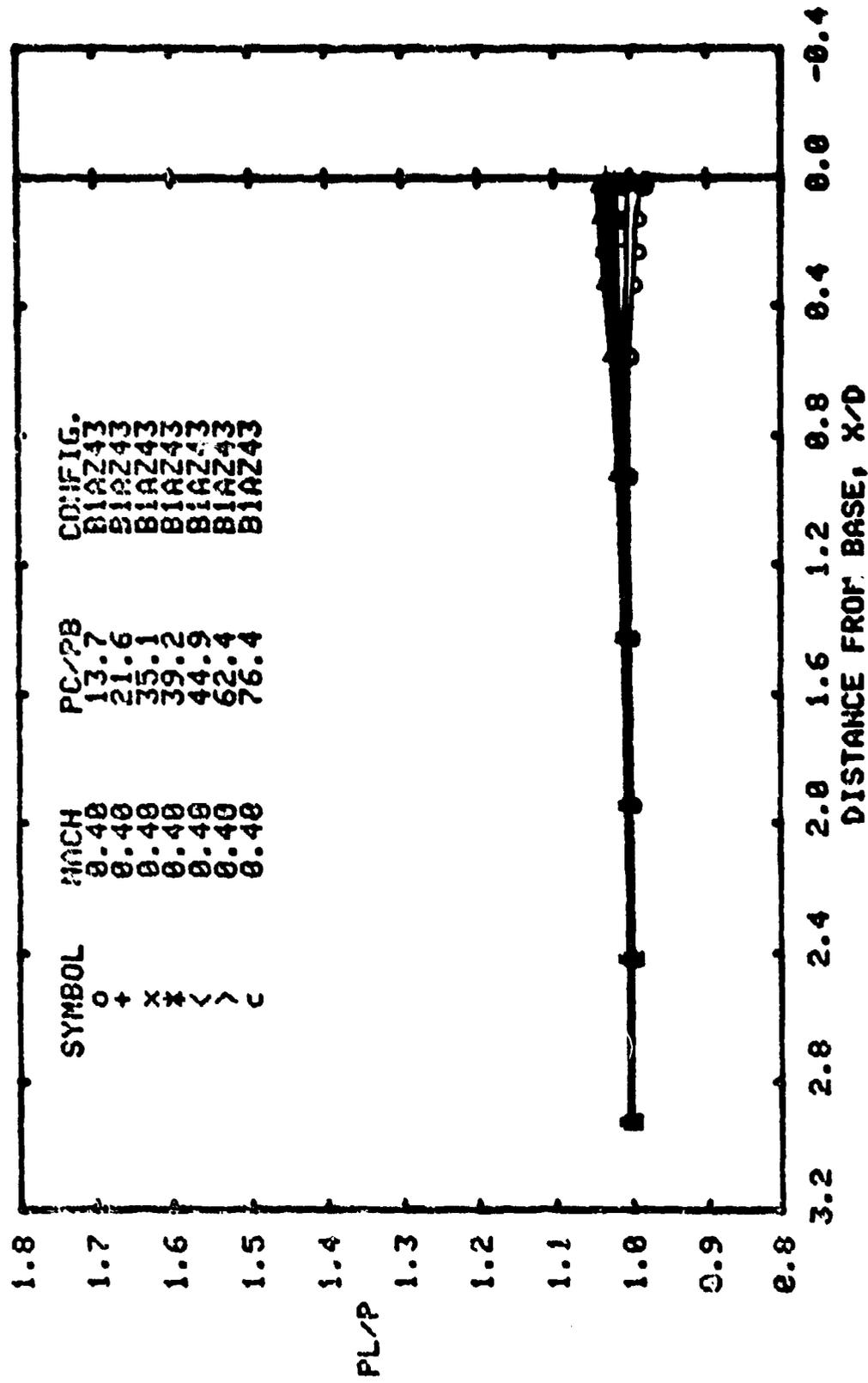
(a). M=0.4

Figure A1: Effect of jet total pressure ratio on body pressure distribution at various free stream Mach numbers. Configuration B1AZ43: $M_J=1.7$, $\theta_N=9.1^\circ$, $D_N/D_B=0.8$.
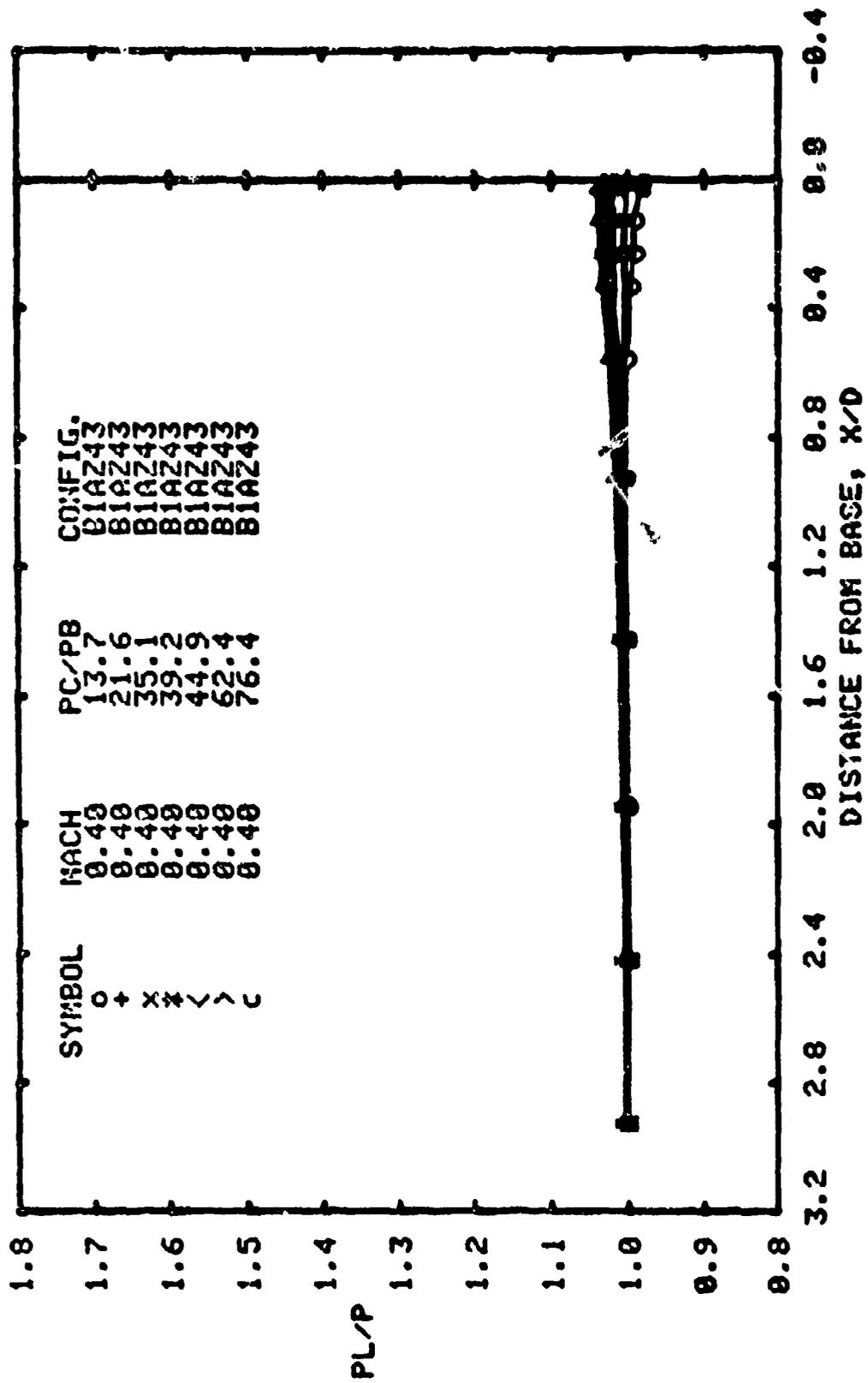
(a). M=0.40

Figure A1: Effect of jet total pressure ratio on body pressure distribution at various free-stream Mach numbers. Configuration B1AZ43: $M_J=1.7$, $\theta_N=9.1°$, $D_N/D_B=0.80$.

(b). M=0.7 cont'd
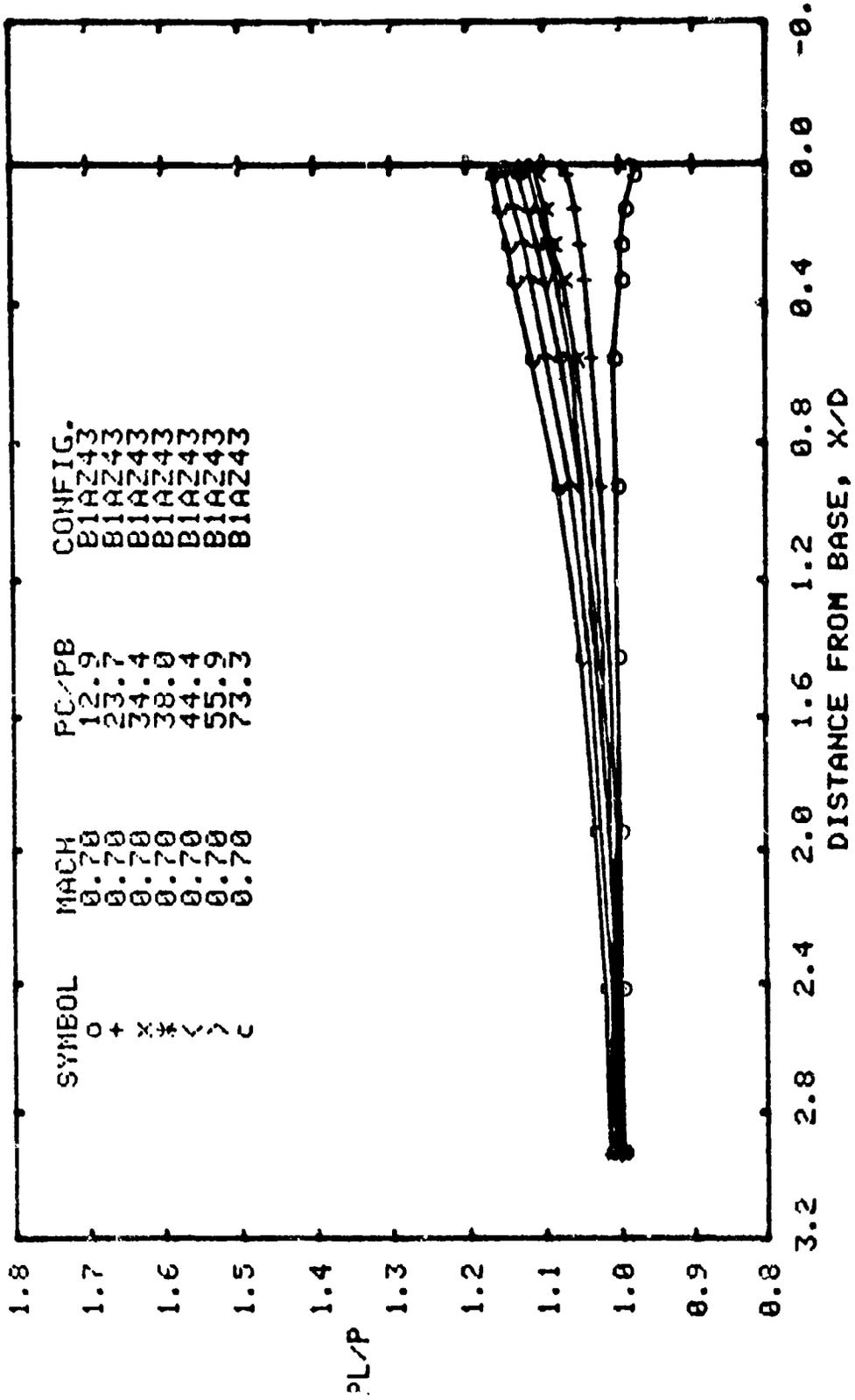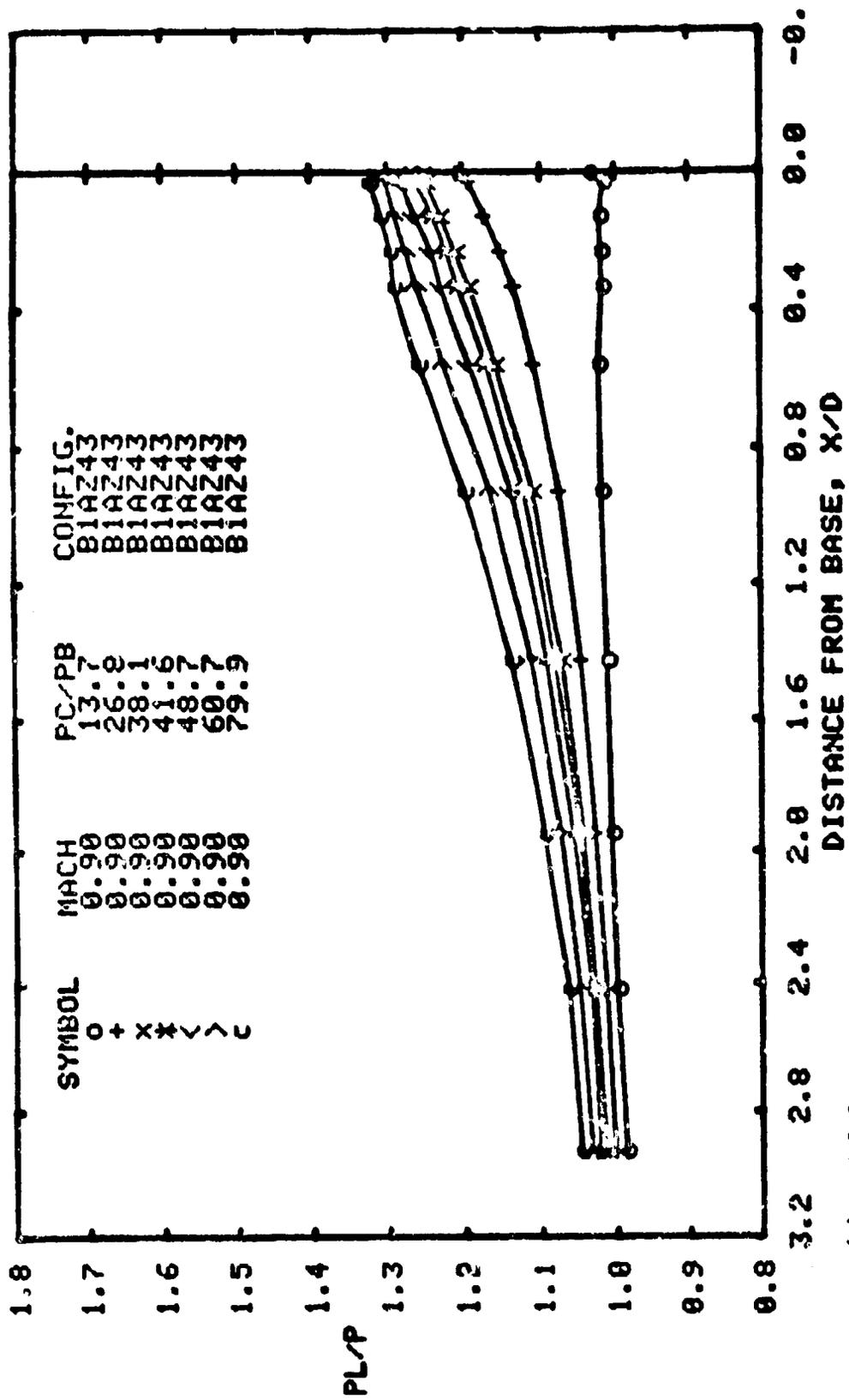
Figure A1: cont'd

(c). M=0.9

Figure A1: Cont'd
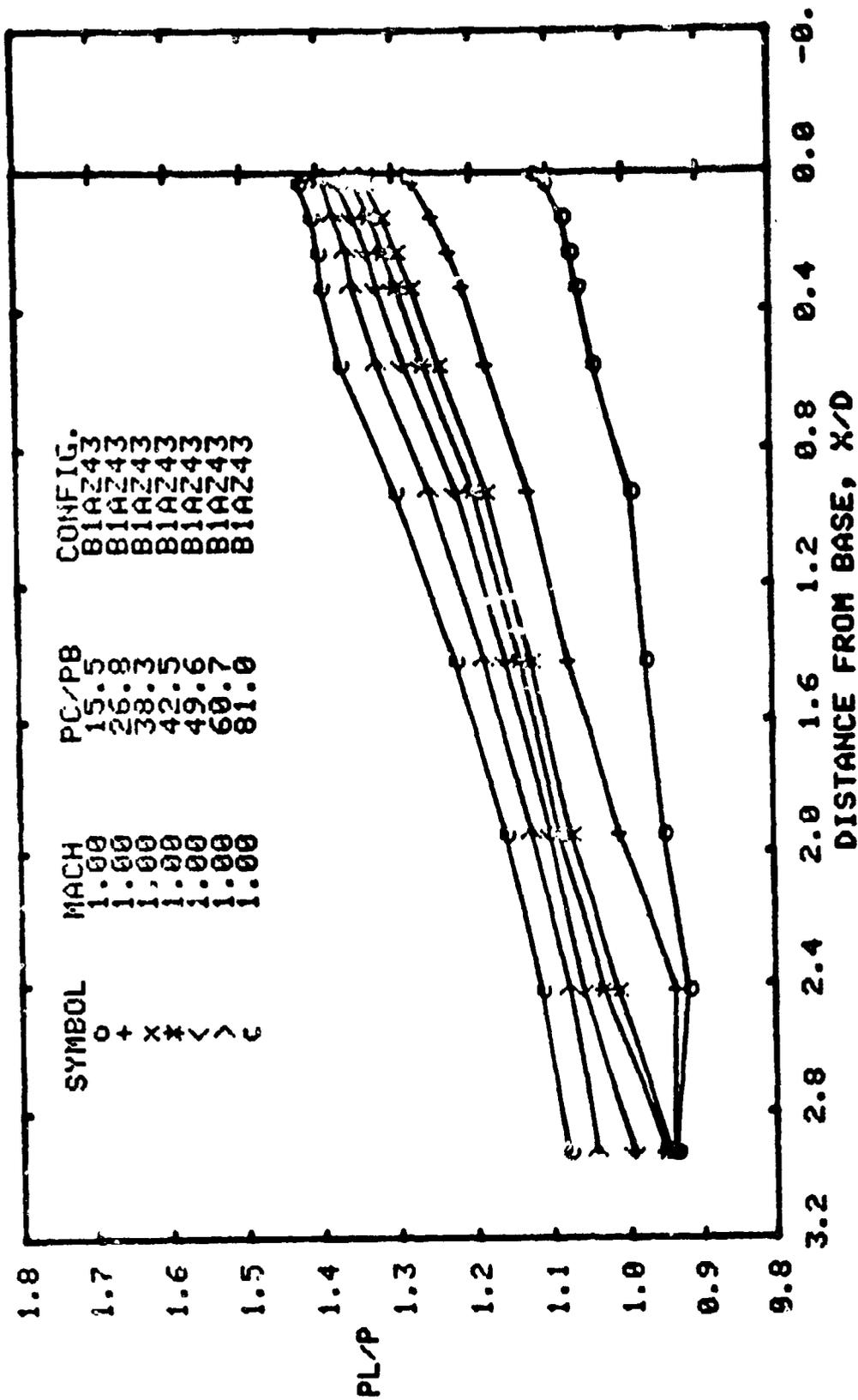
(d). M=1.0
Figure A1: cont'd

(e). M=1.1 cont'd

Figure A1:

(f). M=1.25 cont'd
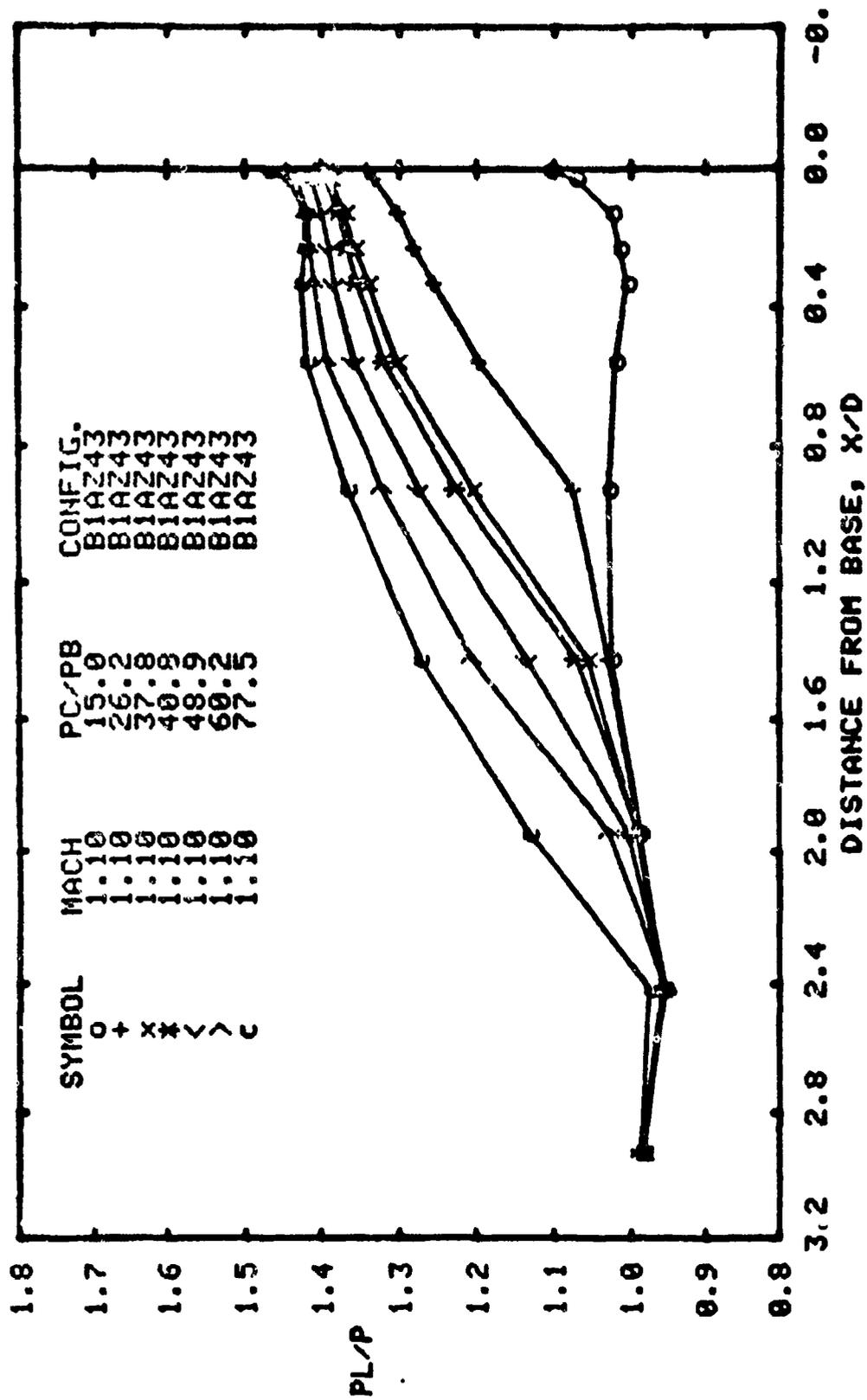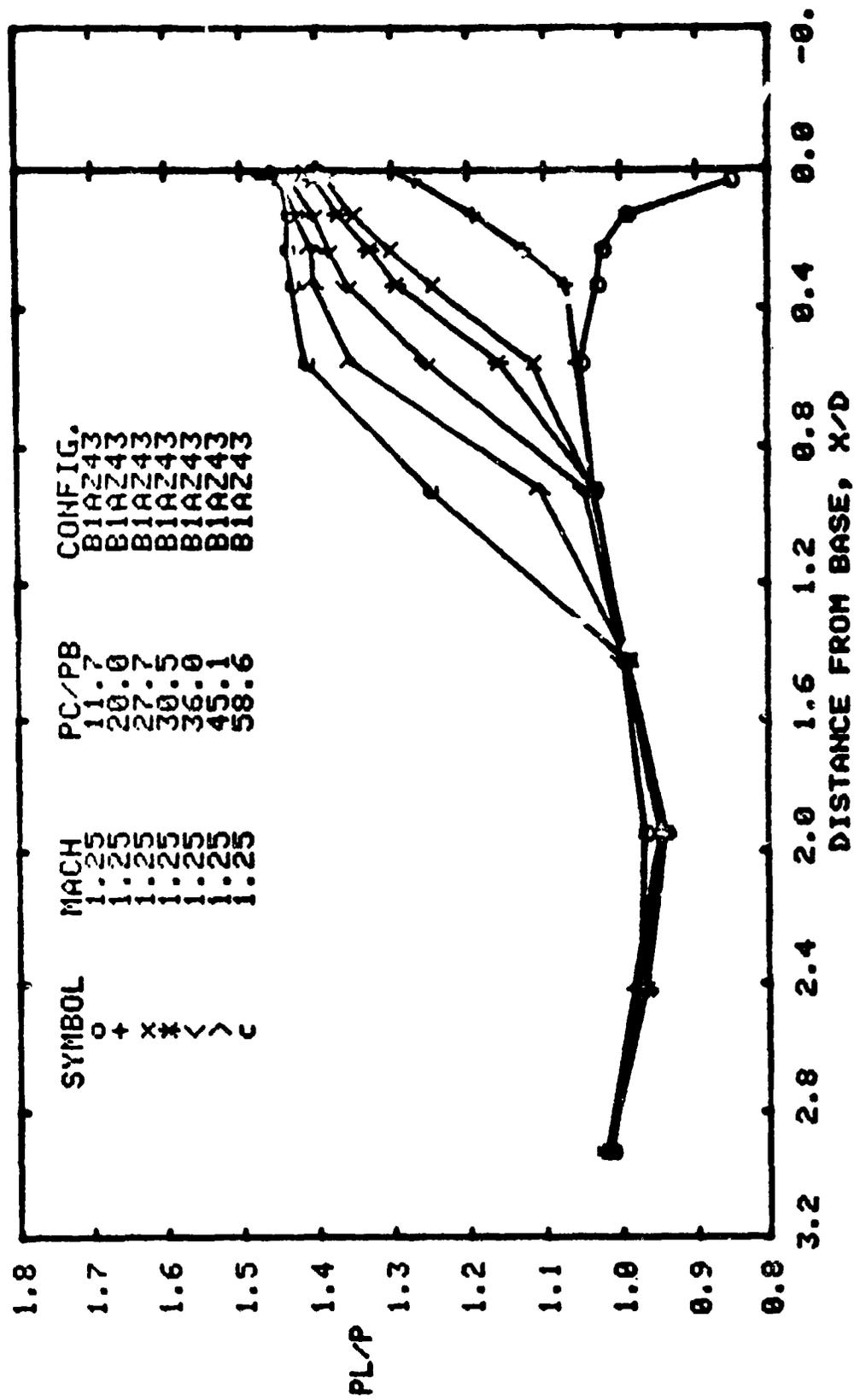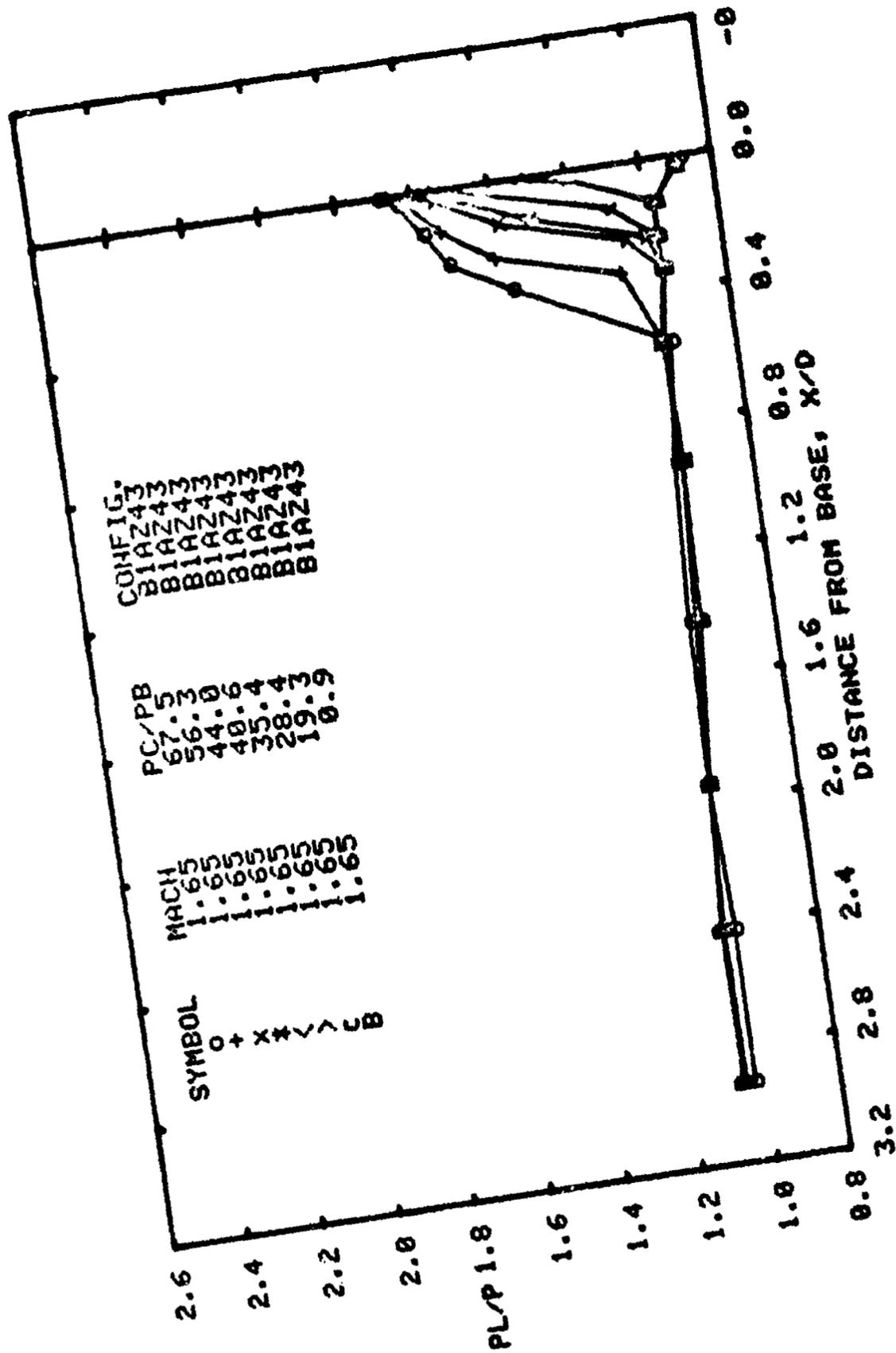
Figure A1: cont'd

