FLIGHT-MEASURED PRESSURE CHARACTERISTICS OF AFT-FACING STEPS IN THICK BOUNDARY LAYER FLOW FOR TRANSONIC AND SUPERSONIC MACH NUMBERS

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SUMMARY

Aft-facing step base pressure flight data were obtained for three step heights for nominal transonic Mach numbers of 0.80, 0.90, and 0.95, and for supersonic Mach numbers of 2.2, 2.5, and 2.8 with a Reynolds number, based on the fuselage length ahead of the step, of about 10^8. Surface static pressures were measured ahead of the step, behind the step, and on the step face (base), and a boundary layer rake was used to obtain boundary layer reference conditions.

A comparison of the data from the present and previous experiments shows the same trend of increasing base pressure ratio (decreasing drag) with increasing values of momentum thickness to step height ratios. However, the absolute level of these data does not always agree at the supersonic Mach numbers. For momentum thickness to height ratios near 1.0, the differences in the base pressure ratios appear to be primarily a function of Reynolds number based on the momentum thickness. Thus, for Mach numbers above 2, the data analyzed show that the base pressure ratio decreases (drag increases) as Reynolds number based on momentum thickness increases for a given momentum thickness and step height.

INTRODUCTION

Aft-facing surface discontinuities such as those formed by wing trailing edges, panel trailing edges, lap joints, or other discontinuities are known to be a source of aircraft drag. Numerous theoretical and experimental studies (refs. 1 to 10) have been conducted for aft-facing steps immersed in turbulent-supersonic boundary layers. In the 1950's, theoretical flow models developed for predicting base pressures were usually simplified by assuming that the approaching boundary layer had either a zero thickness or a thickness approaching zero. For example, Korst's theory (ref. 1) and Chapman's flow model (ref. 2) used this assumption.

In the early 1950's, the data from supersonic experiments by Chapman, Wimbrow, and Kester (ref. 3) established a correlation that accounted for the effect of the approaching boundary layer thickness on the base pressure. In the mid 1960's, Hastings (ref. 4) extended the data base for supersonic flow to include boundary layers and momentum thicknesses that were relatively large compared to the step height (momentum thickness to step height ratio ≈ 2); however, the absolute thickness of the boundary layer, and hence the momentum thickness, was very small (momentum thickness < 0.05 cm). Two aft-facing step experiments (refs. 5 and 6) which had relatively large absolute values of momentum thickness and large values of momentum thickness to step height ratios (2.4 and 1.3, respectively) yielded a lower base pressure ratio (higher drag) than was obtained from the thin boundary layer data (ref. 4) for momentum thickness to step height ratios near 1. The base pressure ratio disagreement became more pronounced as Mach number increased above Mach 2. The reason for the disagreement between the thick and thin boundary layer data obtained at supersonic speeds is not fully understood, primarily because of the limited amount of experimental information. Therefore, the present study was undertaken to acquire additional experimental results to better analyze the differences between the thick and thin boundary layer data.

A YF-12 aircraft was used as a testbed for this study because of its ability to maintain given flight conditions from subsonic to triple-sonic speeds. The study provided thick boundary layer data for Reynolds number conditions that were different from the conditions obtained in the previous studies. This enabled additional insight to be gained into the effect of Reynolds number on aft-facing step drag.

This report presents base pressure data for three step heights at Mach numbers from approximately 0.80 to 0.95 and from approximately 2.2 to 2.8 for Reynolds numbers on the order of 10^8 based on a turbulent flow length of 21.53 meters. The ratio of momentum thickness to step height ranged from about 0.2 to 1.3. Surface static pressures ahead of and behind the step were also measured and are presented. A boundary layer rake was used to measure the local velocity profiles from which the local surface and boundary layer conditions were determined.

SYMBOLS

Physical quantities in this report are given in the International System of Units (SI); however, measurements were taken in U.S. Customary Units. Factors relating the two systems are provided in reference 11.

c_{p_b}	base pressure coefficient, $\dfrac{p_b - p_r}{0.7 M_\infty^2 p_r}$
D	drag, N
h	step height, cm

M	Mach number
p	static pressure, N
R_θ	Reynolds number based on momentum thickness, θ
u	flow velocity, m/sec
x	longitudinal distance from step (positions in front of the step are negative), cm
y	distance above surface (perpendicular to x), cm
δ	boundary layer thickness, cm
θ	momentum thickness, $\int_0^\delta \frac{\rho u}{\rho_e u_e}(1 - u/u_e)\, dy$, cm
ρ	air density, kg/m^3

Subscripts:

b	step face or base of aft-facing step
e	conditions at edge of boundary layer
r	local reference
∞	free stream

DESCRIPTION OF INSTRUMENTATION

The upper surface of the fuselage of a YF-12 aircraft was selected as the location for the experiment. A photograph showing the experiment location on the aircraft is provided in figure 1. In the area where the test was conducted, the fuselage diameter is 162.56 centimeters.

The test section was approximately 0.9 meter wide and 3.2 meters long. It consisted of a ramp region, a reference region, a recovery region, and two boundary layer rake complexes shown in figure 2(a). The ramp region had a slope of approximately 1.12° relative to the surface of the aircraft. This provided a gradual transition for the flow passing from the upper fuselage surface to the reference region height. Between flights, the step heights were changed by raising or lowering the recovery surface relative to the level of the reference region. A typical step installation is shown in figure 2(b). The step heights studied in this experiment were 0.33 centimeter, 0.63 centimeter, and 1.19 centimeters. The reference and recovery regions were parallel to within 0.67°.

Pressure orifices were located along the surfaces of the reference and recovery regions and the step face. These orifices can be seen in figure 2(c). The pressure measured from an orifice location 20.42 centimeters ahead of the step was used as the local reference pressure. An average base pressure was determined by manifolding the pressures from the three base pressure orifices.

A boundary-layer rake complex is shown in figure 3. One rake complex was located in the reference region 51 centimeters ahead of the step; the other was located 30 centimeters behind the step.

TEST CONFIGURATION AND CONDITIONS

Reference boundary-layer characteristics were determined both ahead of and behind the step (test) station. The reference characteristics behind the test station were obtained for a flush configuration. The forward rake was always removed for the flush configuration. These boundary layer data were used to define the momentum thickness used for the aft-facing step data analysis. Surface pressure measurements were also made ahead of and behind the step station for the flush configuration.

Aft-facing step base pressures and the surface pressure distributions were obtained with the forward rake removed for step heights of 0.33, 0.63, and 1.19 centimeters. Data were obtained at nominal Mach numbers of 0.80, 0.90, and 0.95 and at 2.2, 2.5, and 2.8 for each configuration studied.

For the Mach numbers used in the experiment, because of the length of the run to the test station, turbulent flow was assumed to originate at the aircraft nose. The turbulent run length was 21.01 meters for the forward rake station, 21.53 meters for the aft-facing step station, and 21.86 meters for the aft rake station. Momentum thickness for the aft-facing step station was considered to be the average of the values obtained from the forward and aft rakes. Analysis of the boundary layer rake and the Preston probe data indicated that the flow was not fully two-dimensional at the test section; therefore, it was treated as being quasi-two-dimensional. The method used to analyze the boundary layer rake and Preston probe data is provided in reference 8.

The base pressures, surface static pressures, and rake probe pressures were obtained using three 48-port multiplexing valves (scanivalves), each equipped with a differential pressure transducer referenced to a high-resolution, absolute-pressure transducer. Air data quantities, such as free stream values of Mach number and static pressure, were obtained from the airplane's air data system. A description of the air data system can be found in reference 12.

RESULTS AND DISCUSSION

Surface Pressure Distribution

Figures 4 and 5 present the surface static pressure distribution ahead of and behind the step station. In these figures the ratio of surface pressure to local reference pressure is plotted as a function of the distance from the step for representative Mach numbers of 0.80 and 2.2. These data are included to demonstrate the uniform flow conditions that existed at the local reference pressure location and well upstream and well downstream of the step location. Although the curves show the pressure changes caused by the step, it is more convenient to compare the pressure changes for the different step heights by normalizing the distance from the step using the respective step height.

In figure 6, pressure ratio is plotted as a function of the normalized distance, x/h, ahead of and behind the step for each of the nominal Mach numbers used in this study. The pressure rise behind the step was found to occur at a normalized distance of approximately 4 for the transonic data. At Mach numbers equal to or greater than Mach 2.2, the pressure rise occurred at a normalized distance of about 2. Data from other sources are included for comparison in figures 6(a) to 6(c) and 6(e). The data from references 4, 6, and 13, and that shown later from reference 5, were obtained from two-dimensional shapes and were considered to have two-dimensional flow conditions. The trends of data from the various sources were much the same behind the step for all Mach numbers; however, at Mach 0.95, for x/h values below 12, the absolute values of the data from the present study and from reference 13 were significantly different. The larger differences appearing at this Mach number were not surprising because the base pressure could change rapidly for Mach numbers from 0.95 to 1.0 and, in addition, the differences in base pressure for these Mach numbers seemed to be a function of θ/h, as indicated by the results of the present study as well as references 6 and 13. The thicker boundary layer data, and the corresponding larger θ/h values, appeared to decrease the maximum change in base pressure. Further data relating the influence of θ/h on base pressure will be shown in following sections of this report.

Pressure influences caused by the step can be observed further downstream and in the region immediately ahead of the step location. The final pressure ratio recovery behind the step for the present study was slightly greater than 1 for the transonic data (see figs. 4 and 6(a) to 6(c)) and slightly less than 1 for the supersonic data (see figs. 5 and 6(d) to 6(f)).

