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TECHNICAL NOTE 3159

FLIGHT INVESTIGATION AT LARGE ANGLES OF ATTACK OF THE STATIC-PRESSURE ERRORS OF A SERVICE PITOT-STATIC TUBE HAVING A MODIFIED ORIFICE CONFIGURATION

By William Gracey and Elwood F. Scheithauer

Langley Aeronautical Laboratory
Langley Field, Va.

Washington
February 1954

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FLIGHT INVESTIGATION AT LARGE ANGLES OF ATTACK OF THE STATIC-PRESSURE ERRORS OF A SERVICE PITOT-STATIC TUBE HAVING A MODIFIED ORIFICE CONFIGURATION

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SUMMARY

The effect of inclination of the airstream on the static pressure measured by two essentially similar service pitot-static tubes and by one of these tubes with three modified orifice arrangements has been determined in flight. The original orifice configuration consisted of four orifices on the top of the tube within $\pm 20^{\circ}$ of the vertical axis and six on the bottom within $\pm 30^{\circ}$ of the vertical axis. In an attempt to increase the range of insensitivity of the tube to airstream inclination, this orifice configuration was modified in three successive stages. The best of the modified orifice arrangements involved the addition of one orifice to the bottom of the tube along its center line and the enlargement of the two outermost orifices on the bottom. The tests of this configuration were conducted over an angle-of-attack range of -15° to 45°, at Mach numbers from 0.20 to 0.68 and at Reynolds numbers from 0.9×10^5 to 2.7×10^5 (where Reynolds number is based on the local velocity and the diameter of the tube).

The results of the tests of the best of the orifice arrangements showed that, for Mach numbers between 0.20 and 0.68 and for Reynolds numbers between 0.9×10^5 and 1.4×10^5, the error will remain within 2 percent of the impact pressure q_c over an angle-of-attack range of -10° to 30°.

At angles of attack between 30° and 45°, the static-pressure error increases rapidly and reaches values as high as 15 percent of q_c at an angle of attack of 45°. Because of the magnitude of the errors and the fact that the static pressure registered by the tube increases abruptly and erratically at some angle of attack within this range, the usefulness of the tube is limited to angles of attack below 30°.

INTRODUCTION

The National Advisory Committee for Aeronautics has been conducting a series of investigations to devise total- and static-pressure tubes of the rigid (i.e., nonswiveling) type, which would remain insensitive to inclination of the airstream over a wide range of angle of attack throughout the subsonic and supersonic speed ranges. The results of wind-tunnel tests of a number of total-pressure tubes at angles of attack up to 45° at both subsonic and supersonic speeds have been reported in references 1 to 3.

The variation of static-pressure error with angle of attack of a service pitot-static tube having four orifices on the top and six on the bottom of the tube has been determined from wind-tunnel tests at several supersonic speeds over an angle-of-attack range of $\pm 7^{\circ}$ (ref. 4).

A similar tube has since been calibrated in flight over a range of angle of attack of $\pm 45^{\circ}$ at a Mach number of about 0.2. On the basis of the results of these flight tests, the static-pressure-orifice configuration was modified and further tests were conducted over an angle-of-attack range of -15° to 45° at Mach numbers from 0.20 to 0.68.

This paper presents the results of the flight tests of the tubes with the original and modified orifice configurations.

SYMBOLS

p local static pressure at location of test tube

p_t static pressure registered by test tube

p_r static pressure registered by reference tube

$\Delta p = p_t - p$

H total pressure of free stream

q_c impact pressure at location of test tube, $\dfrac{(H - p_t)_{\alpha=0^{\circ}}}{0.995}$

α angle of attack of tube, deg

β angle of sideslip of tube, deg

M local Mach number at location of test tube

R Reynolds number (based on local velocity and diameter of tube)

X longitudinal axis of airplane

Y lateral axis of airplane

Z vertical axis of airplane

Subscripts:

α for a given angle of attack

$\alpha=0^{\circ}$ for zero angle of attack

APPARATUS AND TESTS

Static-Pressure Tubes

A sketch of the service pitot-static tubes which were tested during this investigation is presented in figure 1(a); the arrangement of the static-pressure orifices around the tubes is also shown.

Tubes A and B are the same except for the size of the static-pressure orifices. Although the tubes were built to the same Military specification (ref. 5), they were constructed by different manufacturers, a fact which accounts for the difference in orifice size. The Military specification calls for an orifice diameter of 0.040 ± 0.005 inch. The orifices of tube B (0.043 inch) are, therefore, within the specified tolerance; those of tube A (0.047 inch), which are just one drill size larger, are slightly over the limit.

The three modifications which were made to the orifice configuration of tube B are shown in figure 1(b). The tube was modified in three steps by (1) the addition of one orifice with a diameter of 0.047 inch to the bottom of the tube along its center line and to the rear of the plane of the original orifices (tube B-1), (2) the enlargement of this orifice to 0.052 inch in diameter (tube B-2), and (3) the enlargement of the two orifices at a radial position of 30° from the bottom to 0.052 inch in diameter (tube B-3).

Tests of Tubes A and B at Mach Numbers From 0.20 to 0.24

For the initial tests of tubes A and B and the modified orifice arrangements of tube B, two U-shaped support booms were installed about 2 feet apart on the top of the fuselage of a transport airplane (fig. 2(a)).

One of these booms was alined parallel to the center line of the fuselage and clamped in place. The other was designed so that it could be rotated parallel to the XY-plane through an angular range of ±45° from the fuselage center line. The test pitot-static tube was mounted on the rotary boom, and a similar pitot-static tube which was used as a static-pressure reference and for the measurement of impact pressure, was installed on the fixed boom. The rotary boom was designed so that the static-pressure orifices of the test tube were on the axis of rotation and, thus, would remain at the same point in the airstream for all angular settings of the boom. The boom for the reference tube was made the same as the rotary boom in order that the blocking effects of the two supports would be the same and a more sensitive differential-pressure recorder could be used. On the inside of the fuselage, the rotary boom was equipped with an angular scale and a means for manually setting the boom to any desired angle within a range of ±45°.

For the tests of tubes A and B at angles of attack, the test and reference tubes were mounted on the booms with the vertical axis of the tubes parallel to the Y-axis of the airplane. The tests were conducted in level flight at Mach numbers of 0.20, 0.22, and 0.24 and at an altitude of about 5,000 feet. At each of these speeds, the test-tube setting was varied by 5° increments through an angular range of -15° to 45°. For each setting of the boom, the difference between the static pressure registered by the test tube and that registered by the reference tube was measured by a standard NACA differential-pressure recorder having a range of 3 inches of water and a highly probable precision of ±0.008 inch of water. At the same time, measurements of the impact and ambient pressures were obtained from the total and static pressures registered by the reference tube.

On succeeding flights, tests were conducted to determine the air-flow direction at the two tube locations. The direction of the airflow ahead of the two booms was investigated by installing air-flow-direction vanes in the region occupied by the two tubes (fig. 2(b)). The results of the tests of flow alinement in the XY-plane of the airplane showed that the air-flow direction at the two stations was very nearly parallel and within 2° of the center line of the fuselage. Tests in the XZ-plane showed the flow to be alined with the longitudinal axis of the tube to within 1°.

Following the air-flow-direction tests, tube B was tested at angles of sideslip by mounting the test and reference tubes with the vertical axis of the tubes parallel to the Z-axis of the airplane. On subsequent flights, tube B was calibrated at angles of attack with the static-pressure orifices modified as shown in figure 1(b).

Tests of Tube C-3 at Mach Numbers From 0.30 to 0.68

After the completion of the tests on the transport airplane, a rotary boom was installed below the nose section of a fighter airplane (fig. 3) for tests of tube B-3 at higher speeds. Tube B-3, however, was damaged after its removal from the transport airplane, so another tube, designated C-3 which had the same orifice size and arrangement was used for the rest of the tests.

The tube was installed on the rotary boom so that the vertical axis of the tube was alined with the Y-axis of the airplane. As in the tests on the transport airplane, the boom was built to allow the orifices to remain at the same location in the air stream as the boom rotated. Rotation was accomplished by a motor and gear system which, when actuated, caused the boom to oscillate continuously through an angular range of -20° to 45° at a rate of about 4° per second. Errors due to pressure lag determined by stopping the boom at various angles of attack and comparing the pressure measurements with those obtained when the boom was rotating were found to be negligible. The angular position of the boom was measured by a mechanical-optical-type position recorder connected to the upper end of the boom shaft.

The variation of static-pressure error with angle of attack of the test tube was determined by measuring the difference between the pressure registered by the test tube and that registered by a pitot-static tube mounted ahead of the fuselage nose (fig. 3). The differential-pressure recorder for these tests had a range of 10 inches of water and a highly probable precision of ±0.025 inch of water. The fuselage nose boom also provided measurements of impact and ambient pressures.

Prior to the testing of tube C-3, the direction of the air flow in the vicinity of the test tube was determined by installing a vane-type flow-angle recorder on the rotary boom fixed at zero angle. The vane was oriented to measure flow direction in a vertical plane, and the angle of flow was determined at various speeds throughout the speed range. As a result of this calibration, the rotary boom was adjusted so that the test tube would be alined with the airstream at an indicated airspeed of 250 mph. Most of the tests were conducted at constant indicated airspeed of 250 mph in order that the angle of attack of the airplane (and hence the sideslip of the test tube) would be constant; a value of 250 mph was chosen since, at this speed, the Mach number could be varied over the widest range within the altitude capabilities of the airplane. When the boom was alined with the airstream at 250 mph, the calibration indicated that for tests at a few other indicated speeds, which were included in the investigation, the variation in air-flow direction would be no greater than $\pm 2^{\circ}$. During the tests of tube C-3, deviations in angle of sideslip of the airplane (with resulting errors in angle of attack of the tube) were measured by means of a flow-direction vane on the fuselage nose boom.