(g). M=1.65

Figure A1: cont'd

74
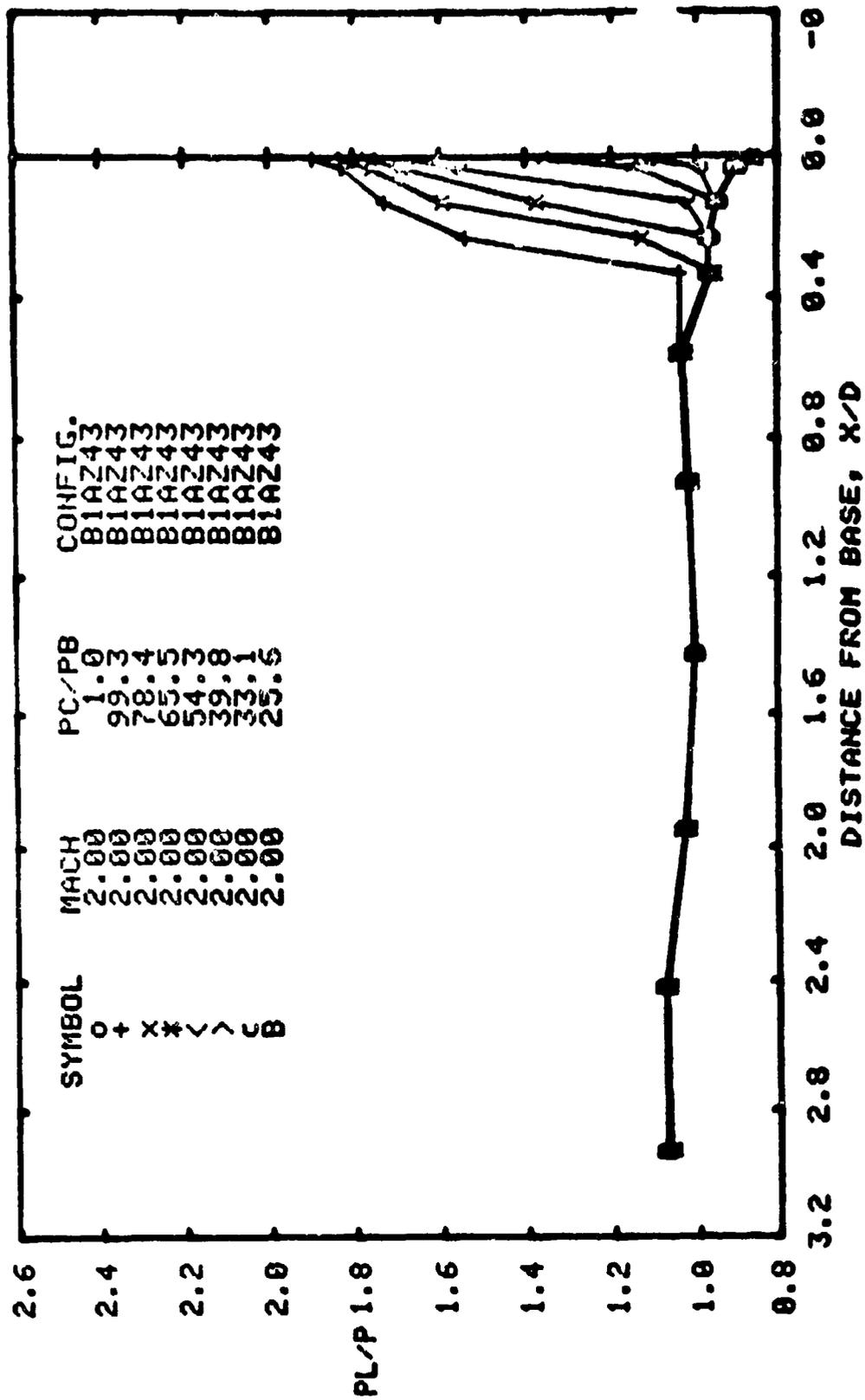
(h). M=2.0

Figure A1: cont'd
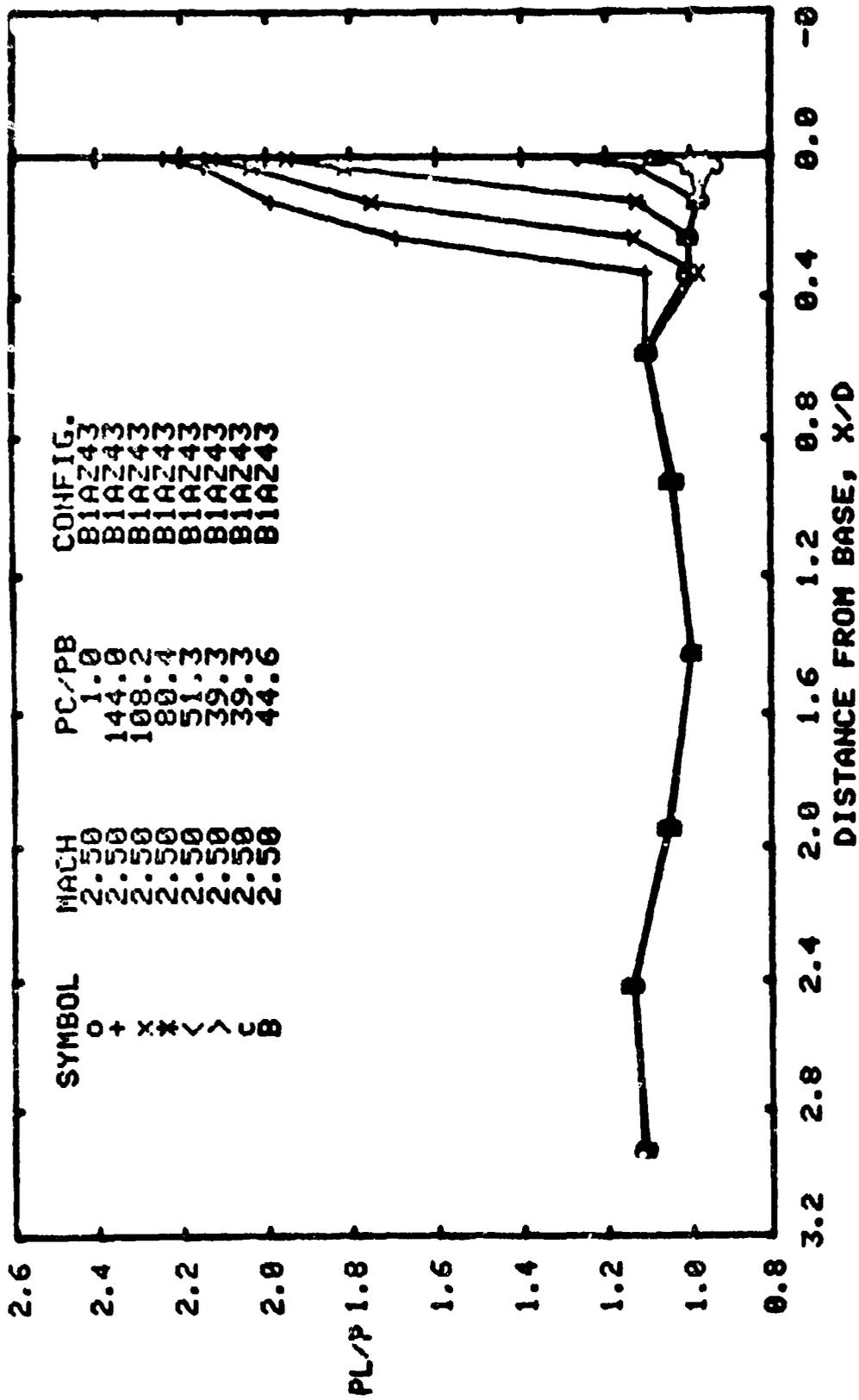
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Figure A1: concl'd.
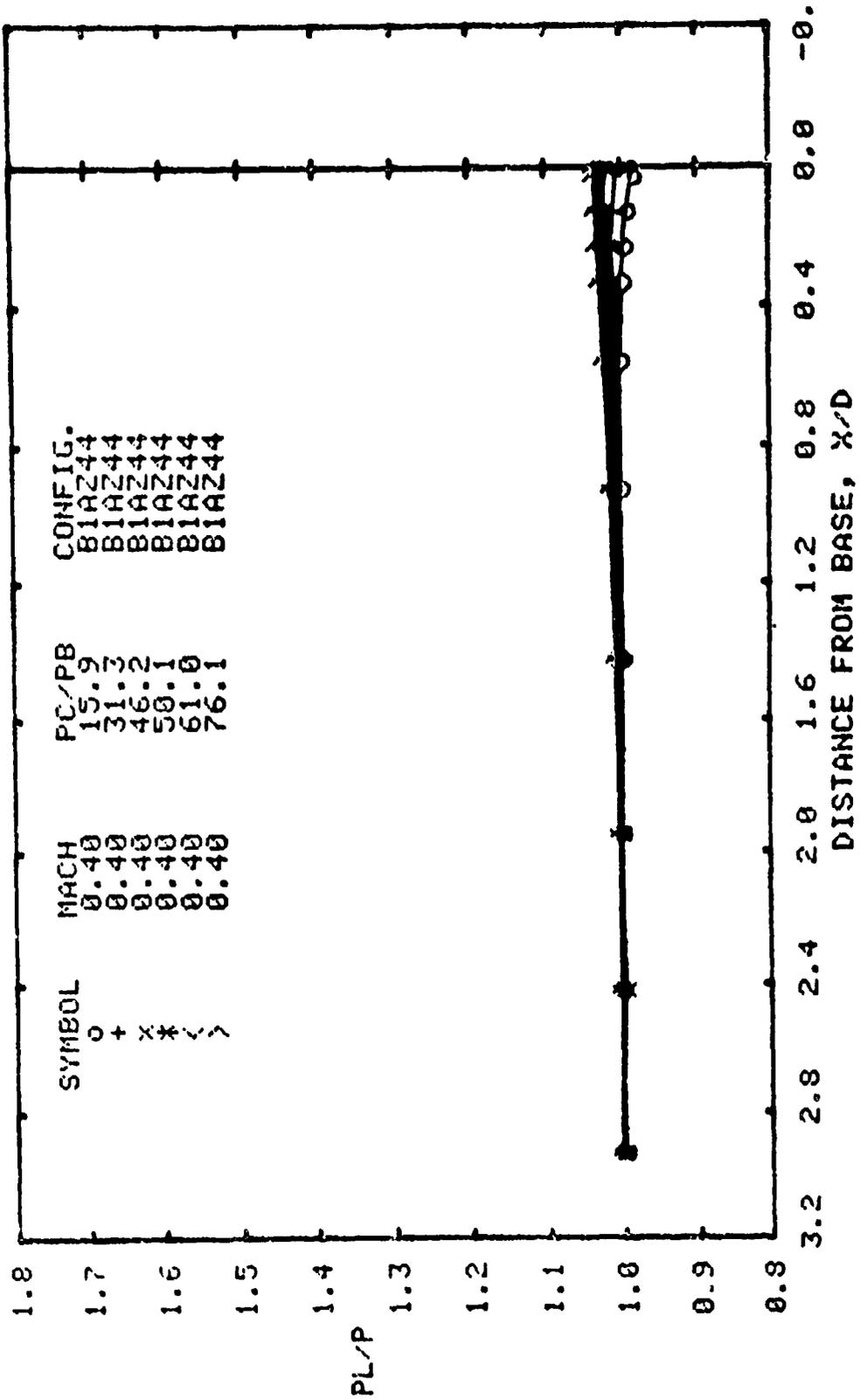
(a). M=0.4

Figure A2: Effect of jet total pressure distribution at various free-stream Mach numbers. Configuration B1AZ44: $M_J=2.0$, $\theta=13.6$, $D_N/D_B=0.8$

(b). M=0.7: cont'd

Figure A2:

78

(c). M=0.9 cont'd
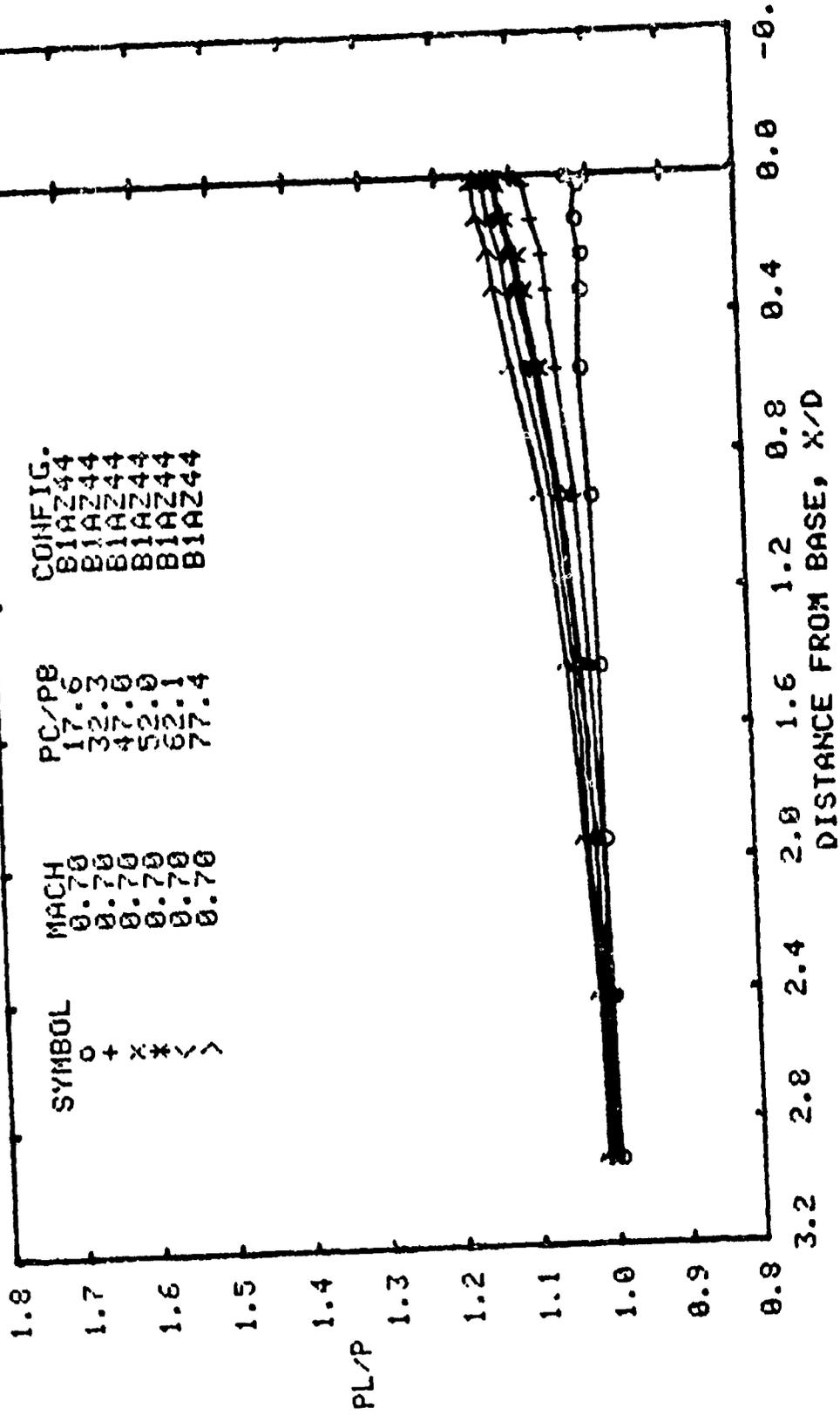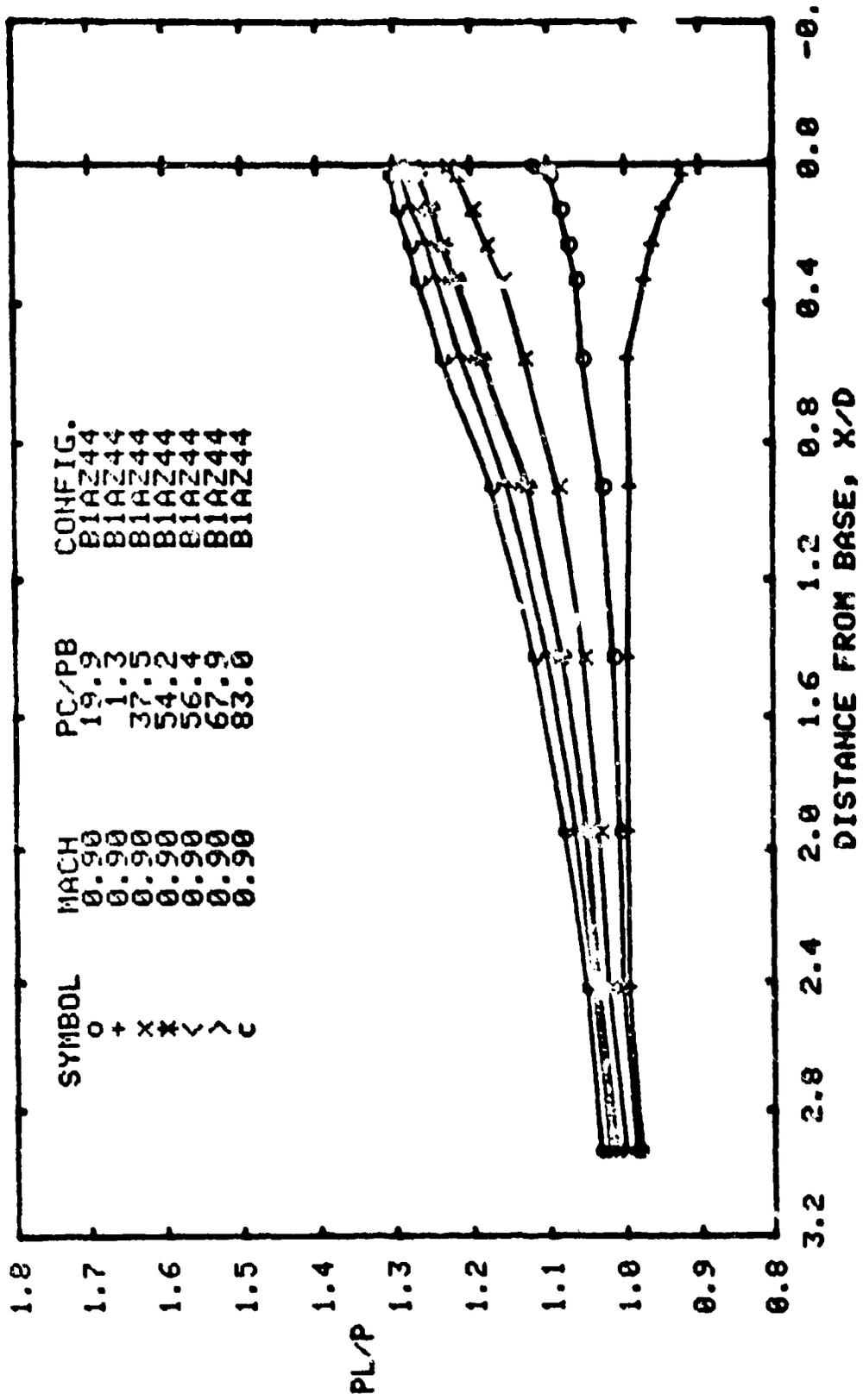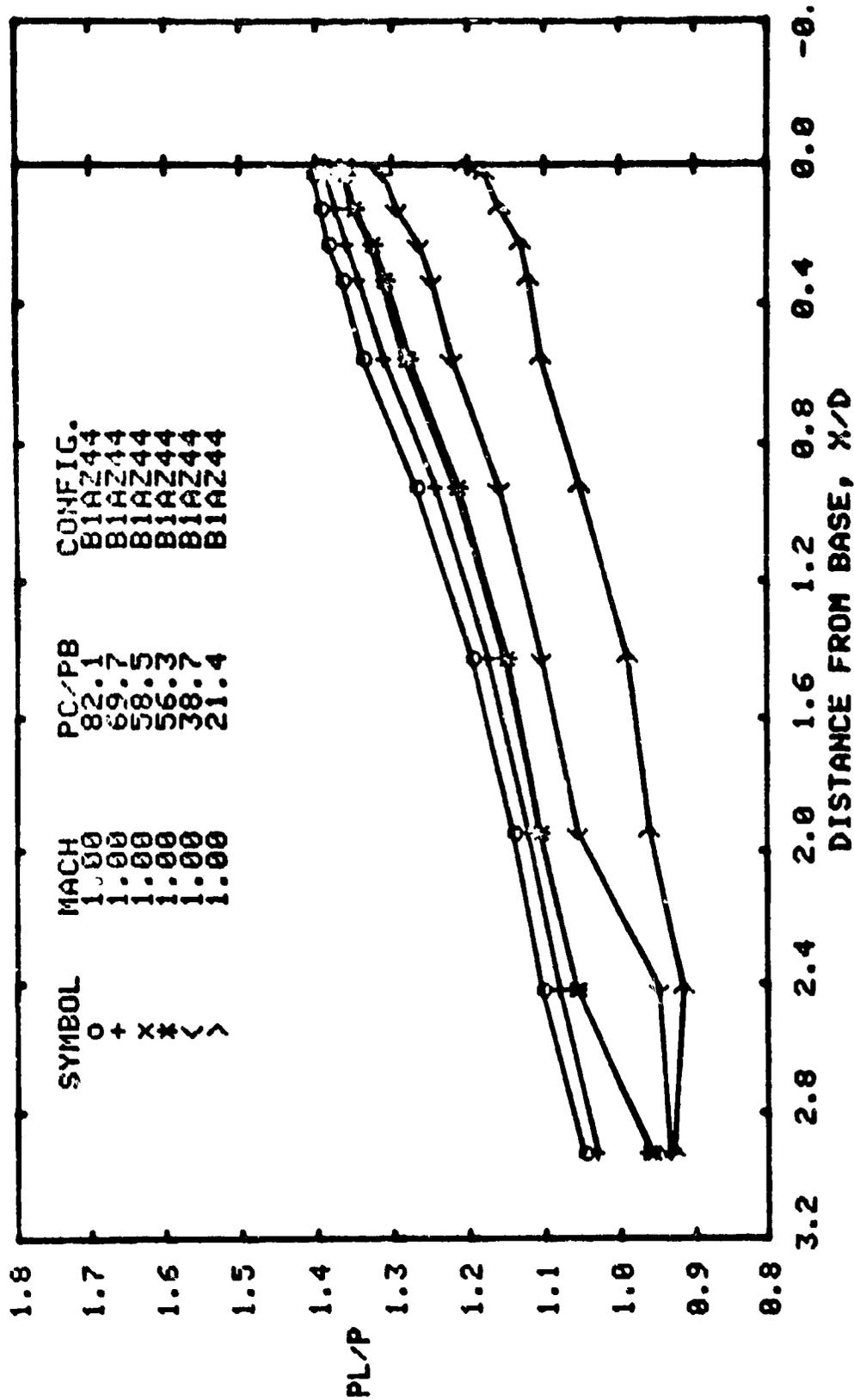
Figure A2:

(d). M=1.0
Figure A2: cont'd
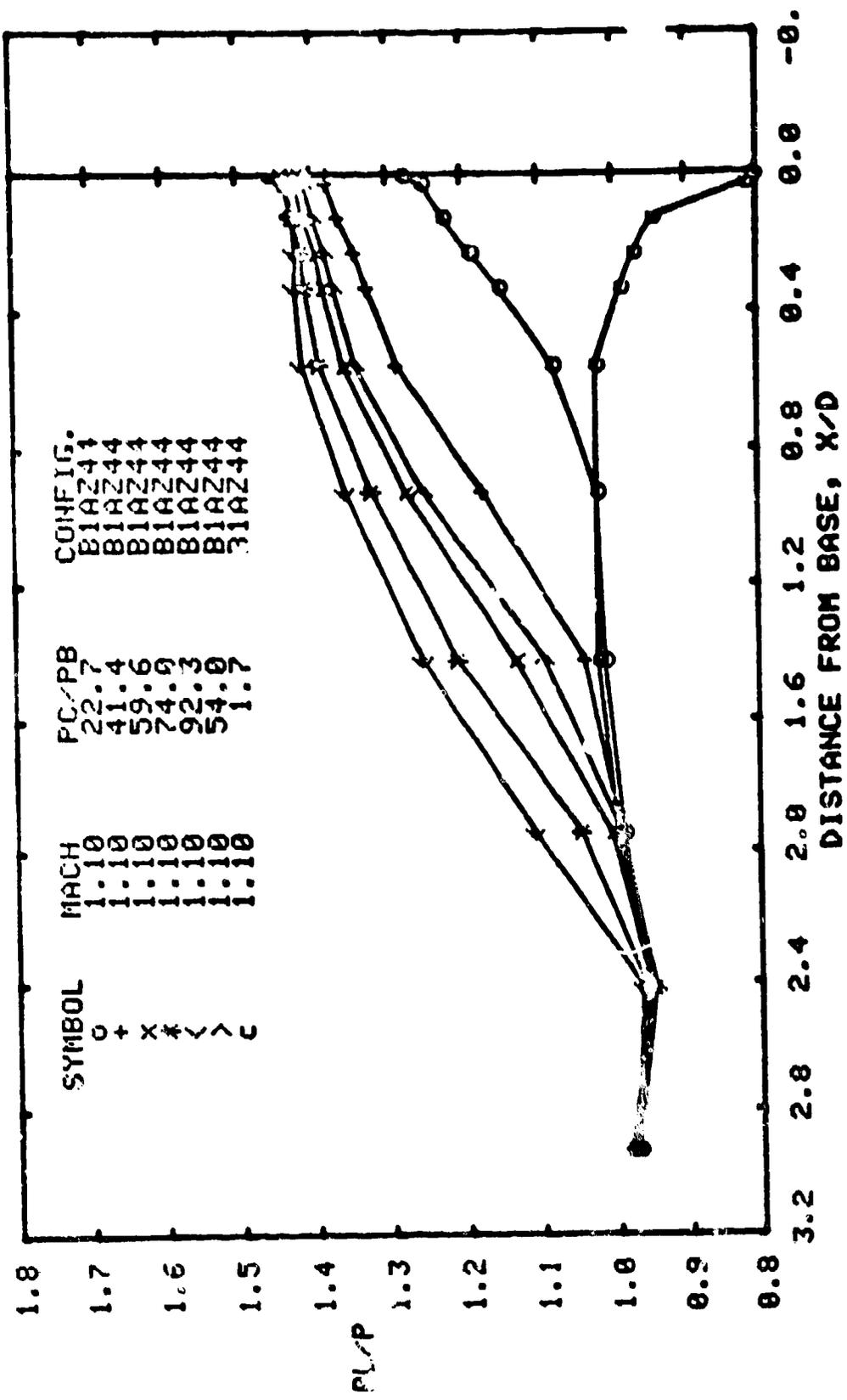
(e). M=1.1

Figure A2: cont'd
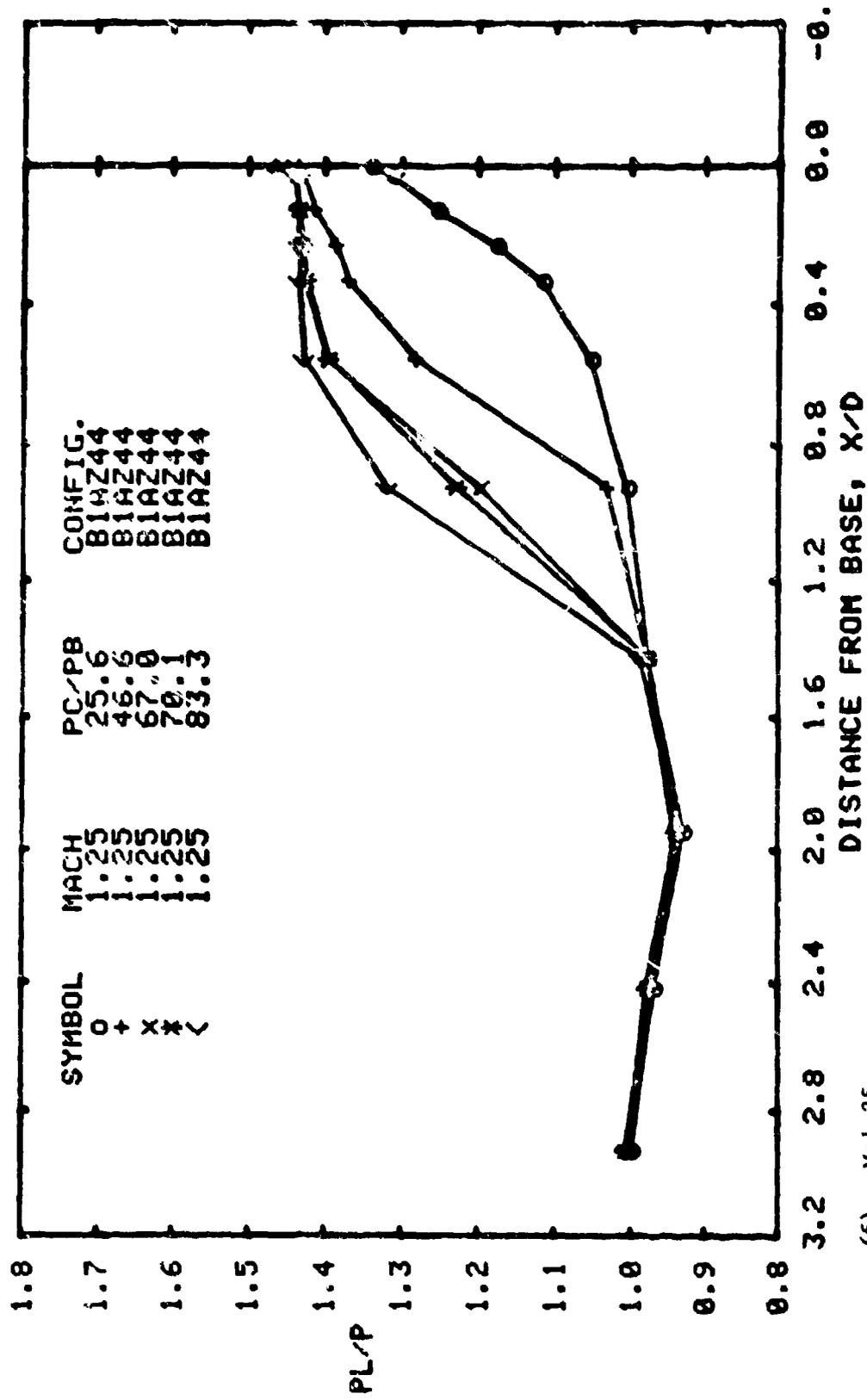
(f). M=1.25
Figure A2: cont'd