The effect of step base pressure on the upstream reference region pressures can be seen in figures 4 and 6(a) to 6(c). As shown, the lower pressures in the base region propagated upstream and influenced the pressure region immediately ahead of the base. This did not occur at the supersonic flow conditions (figs. 5 and 6(d) to 6(f)).

Base Pressures

The base pressure ratio, p_b/p_r, for a given Mach number has been shown to be a function of θ/h, with p_b/p_r increasing (drag decreasing) as θ/h increases. A substantial amount of such base pressure data at supersonic Mach numbers exists for θ/h values less than 1.0, as indicated in references 9 and 10. However, corresponding data at transonic speeds for θ/h values greater than or equal to 1.0 are quite limited.

Base pressure results from the flight experiments of the present study and reference 6, and from the wind tunnel experiments of references 4 and 5, include data for θ/h values near 1.0. Base pressure ratio values from the present experiment, and from some previous experiments, are shown as a function of θ/h in figure 7. Tabulated data for the present experiment are also provided in table 1. The data shown in figure 7 established the expected trend of increasing base pressure ratio (decreasing drag) with increasing θ/h values. However, the absolute level of these data did not always agree at the supersonic Mach numbers for the θ/h values shown. For example, for values of θ/h near 1.0, the maximum spread in p_b/p_r increased with Mach number from less than 0.1 at about Mach 2.2 to 0.2 at about Mach 2.8. When the differences for Mach 2.8 shown in figure 7(f) were converted into drag penalties representative of discontinuities found on a supersonic cruise airplane, the results were as provided in the following table.

Drag penalty for a 30.5-meter, aft-facing step (lap joint) at a cruise altitude of 20,000 meters and with a step height of 2 millimeters.

Data source	M	θ/h	R_θ	Drag, N	$\frac{D - D_{ref.\ 4}}{D_{ref.\ 4}}$, percent
Wind tunnel (ref. 4)	2.8	0.7	4.1×10^3	129	---
Flight (present study)	2.9	0.7	7.9×10^3	165	27
Wind tunnel (ref. 5)	2.8	0.7	4.3×10^5	205	59

Note that the difference between the step (lap joint) drag penalty of the present experiment and that reported in reference 4 amounts to 27 percent. The corresponding Reynolds numbers based on momentum thickness are 7.9×10^3 and 4.1×10^3, respectively. Furthermore, the wind tunnel results from reference 5, with $R_\theta = 4.3 \times 10^5$, indicate a drag penalty 59 percent greater than that obtained from the results of reference 4. As indicated by the trend shown in the preceding table, these significant differences appear to be associated with the Reynolds number based on momentum thickness.

The variation of base pressure ratio with R_θ for a given θ/h value near 1.0 is shown in figures 8(a) and 8(b) for test Mach numbers above 2.4. The data from the various sources indicate that there is a relationship between base pressure ratio and R_θ for a given value of M and θ/h. A carefully controlled experiment covering a wide range of the important variables will be required to establish a firm relationship between the influencing variables and base pressure.

Data from the various experiments, in the form of base pressure ratio, p_b/p_r, as a function of θ/h have been shown to be effective for observing the degree to which Reynolds number, and hence viscosity, influences these pressures; however, the method provides little direct information on the resulting drag. The base pressure coefficient, which is directly related to base drag, is plotted as a function of Mach number in figure 9. Results from this and other experiments, and from the incompressible semiempirical estimate of Hoerner (ref. 14), are shown in figure 9(a) for Mach numbers up to approximately 1.0. Hoerner's incompressible estimate uses θ/h to account for viscous effects. The incompressible estimates shown were based on θ/h values that correspond to the experimental data presented in figure 9(a).

In general, θ/h effects caused the vertical spread seen in the base pressure coefficient for a given Mach number, both for the various experimental data and for Hoerner's estimate. For Mach numbers less than 0.9, Hoerner's estimate adequately accounts for the magnitude of the vertical spread found in the experimental data, thus indicating that Hoerner's estimate adequately accounts for the viscous effects. Especially significant is the fact that, although Hoerner's expression was derived from relatively low Reynolds number water tunnel data, it appears to provide valid estimates of the viscous effects (though not necessarily the absolute levels) for Reynolds numbers based on momentum thickness which are quite large (up to 10^5). When compared with the other data from the flight experiments, the absolute level of the results from reference 13, at Mach numbers below the point of the steep transonic rise, graphically illustrates the strong influence of θ/h on base pressure.

The variation of the base pressure coefficient with Mach number at supersonic speeds is shown in figure 9(b) for flight data from the present experiment and from reference 6. The effect of θ/h on the vertical spread of the data is about the same as for the transonic flight data and the incompressible estimate, both of which are presented in figure 9(a). A simple expression, $c_{p_b} = -0.7/M^2$, has been included in figure 9(b) as an approximation of the decay behavior of the base pressure coefficient with Mach number.

CONCLUDING REMARKS

Aft-facing step data for thick boundary layer, turbulent flow conditions were obtained from several flights of the YF-12 airplane at nominal Mach numbers of 0.80, 0.90, and 0.95 and 2.2, 2.5, and 2.8. The data were analyzed and compared with other flight and wind tunnel data and with an incompressible estimate. Analysis of the data showed the following results.

When distance from the step was expressed in terms of step height, the surface static pressure rise behind the step occurred at a normalized location of approximately 4 for all of the transonic data. The surface static pressure rise behind the step occurred at a normalized location of approximately 2 for all of the data above Mach 2.0.

The data from the present experiment and other experiments show the same trend of increasing base pressure ratio (decreasing drag) with increasing values of θ/h; however, the absolute level of the data do not always agree at the supersonic Mach numbers for the momentum thickness to step height ratios presented. The differences in level of base pressure ratio or drag appear to be primarily a function of Reynolds number based on momentum thickness, as shown by the data for momentum thickness to step height ratios near 1.0. For Mach numbers above 2.0, with a given momentum thickness and step height, the base pressure ratio decreases (drag increases) as Reynolds number based on momentum thickness increases.

For Mach numbers less than 0.9, the magnitude of the vertical spread in the base pressure coefficient for the experimental data is adequately accounted for by Hoerner's estimate. This indicates that Hoerner's estimate adequately accounts for viscous effects for values of Reynolds numbers, based on momentum thickness, up to 10^5.

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TABLE 1.—STEP PARAMETERS

h, cm	M_∞	p_b/p_r	θ, cm	$R_\theta \times 10^4$
0.33 0.63 1.19	0.86 0.82 0.83	0.94 0.94 0.93	0.41	3.7
0.33 0.63 1.19	0.90 0.92 0.92	0.94 0.92 0.92	0.48	4.9
0.33 0.63 1.19	0.99 0.96 0.98	0.95 0.94 0.92	0.43	4.0
0.33 0.63 1.19	2.26 2.23 2.23	0.55 0.48 0.45	0.28	1.4
0.33 0.63 1.19	2.54 2.50 2.50	0.50 0.43 0.38	0.25	0.96
0.33 0.63 1.19	2.89 2.85 2.81	0.51 0.42 0.34	0.23	0.79