Preliminary tests of tube C-3 were conducted at indicated airspeeds of from 215 to 275 mph and at altitudes ranging from 1,000 to 35,000 feet, with corresponding variations in Mach number of from 0.30 to 0.68. Additional tests were conducted at $M = 0.39$, 0.50, and 0.57 at low altitudes in order to obtain data at higher Reynolds numbers.

RESULTS AND DISCUSSION

The results of the flight tests of the service pitot-static tubes with the original and modified orifice arrangements are presented in figures 4 to 8. The static-pressure errors are presented as fractions of the impact pressure q_c and are plotted as a function of the angle of attack α or angle of sideslip β of the tube. The static-pressure error, Δp, was obtained from the following relation:

$$\Delta p = p_t - p = \left(p_t - p_r\right)_\alpha - \left(p_t - p_r\right)_{\alpha=0^\circ} + 0.005q_c$$

where $\left(p_t - p_r\right)_\alpha$ is the static-pressure difference with the test tube at angles of attack; $\left(p_t - p_r\right)_{\alpha=0^\circ}$ is the static-pressure difference with the test tube at $\alpha = 0^\circ$; and $0.005q_c$ is the error of the test tube at $\alpha = 0^\circ$, as obtained from a wind-tunnel calibration of the tube over a Mach number range of 0.1 to 0.9. Similarly, the impact pressure at the location of the test tube was derived from the equation:

$$q_c = \frac{\left(H - p_t\right)_{\alpha=0^\circ}}{0.995} = \left(H - p_r\right) - \left(p_t - p_r\right)_{\alpha=0^\circ} + 0.005q_c$$

$$= \left(H - p_t\right)_{\alpha=0^\circ} + 0.005q_c$$

where $H - p_r$ is the impact pressure measured by the reference tube.

Initial Calibrations at Mach Numbers From 0.20 to 0.24

Tubes A and B.- The variation of static-pressure error with angle of attack of tubes A and B is shown in figures 4 and 5. Each point shown on these curves is the average of two readings taken a few minutes apart during the same test. For this series of tests the precision of the data at $\alpha < 25^\circ$ was about ±0.05 percent of q_c; at $\alpha = 30^\circ$ to 45° the precision was of the order of ±0.4 percent of q_c.

The Military specification (ref. 5) to which these tubes were built specifies that, for indicated airspeeds up to 250 mph, the static-pressure error at angles of attack between -10° and 16° shall differ from the error at zero angle by no more than 0.15 inch of water. For the indicated speeds covered by the present tests, this pressure difference corresponds to a static-pressure error between 1.2 and 1.8 percent of q_c. Figures 4 and 5 show that both of the tubes meet this Military specification and that, within the specified angle-of-attack range, the effect of the difference in orifice size is small. At angles of attack above 16°, however, the calibrations differ appreciably; thus, it is indicated that differences in orifice diameter as small as 0.004 inch have a pronounced effect on the sensitivity of this type of tube at the higher angles.

The calibration of tube B at angles of sideslip is given in figure 6. Because of the unsymmetric orifice arrangement, there is, as expected, a wide difference in the sensitivity of the tube to angles of attack and sideslip. At angles of attack, for example, the static-pressure error remains within 1 percent of q_c from -15° to 18°, whereas, at angles of sideslip, the error is within 1 percent over a range of only about $\pm 5^{\circ}$.

Modified orifice arrangements of tube B.- For the initial modification to tube B (designated B-1), one orifice, 0.047 inch in diameter, was added to the bottom of the tube along its center line and to the rear of the plane of the original orifice (fig. 1(b)). As shown in figure 7(a), the static-pressure error at positive angles of attack was reduced to a maximum of about $1\frac{1}{2}$ percent of q_c for angles of attack up to 45°. In an attempt to reduce the error at positive angles still further, the orifice along the bottom center line was enlarged to a diameter of 0.052 inch (tube B-2). The calibration of this orifice arrangement (fig. 7(b)) showed that the error was reduced at angles of attack between 20° and 40° but was increased slightly at angles of attack in the region of 15°. From an examination of the trends of the calibrations of tubes B, B-1, and B-2, it appeared that any additional enlargement of the orifice along the bottom center line would result in a still greater increase in the error at $\alpha = 15^{\circ}$ and, quite probably, in the vicinity of 40°. Additional orifice area was therefore provided by enlarging the two orifices at the 30° radial position to a diameter of 0.052 inch (tube B-3). A calibration of this arrangement (fig. 7(c)) showed the error to be reduced at $\alpha = 15^{\circ}$ and to remain within 1 percent up to $\alpha = 40^{\circ}$. This arrangement is, therefore, the best of those tested in this Mach number range.

Final Orifice Configuration

Calibration at Mach numbers from 0.30 to 0.68.- Calibrations of tube C-3 at Mach numbers from 0.30 to 0.68 and at Reynolds numbers

from 1.1×10^5 to 2.4×10^5 are given in figure 8. Each of the test points shown on the curves represents the average of two readings taken from different cycles of the boom traverse, with the tube approaching a given angle from different directions. The precision of the data for this series of tests was ±0.05 percent of q_c for α below 30° and ±0.4 percent of q_c for α above 30°. Comparison of the calibrations shows that between $\alpha = -10^\circ$ and 30° the variation of static-pressure error with angle of attack is relatively small and the magnitude of the errors is less than about 3.5 percent of q_c. For $\alpha > 30^\circ$, however, the variation of static-pressure error with angle of attack became erratic in addition, the magnitude of the errors increased rapidly and reached values as high as 15 percent of q_c at $\alpha = 45^\circ$. The erratic behavior of the pressure registered by the test tube at angles of attack above 30° consisted of oscillations with an amplitude of ±0.25 percent of q_c. As the angle of attack increased, the amplitude of the oscillations steadily increased to about ±1 percent of q_c at $\alpha = 45^\circ$. In most of the tests there was superimposed on these oscillations a pressure discontinuity accompanied by fluctuations which had amplitudes as large as the discontinuity. The magnitude of the pressure discontinuities and the angle-of-attack range over which the large-amplitude fluctuations persisted are shown on the calibrations as a hatched area. Because of the magnitude of the errors and the erratic pressure fluctuations in this angle-of-attack range, the usefulness of the tube is limited to angles of attack below 30°.

Effect of Mach and Reynolds numbers on static-pressure errors.- In order to show the manner in which the static-pressure error at the higher angles of attack varies with Mach number and Reynolds number, the errors at $\alpha = 15^\circ$, 20°, 25°, and 30° have been replotted as a function of Mach and Reynolds numbers in figure 9. The data shown in this figure were obtained with tubes B-3 and C-3 and were derived from figures 7(c) and 8 and from other tests conducted during the investigation. Figure 9 shows that the error at a given angle of attack increases with both Mach and Reynolds numbers and that for the Reynolds number range at which most of the data were obtained $\left(0.9 \times 10^5 \text{ to } 1.4 \times 10^5\right)$, the increase in error is generally of the order of 1 to 2 percent of q_c for the Mach number range investigated. On the basis of the results of the tests of tubes B-3 and C-3, it is concluded that for Reynolds numbers between 0.9×10^5 and 1.4×10^5, and for Mach numbers between 0.20 and 0.68, the static-pressure error for a tube with this orifice arrangement will remain within 2 percent of q_c over an angle-of-attack range of -10° to 30°.

CONCLUSIONS

A flight investigation was made to determine the effect of inclination of the airstream on the static pressure measured by two essentially similar service pitot-static tubes and by one of these tubes with three modified orifice arrangements. The original orifice configuration consisted of four orifices on the top of the tube within $\pm 20^{\circ}$ of the vertical axis and six on the bottom within $\pm 30^{\circ}$ of the vertical axis. The best of the modified orifice arrangements involved the addition of one orifice to the bottom of the tube along its center line and the enlargement of the two outermost orifices on the bottom. The following conclusions apply to this modified orifice arrangement:

1. For Mach numbers between 0.20 and 0.68 and for Reynolds numbers between 0.9×10^5 and 1.4×10^5 (where Reynolds number is based on the local free-stream velocity and the diameter of the tube), the static-pressure error will remain within 2 percent of the impact pressure q_c over an angle-of-attack range of -10° to 30°.

2. At angles of attack between 30° and 45°, the static-pressure error increases rapidly, and reaches values as high as 15 percent of q_c at an angle of attack of 45°. Because of the magnitude of the errors and the fact that the static pressure registered by the tube increases abruptly and erratically at some angle of attack within this range, the usefulness of the tube is limited to angles of attack below 30°.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., October 20, 1953.

