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RESEARCH MEMORANDUM

INVESTIGATION OF THE AERODYNAMIC AND ICING CHARACTERISTICS OF A RECESSED FUEL CELL VENT ASSEMBLY

III - NACA FLUSH-INLET-TYPE VENT

By Robert S. Ruggeri

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Cleveland, Ohio

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RESEARCH MEMORANDUM

INVESTIGATION OF THE AERODYNAMIC AND ICING CHARACTERISTICS OF A RECESSED FUEL CELL VENT ASSEMBLY

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SUMMARY

An investigation has been conducted in the Cleveland icing research tunnel to determine aerodynamic and icing characteristics of two NACA flush-inlet-type fuel cell vent installations. In the first installation, the vent tubes were mounted in the rear wall of the vent; in the second installation, the tubes were mounted in the vent-ramp floor. The vents were aerodynamically investigated to obtain vent-tube static-pressure differentials and pressure surveys over the ramp surface as a function of tunnel-air velocity and angle of attack. Icing experiments were made to determine vent-tube pressure differential and air-flow losses for several icing conditions at tunnel-air velocities of 220 and 370 feet per second.

Preliminary experiments, the results of which led to the design of the NACA flush-type inlets, showed that fairing a parallel wall recessed-type vent to approximate a flush inlet developed at the NACA Ames laboratory approximately doubled the vent-tube pressure differential. The use of ram scoops did not improve the pressure characteristics of the vents for the configurations investigated.

In general, the aerodynamic characteristics of both NACA flush-type vents were satisfactory with respect to marginal vent-tube pressure-differential requirements for the conditions investigated. The vent-tube pressure differentials for the flush-inlet-type vent with rear-wall tube mounting reached a predetermined marginal value after 6 to 8 minutes of icing; whereas the vent with ramp-floor tube mounting reached this marginal value after only 4 minutes in icing conditions. Vent-tube air-flow losses for the NACA flush-inlet-type

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vents were in the order of 21 percent for icing periods up to 60 minutes. Ice formations on the wing surface ahead of the vent ramp, rather than icing of the vent itself, caused a rapid loss in vent-tube pressure differential during the first few minutes in an icing period. The flush-inlet-type vents were superior to the recessed vents previously investigated in respect to marginal vent-tube pressure differentials and icing tolerance.

INTRODUCTION

In previous investigations of recessed fuel-cell vent installations (references 1 and 2), difficulty was experienced in obtaining a satisfactory vent-tube static pressure at low air velocities and at angles of attack up to 12°. The Douglas Aircraft Company had recommended a minimum positive pressure differential of 2 inches of water between the interior of the fuel cell and the fuel-cell compartment for satisfactory operation of the fuel cell. In an effort to obtain a greater pressure differential, a series of experiments were conducted in which two original vent installations (fig. 1, configurations A and B) were modified by fairing the vent with modeling clay to approximate an NACA flush inlet (fig. 1, configurations C, D, and E). Of the several configurations investigated, only configuration C showed a large enough increase in vent-tube static-pressure differential over the original vents to warrant further study. The results of this particular investigation are briefly discussed. On the basis of these results, a new vent installation, which consisted of an NACA flush inlet with the vent tubes located in the rear wall of the assembly, was designed and investigated. Experiments were also conducted on this vent installation with the vent tubes located in the ramp floor.

Additional experiments on the original and modified installations were made using a ram scoop extending upstream from the rear of the vent to a point 1/4 inch forward of the vent-tube openings (fig. 1, configurations E and F). These ram scoops were raised by increments from an original flush position on the lower wing surface to a maximum of 3/8 inch above that surface. A further increase in the ram-scoop height above the wing surface was believed to be detrimental to the icing characteristics of the vent.

The investigations of the modifications of the original vent installation and the NACA vent installations were conducted in the Cleveland icing research tunnel as a part of a general study of aircraft icing.

APPARATUS AND INSTRUMENTATION

An investigation to determine the aerodynamic and icing characteristics of NACA flush-inlet-type vent installations was conducted in the 6- by 9-foot test section of the Cleveland icing research tunnel. The vent installations were mounted on an NACA 65,2-216 airfoil section of 8-foot chord (fig. 2) with the rear wall of the vents located at 67 percent of chord on the lower surface of the airfoil. The leading edge of the airfoil section was equipped with an external electric heater extending to 20 percent of chord.

The vent installations consisted of a typical flush-inlet ramp, as shown in figure 3, which is similar to the flush inlet developed at the Ames laboratory. Three vent tubes $1\frac{1}{4}$ inches in diameter and one vent tube 1 inch in diameter were located in either the rear wall or the ramp floor of the vent, as shown in figure 4. A table of ordinates for the side-wall divergence is presented in this figure. The dimensions given are for the flush-inlet-type vents used in this investigation.