82
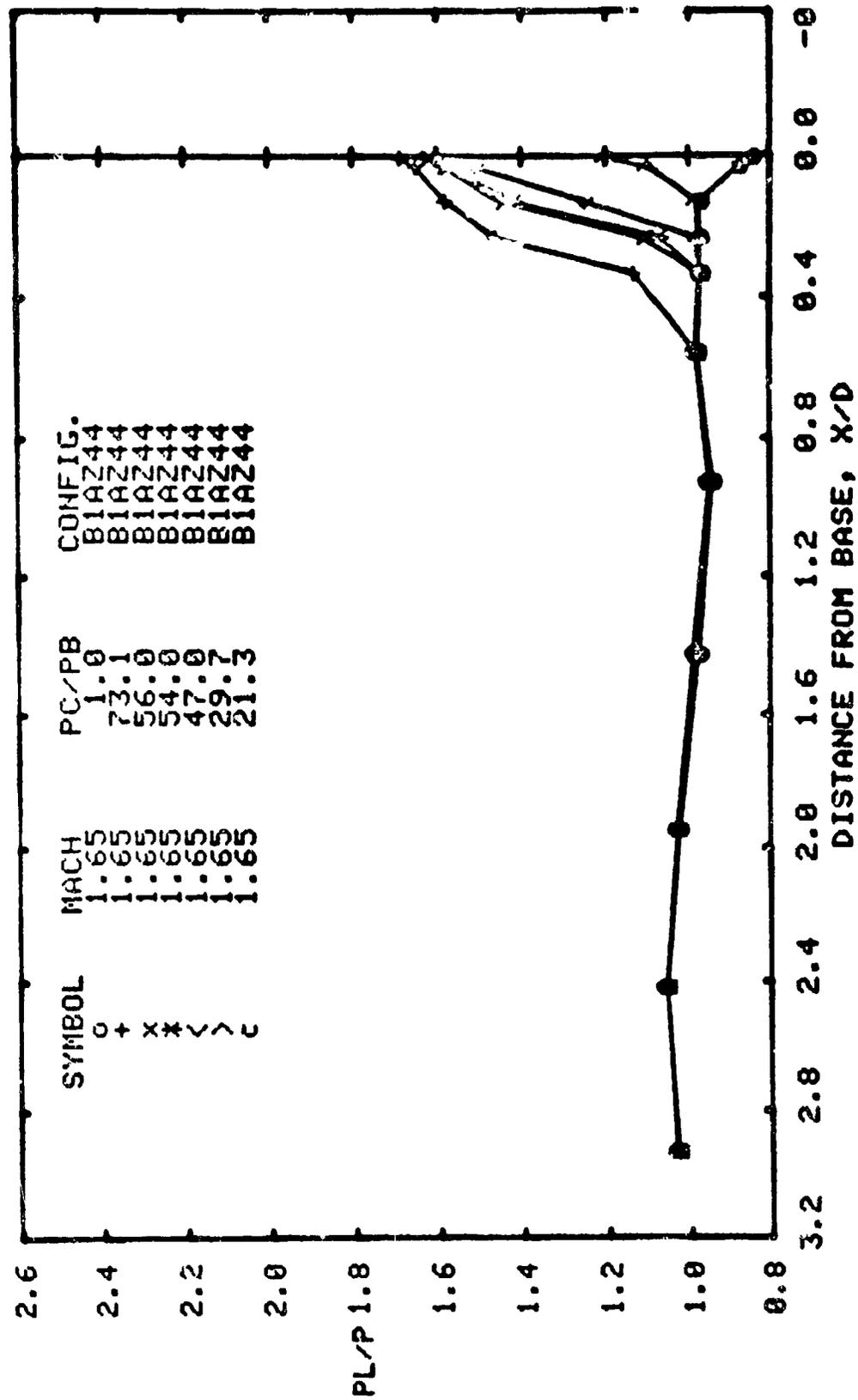
(g). M=1.65

Figure A2: cont'd

83

(h). M=2.0 cont'd
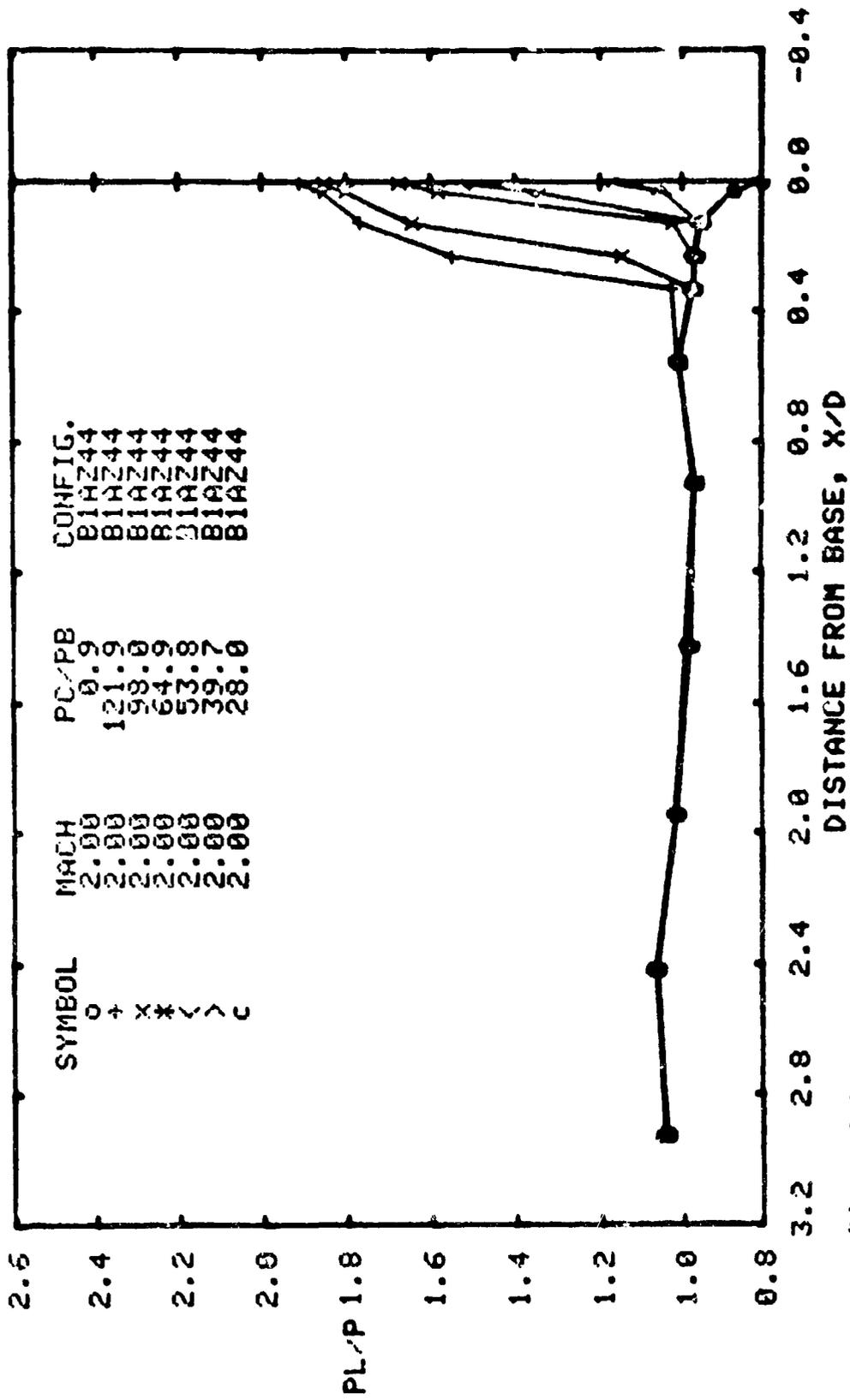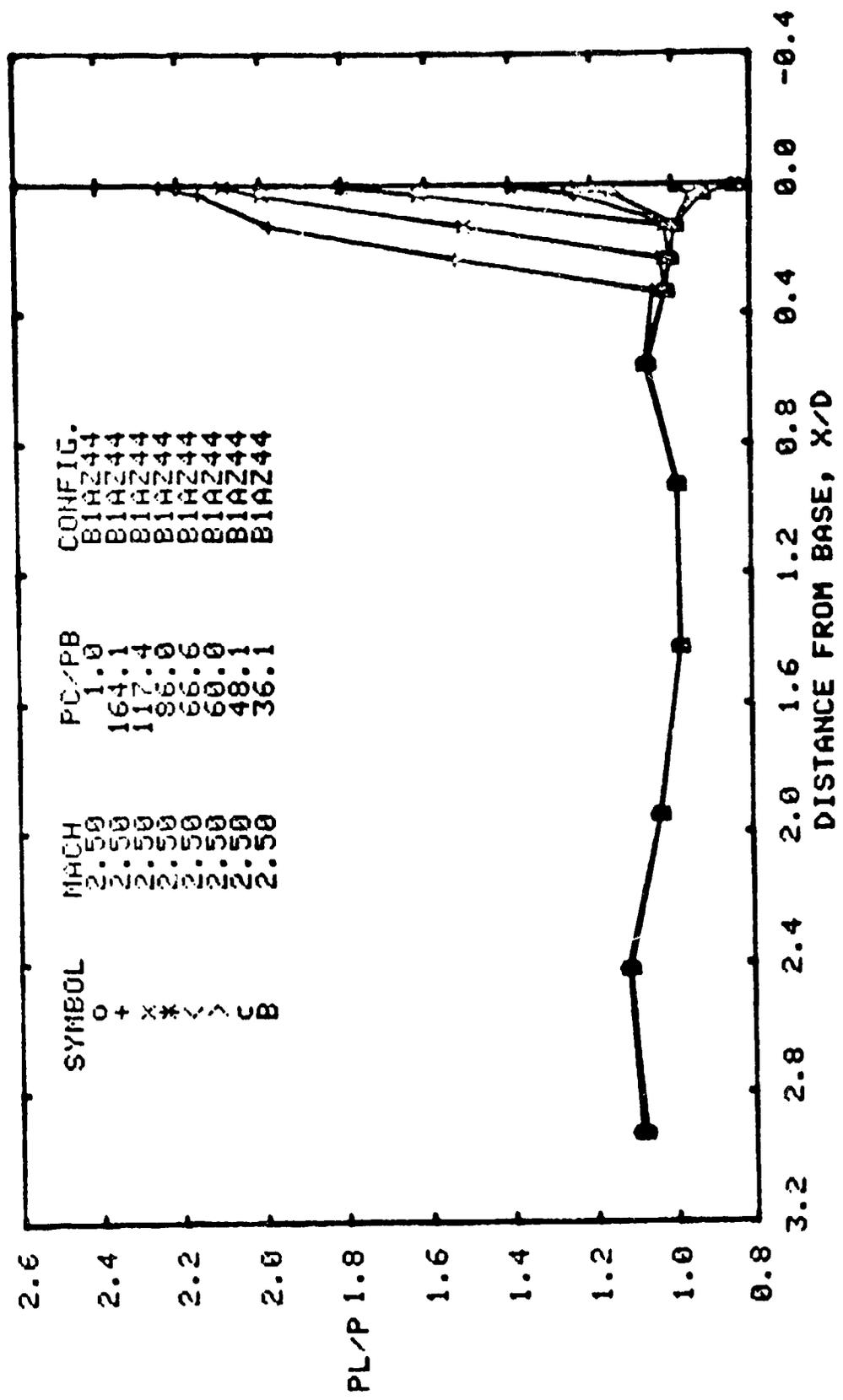
Figure A2:

(1). M=2.5

Figure A2: concl'd.
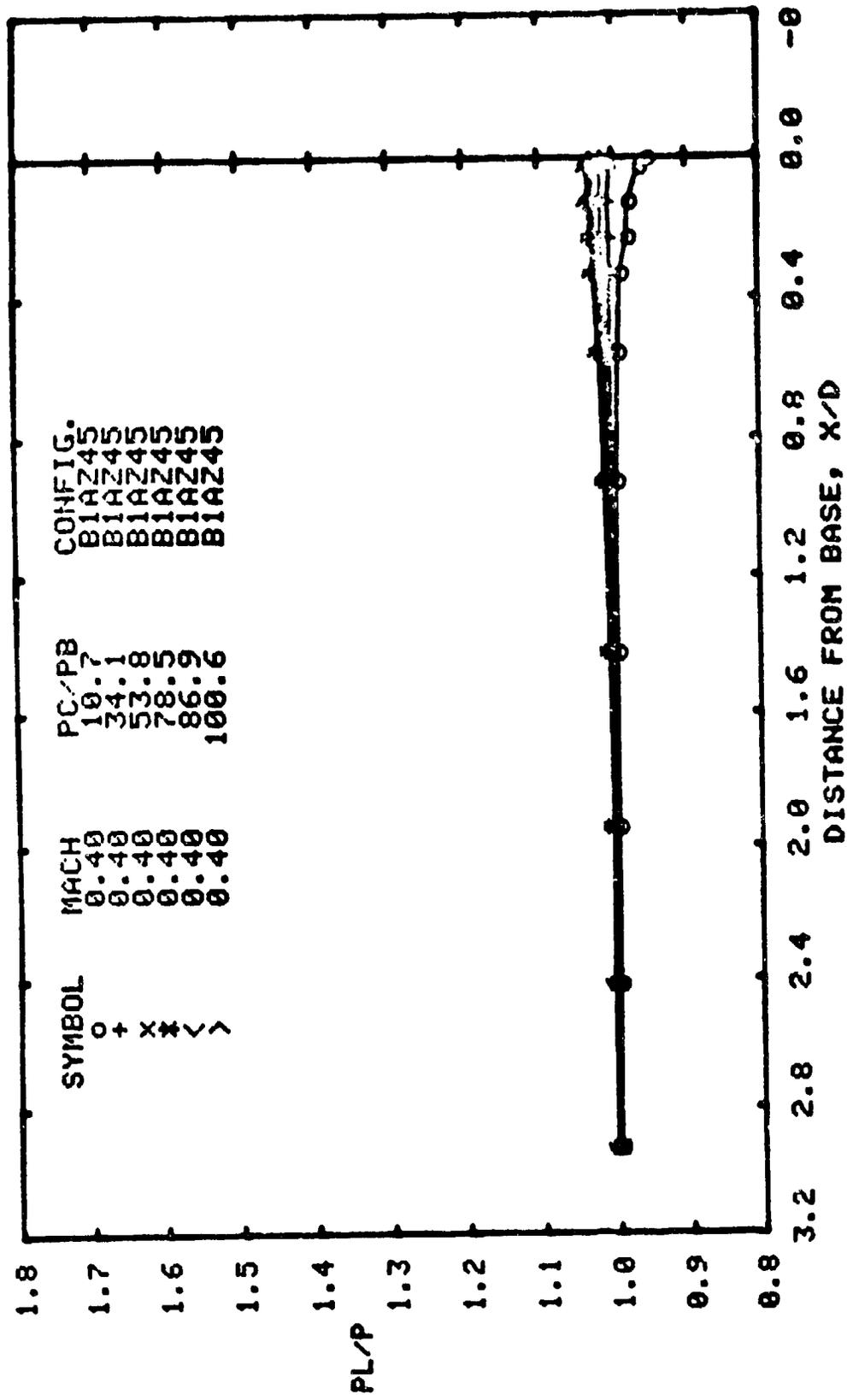
(a). M=0.4

Figure A3: Effect of jet total pressure ratio on body pressure distribution at various free stream Mach numbers. Configuration B1AZ45: $M_J=2.4$, $\theta_n=19.35$, $D_N/D_B=0.8$.

(b). M=0.7 cont'd

Figure A3: cont'd

87
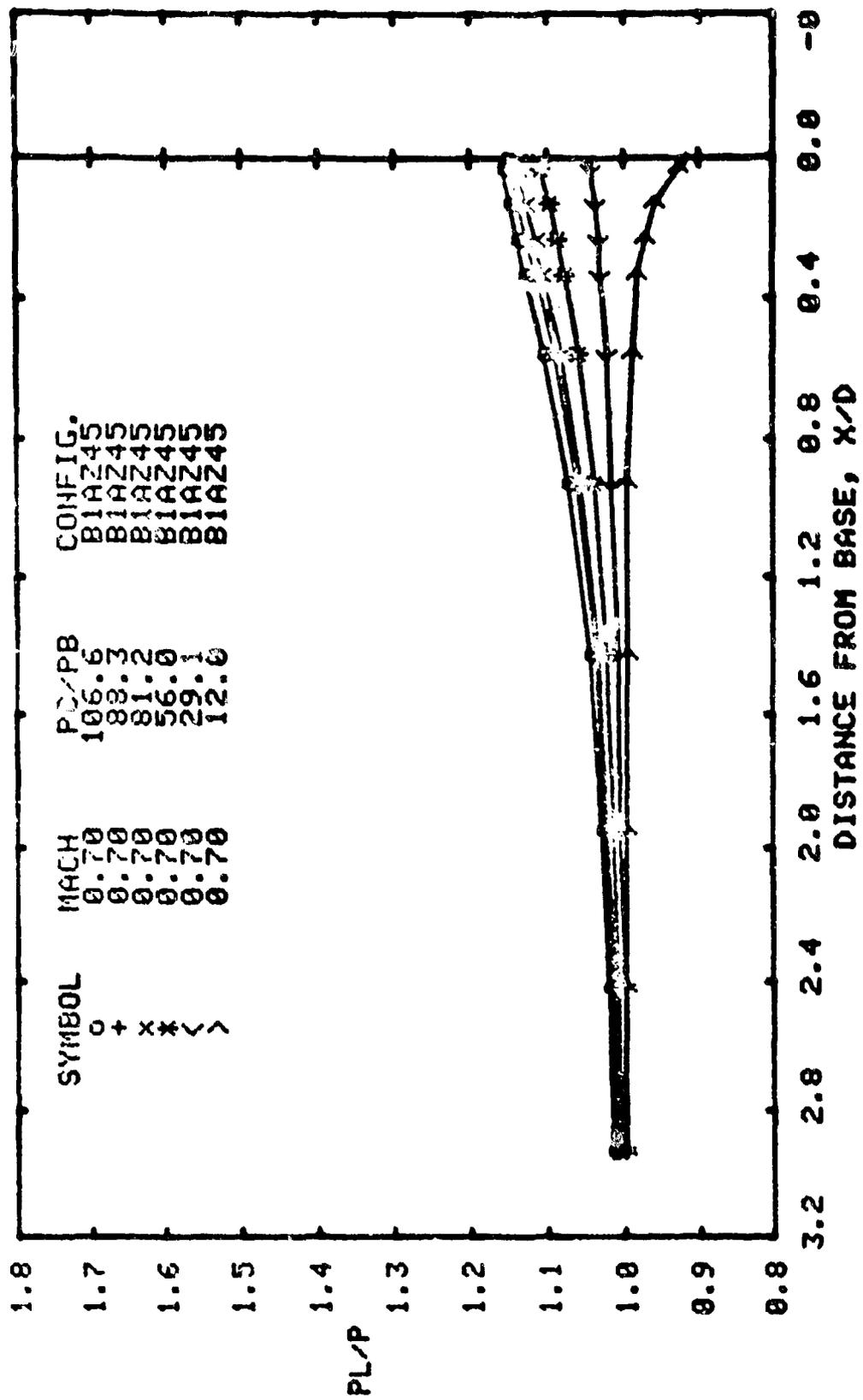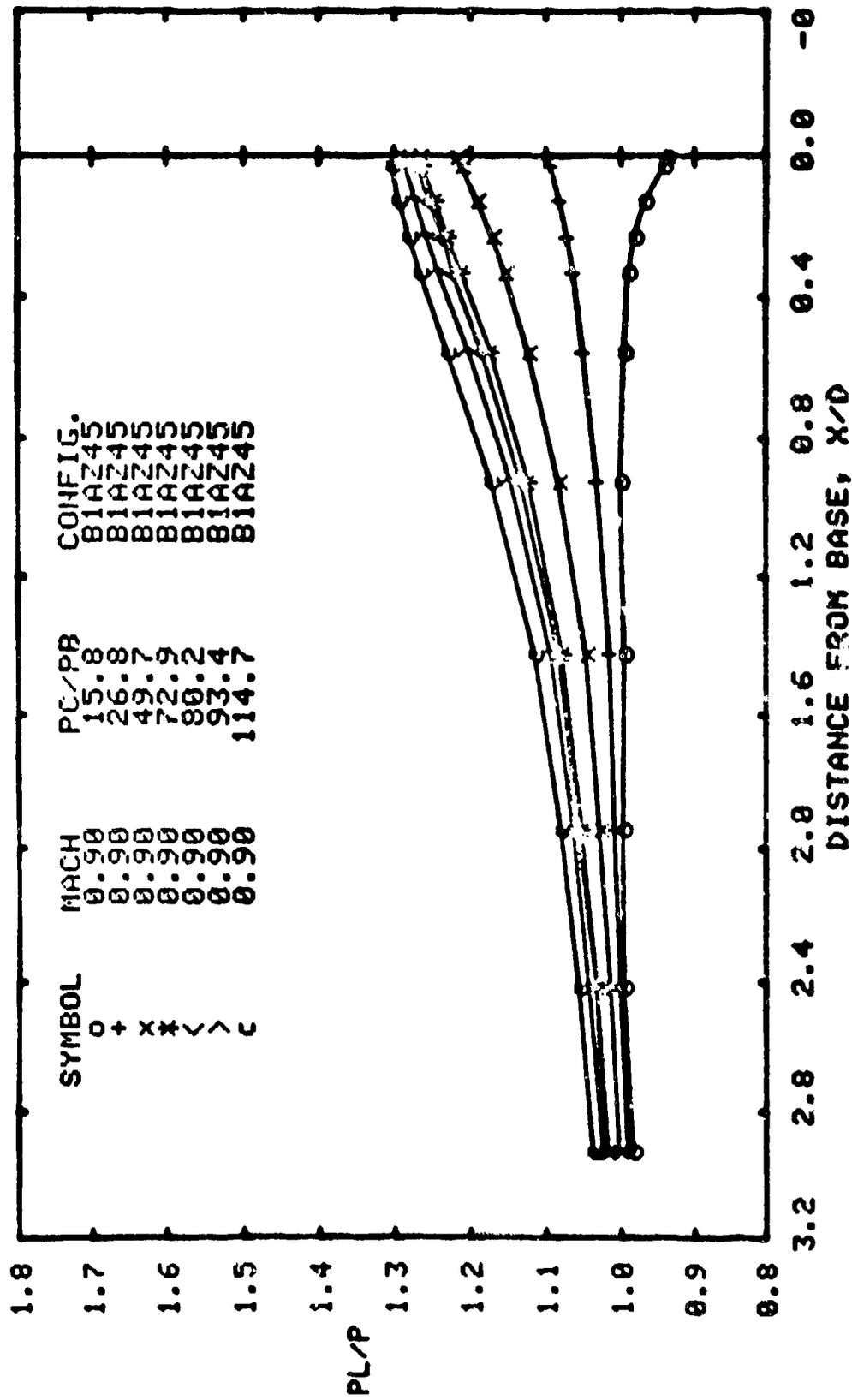
(c). M=0.9
Figure A3: cont'd
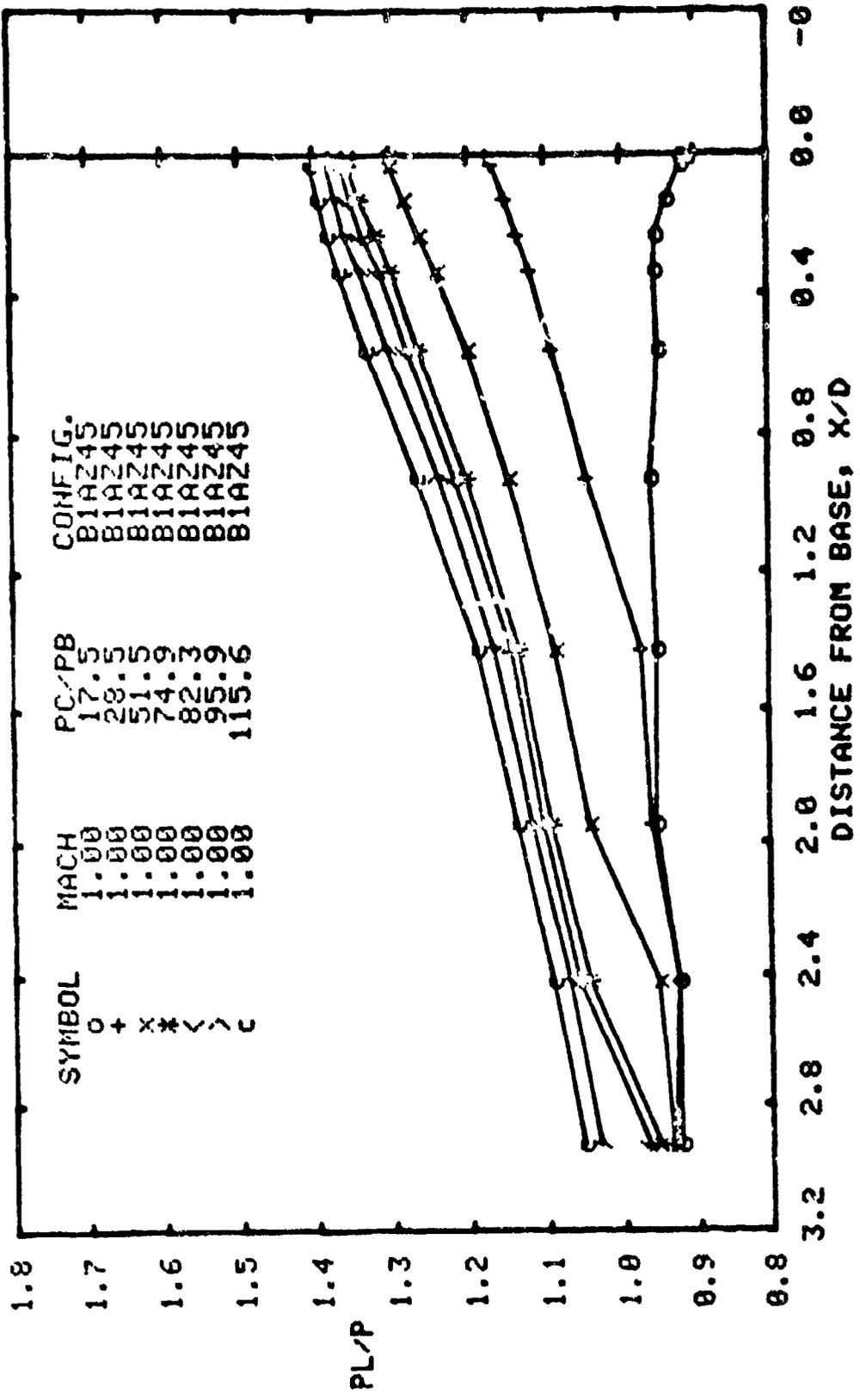
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Figure A3: cont'd
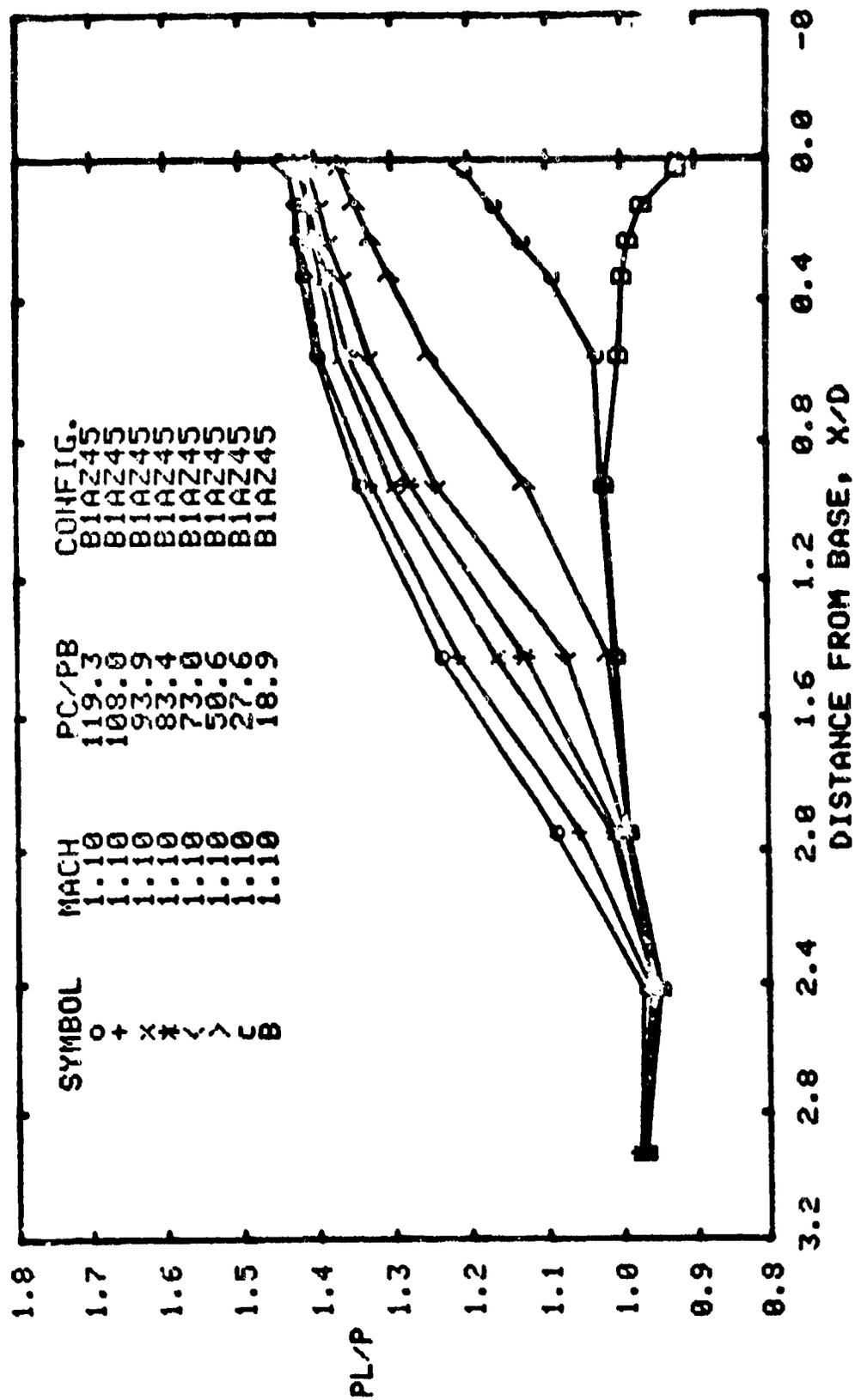
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Figure A3: cont'd
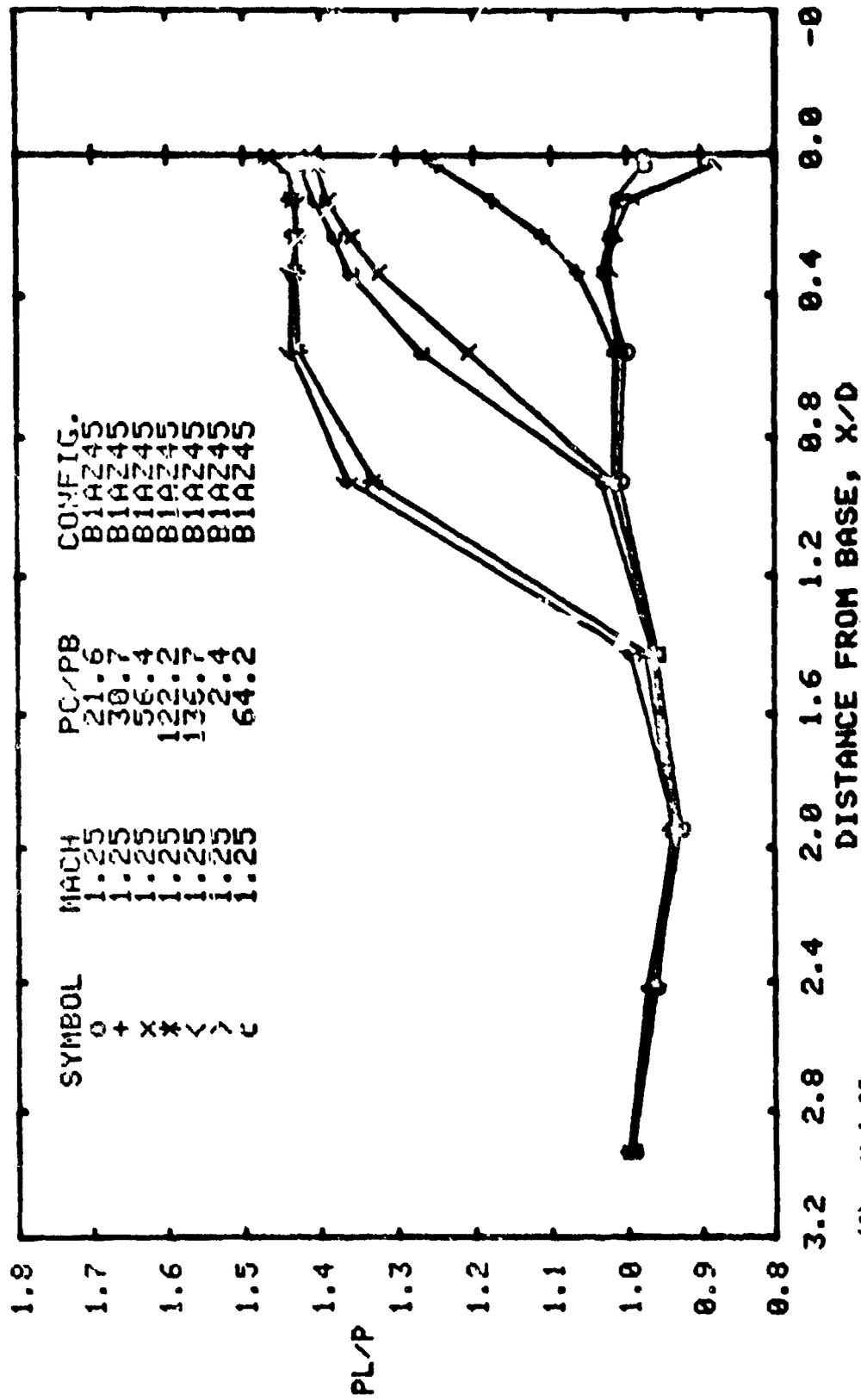
(f). M=1.25
Figure A3: cont'd