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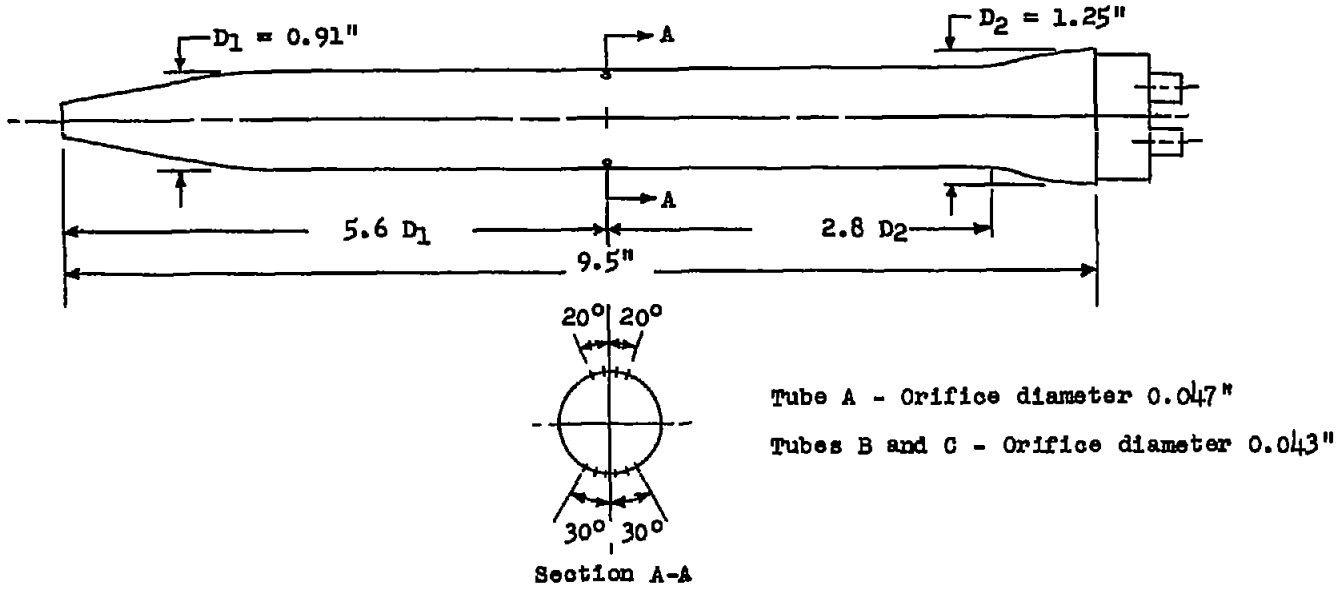
1. Gracey, William, Letko, William, and Russell, Walter R.: Wind-Tunnel Investigation of a Number of Total-Pressure Tubes at High Angles of Attack - Subsonic Speeds. NACA TN 2331, 1951. (Supersedes NACA RM L50G19.)

2. Gracey, William, Coletti, Donald E., and Russell, Walter R.: Wind-Tunnel Investigation of a Number of Total-Pressure Tubes at High Angles of Attack - Supersonic Speeds. NACA TN 2261, 1951.

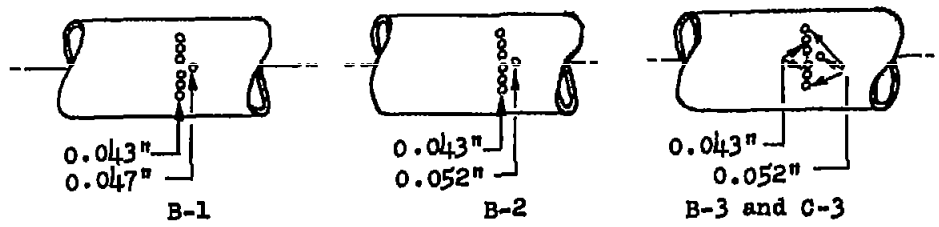
3. Russell, Walter R., Gracey, William, Letko, William, and Fournier, Paul G.: Wind-Tunnel Investigation of Six Shielded Total-Pressure Tubes at High Angles of Attack - Subsonic Speeds. NACA TN 2530, 1951.

4. Hasel, Lowell E., and Coletti, Donald E.: Investigation of Two Pitot-Static Tubes at Supersonic Speeds. NACA RM L8I02, 1948.

5. Anon.: Military Specification Tubes; Pitot Static, Unheated, Aircraft. Military Specification, MIL-T-5690, Mar. 10, 1950.



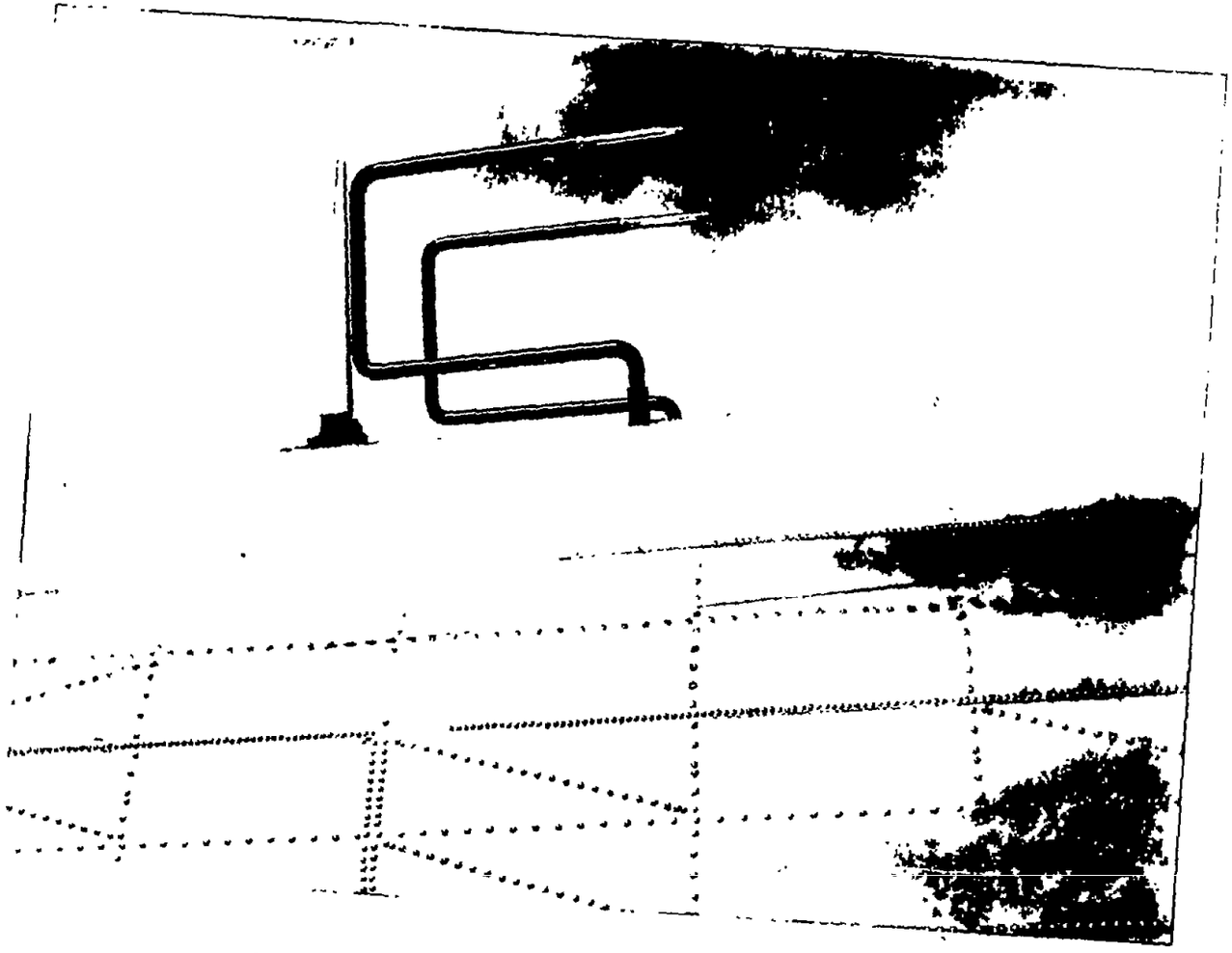
(a) Side view and orifice arrangement of service pitot-static tubes.



Bottom views (orifices on top same as for original arrangement)

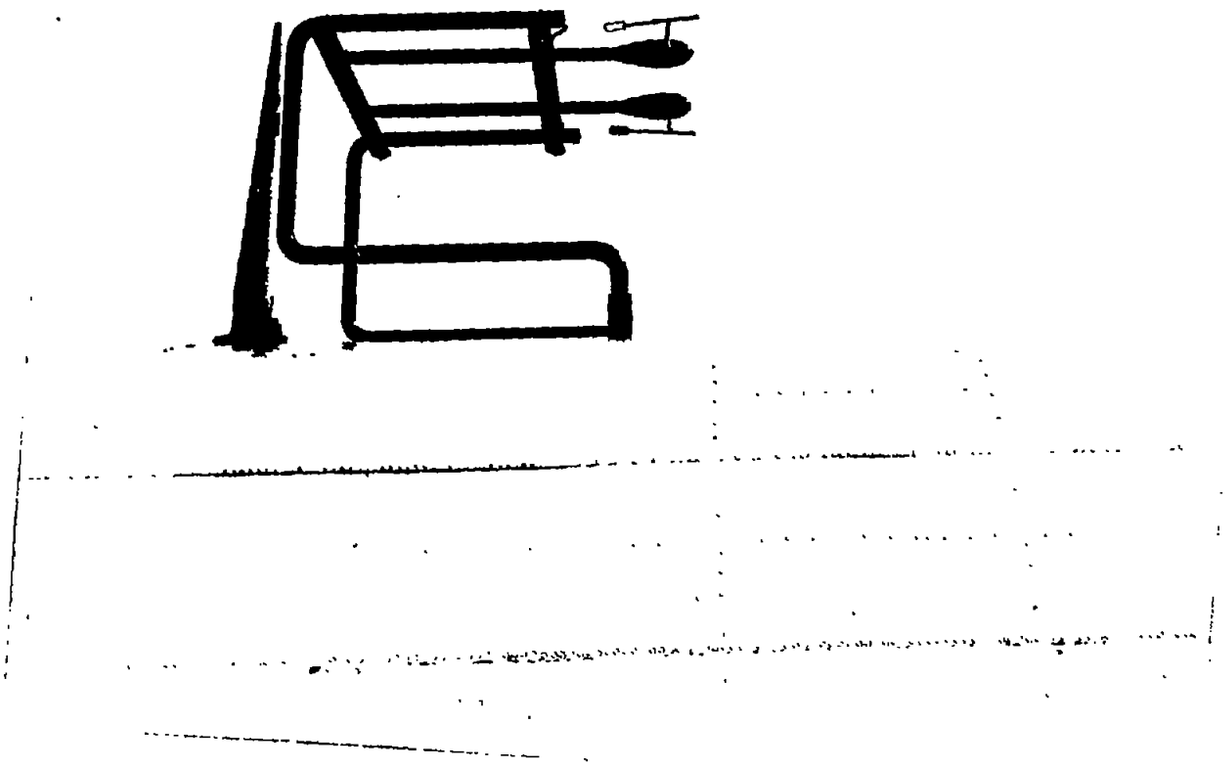
(b) Modified orifice arrangements of tubes B and C.