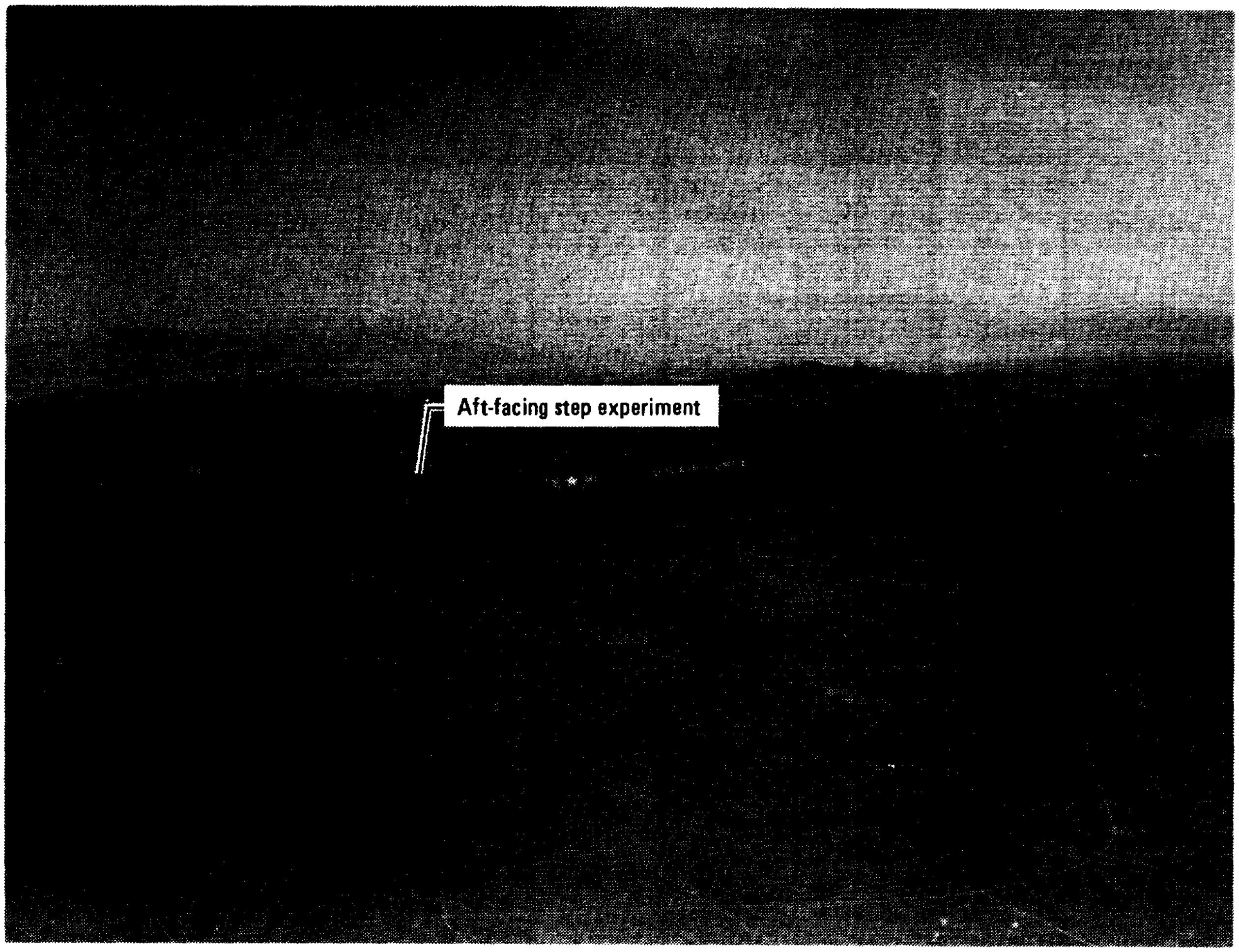
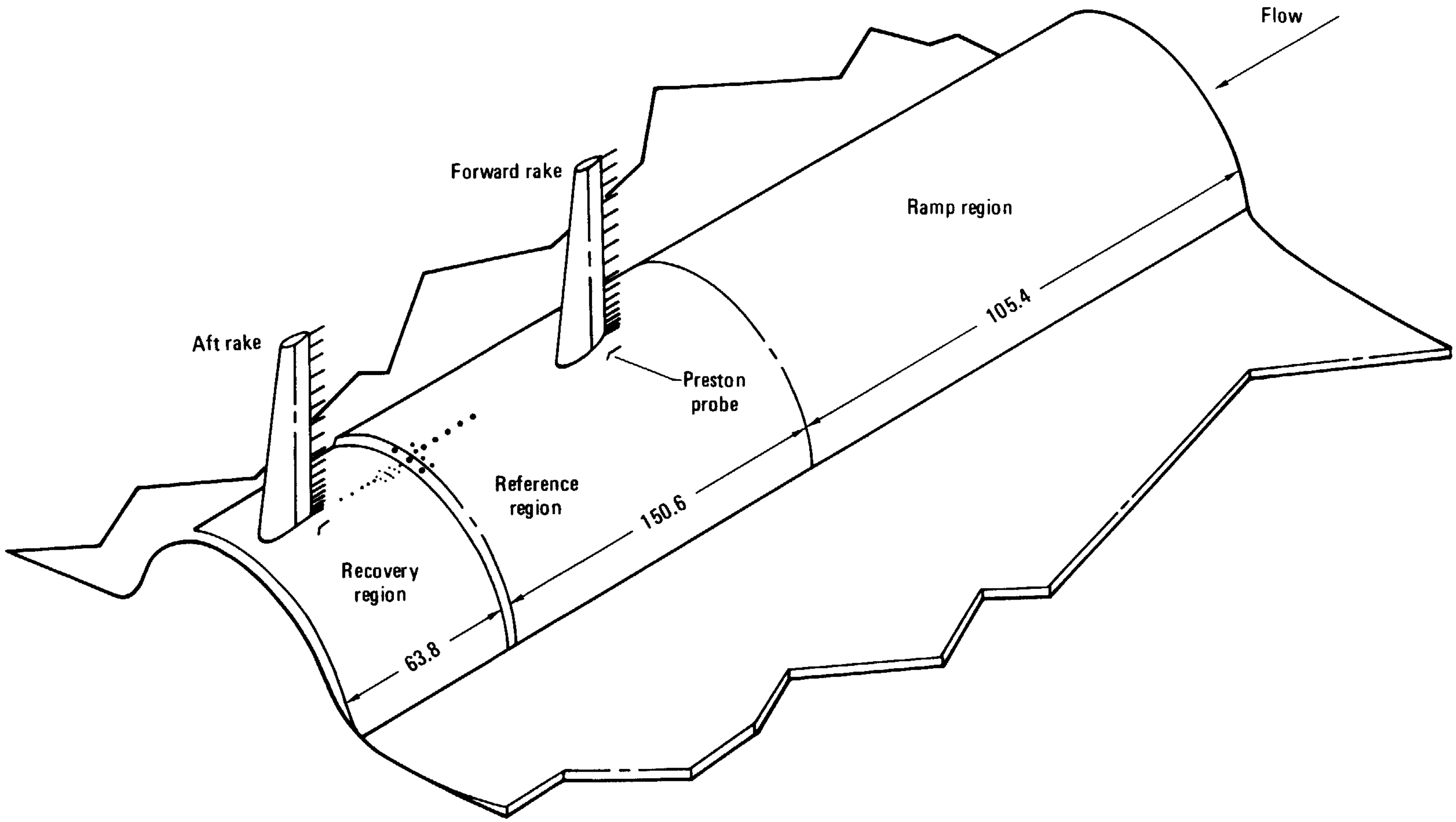


Figure 1.—YF-12 airplane in flight showing location of the aft-facing step experiment.

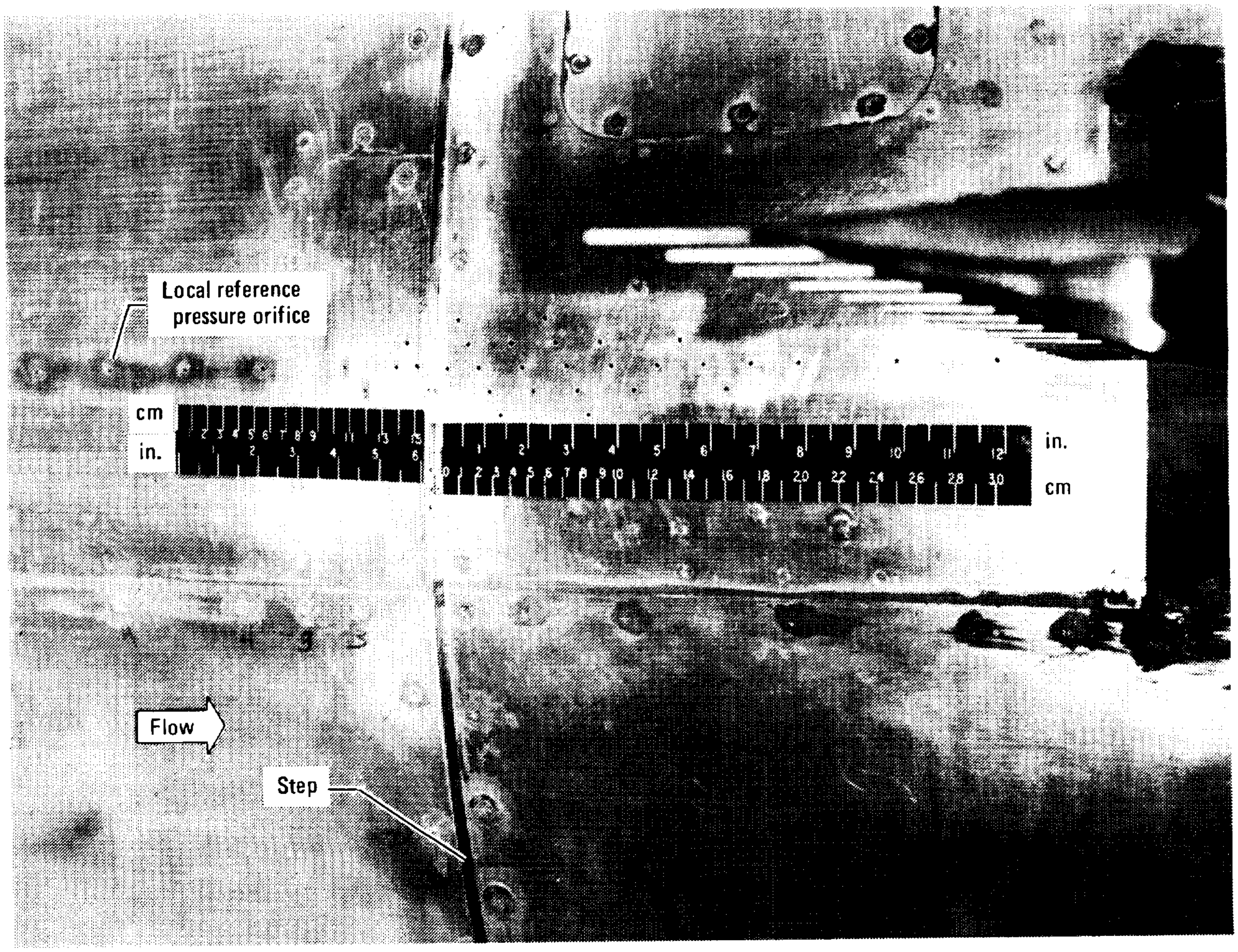


(a) Sketch showing relative location of components. Dimensions in centimeters.

Figure 2.—Sketch and photograph of the aft-facing step experiment.

(b) Experiment viewed from rear. The boundary layer complex is in the aft location and the step height is 0.63 centimeter.

Figure 2.—Continued.



(c) Top view of step region showing location of pressure orifices. Step height is 1.19 centimeters.

Figure 2.—Concluded.