91
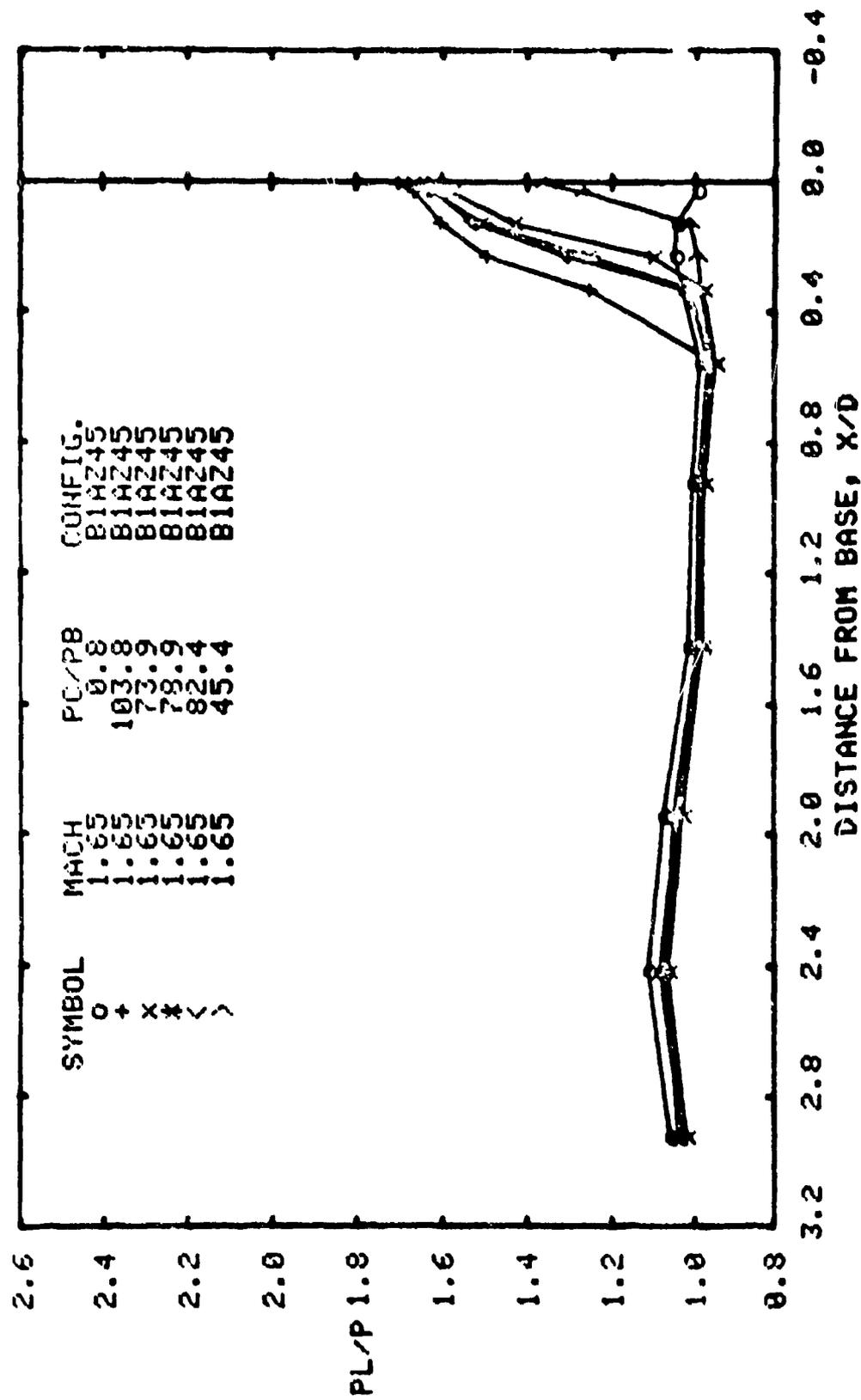
(g). M=1.65
Figure A3: cont'd

92

(h). M=2.0 concl'd.
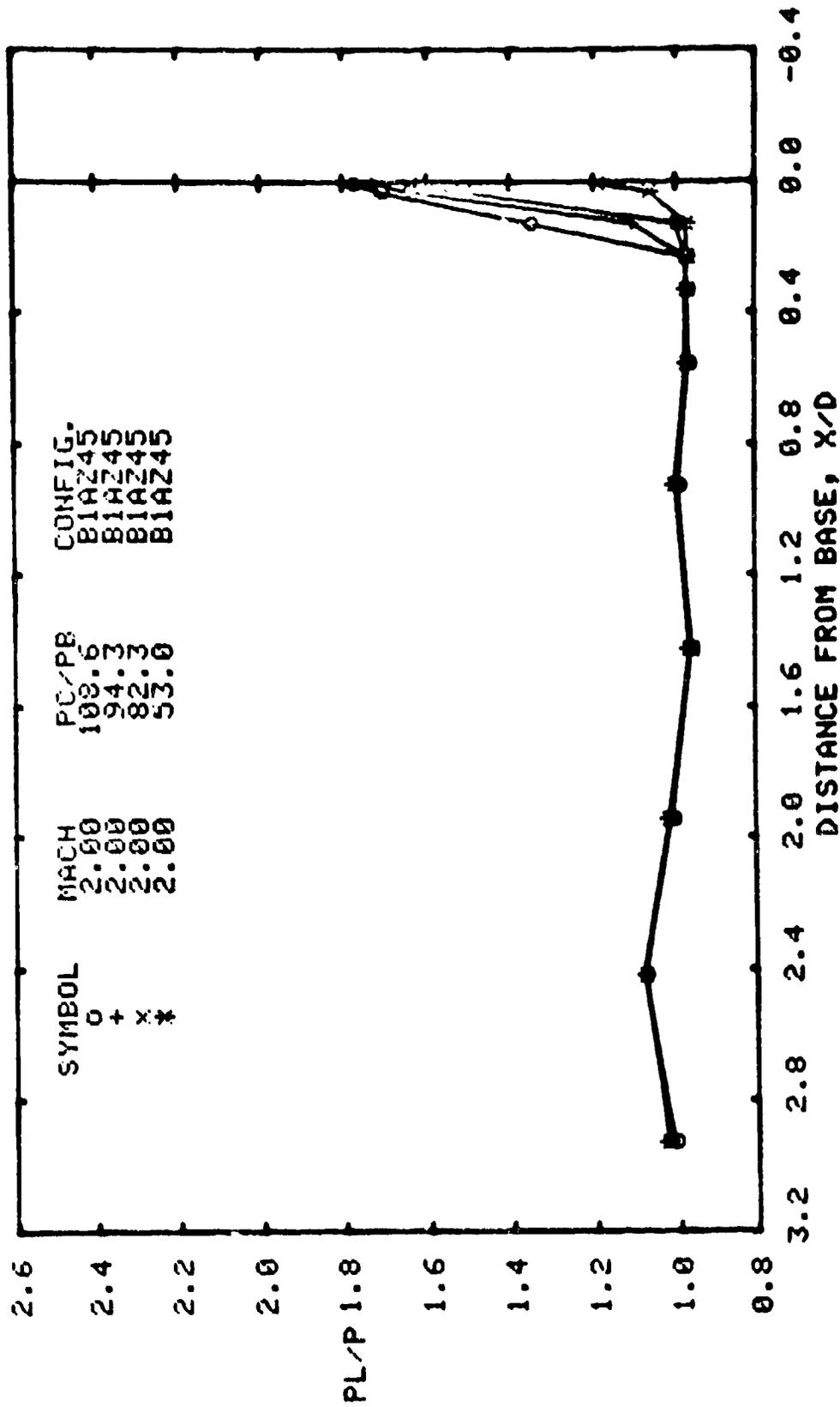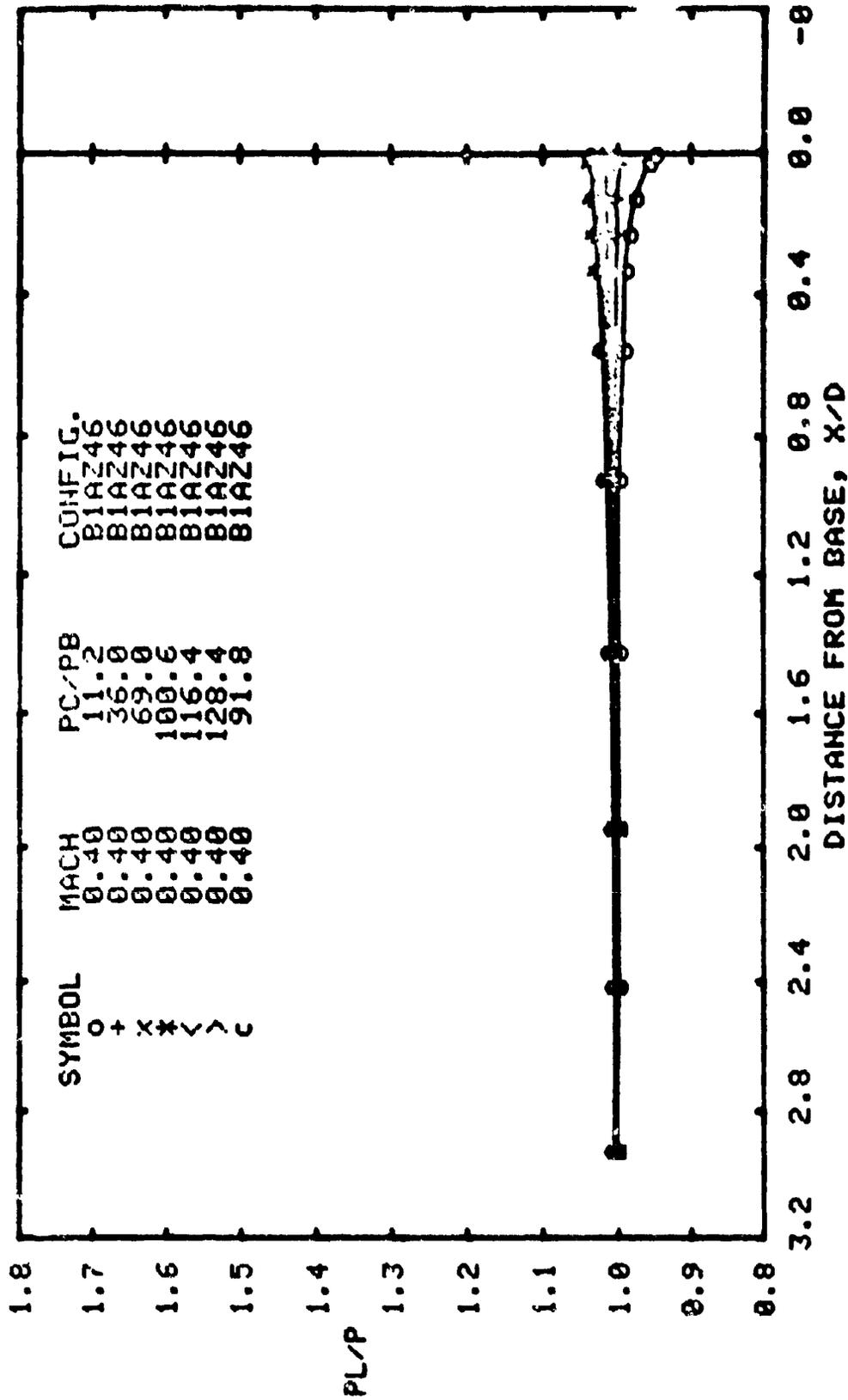
Figure A3:

Figure A4: Effect of jet total pressure ratio on body pressure distribution at various free stream Mach numbers. Configuration B1AZ46: M_J=2.7, θ_N=23.3°, D_N/D_B=0.8.

(a). M= 0.4

94
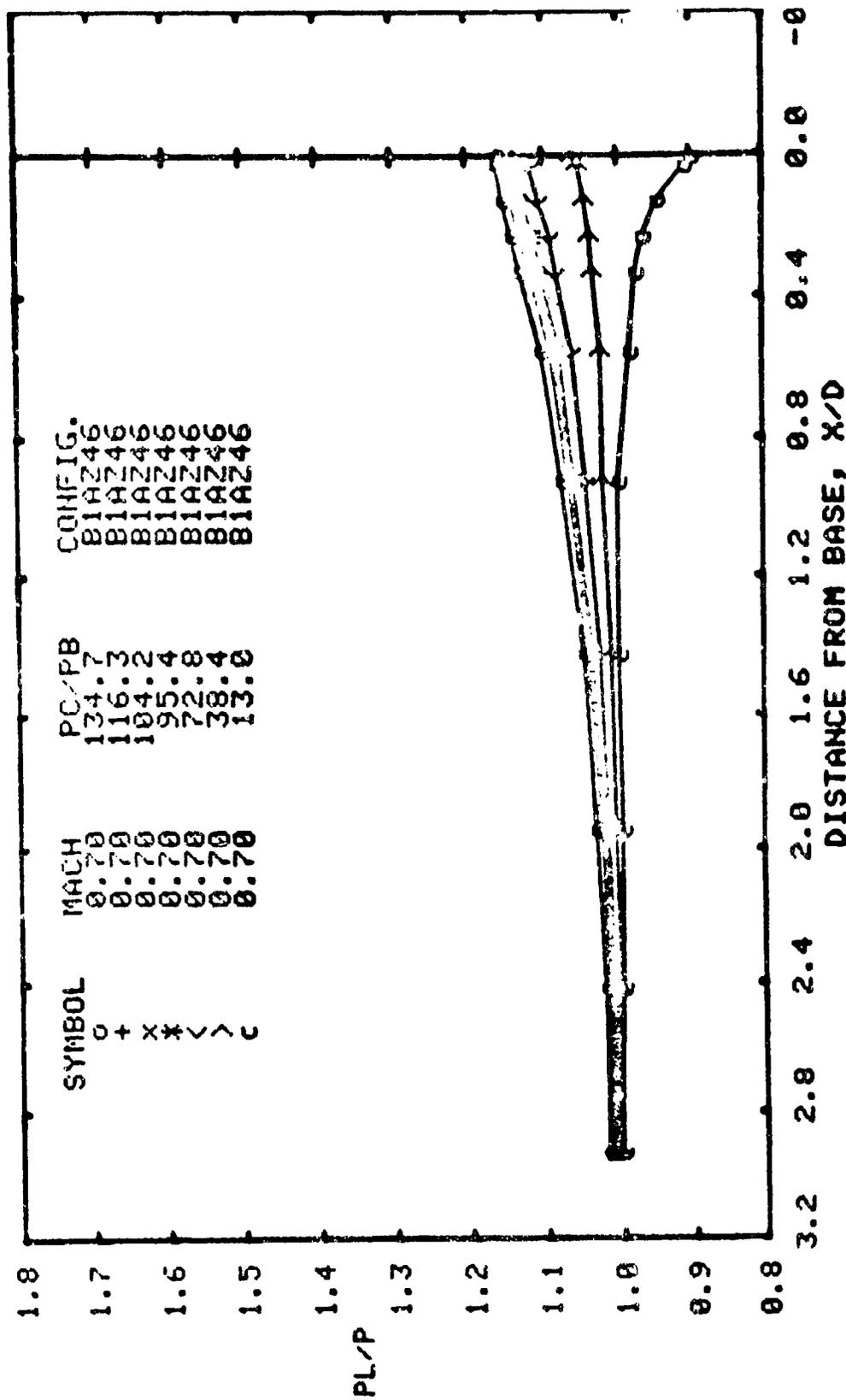
(b). M=0.7
Figure A4: cont'd
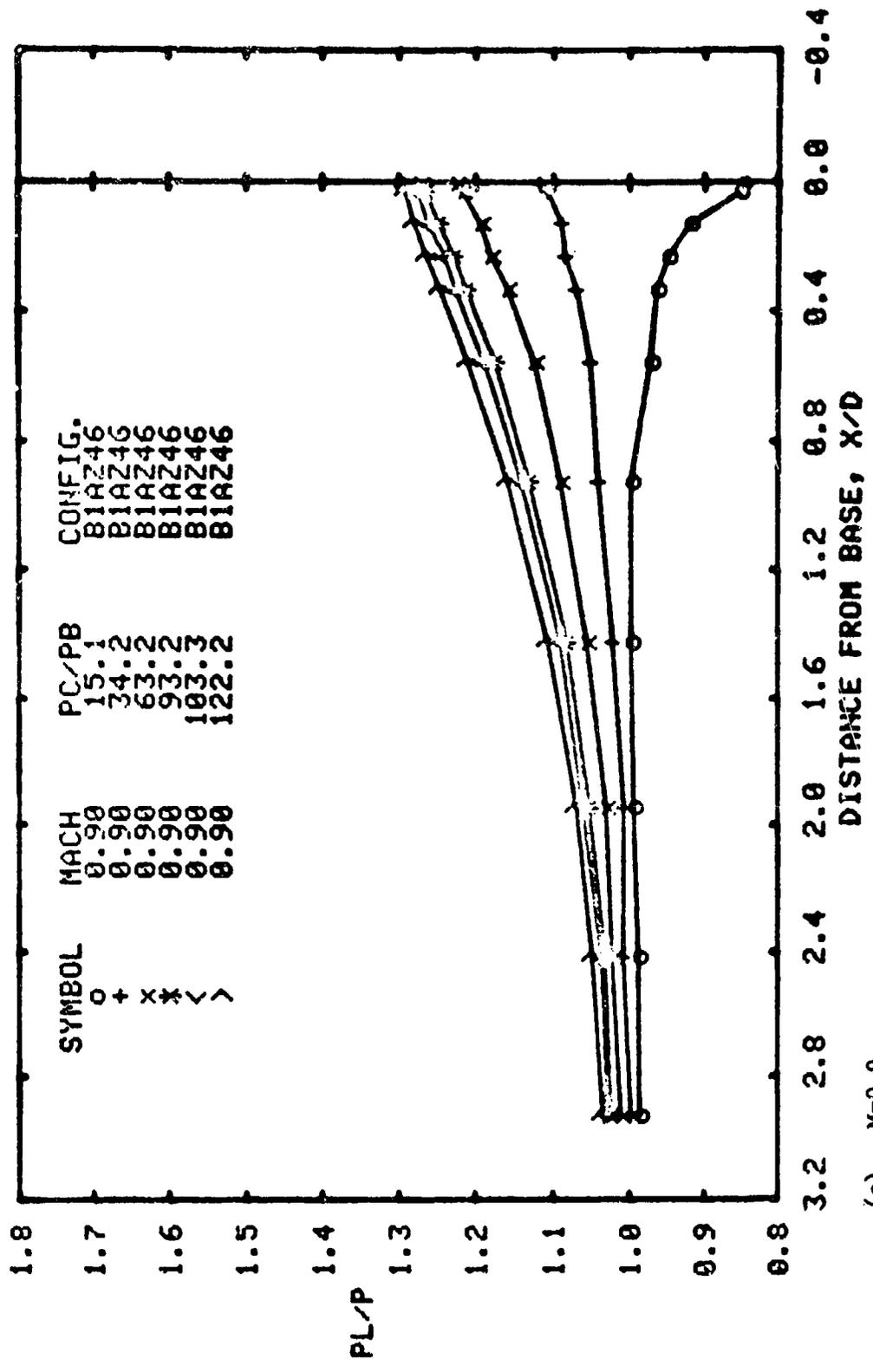
(c). M=0.9

Figure A4: cont'd

96

(d). M=1.0

Figure A4: cont'd

97

(e). M=1.1 cont'd

Figure A4:

98

(f). M=1.25
Figure A4: cont'd

SYMBOL   MACH   PC/PB   CONFIG.

SYMBOL	MACH	PC/PB	CONFIG.
o	1.65	122.0	B1A2Z46
+	1.65	109.0	B1A2Z46
x	1.65	92.3	B1A2Z46
*	1.65	72.5	B1A2Z46
∨	1.65	63.5	B1A2Z46
∧	1.65	49.7	B1A2Z46
G	1.65	24.4	B1A2Z46
8	1.65	0.7	B1A2Z46