Figure 1.- Diagram of service pitot-static tubes showing original and modified orifice arrangements.



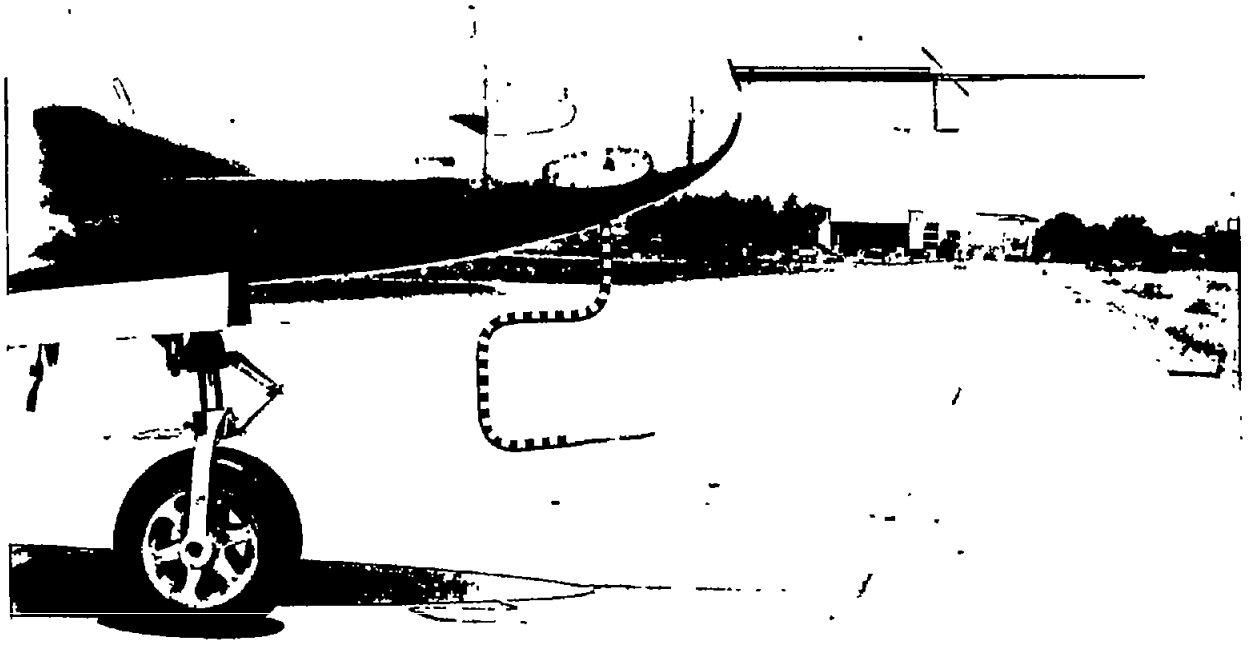
(a) Installation of service pitot-static tubes. L-82102

Figure 2.- Support booms located above fuselage of transport airplane.



(b) Flow-direction vanes used to check angle of flow over service tubes. L-82103.1

Figure 2.- Concluded.



L-75890

Figure 3.- View of fighter airplane showing modified service tube installed underneath nose and combination pitot-static—flow-direction boom located ahead of the nose of the airplane.

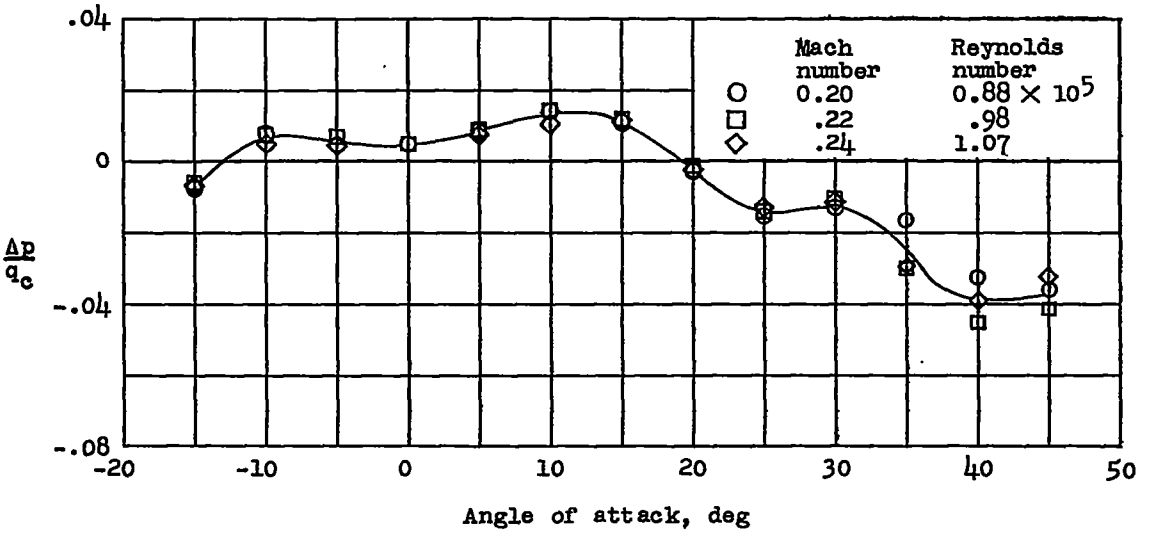


Figure 4.- Variation of static-pressure error of tube A with angle of attack.

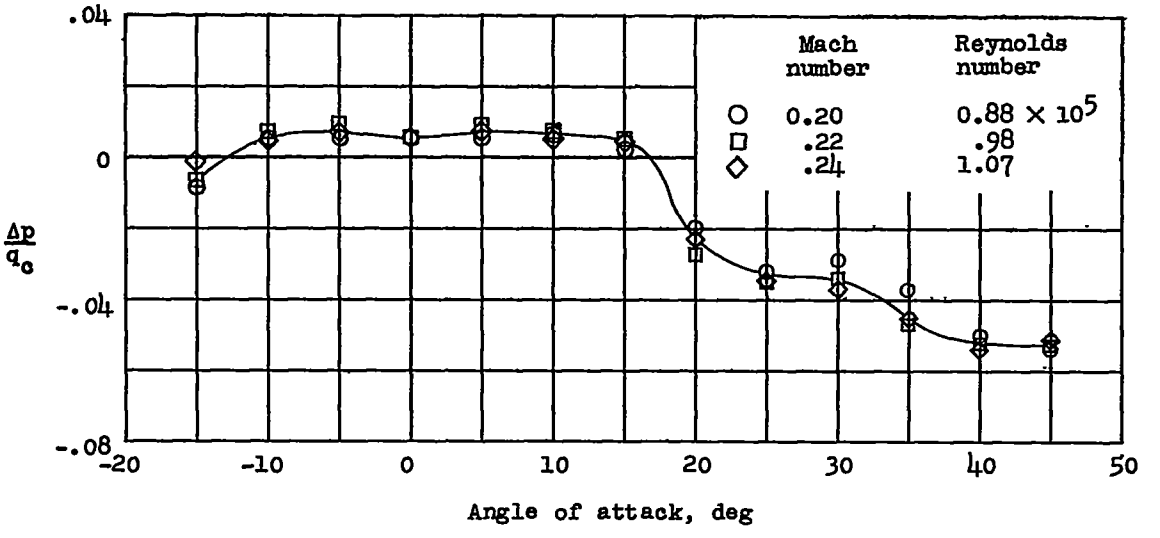


Figure 5.- Variation of static-pressure error of tube B with angle of attack.