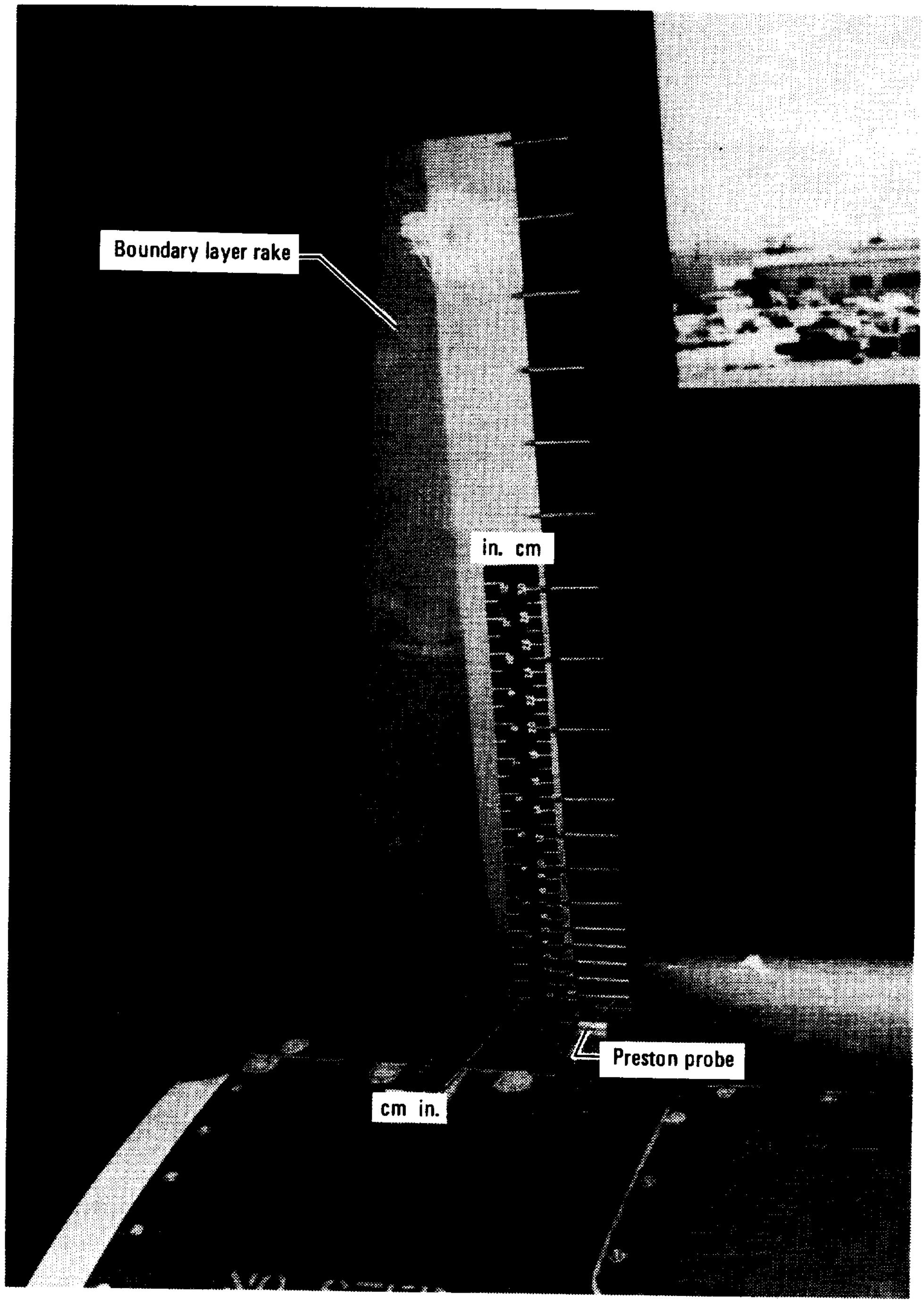


Figure 3.—A closeup view of a boundary layer rake complex.

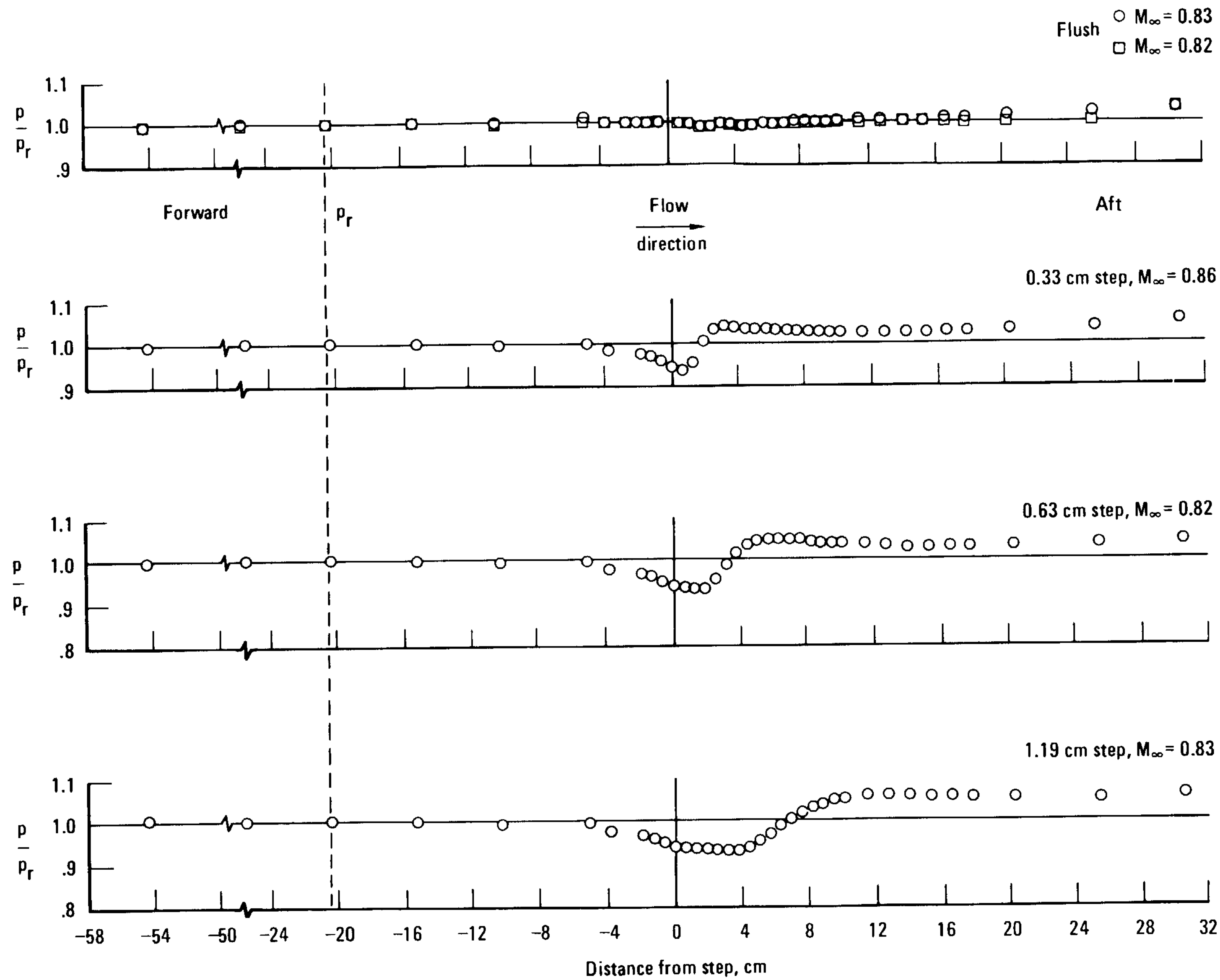


Figure 4.—Variation of the pressure ratio with distance from the step location. $M_\infty \approx 0.80$.