PL/P
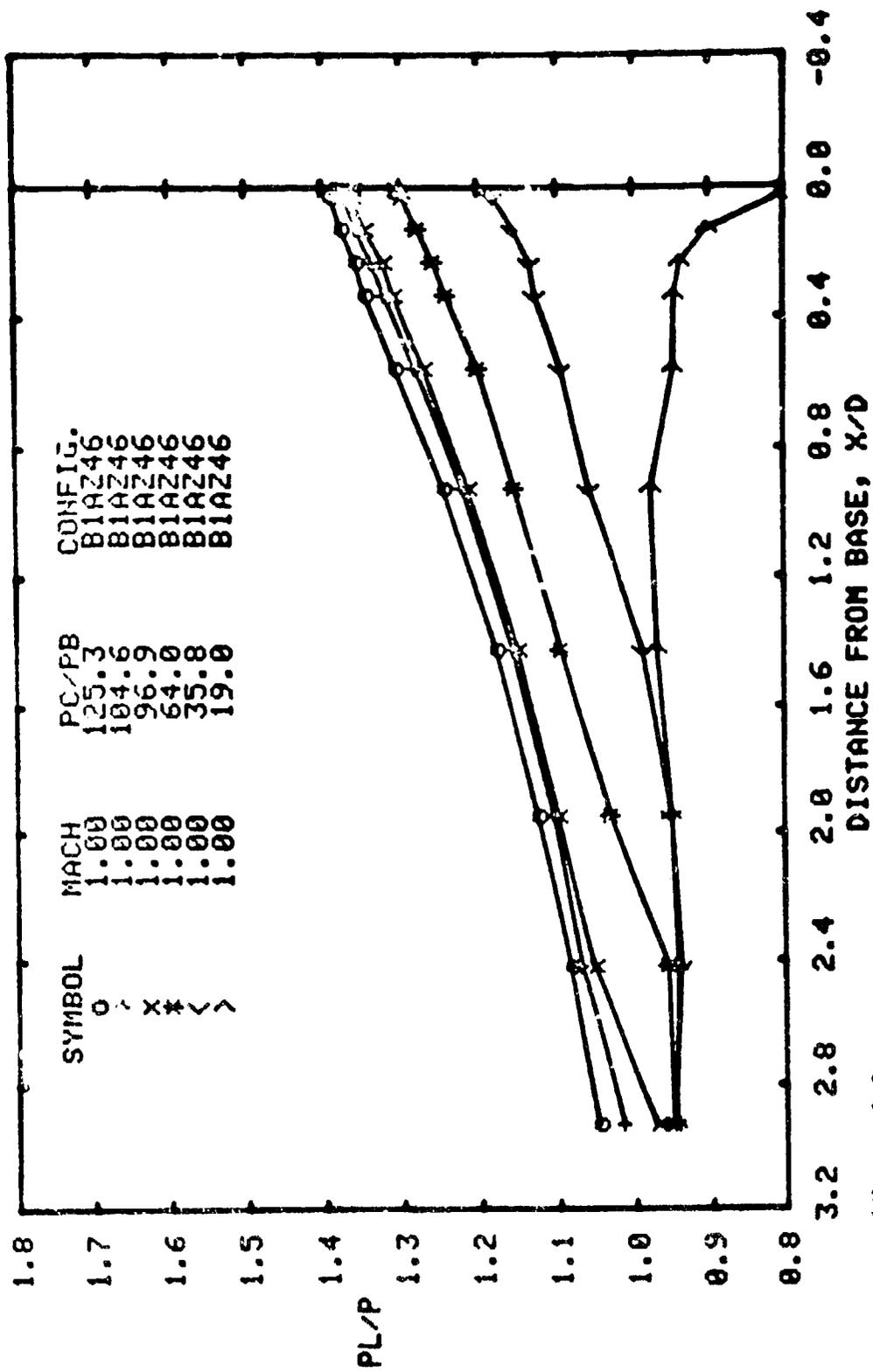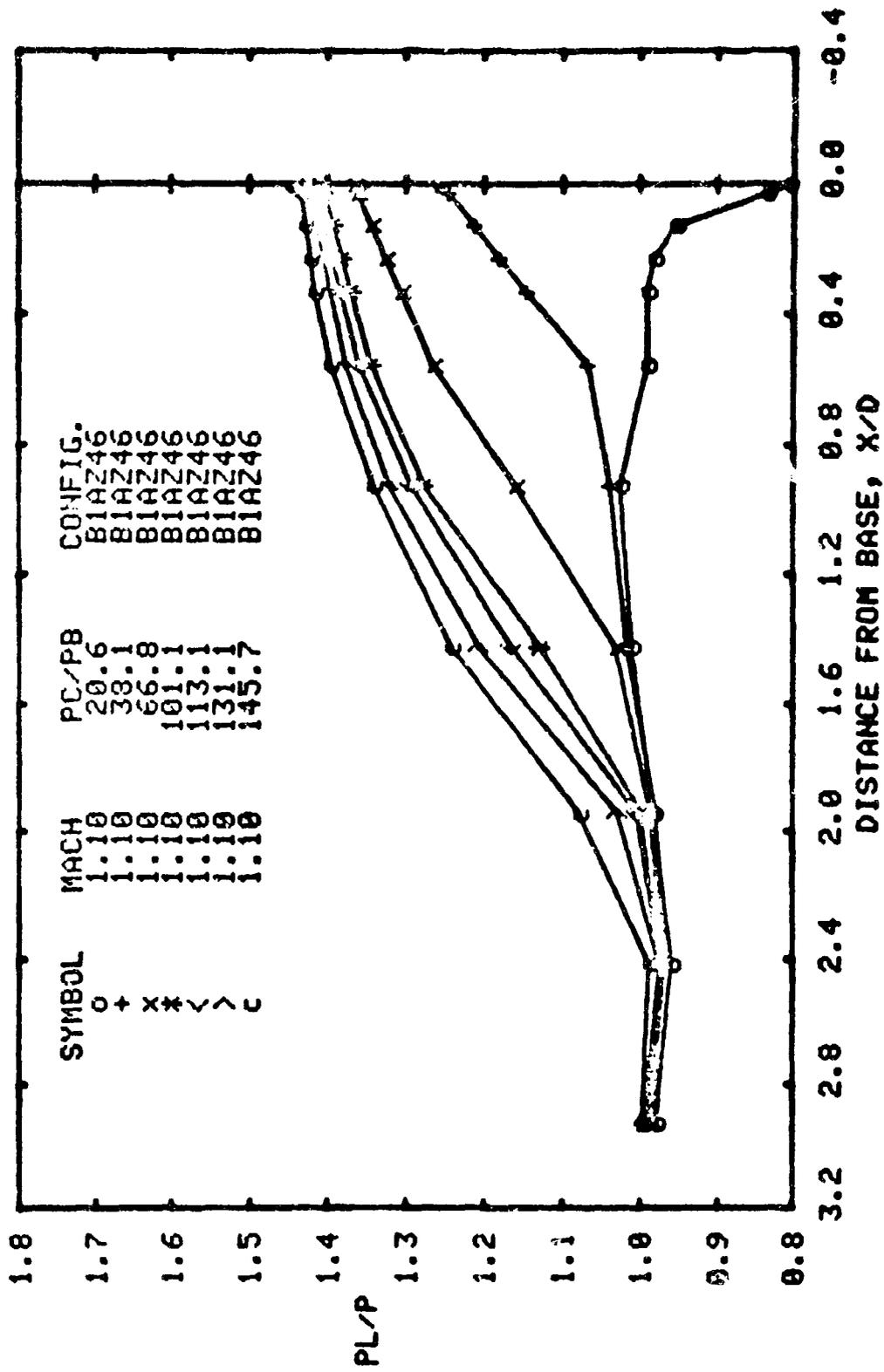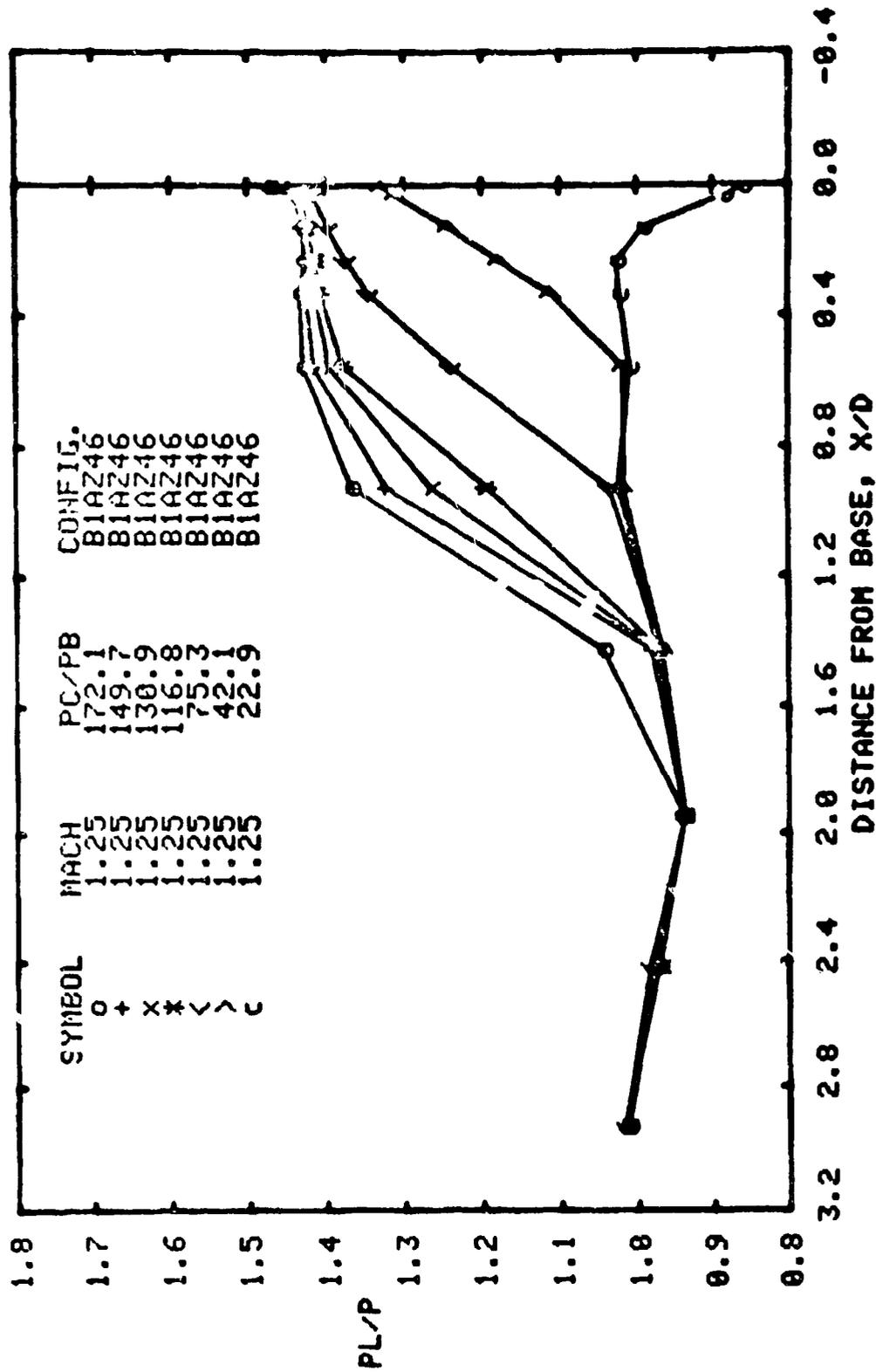
DISTANCE FROM BASE, X/D
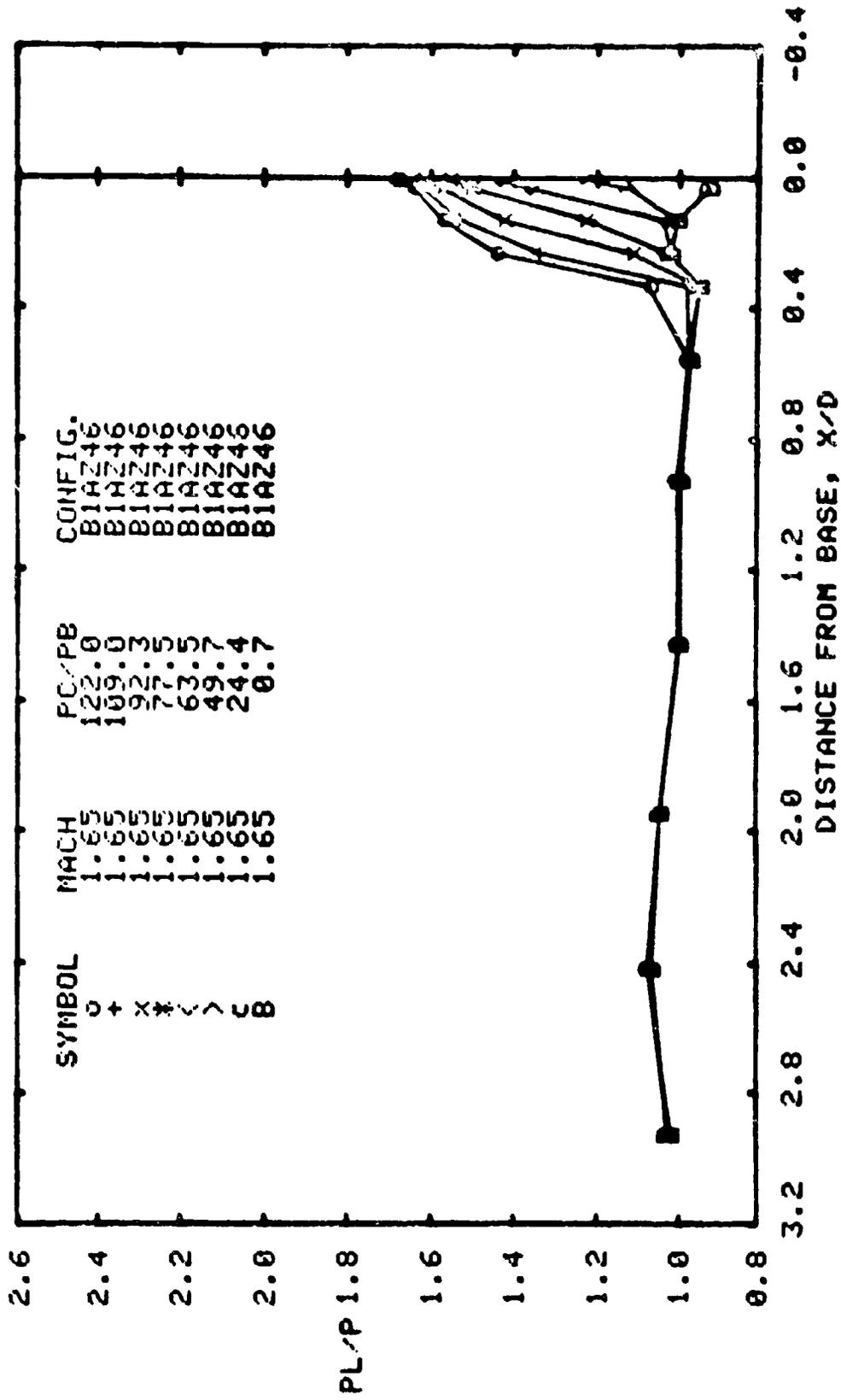
(g).   M=1.65
Figure A4:   cont'd

100

(h). M=2.0
Figure A4: cont'd

101

SYMBOL	MACH	PC/PB	CONFIG.
O	2.50	274.7	B1A2Z46
+	2.50	215.5	B1A2Z46
X	2.50	151.3	B1A2Z46
*	2.50	123.4	B1A2Z46
∨	2.50	93.7	B1A2Z46
∧	2.50	100.9	B1A2Z46
⊏	2.50	51.8	B1A2Z46
⊏	2.50	29.8	B1A2Z46
B	2.58	-0.6	B1A2Z46

PL/P

DISTANCE FROM BASE, X/D
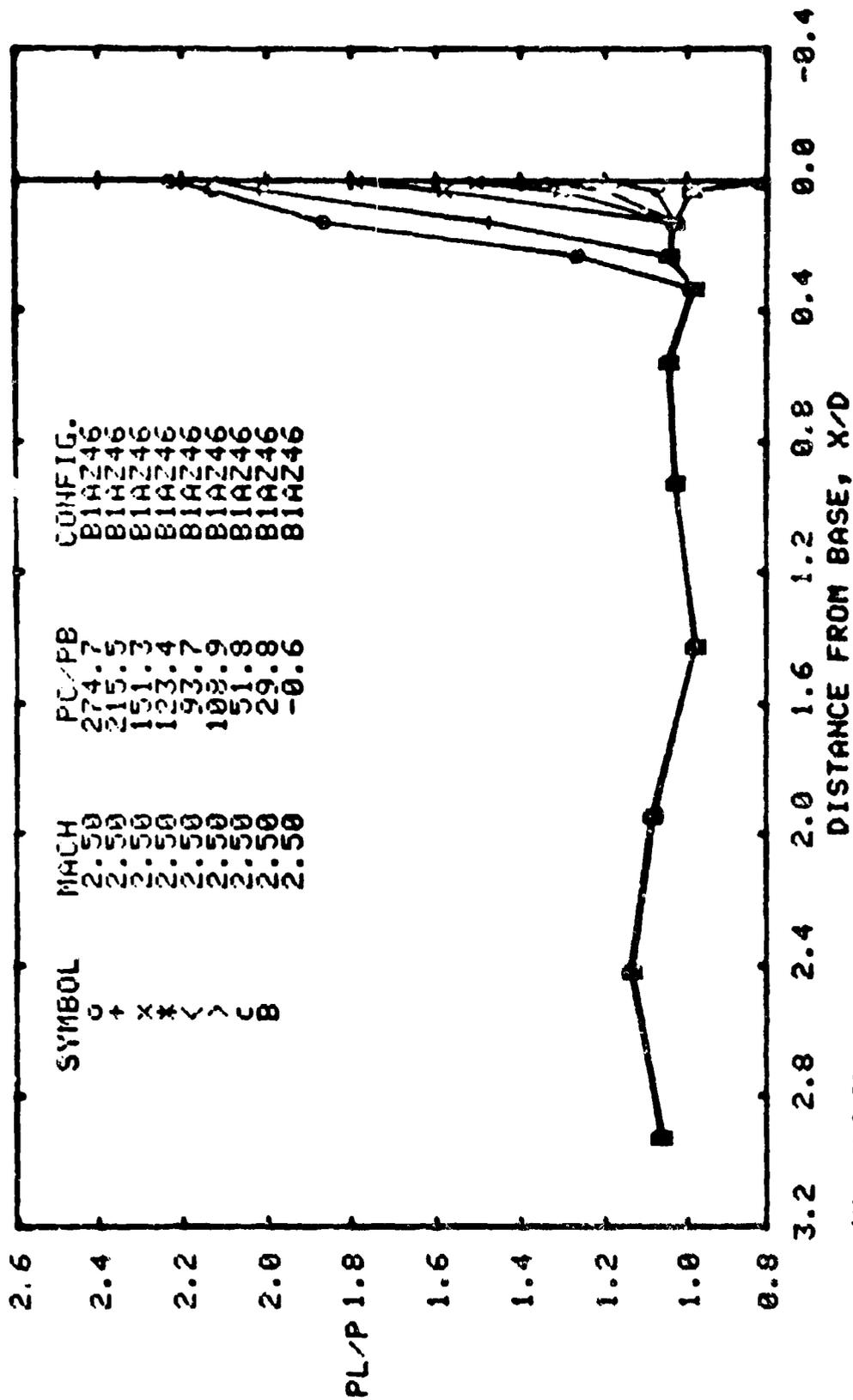
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Figure A4: concl'd.
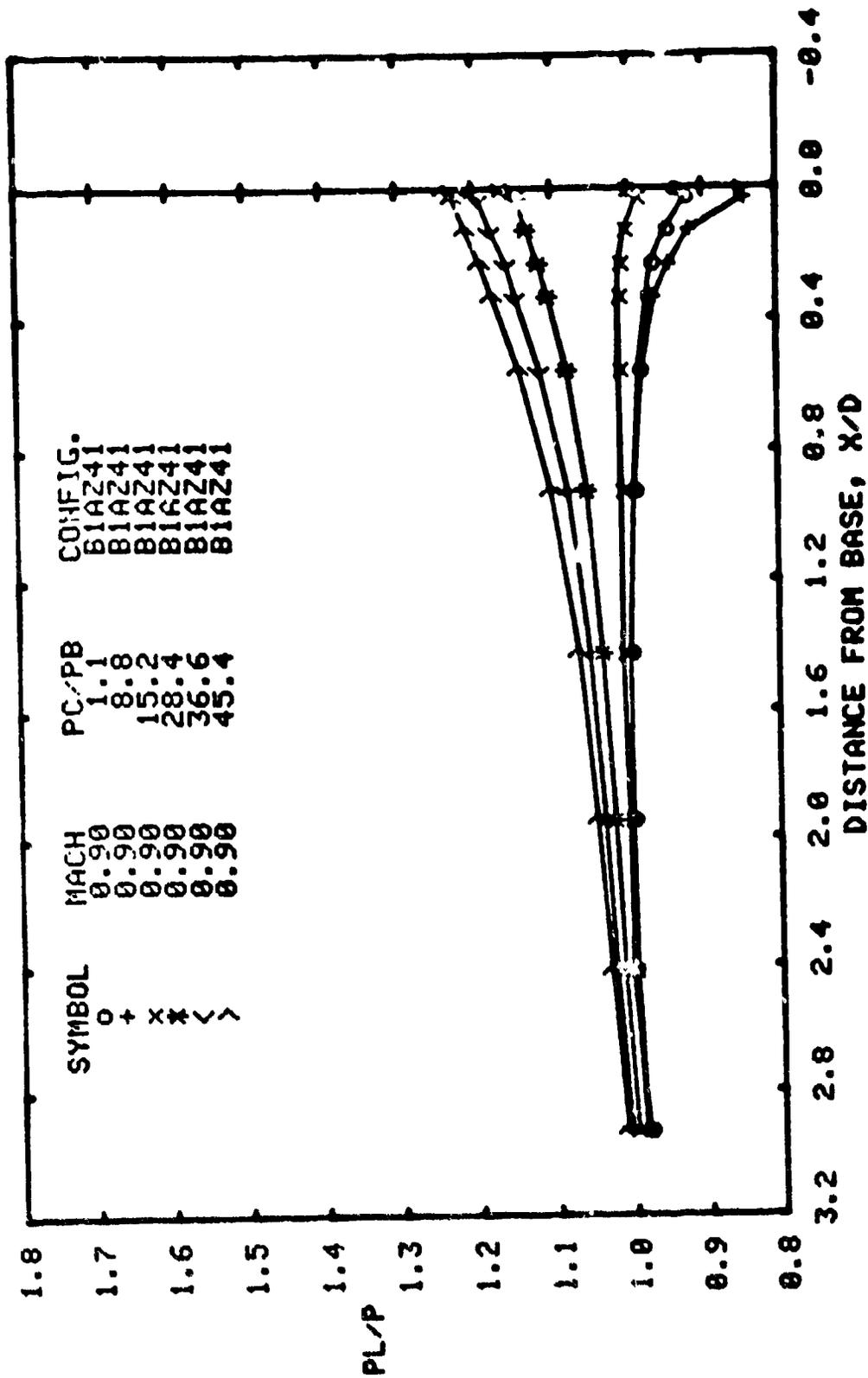
Figure A5: Effect of jet total pressure ratio on body pressure distribution at various free stream Mach numbers. Configuration B1AZ41: $M_J=1.76$, $\theta_N=3.95^\circ$, $D_N/D_B=0.8$.

(a). $M=0.9$

(b). M=1.0

Figure A5: cont'd

104

SYMBOL	MACH	PC/PB	CONFIG.
o	1.25	14.1	B1A241
+	1.25	19.7	B1A241
x	1.25	32.9	B1A241
*	1.25	39.4	B1A241
<	1.25	45.2	B1A241
>	1.25	58.5	B1A241

DISTANCE FROM BASE, X/D

PL/P
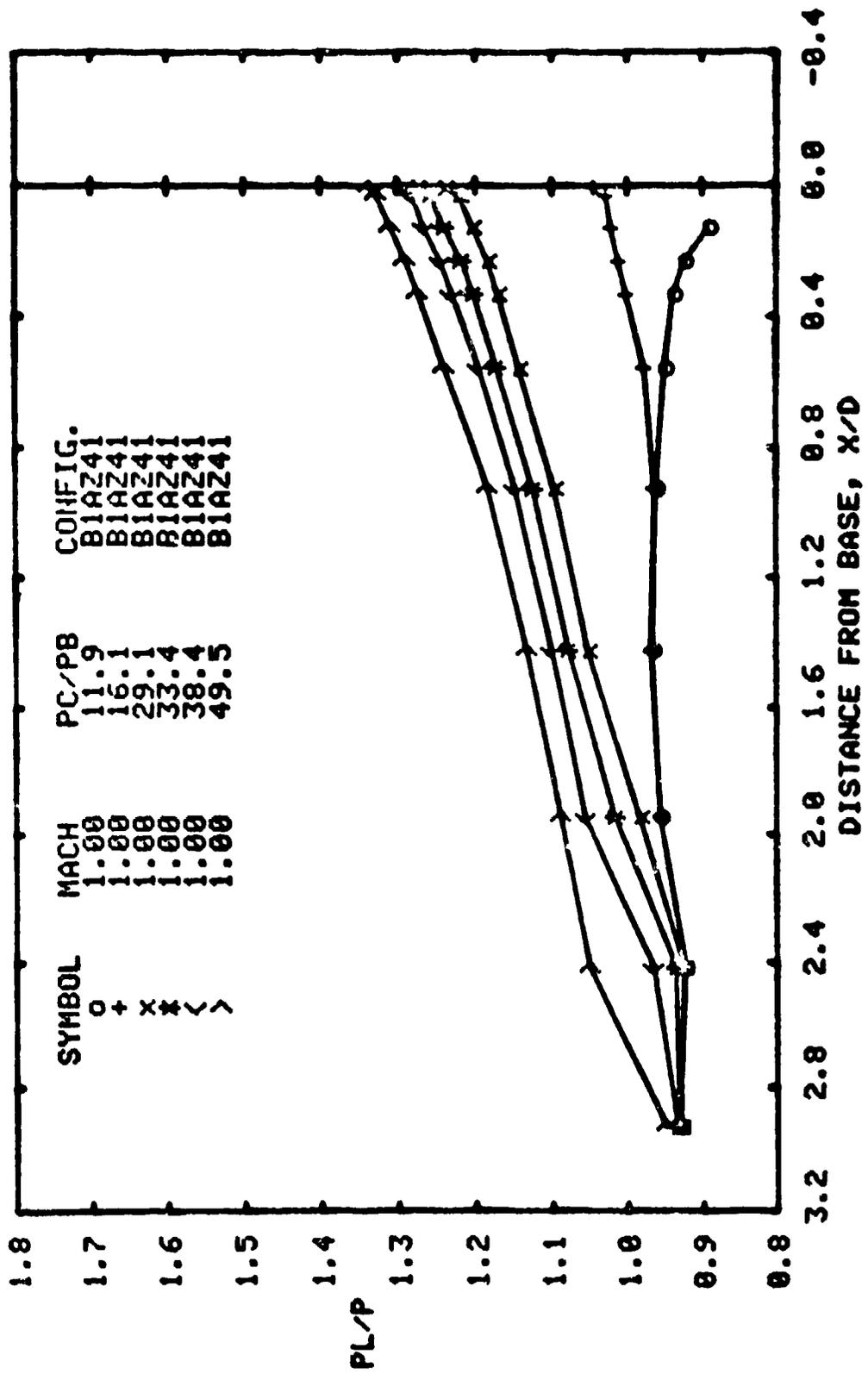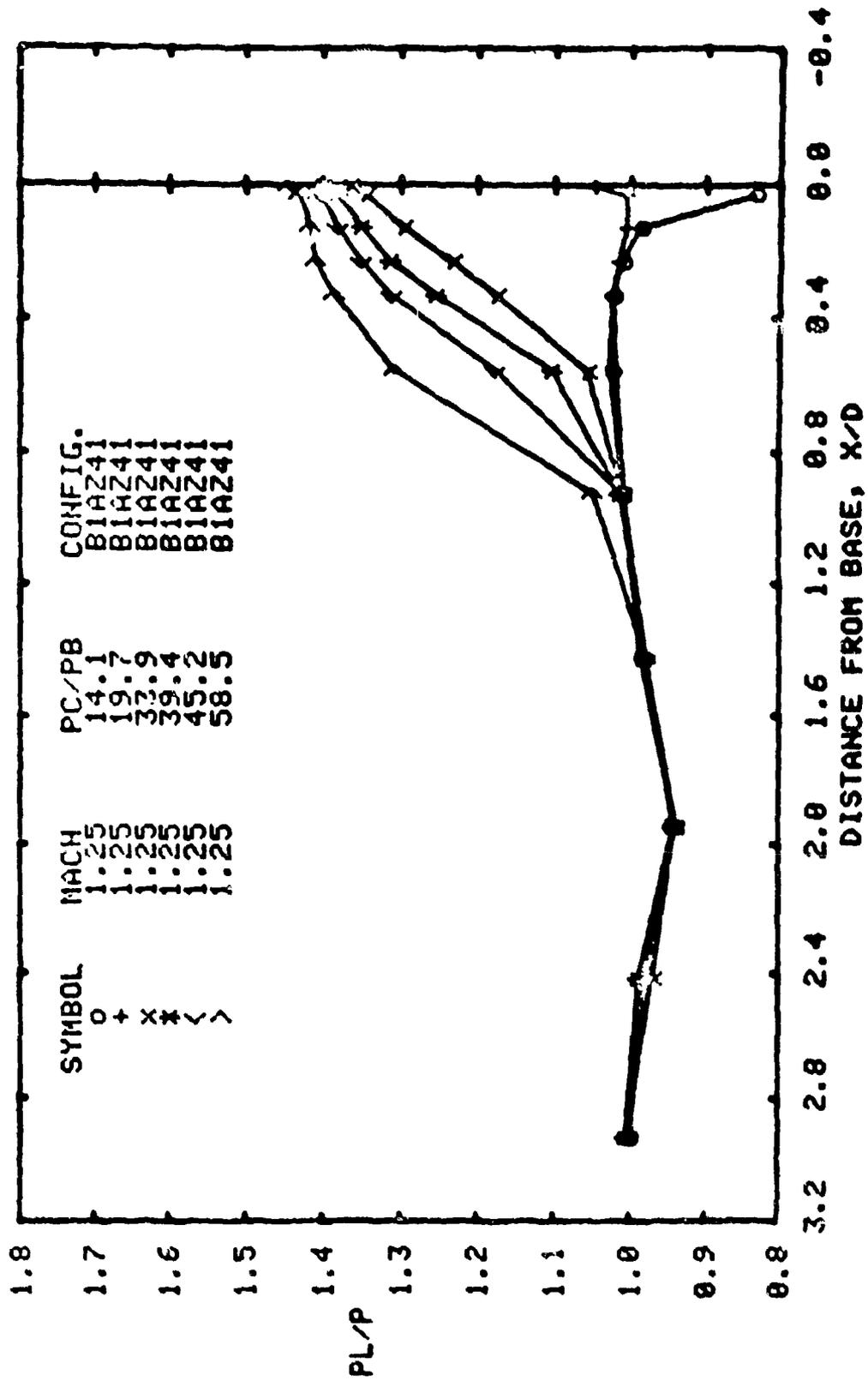
(c). M=1.25

Figure A5: cont'd

105

(d). M=1.6 cont'd

Figure A5:

(e). M=1.75

Figure A5: cont'd

CONFIG.
B1A2Z41
B1A2Z41
B1A2Z41
B1A2Z41
B1A2Z41
B1A2Z41
B1A2Z41

SYMBOL
O
+
X
*
∨
∧
C
B

DISTANCE FROM BASE, X/D

PL/P

(f). M=2.0 concl'd.
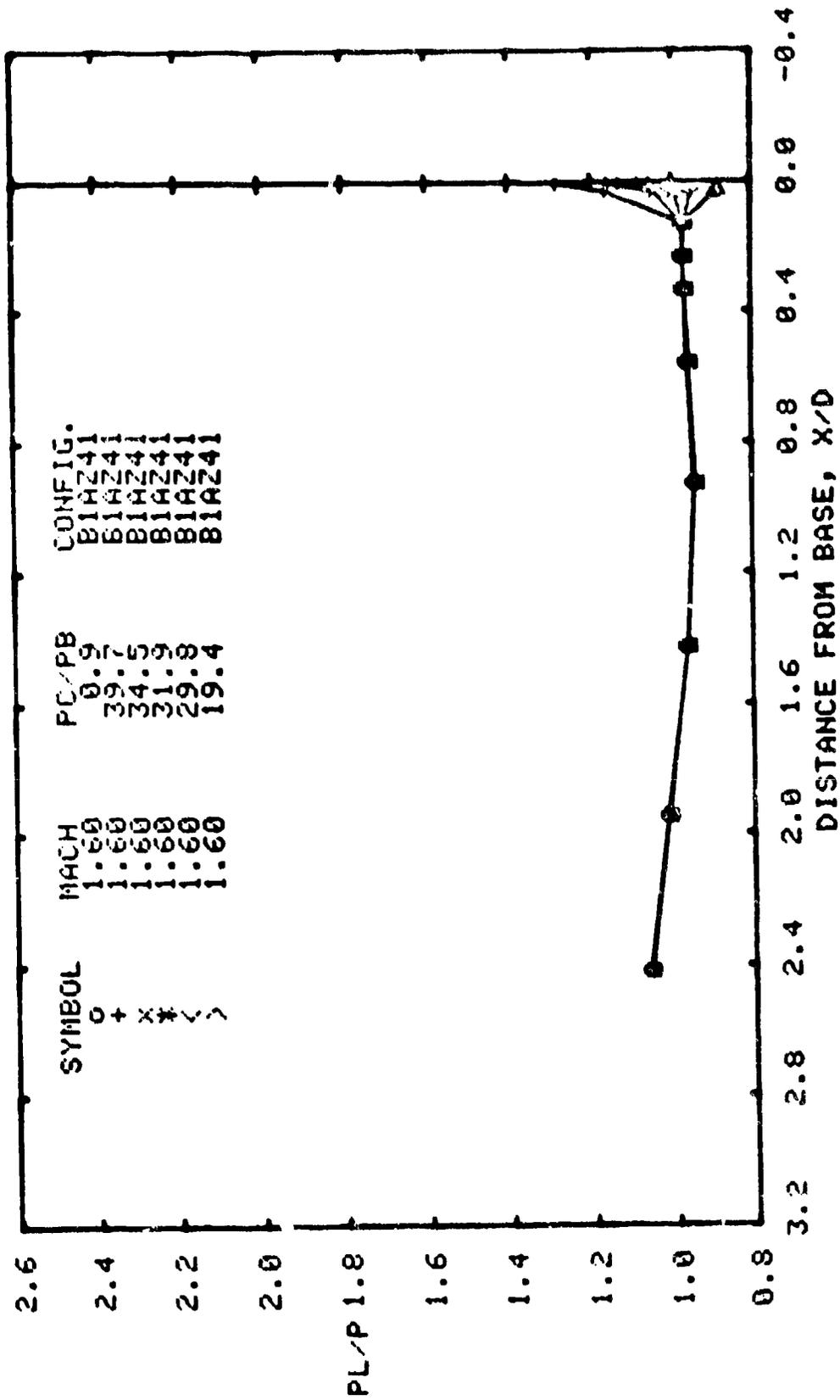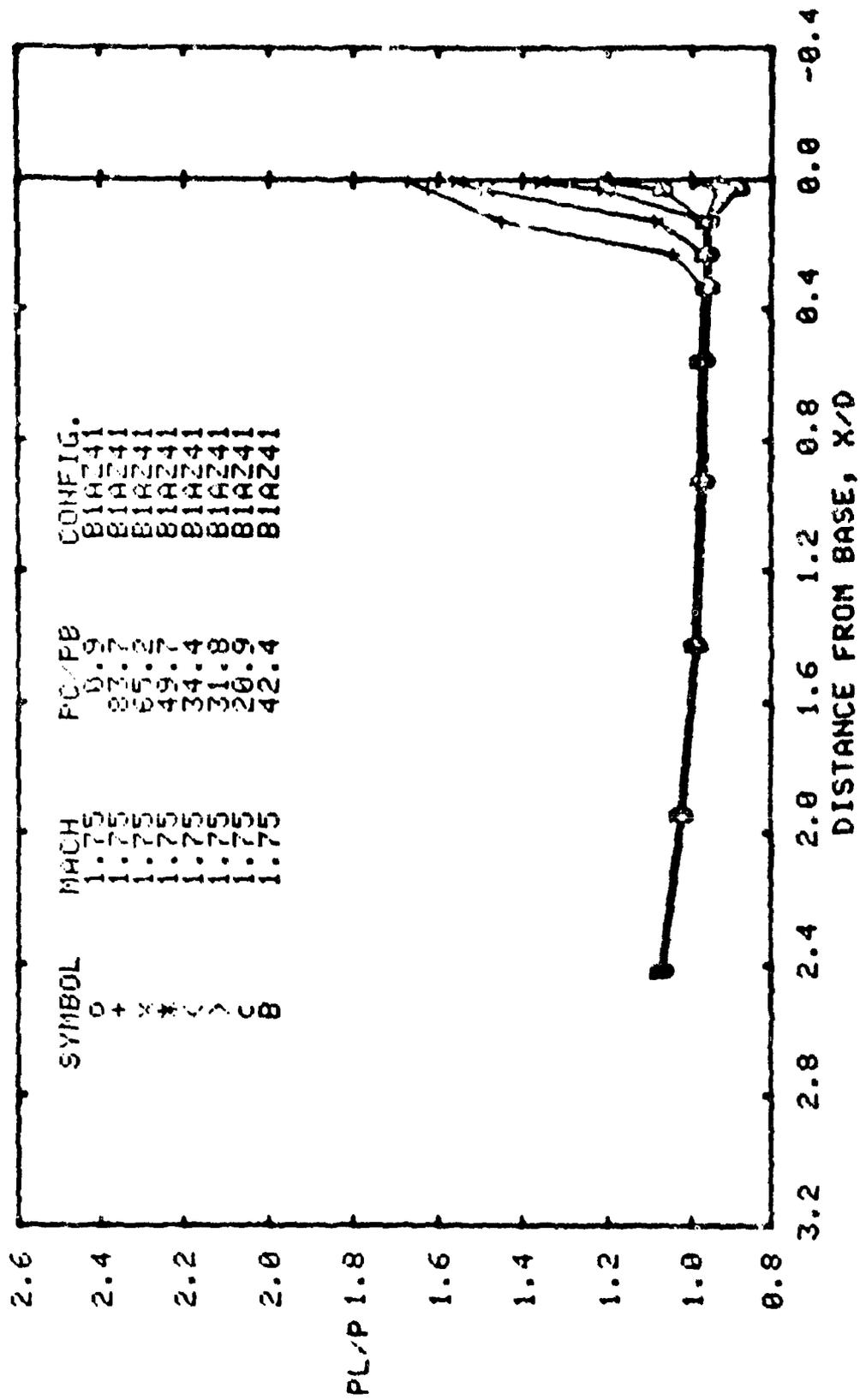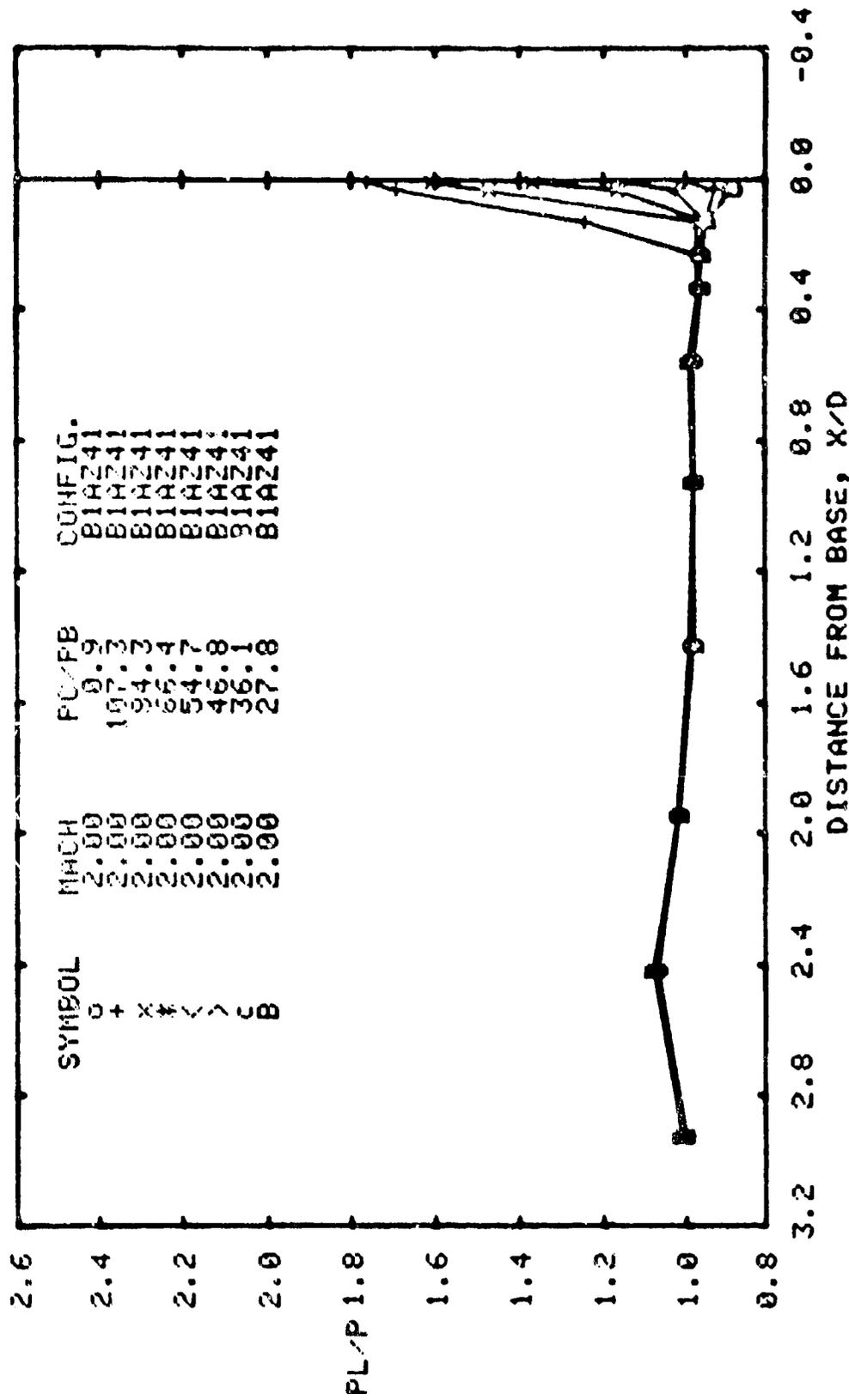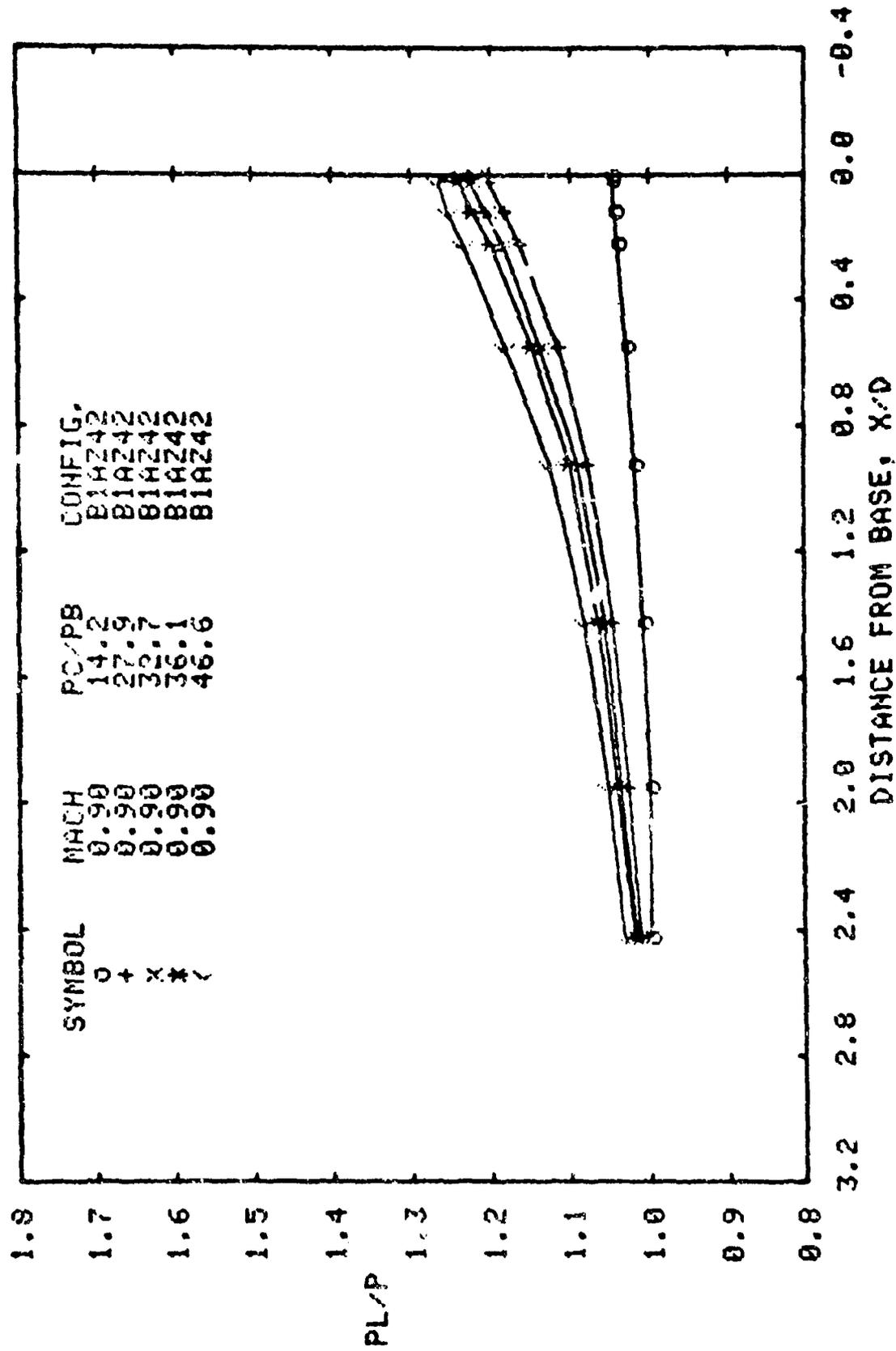
Figure A5:

(a). M=0.90

Figure A6: Effect of jet total pressure ratio on body pressure distribution at various free stream Mach numbers. Configuration R1AZ42: M_J=1.76, q_N=3.95, D_N/D_B=.93.
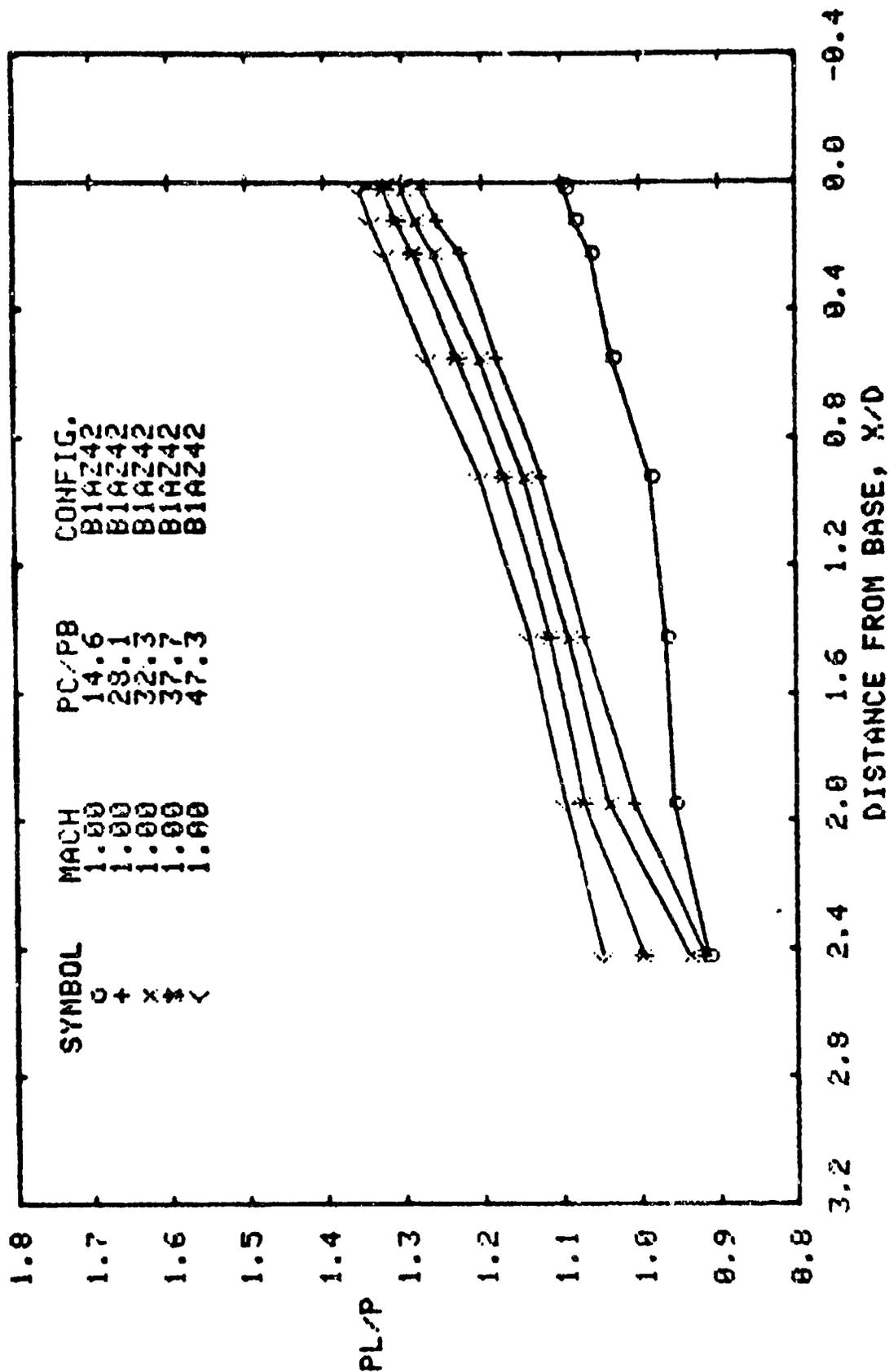
(b). M=1.00

Figure A6: cont'd.
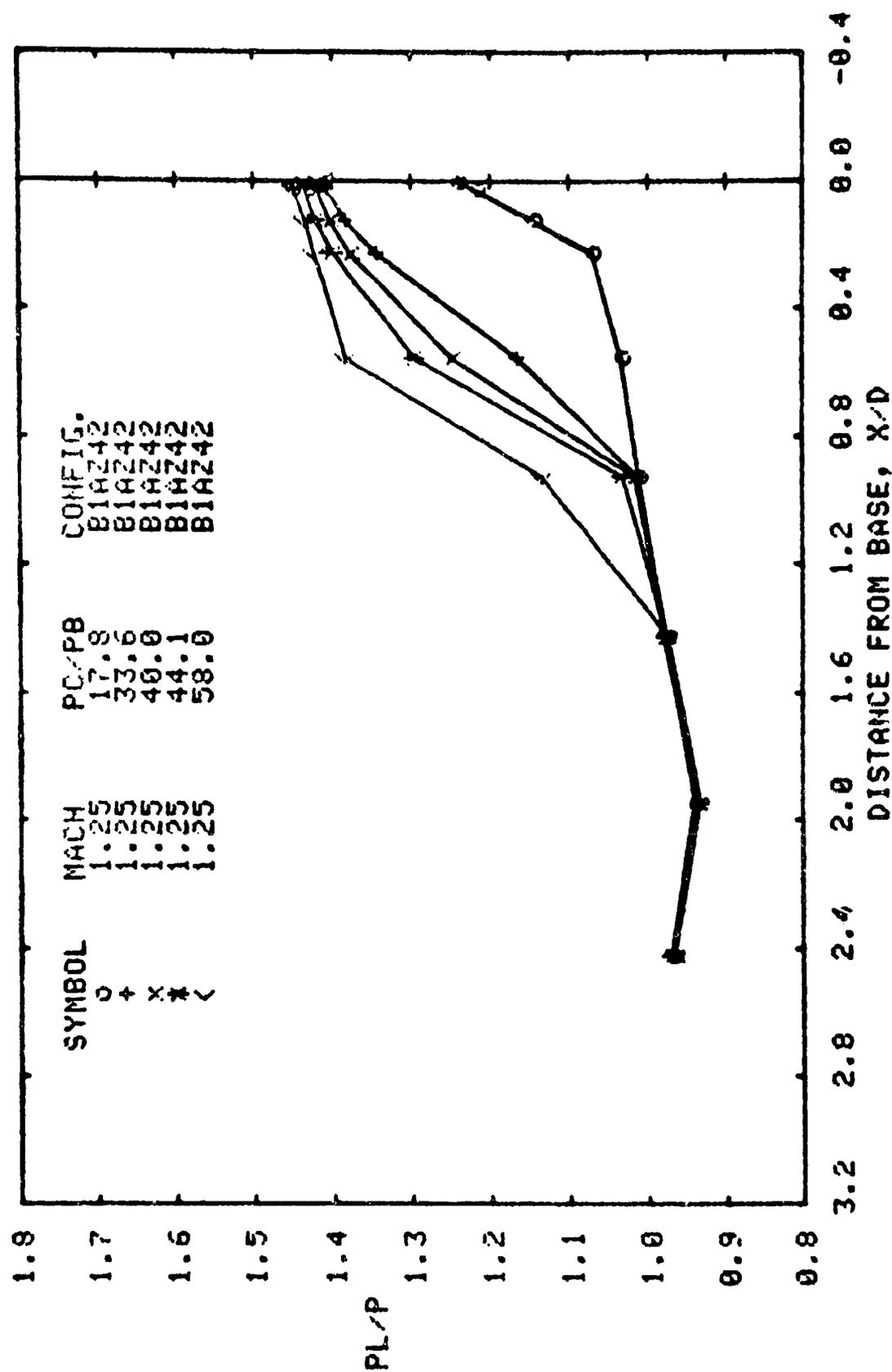
(c). M=1.25
Figure A6: cont'd;

111
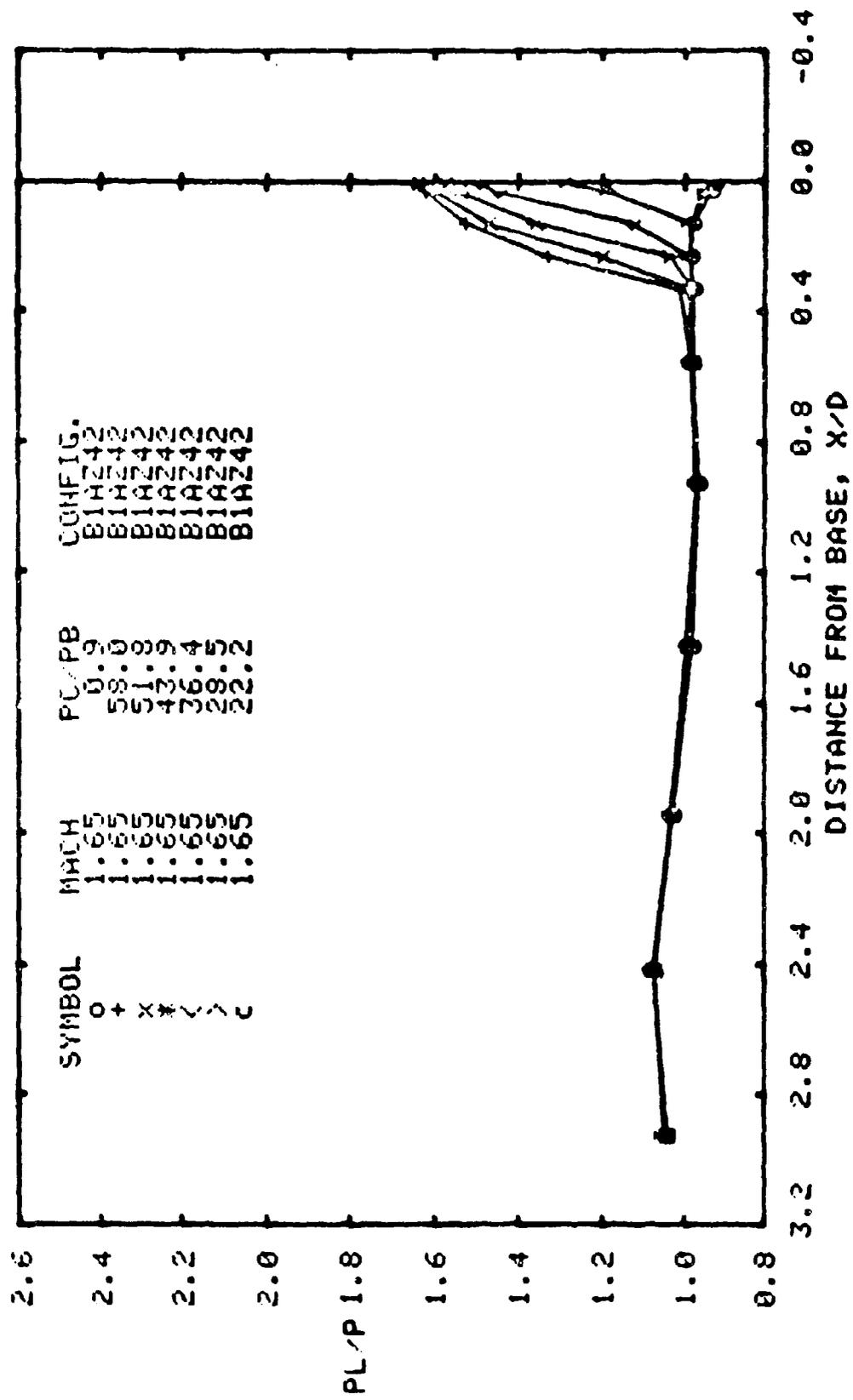
(d). M=1.65
Figure A6: cont'd

112

(e). M=1.75
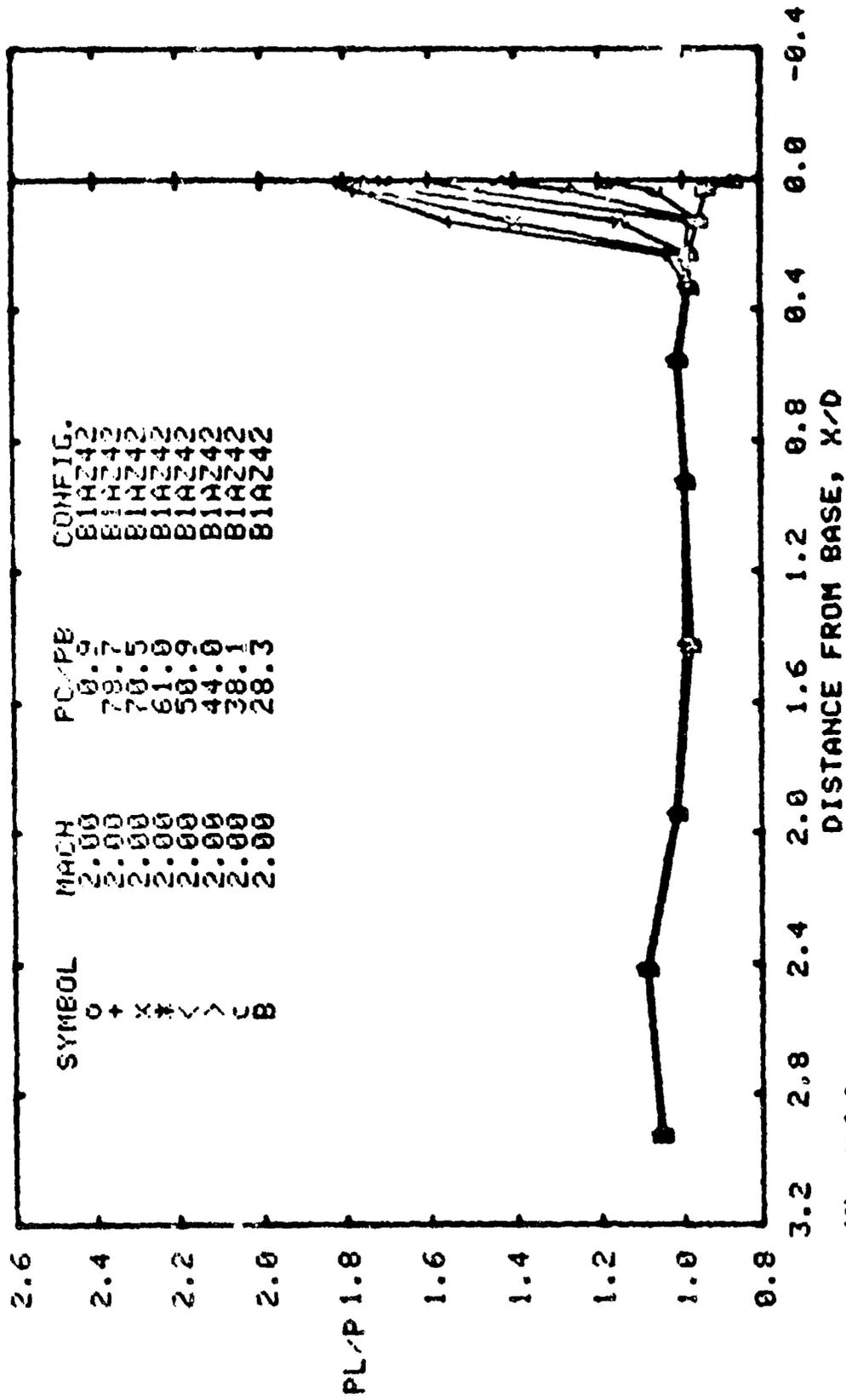
Figure A6: cont'd

(f). M=2.0

Figure A6: concl'd.

114
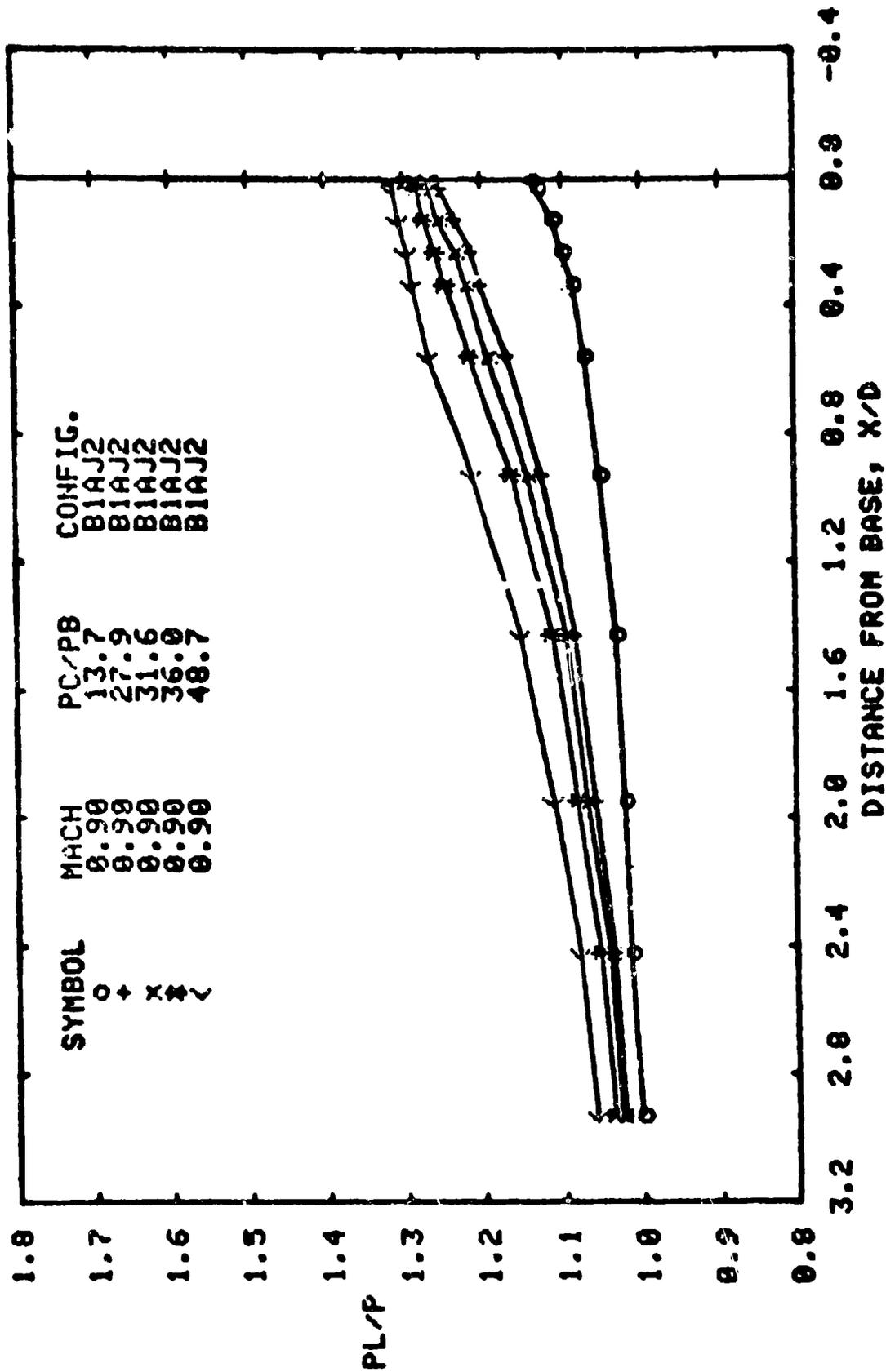
Figure A7: Effect of normal jet simulator pressure ratio on body pressure distribution at various free stream Mach numbers. Configuration B1AJ2.