The vent pressure and air-flow instrumentation was similar to that used in references 1 and 2. The locations of ramp-surface static-pressure tubes are shown in figure 4.

PROCEDURE

Aerodynamic. - The ramp-surface static-pressure distribution was determined for tunnel-air velocities of 220 and 370 feet per second with no air flow through the vent tubes and for a range of angles of attack from 0° to 12°. The vent-tube static pressures, obtained at a point 1 inch inside the vent-tube openings, were determined as a function of angle of attack and tunnel-air velocity.

Icing. - Icing investigations were conducted for icing periods of 30 to 60 minutes at ambient-air temperatures from 20° to 23° F. The conditions for these experiments were: angles of attack around 7° and 14°, and tunnel-air velocities of 370 and 220 feet per second, respectively. The liquid-water content for the icing conditions ranged from 1.0 to 1.5 grams per cubic meter with a droplet size of 15 microns by volume maximum. A simulated freezing-rain investigation was conducted on the flush-type inlet with vent tubes mounted in the rear wall for a period of 30 minutes at an ambient-air temperature of 20° F. The conditions for this experiment were:

angle of attack, 12°; tunnel-air velocity, 220 feet per second; liquid-water content, 1.8 grams per cubic meter; droplet size, larger than 20 microns.

Measurements of vent-tube air flow and static pressure were obtained throughout the icing period. The vent air flow at the beginning of an icing period ranged from 0.56 to 0.60 pound per minute through the large vent tubes, which simulated an air flow through the vent lines for a descent in altitude at the rate of 3000 feet per minute.

RESULTS AND DISCUSSION

Aerodynamic

The aerodynamic investigations showed that the tunnel blocking effect by the wing at high angles of attack affected the measurement of the free-stream static pressure. The results presented herein are not corrected for tunnel blocking and wall effects.

Vent modification C. - A comparison of vent-tube static-pressure differentials for the original vent A and the faired vent C (fig. 1) is shown in figure 5 as a function of angle of attack at a tunnel-air velocity of 220 feet per second. The static-pressure differential is defined as p_s-p_0, where p_s is the static pressure measured 1 inch inside the vent-tube opening and p_0 is the free-stream static pressure. In order to obtain a greater length-width ratio than that of the original vent, only the two adjacent large-diameter vent tubes were used in the modification.

The results show that fairing the side walls approximately doubled the pressure differential at the tube opening as compared with the original installation. With the faired vent, an adequate pressure differential was obtained at angles of attack over 3°; whereas with the original vent this differential was obtained at angles of attack over 8°.

NACA flush-inlet-type vents. - The variation of ramp-surface pressure with angle of attack for both flush-inlet-type vents is shown in figure 6. The surface-pressure distribution is plotted as $\frac{p-p_0}{q_0}$, where p is the local static pressure on the ramp surface and q_0 is the free-stream velocity pressure. The pressure distribution shows the characteristics that were observed for the vent ramps of references 1 and 2, that is, a high negative pressure at the upstream end of the ramp and a high positive pressure at the rear wall of the vent. The center lines of the vent tubes were located in regions of high positive pressure. As the angle of attack was increased, all surface pressures became more positive.

Rear-wall vent-tube mounting. - The variation of vent-tube static-pressure differential p_s-p_0 for the flush-inlet-type vent with tubes mounted in the rear wall is shown in figure 7 for various angles of attack at a tunnel-air velocity of 220 feet per second. In general, satisfactory pressure differentials were obtained at all angles of attack investigated. The outer vent tubes (1 and 4) show a decreased pressure differential compared to the inner vent tubes (2 and 3). This difference in pressure differentials is due to the proximity of the outer tubes to the side walls of the vent and the rather large divergence of the side walls. At a tunnel-air velocity of 370 feet per second, the pressure differentials of the various tubes were inconsistent, although satisfactory values ranging from 8 to 12 inches of water were attained for angles of attack from 0° to 8°.

Ramp-floor vent-tube mounting. - The variation of vent-tube static-pressure differentials for the flush-inlet vent with tubes mounted in the ramp floor is shown in figure 8 for various angles of attack at a tunnel-air velocity of 220 feet per second. Inner tubes 2 and 3 showed satisfactory pressure differentials at all angles of attack investigated; whereas outer tubes 1 and 4 did not attain the required pressure differential of 2 inches of water at angles of attack less than 4°. This difference in pressure differential was also caused by the close proximity of the vent side walls to the outer tubes and the rather large divergence of the walls.

Icing

The icing investigations were conducted primarily at extremely high angles of attack in order to expose the vent-tube openings to the maximum direct water impingement. Because of the high angles of attack, large liquid-water concentrations, and long icing periods, the vent installation was subjected to more severe icing conditions than would normally be encountered in flight.