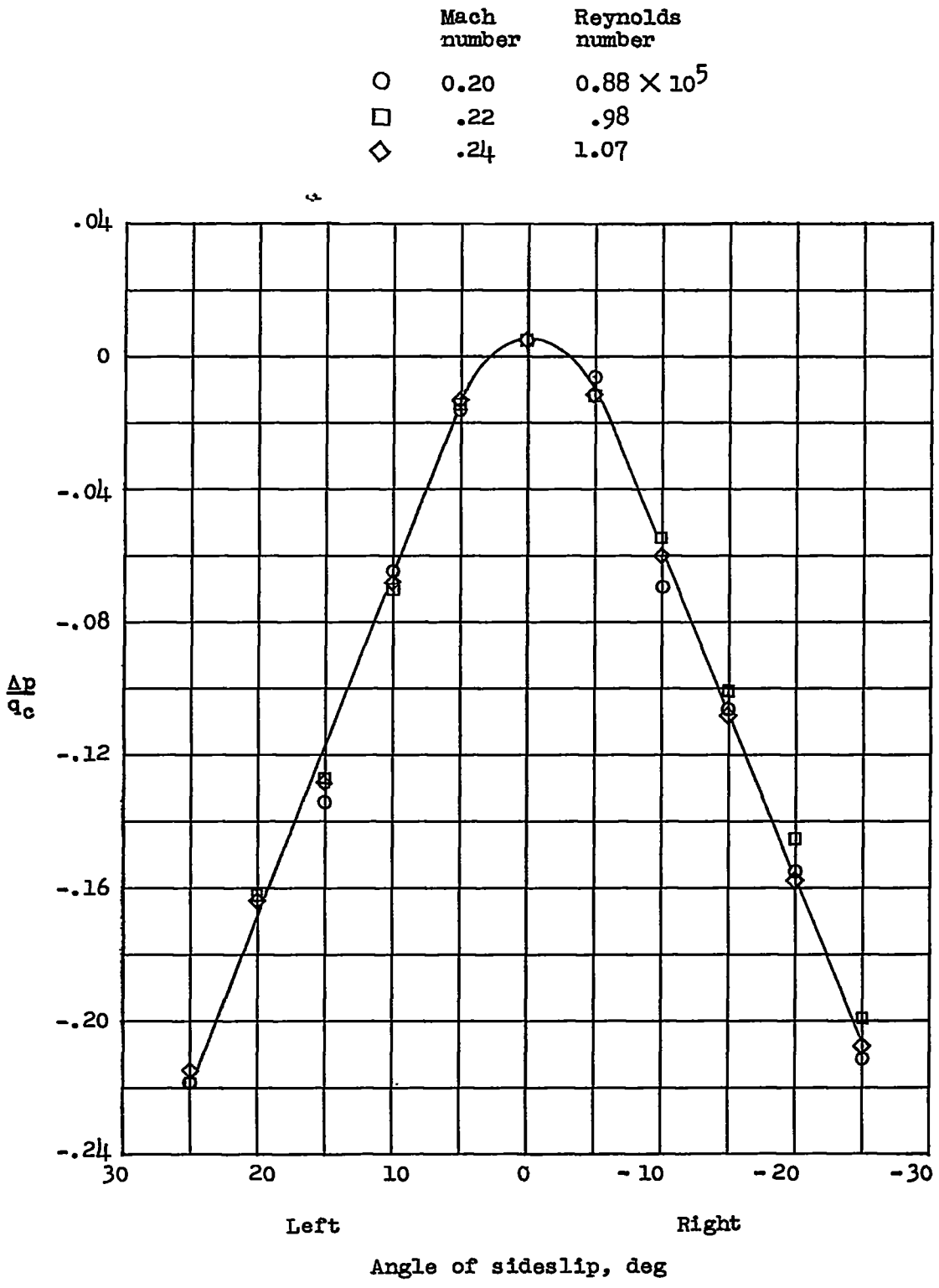
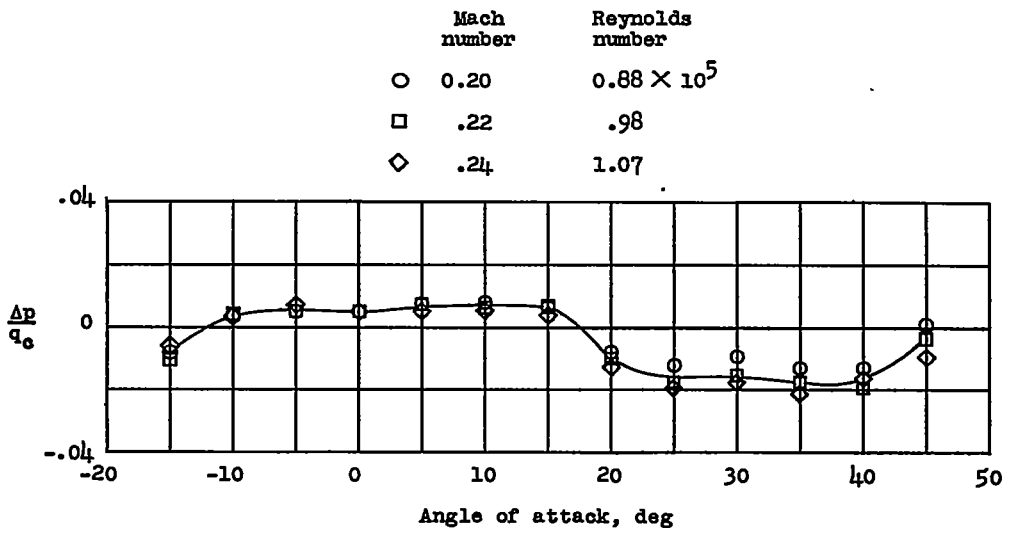
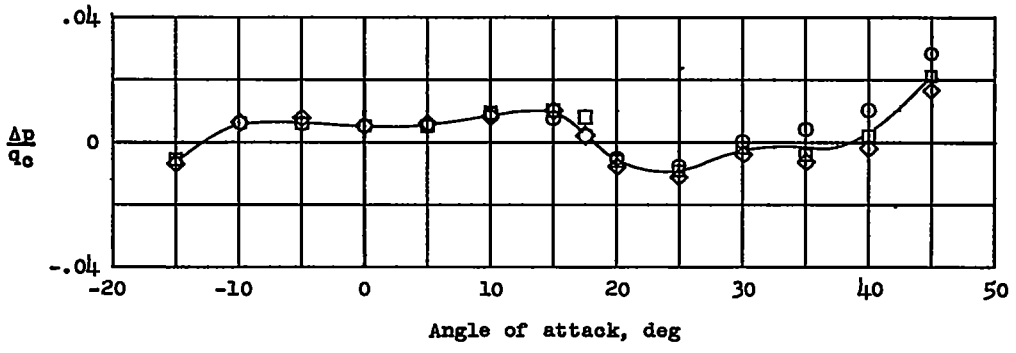


Figure 6.- Variation of static-pressure error of tube B with angle of sideslip.

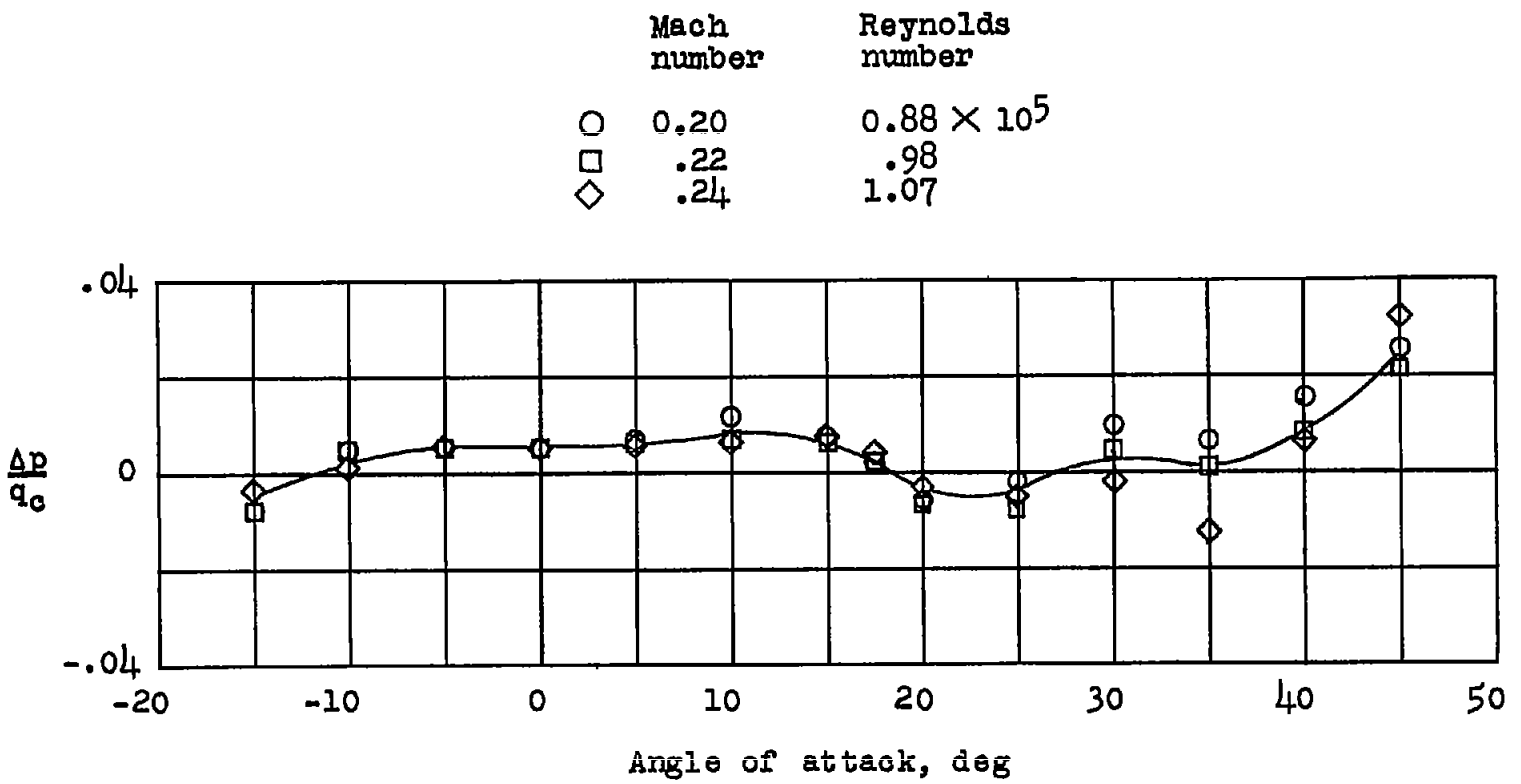


(a) Orifice modification B-1.