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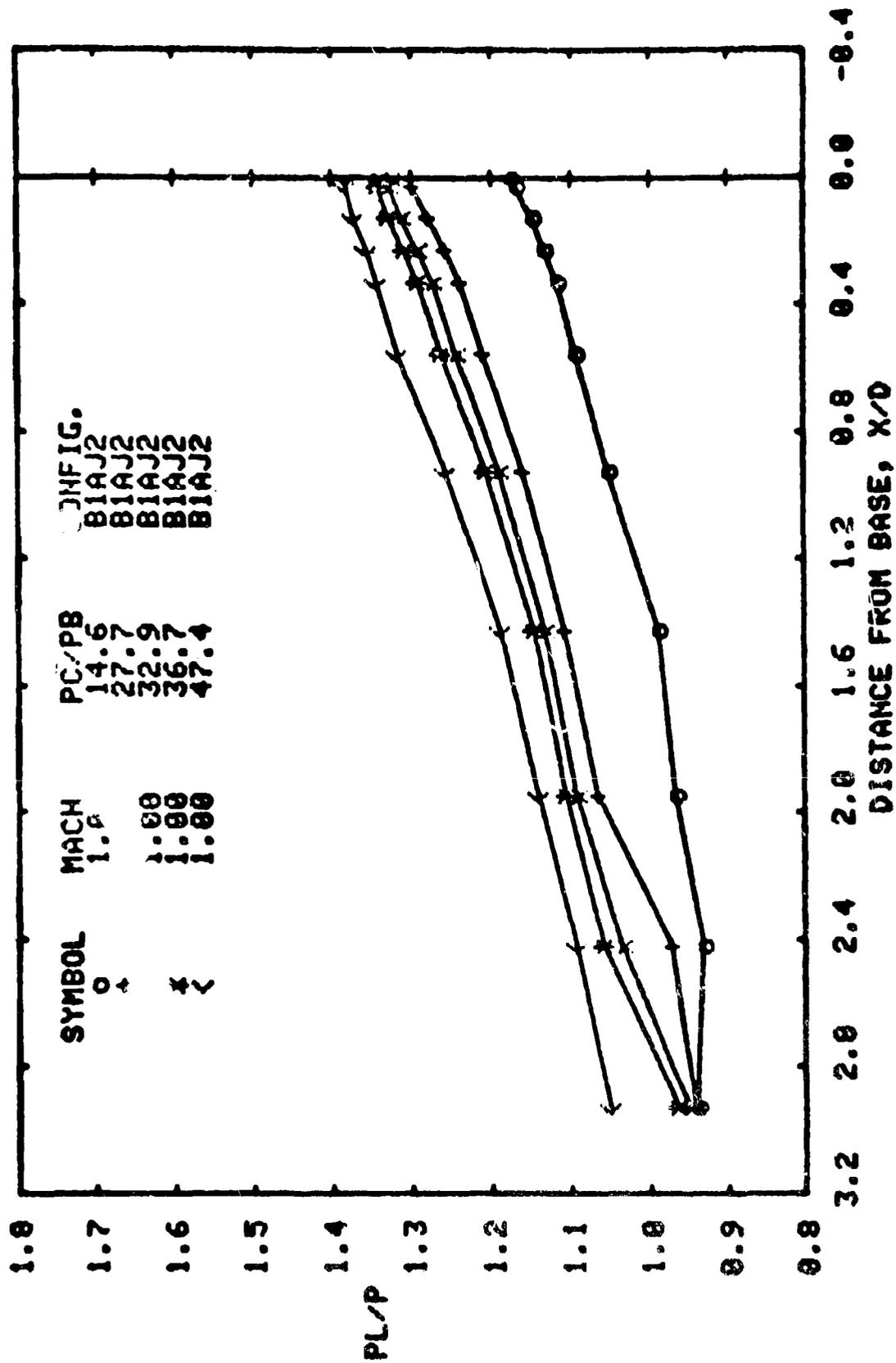
(b). M=1.0

Figure A7: cont'd.
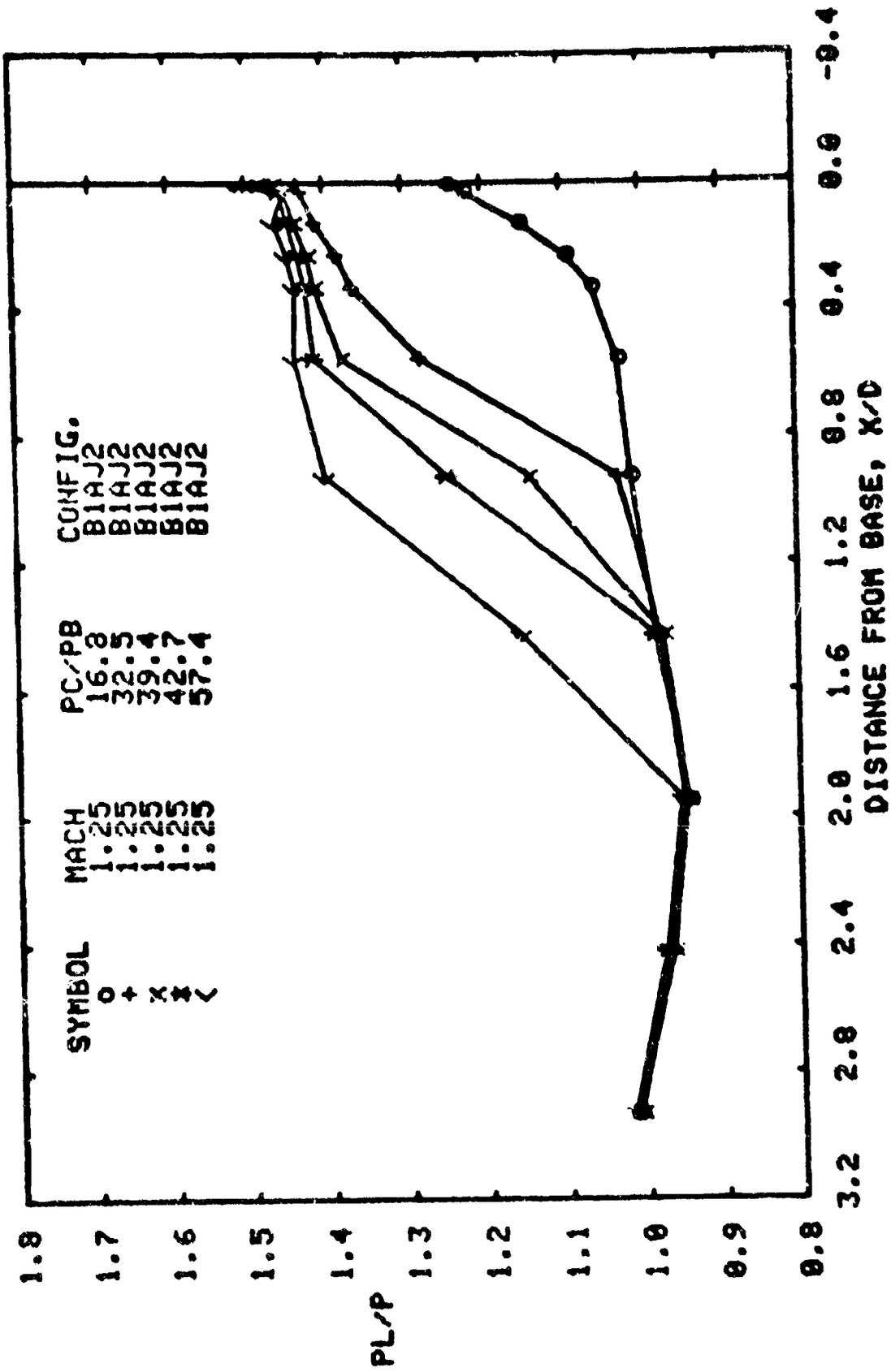
(c). M=1.25

Figure A7: cont'd.
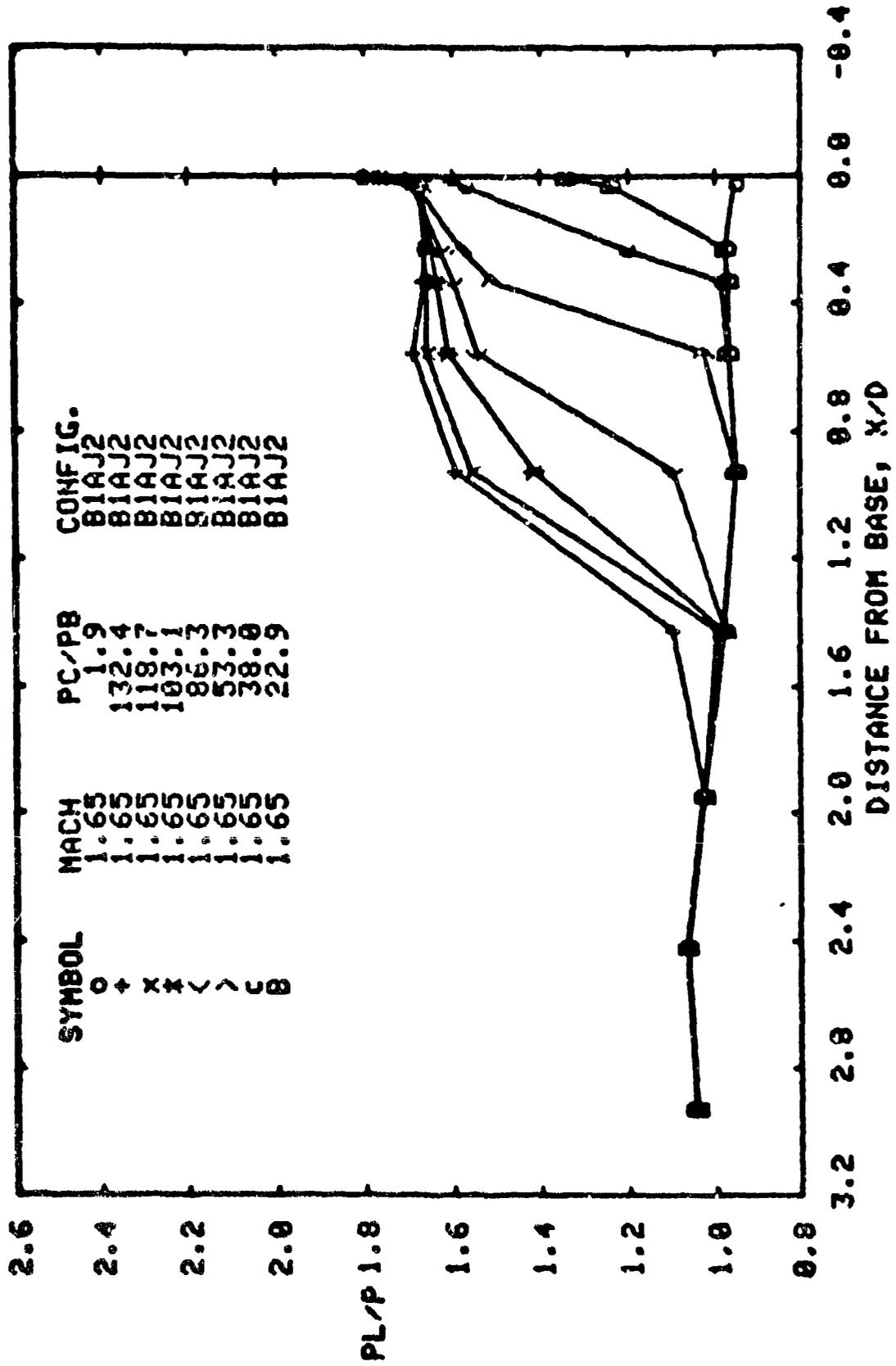
(d). M=1.65
Figure A7: cont'd.

113

(e). M=2.0 cont'd.

Figure A7:

119
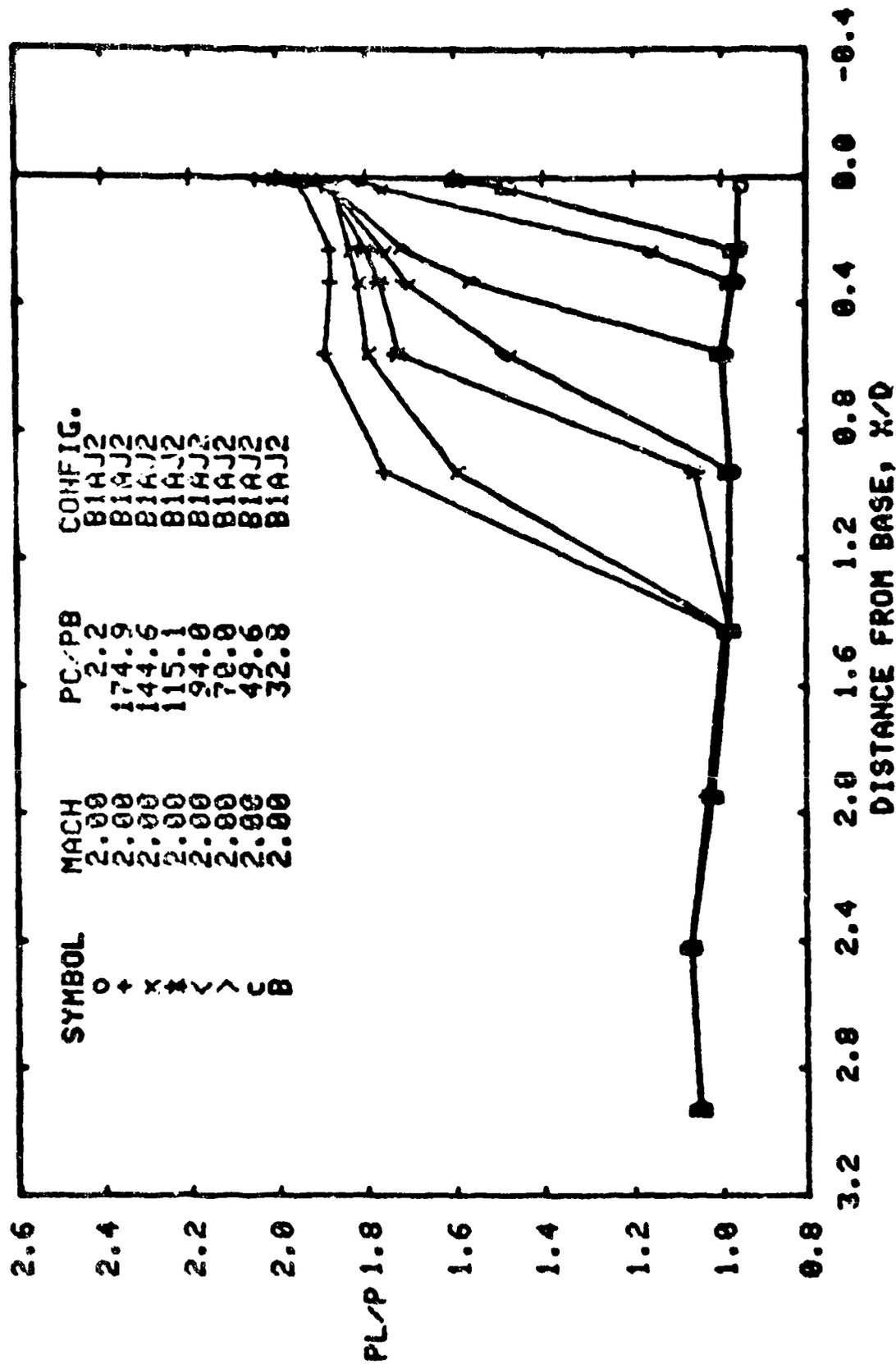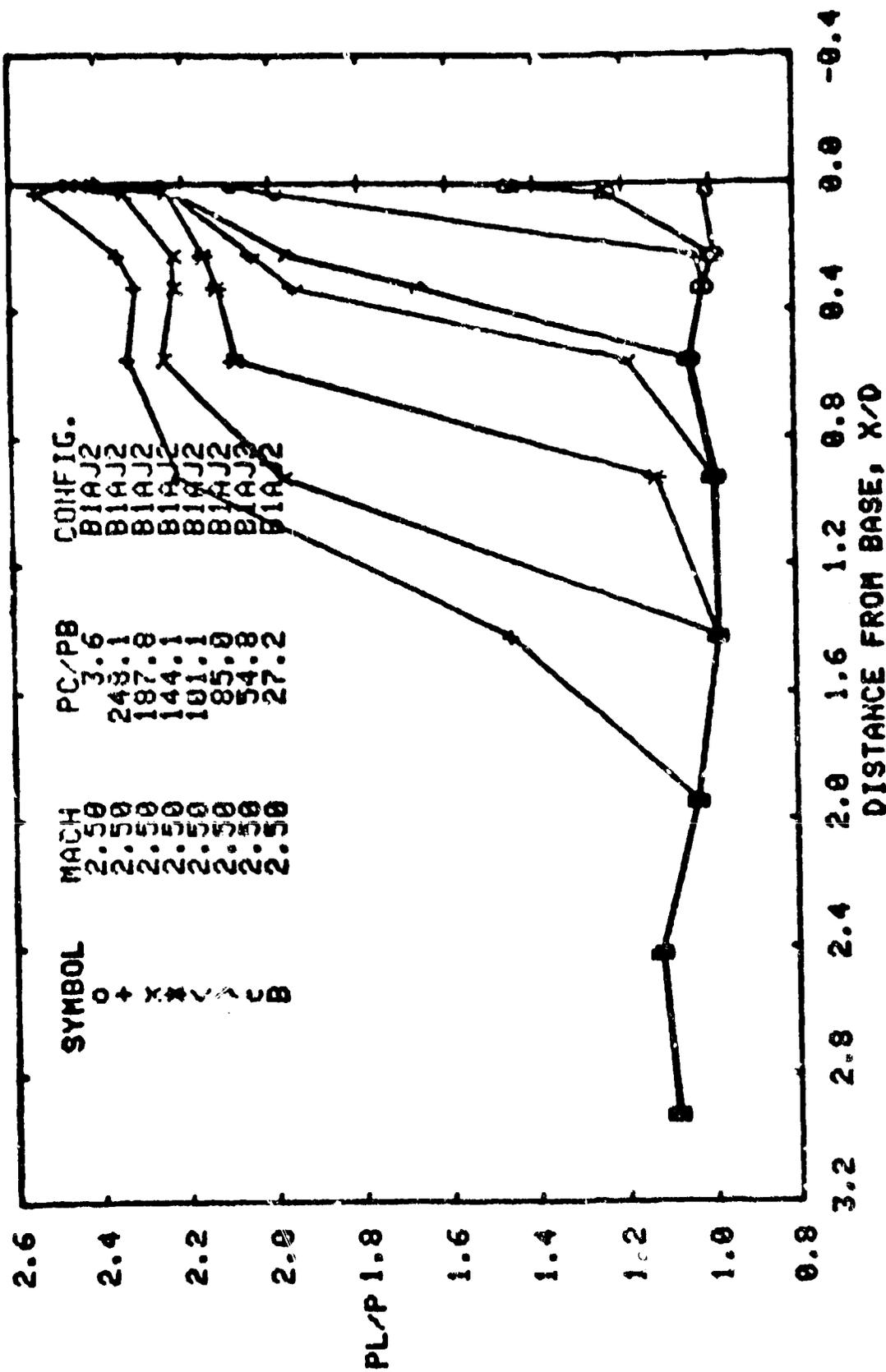
(f). M=2.50

Figure A7: concl'd.
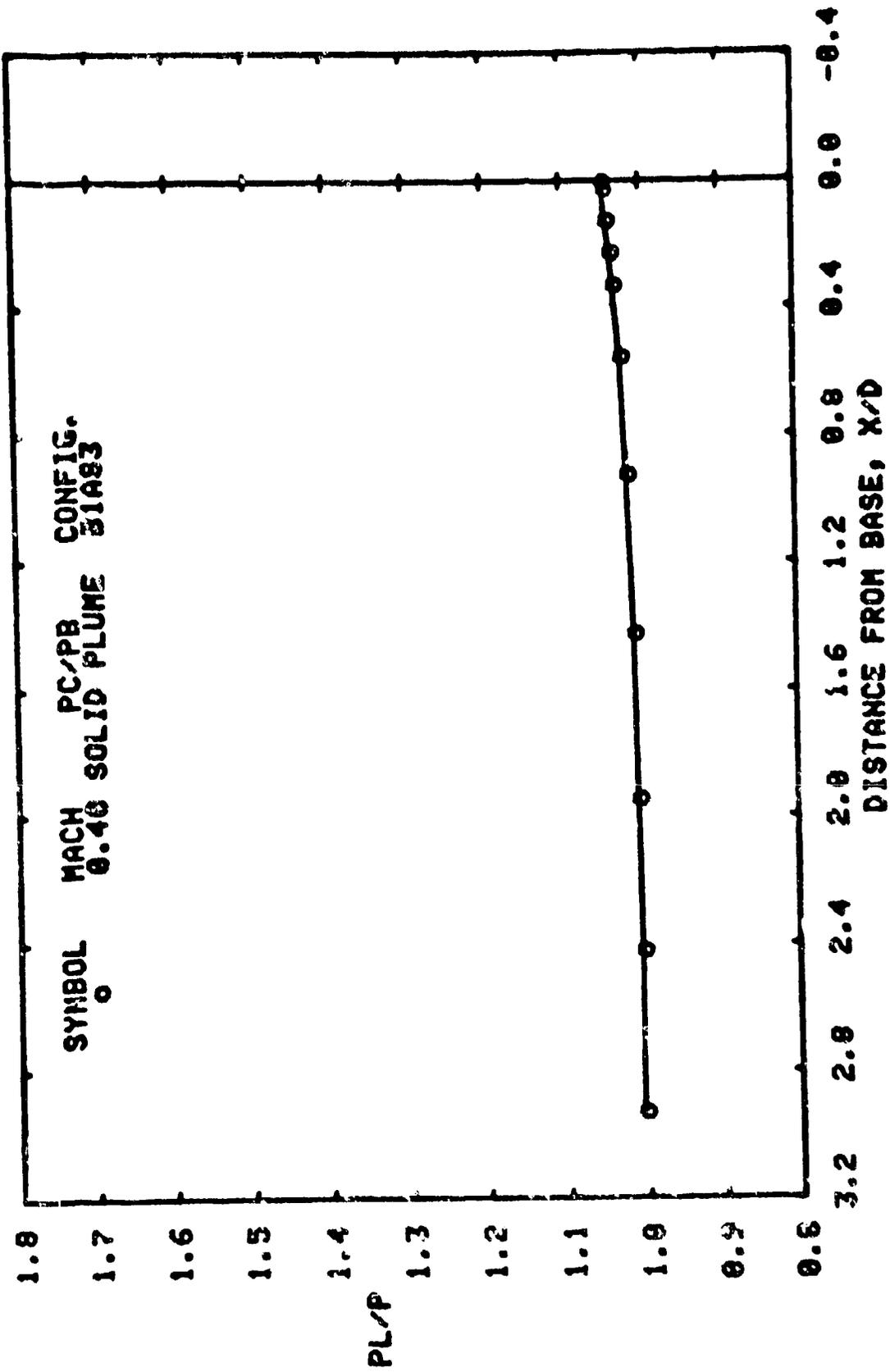
(a). M=0.40

Figure A8: Effect of solid plume simulator on body pressure distribution. Configuration B1AS3.
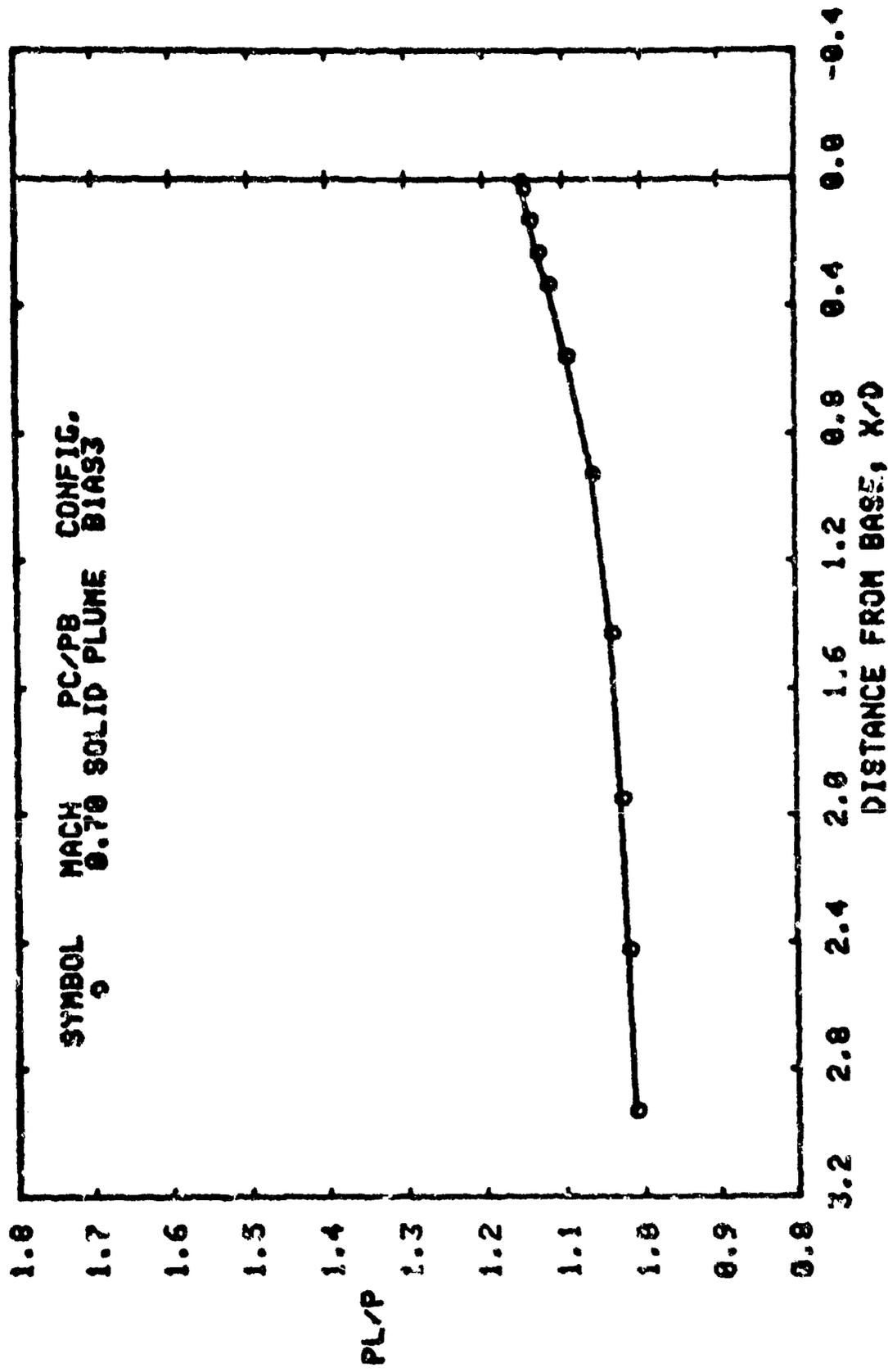
(b). M=0.90
Figure A8: cont'd.

122
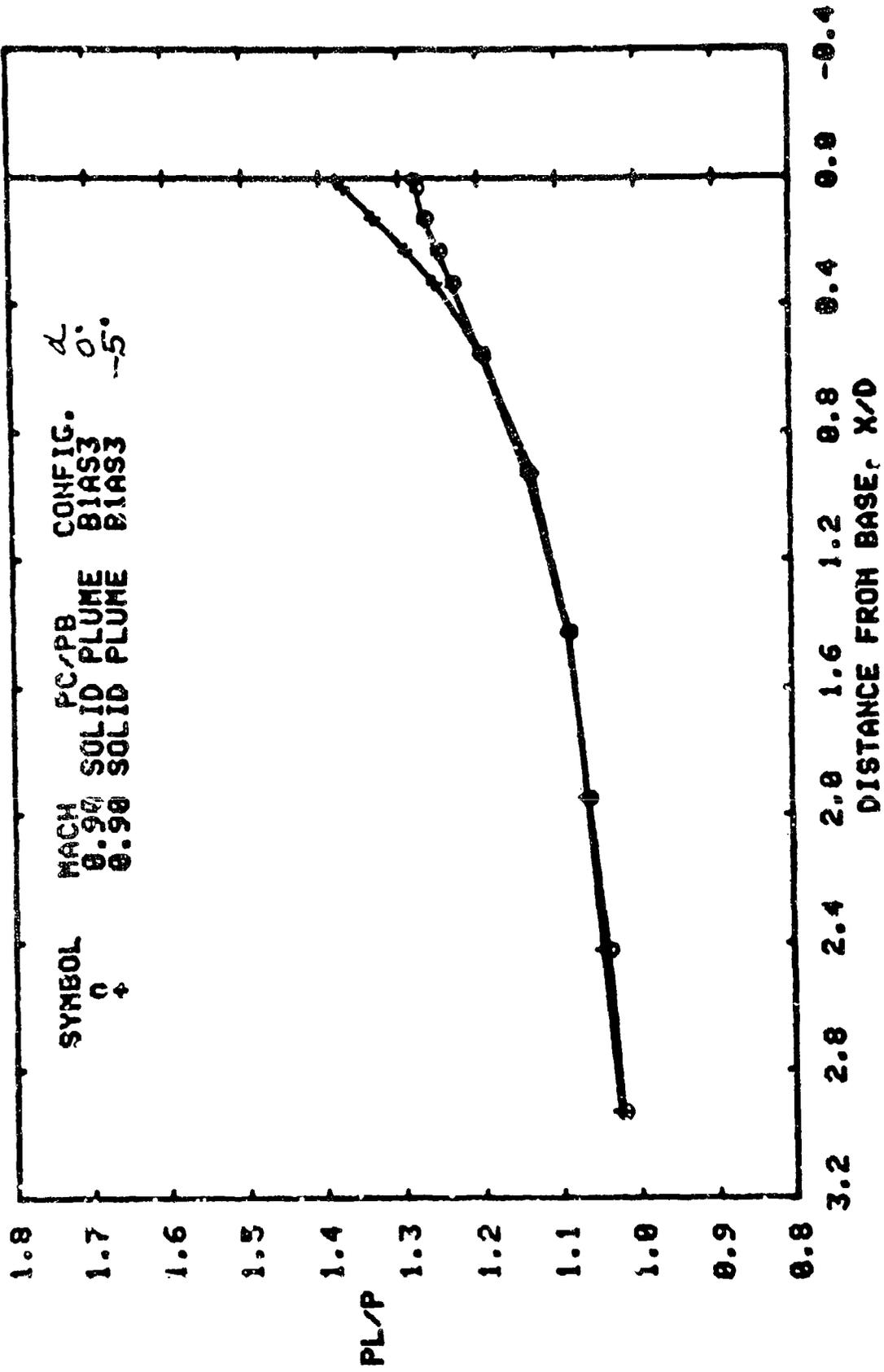
(c). M=0.90
Figure A8: cont'd.

(d). M=1.00 cont'd.

Figure A8: cont'd.