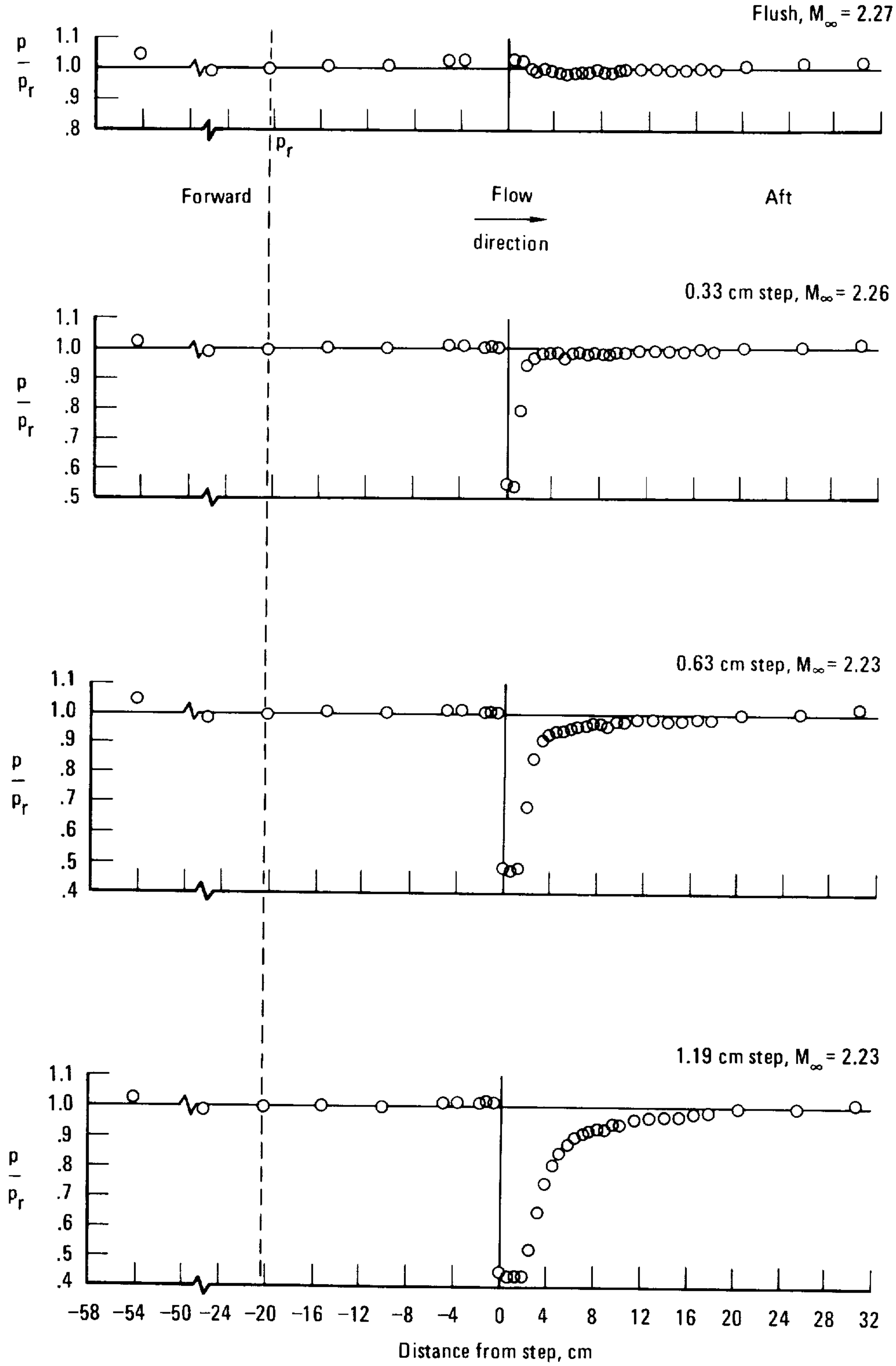
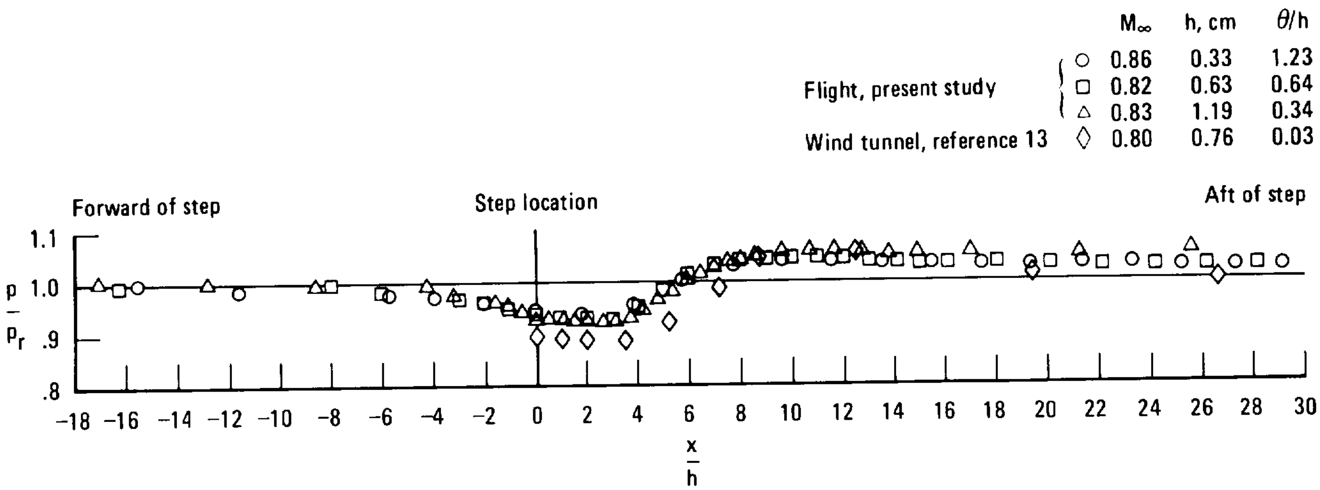
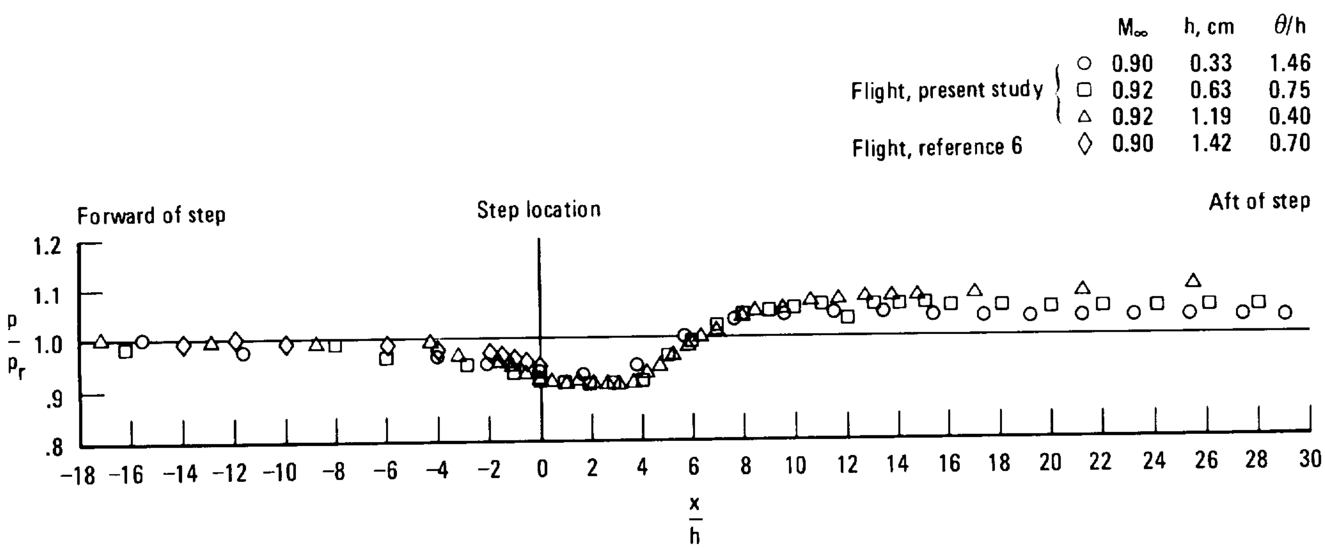


Figure 5.—Variation of the pressure ratio with distance from the step location. $M_\infty \approx 2.20$.

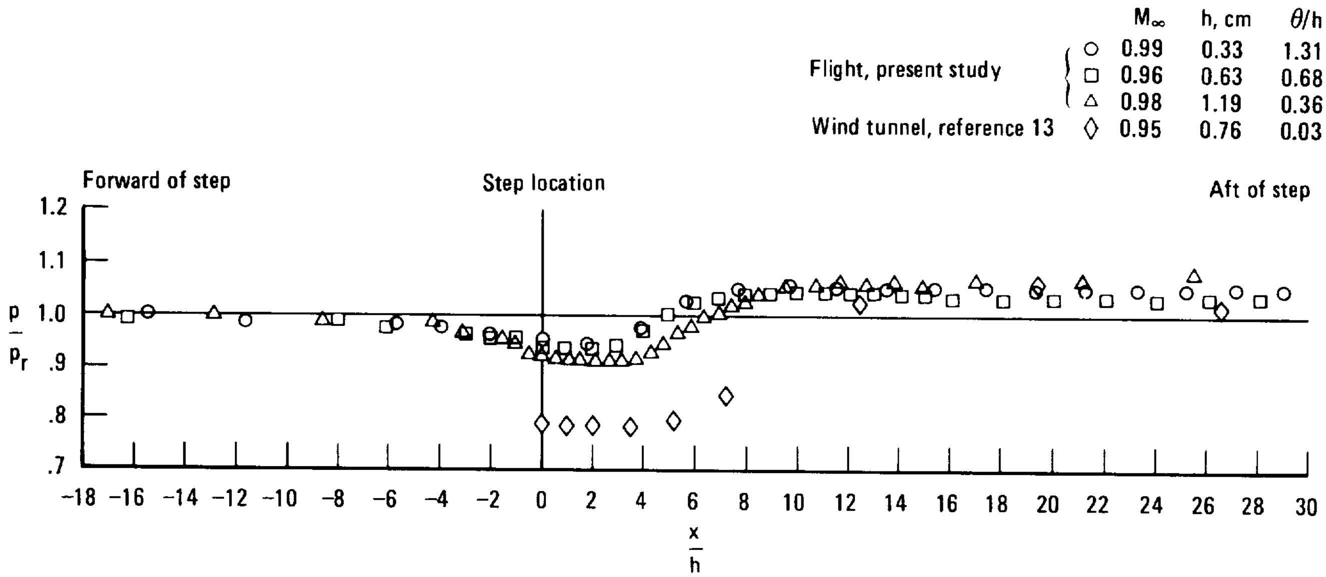


(a) Mach number near 0.80.