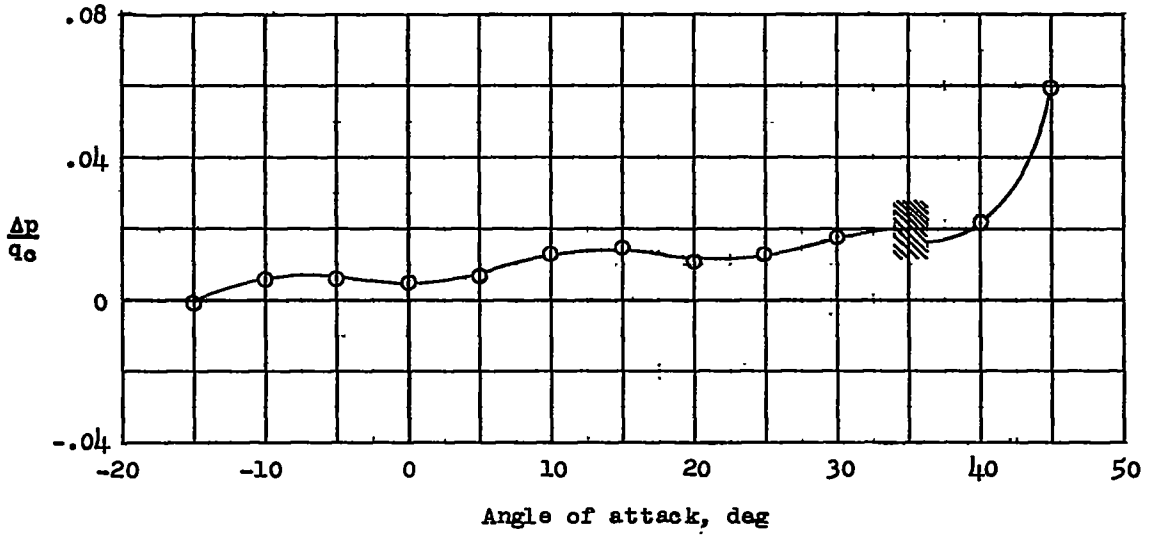
(b) Orifice modification B-2.

Figure 7.- Variation of static-pressure error of tube B with angle of attack for different orifice modifications.

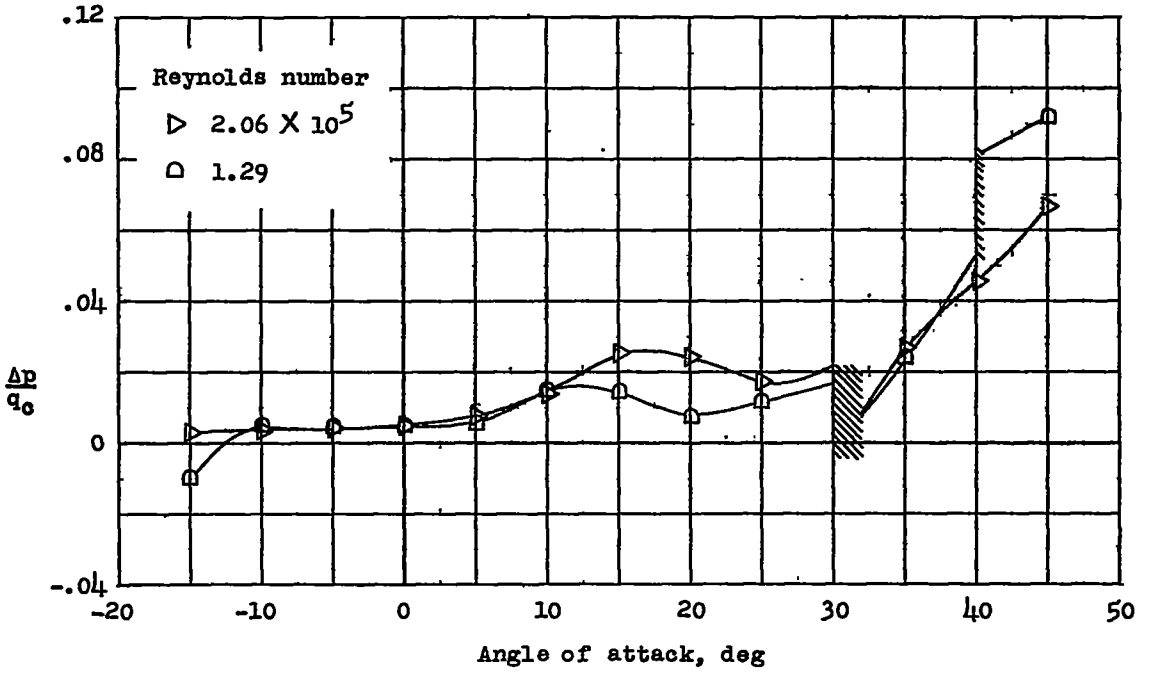


(c) Orifice modification B-3.

Figure 7.- Concluded.

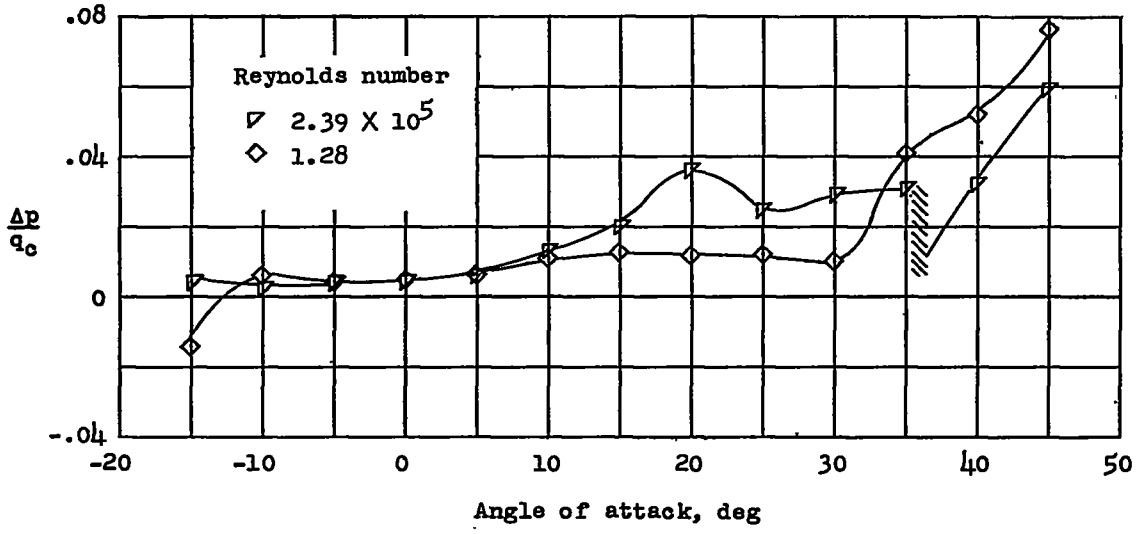


(a) M = 0.30; R = 1.65 × 10^5.

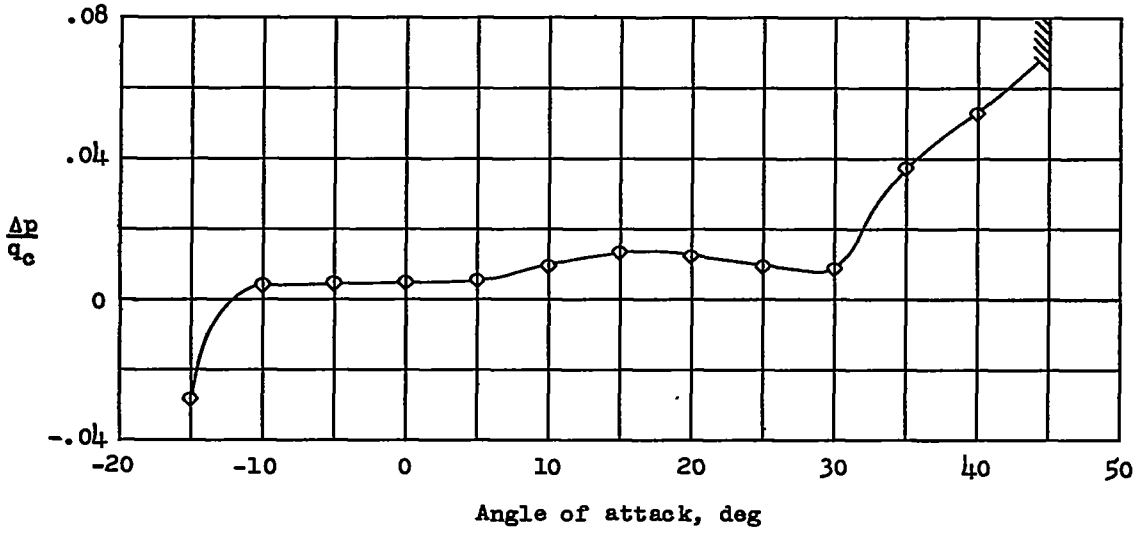


(b) M = 0.39.

Figure 8.- Variation of static-pressure error of tube C-3 with angle of attack over a range of Mach numbers and Reynolds numbers.