SYMBOL   MACH   PC/PB   CONFIG.
  o   1.18 SOLID PLUME   BIAS3

PL/P

DISTANCE FROM BASE, X/D

125
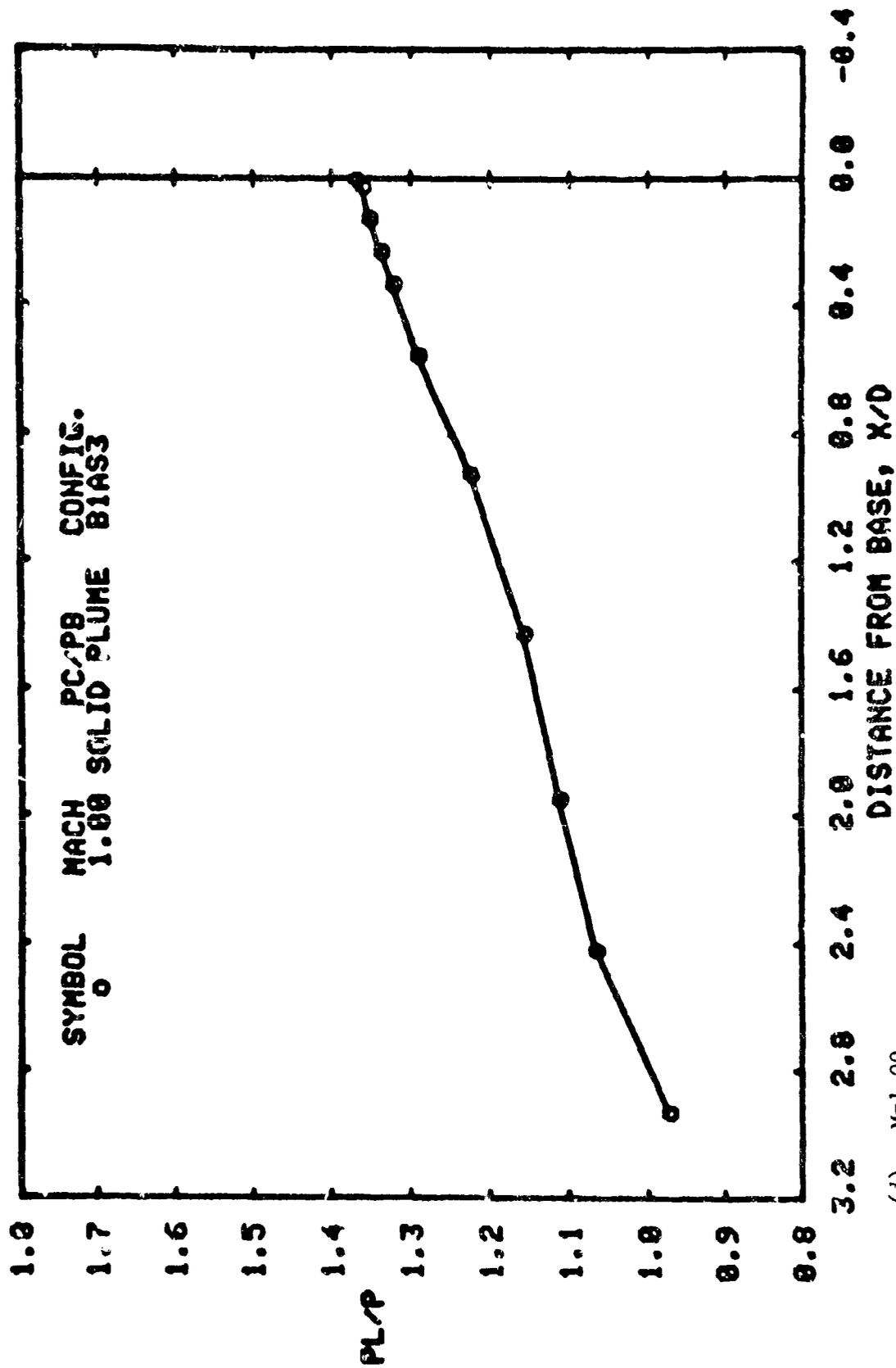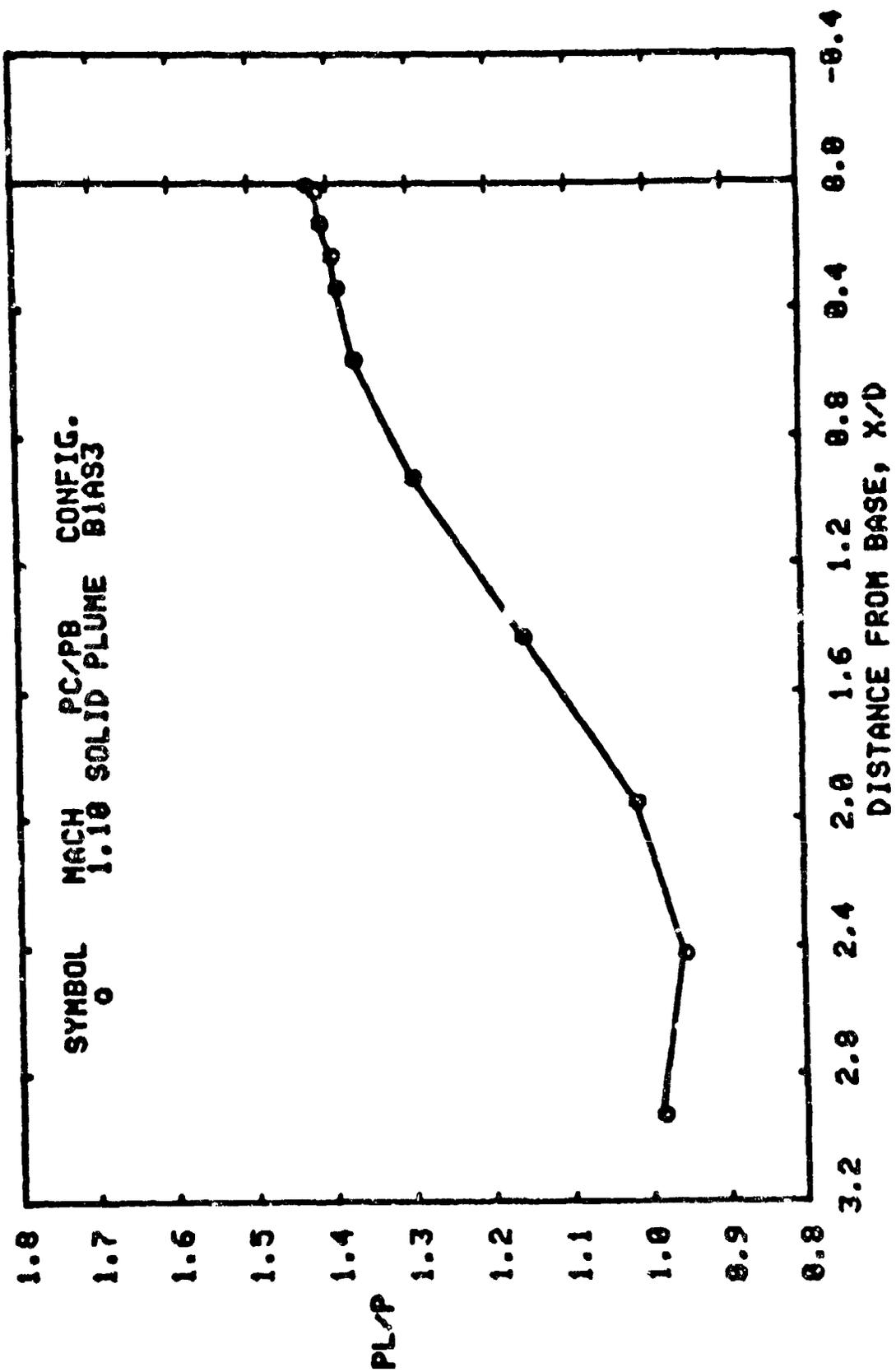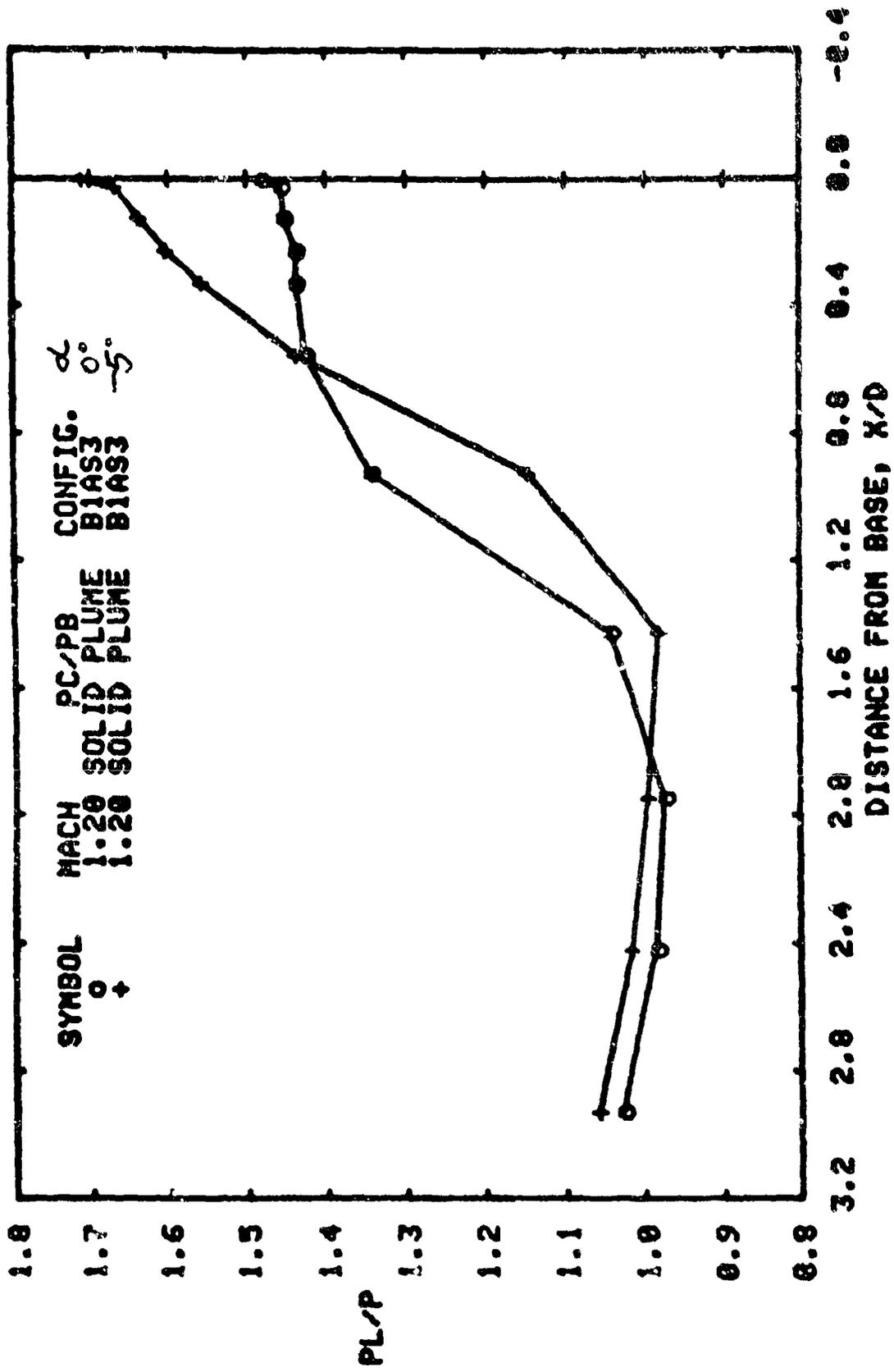
(f). M=1.20
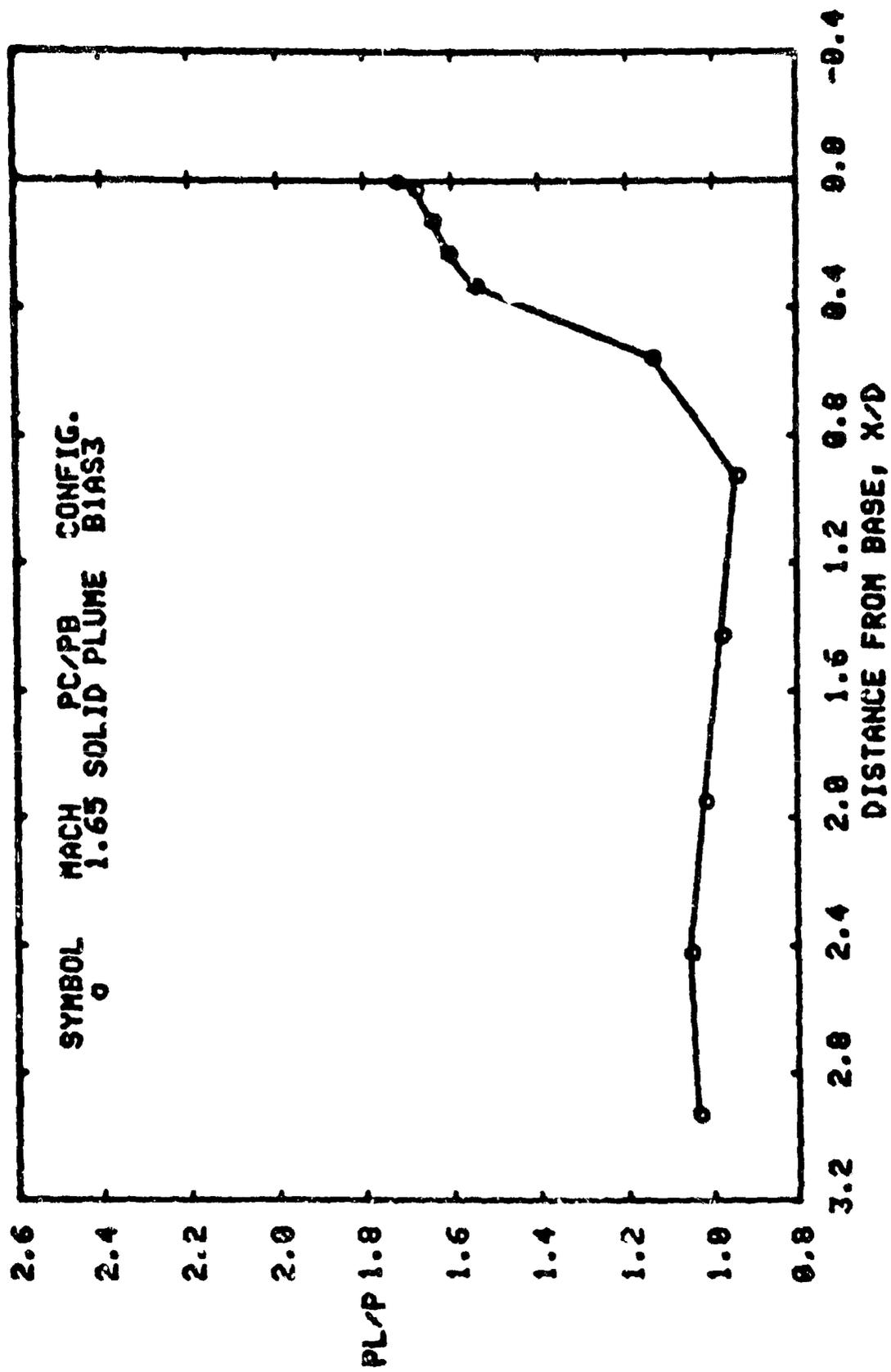
Figure A8: cont'd.

(g). M=1.65
Figure A8: cont'd.

127

(h). M=2.0 cont'd.

Figure A8:

128

(i). M=2.5 concl'd.

Figure A8: concl'd.

129
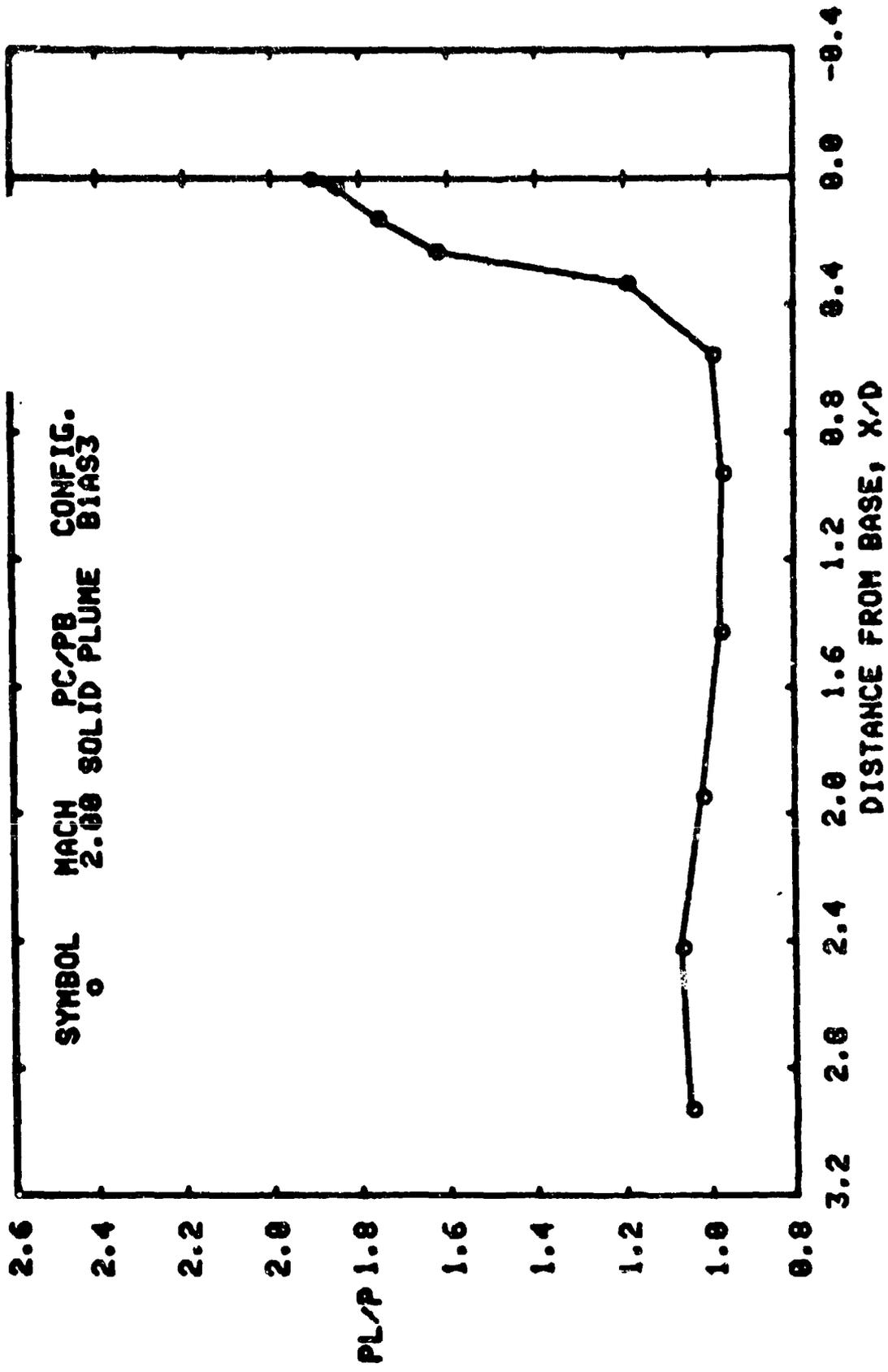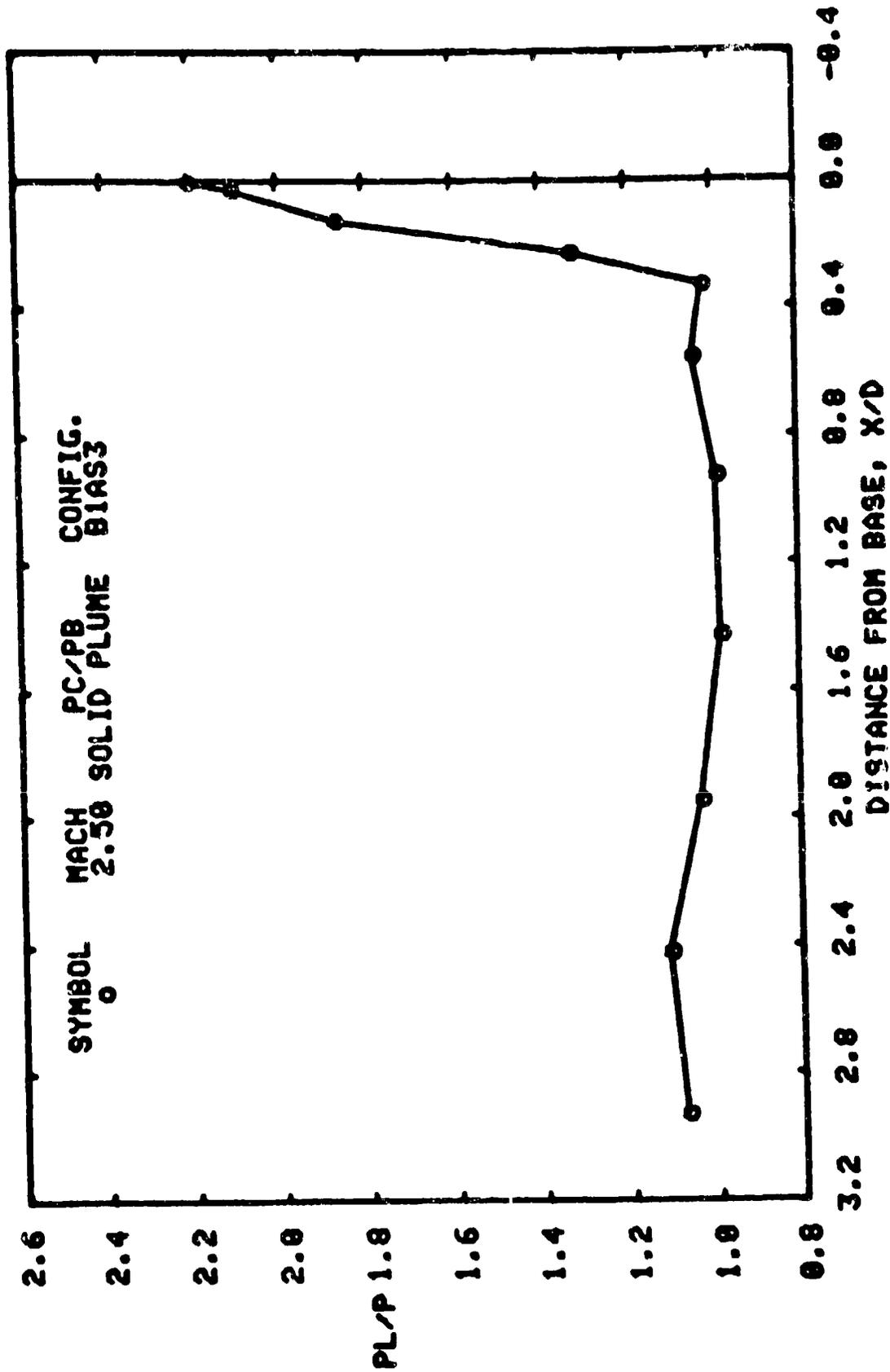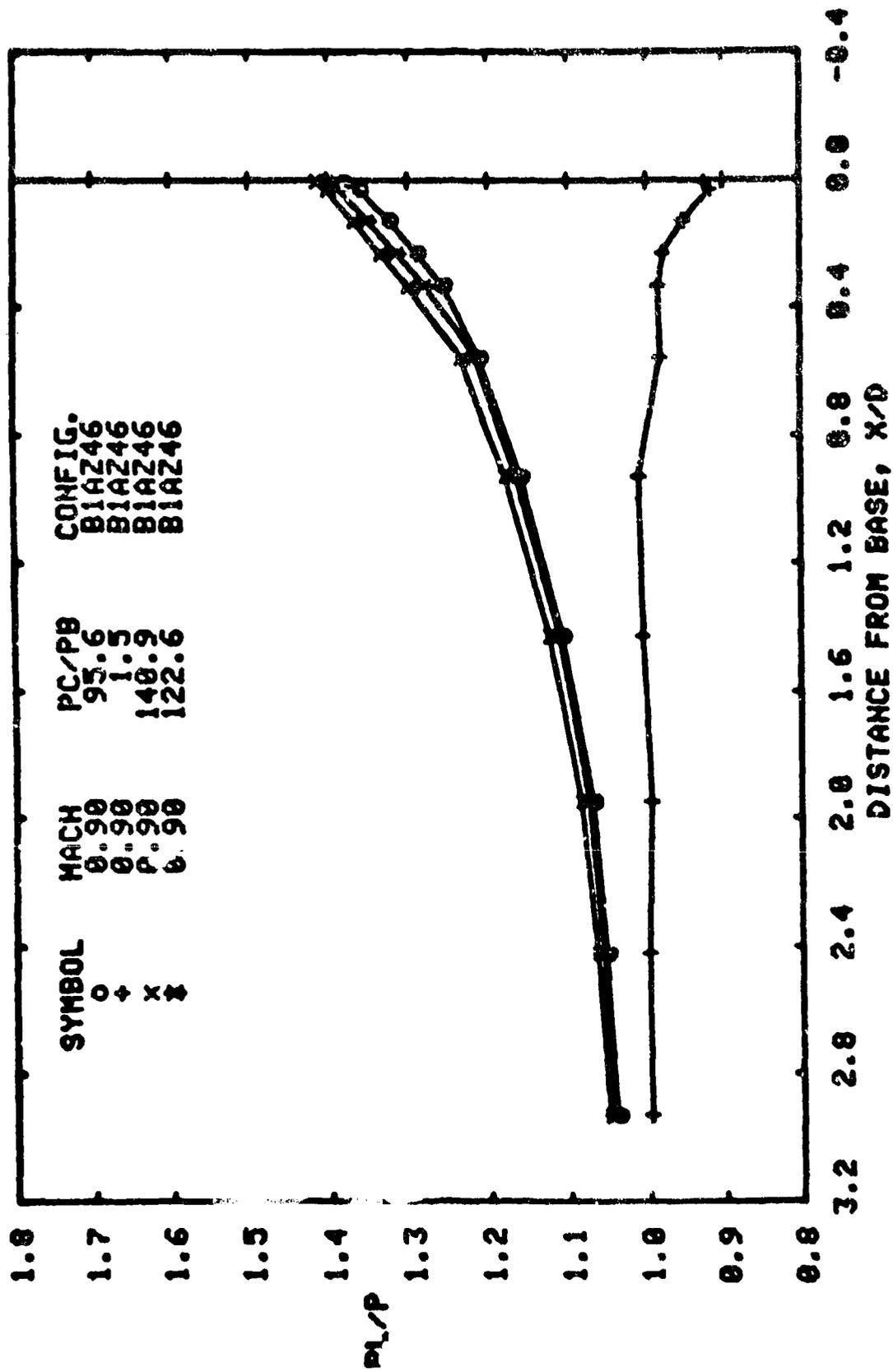
Figure A9: Effect of jet total pressure on body pressure distribution at an angle of attack of -5°. Configuration B1AZ46: $M_J=2.7$, $\theta_N=23.3$, $D_N/D_B=0.8$.

(a). M=0.90

(b). M=1.25 cont'd.
Figure A9: cont'd.

131
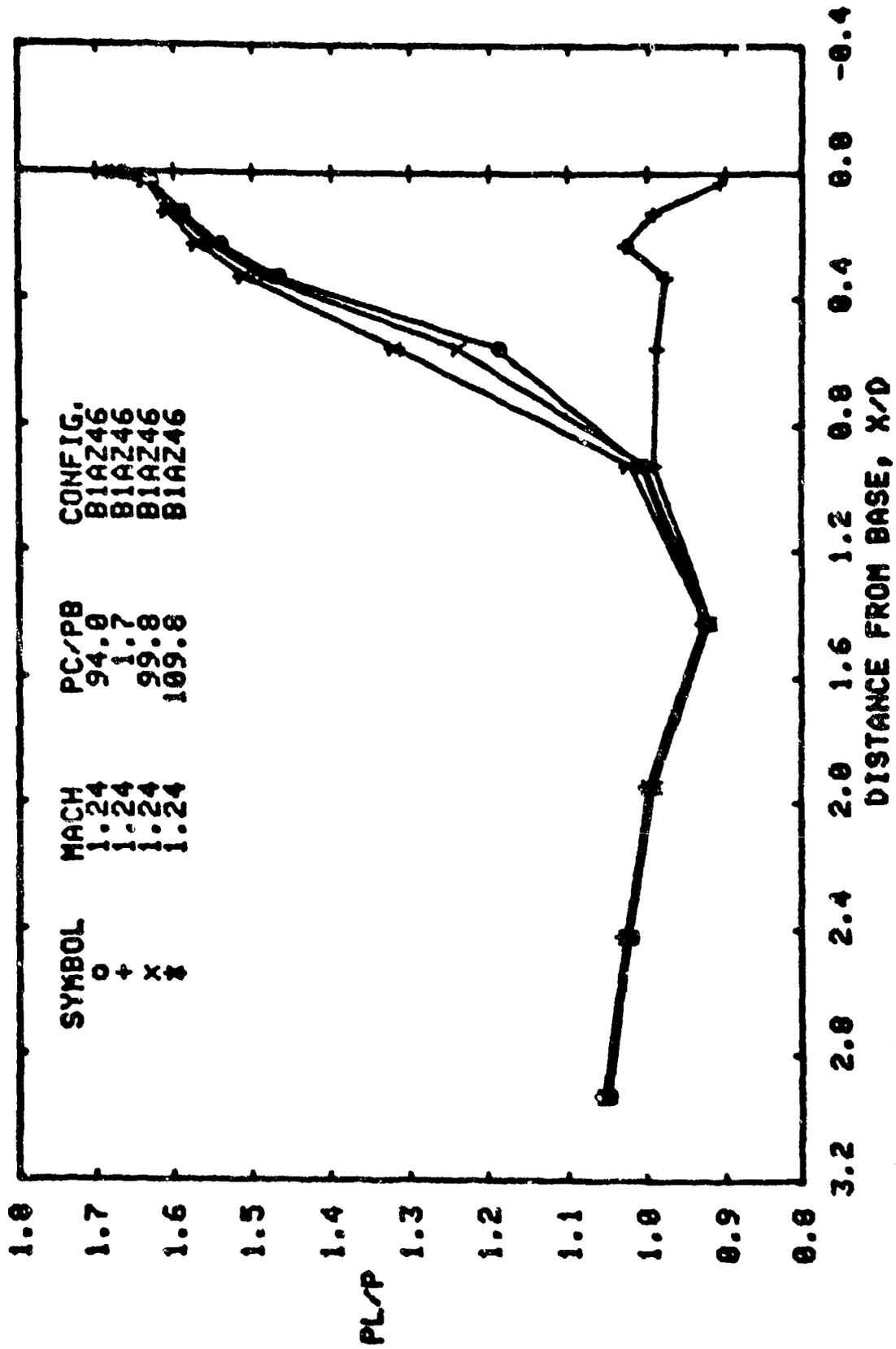
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