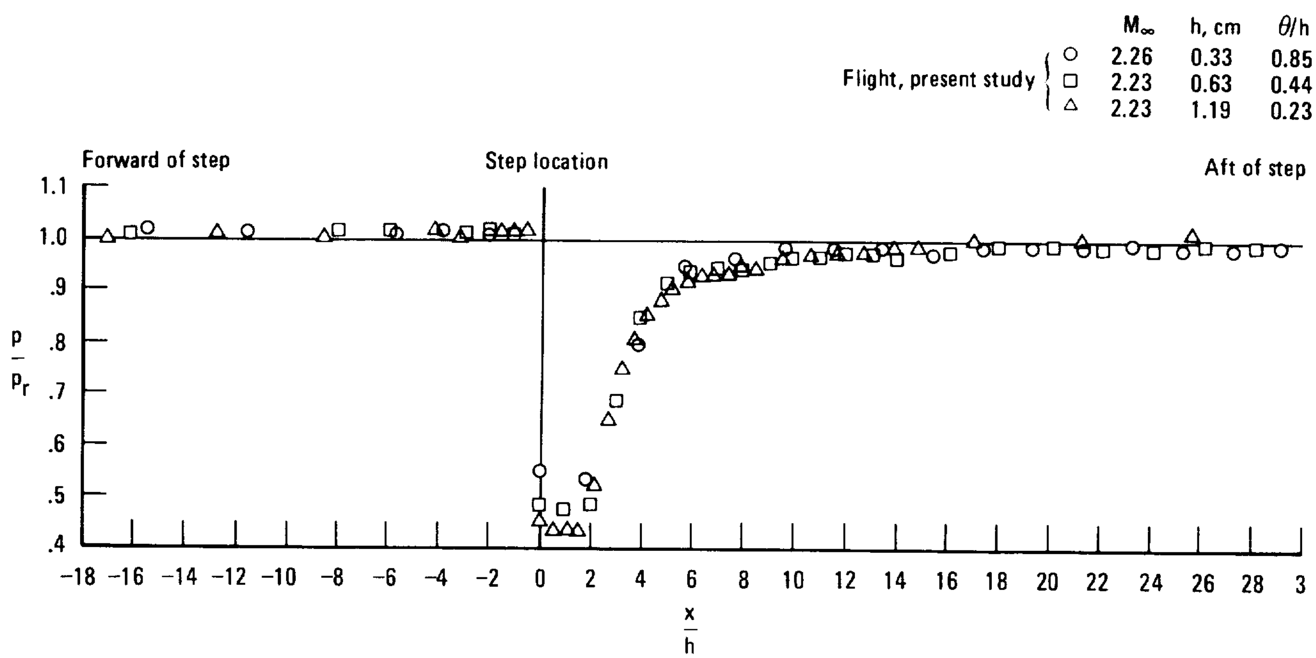


(b) Mach number near 0.90.

Figure 6.—Variation of the pressure ratio as a function of step height.

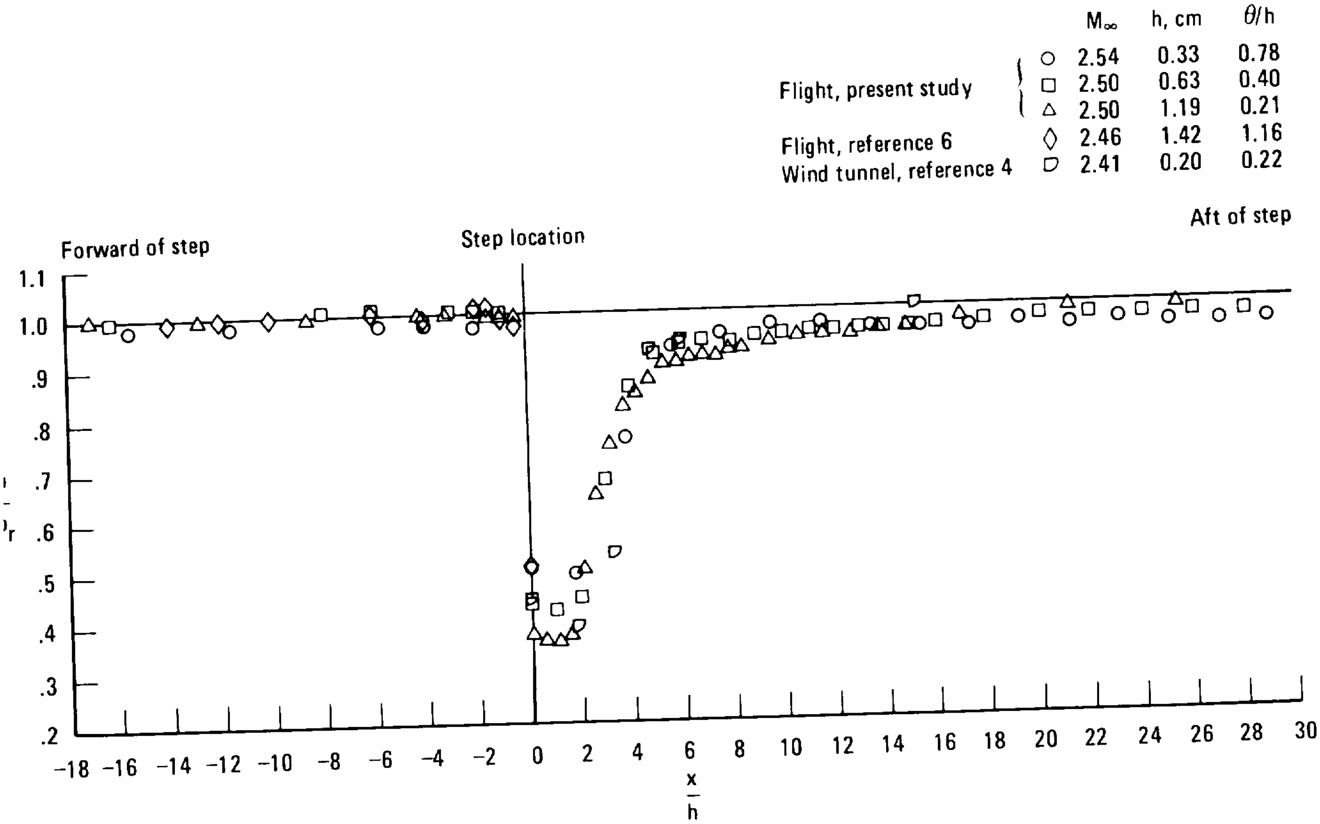


(c) Mach number near 0.95.

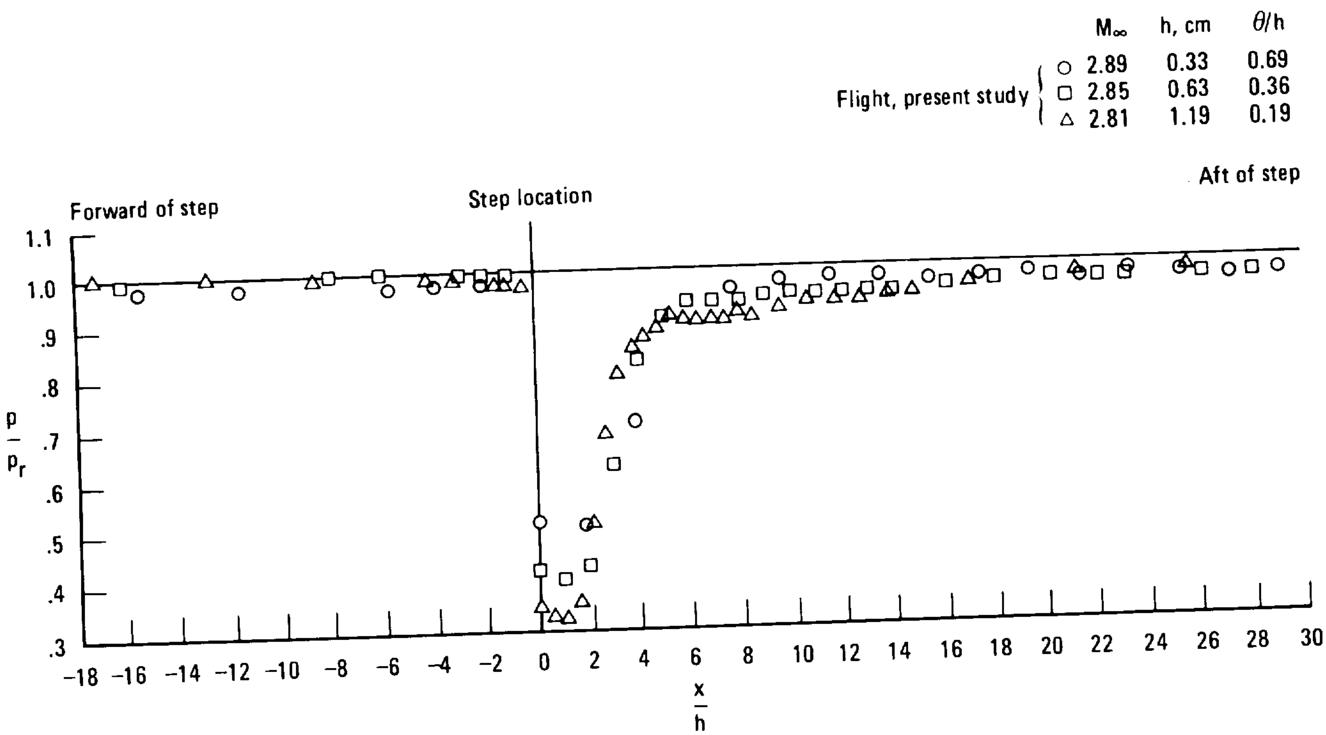


(d) Mach number near 2.20.

Figure 6.—Continued.

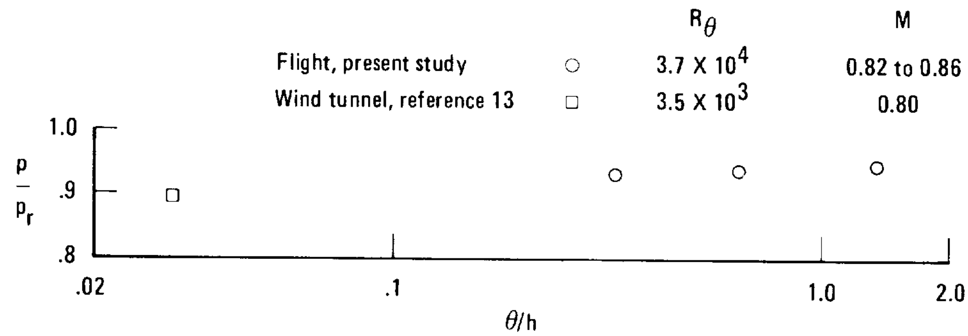


(e) Mach number near 2.50.