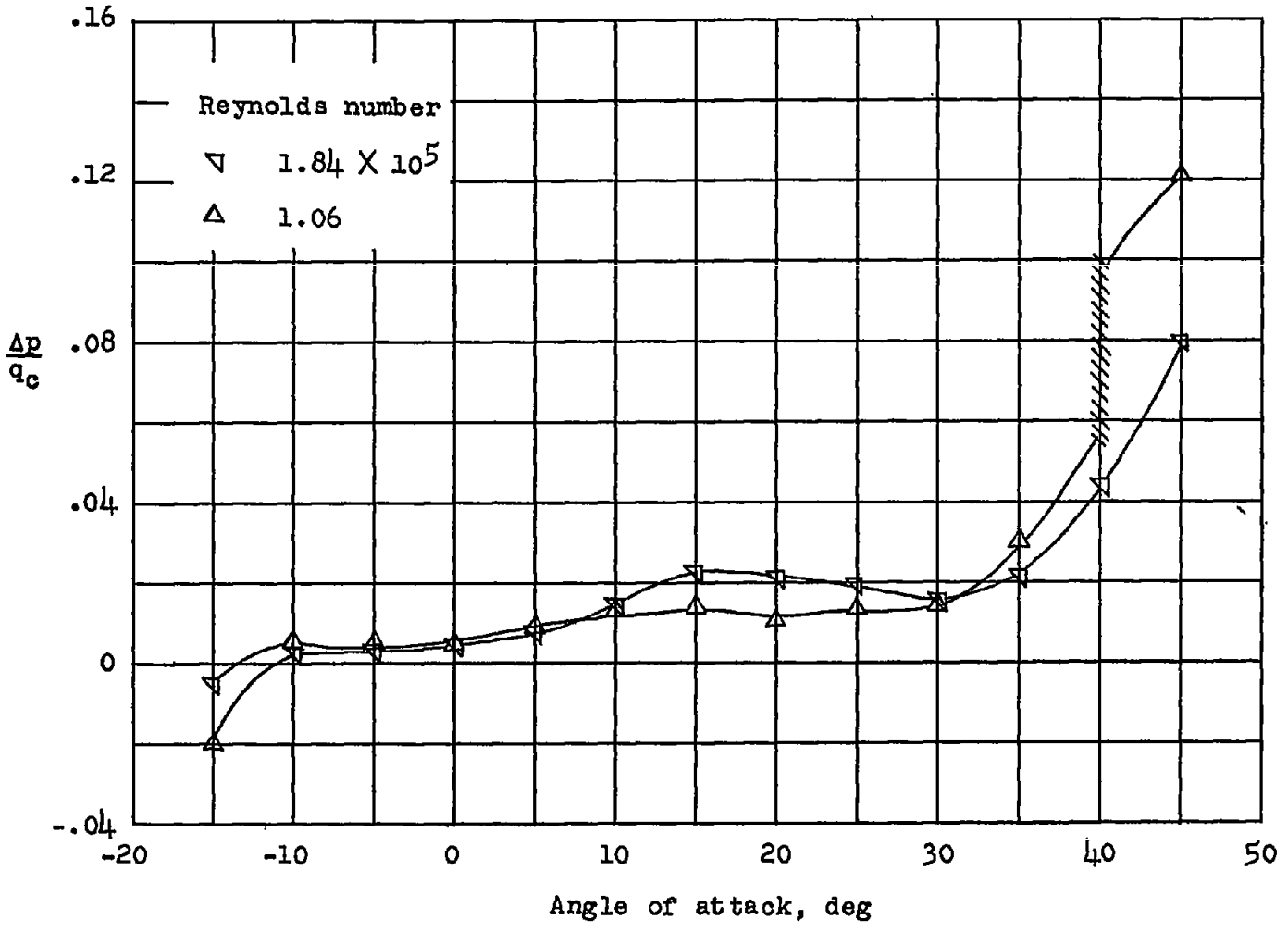


(c) M = 0.50.



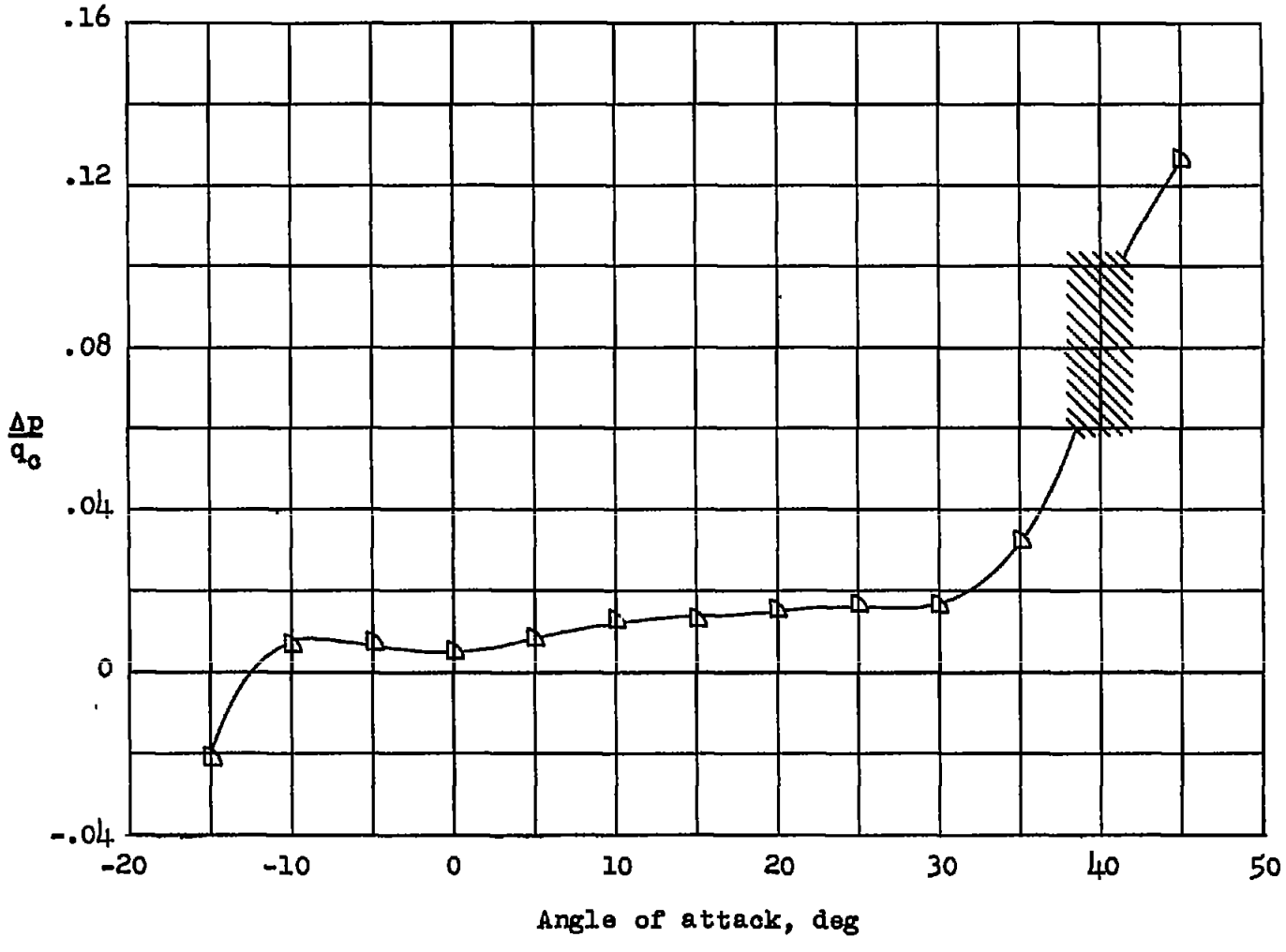
(d) M = 0.54; R = 1.20 × 10^5.

Figure 8.- Continued.



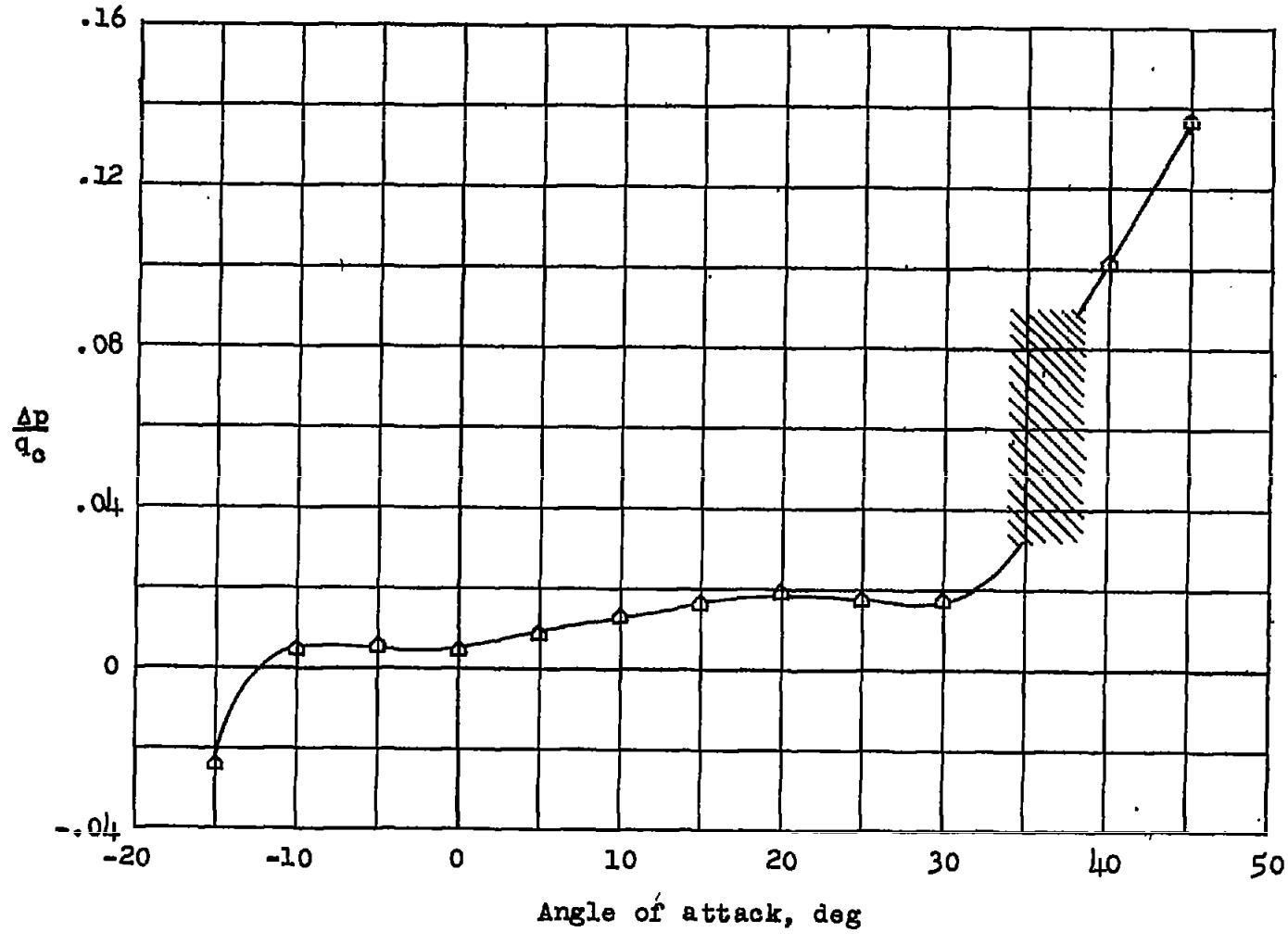
(e) M = 0.57.