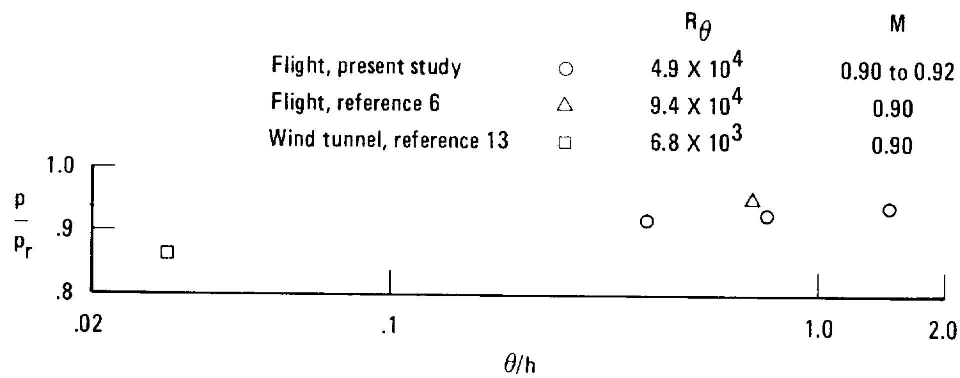


(f) Mach number near 2.80.

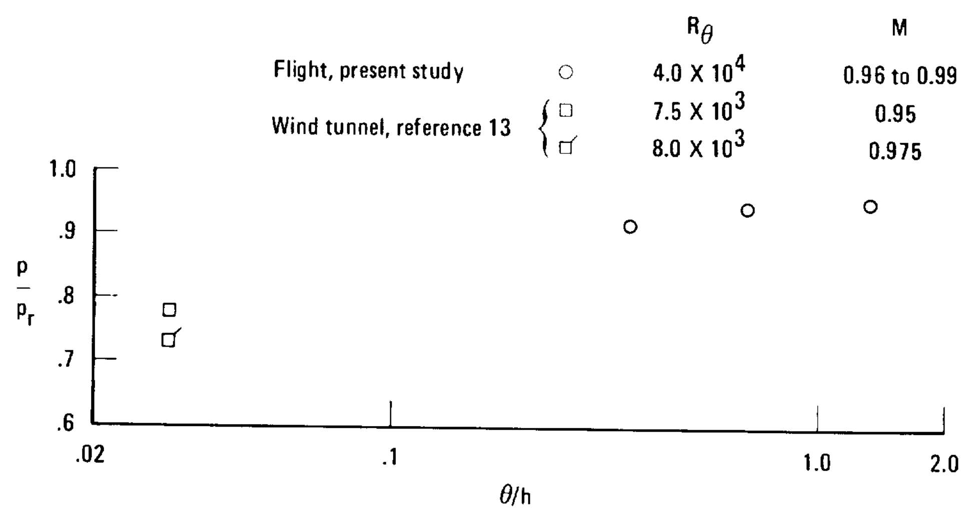
Figure 6.—Concluded.



(a) Mach number near 0.80.

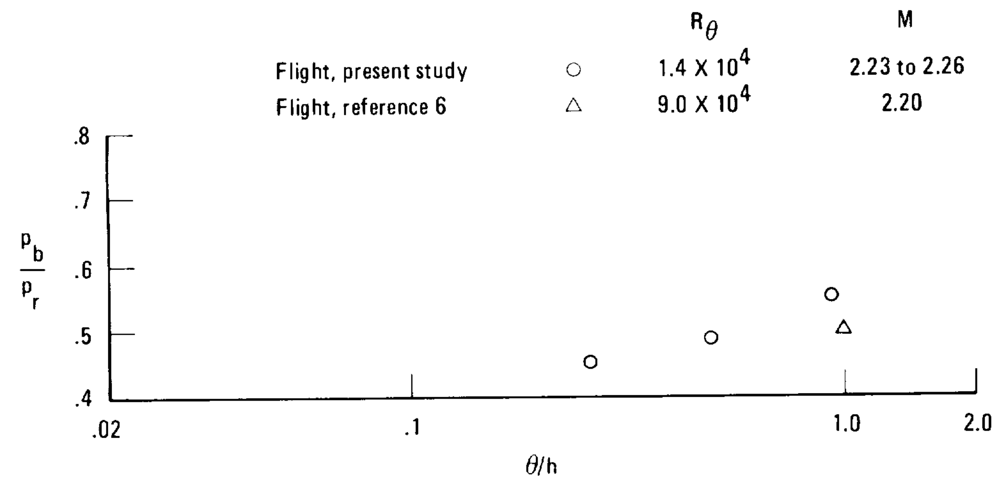


(b) Mach number near 0.90.

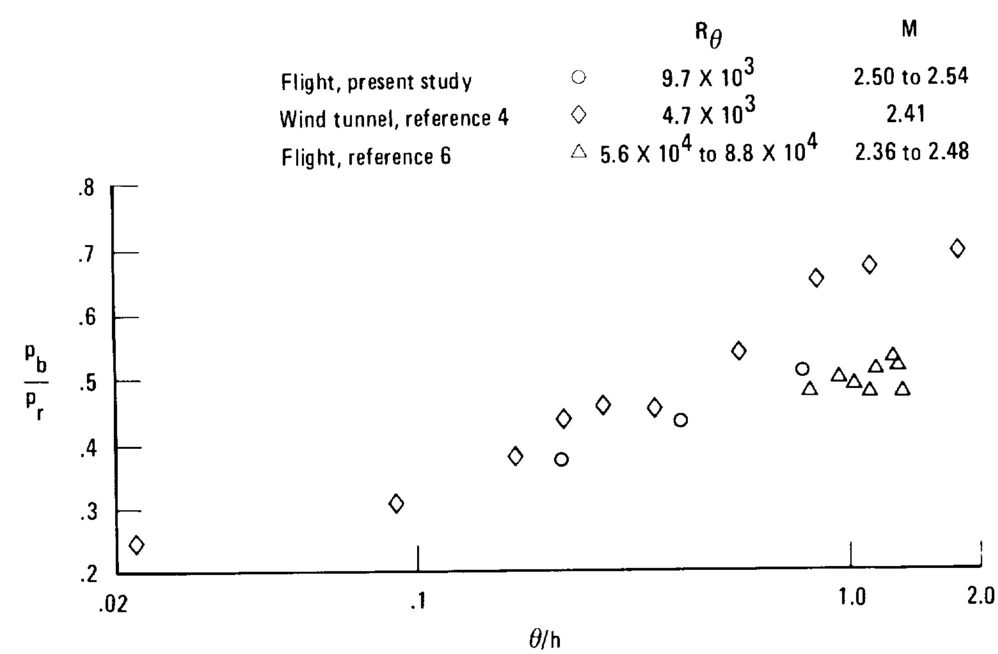


(c) Mach number near 0.95.

Figure 7.—Base pressure ratio as a function of momentum thickness and step height.

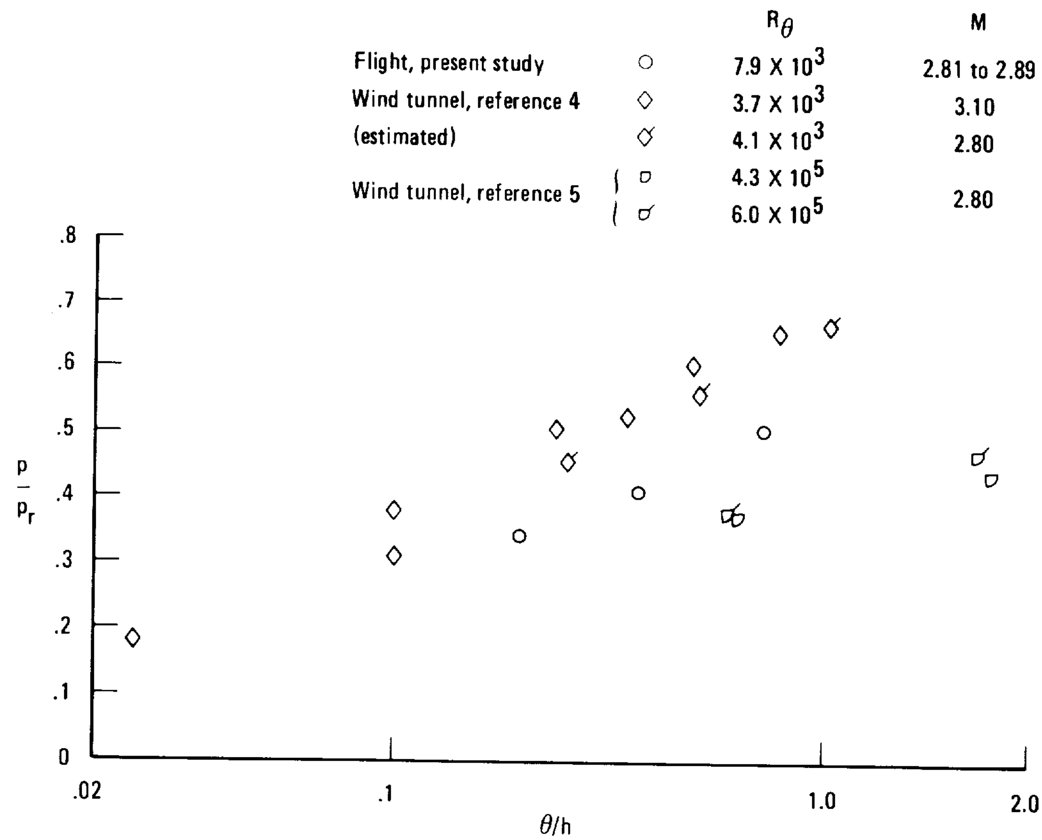


(d) Mach number near 2.20.



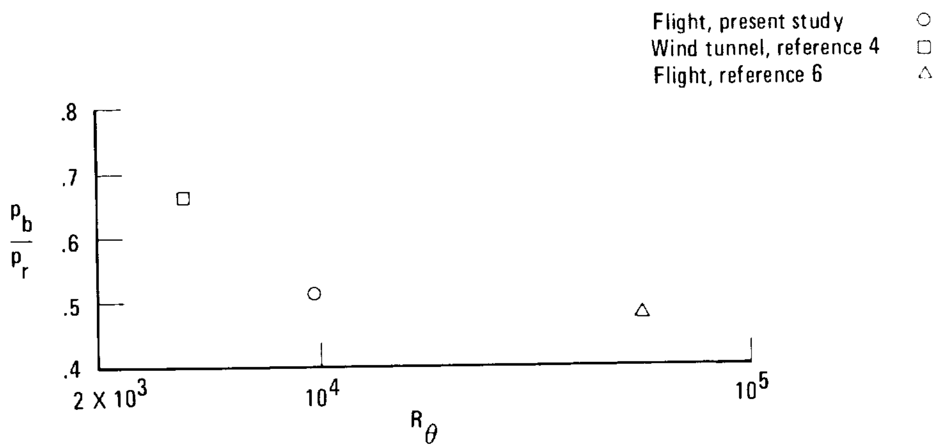
(e) Mach number near 2.50.

Figure 7.—Continued.

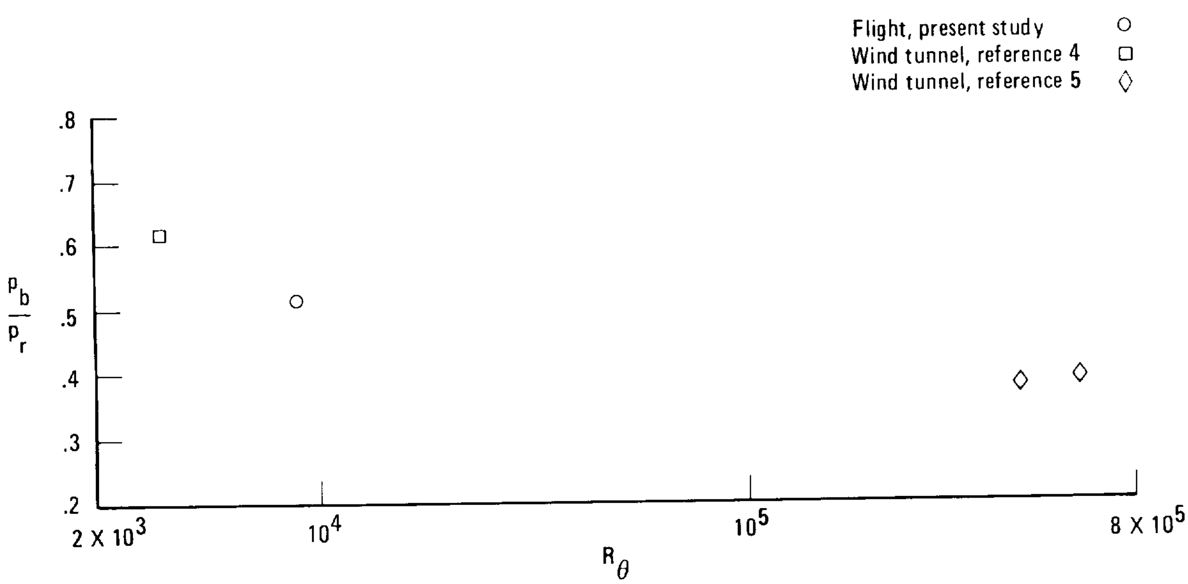


(f) Mach number near 2.80.

Figure 7.—Concluded.

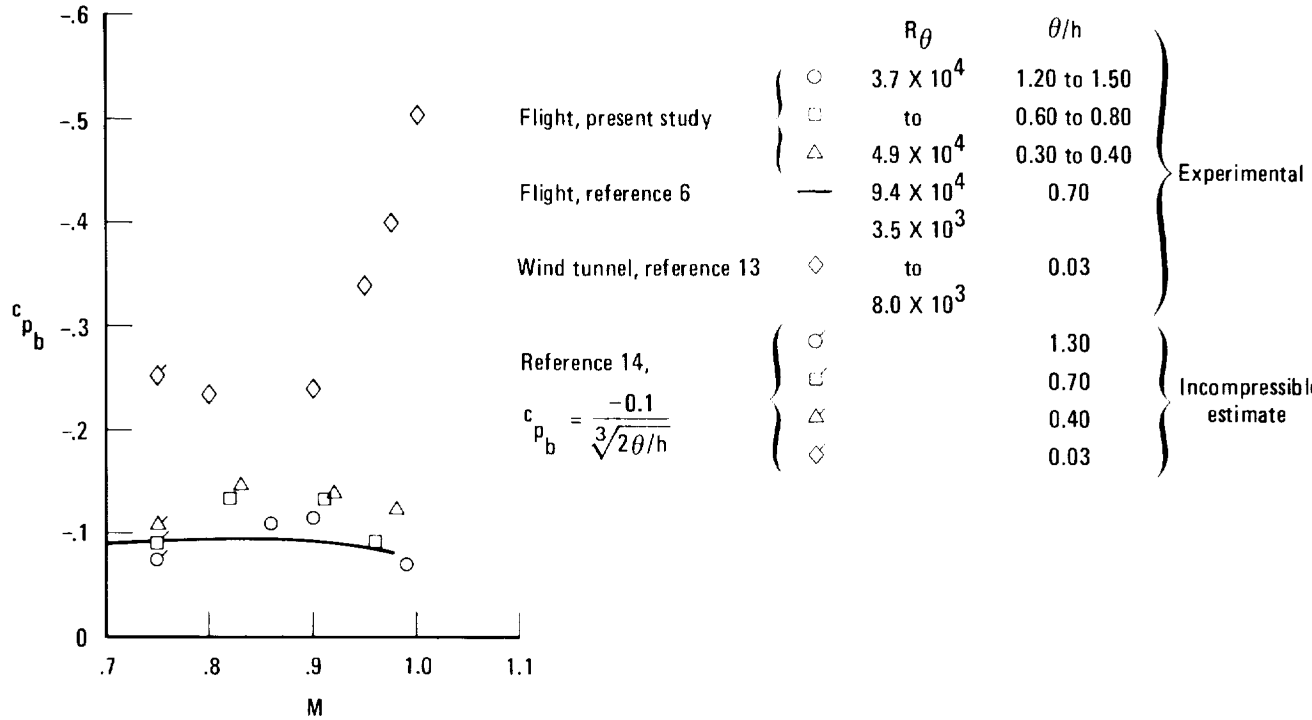


(a) θ/h = 0.80, Mach number from 2.40 to 2.50.

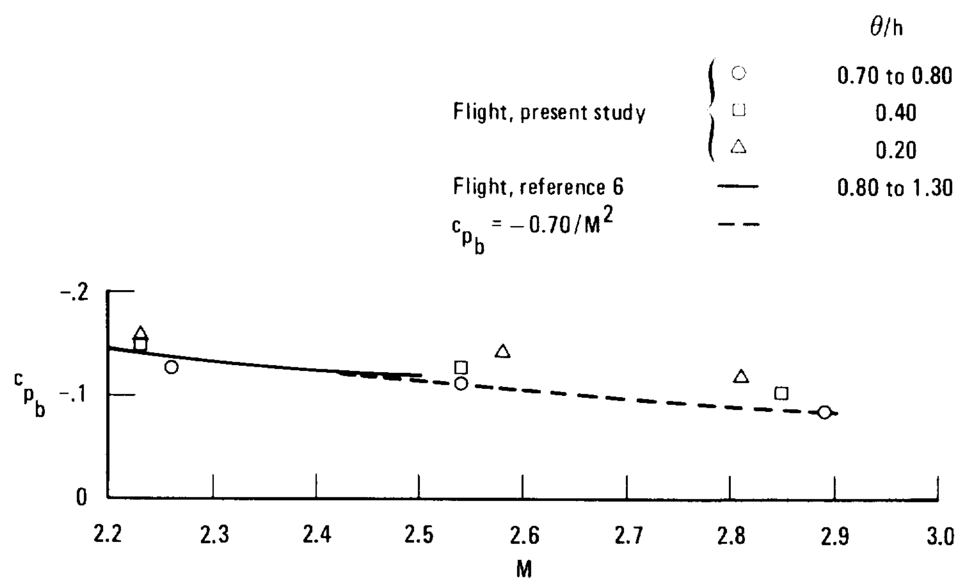


(b) θ/h = 0.70, Mach number near 2.80.

Figure 8.—Base pressure ratio as a function of Reynolds number based on momentum thickness.



(a) Mach number below 1.00. R_θ and θ/h values of reference 6 are for a Mach number of 0.90.



(b) Mach numbers above 2.00.

Figure 9.—Variation of aft-facing step base pressure coefficient data with Mach number (including an incompressible estimate).