Figure 8.- Continued.



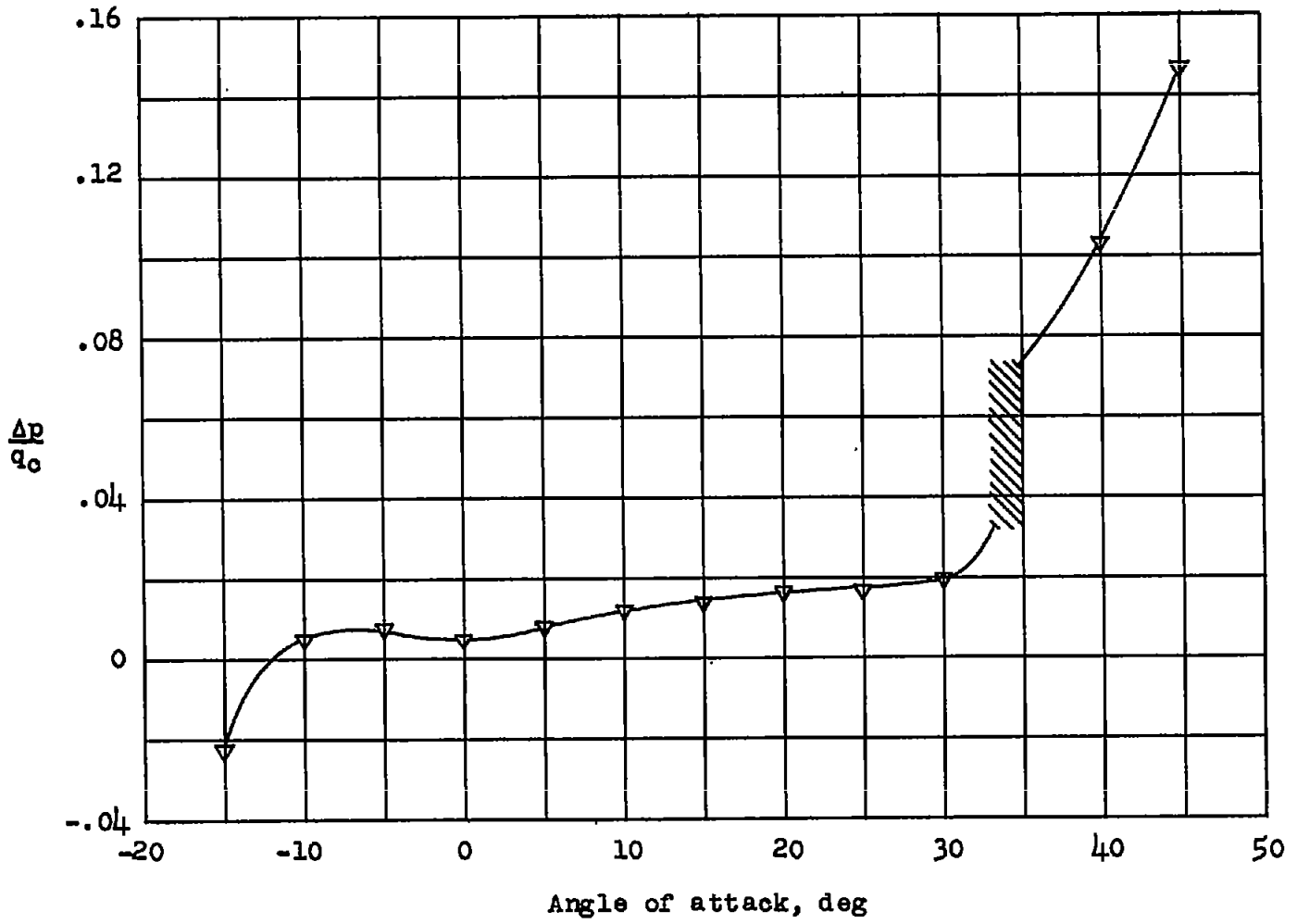
(f) $M = 0.60$; $R = 1.11 \times 10^5$.

Figure 8.- Continued.



(g) M = 0.64; R = 1.18×10^5.

Figure 8.- Continued.



(h) M = 0.68; R = 1.26 × 10^5.

Figure 8.- Concluded.

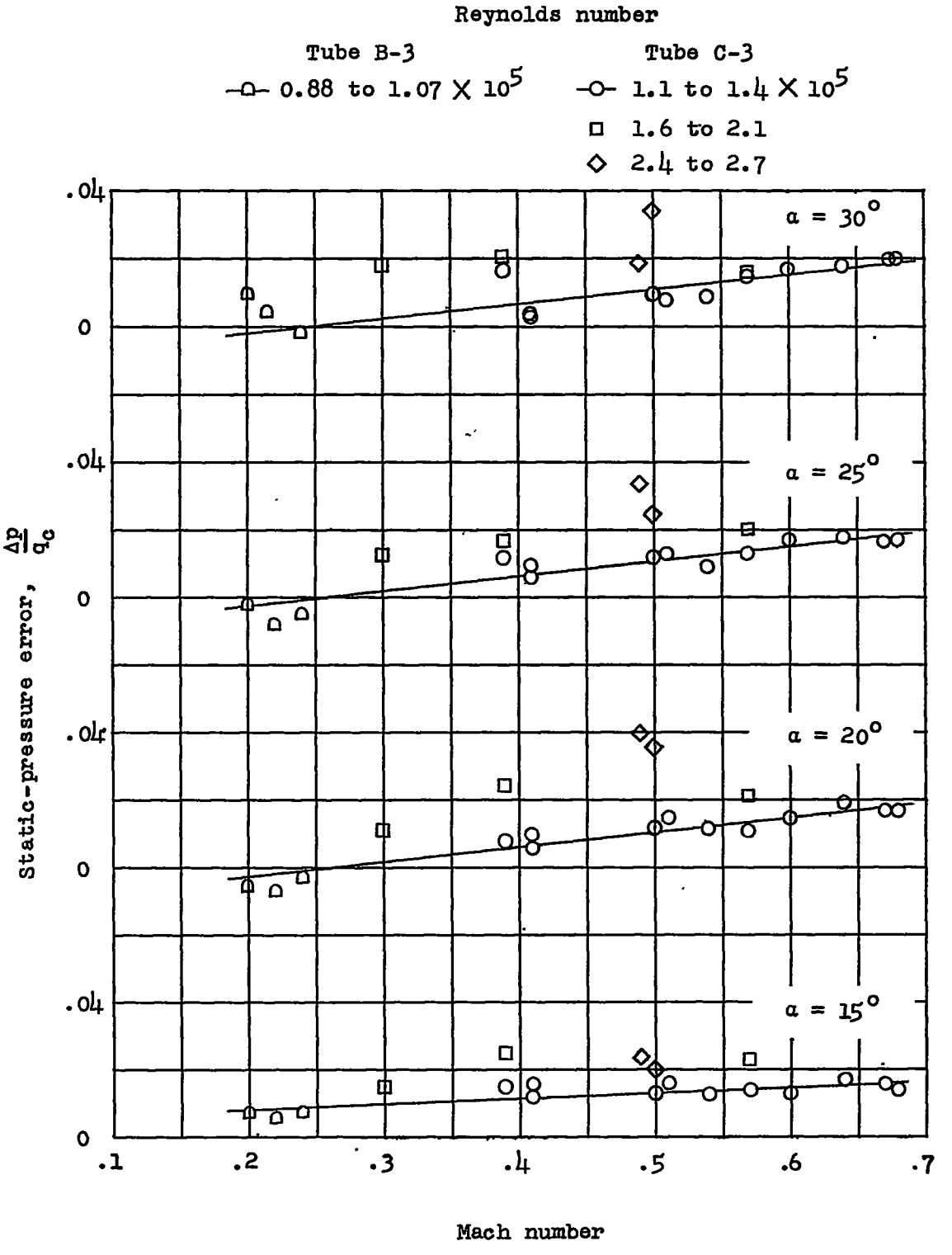


Figure 9.- Variation in static-pressure error of tubes B-3 and C-3 with Mach number and Reynolds number.

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