In general, the icing characteristics of the NACA flush-inlet-type vents (fig. 4) are similar to, but more severe than, those observed for the vents discussed in references 1 and 2.

Rear-wall tube mounting. - Typical ice formations following icing periods of 30 and 60 minutes are shown in figure 9 for the following icing conditions: tunnel-air velocity, 220 feet per second; angle of attack, 12°; ambient-air temperature, 20° F; and liquid-water content, 1.5 grams per cubic meter.

The tendency for the ice formation to build up and protrude into the air stream is shown in figure 9(a). The resulting scooping effect maintained or increased the static-pressure differential in the inner tubes until the ice was blown off after 40 minutes of icing. At the conclusion of the 60-minute icing period (fig. 9(b)), the area of the large-diameter tubes was halved and the diameter of the small vent tube was reduced to approximately 3/16 inch.

The increased ice formations on this vent appear to have no more effect on the pressure-differential losses than the lesser ice formations noted in references 1 and 2. The pronounced tendency for the ice formations at the rear wall of the vent to form a scoop above the inner vent tubes (fig. 9(a)) is shown in figure 10 by the increase in the static-pressure differentials of tubes 2 and 3. The removal of the scoop by ice blow-off caused an immediate decrease in pressure differential.

Because the pressure differential at the start of an icing period was considerably greater than that reported in reference 1, the icing tolerance was increased from about 2 to 3 minutes on the original vents to 6 to 8 minutes on the NACA flush-inlet-type vent. The icing tolerance is defined as the time required to decrease the vent-tube pressure differential to 2 inches of water in an icing condition.

In icing conditions, the vent-tube air flow decreased with time, as shown in figure 11. The air-flow loss shown represents a 21-percent reduction for an icing period of 60 minutes and is typical of all vent tubes.

The vent installation was also investigated at a tunnel-air velocity of 370 feet per second and at an angle of attack of 7°

for an icing period of 30 minutes under the following icing conditions: liquid-water content, 1.0 gram per cubic meter; and ambient-air temperature, 20° F.

The results showed that the icing characteristics for the vent were similar to, but less severe than, those in the experiments at low air velocity and high angle of attack. The vent-tube pressure differentials remained much greater than the marginal requirements throughout the icing period and the vent-tube air-flow losses were negligible.

In the simulated freezing-rain condition, the pressure differential losses for the vent occurred more rapidly than during an icing condition. The rapid pressure-differential loss was caused by the large ice formations on the wing surface ahead of the inlet ramp. These ice formations were considerably more severe than those observed for the icing conditions.

Ramp-floor tube mounting. - Typical progressive ice formations for the vent with the tubes mounted in the ramp floor are shown in figure 12 for 15- and 45-minute icing periods. The icing conditions were the same as those described for figure 9.

The icing characteristics of the flush-inlet-type vent with tubes mounted on the ramp floor are similar to those observed for the vent with tubes mounted in the rear wall. The reduction of the vent-tube areas due to icing, however, was not appreciable.

The variation of vent-tube static-pressure differential with time for the 45-minute icing period is shown in figure 13. The marginal pressure differential for the outer tubes was reached after only 4 minutes of icing. With no scooping effect caused by ice formations, the inner tubes reach the marginal pressure differential after 10 minutes of icing. Tube 2 maintained a high static-pressure differential throughout the icing period because of the scooping effect of the ice formation above the tube, as shown in figure 12. A typical reduction in vent-tube air flow of approximately 21 percent for the icing conditions described for figure 12 is shown in figure 14.

Effect of wing icing on vent-tube pressure characteristics. - It has been determined that an increasing boundary-layer thickness ahead of a flush-inlet ramp has a detrimental effect on the pressure recovery at the inlet. During the icing investigation of a flush-inlet-type vent, visual observations failed to detect ice on the ramp or in the vent tubes for the first few minutes of an icing period, during which time the wing surface became coated with ice and the vent-tube pressures decreased rapidly. Because the vent was free of ice, it follows that the wing-surface ice was responsible for the rapid pressure losses noted during the first few minutes of an icing period, as shown in figures 10 and 13. When the complete wing was de-iced at the end of an icing period and the vent remained iced, a large increase in vent-tube static-pressure differentials resulted. The reverse situation was also investigated; that is, the vent was de-iced while the wing-surface ice formations remained. The results showed no appreciable increase in vent-tube pressure differentials.

Comparison of Recessed and Flush-Inlet-Type Vents

Under the same aerodynamic and icing conditions, the flush-inlet-type vent proved superior to the recessed vents of references 1 and 2 with respect to marginal vent-tube pressure differentials and icing tolerance.

The flush-inlet-type vent with rear-wall tube mounting gave satisfactory vent-tube pressure differentials at all angles of attack investigated for a tunnel-air velocity of 220 feet per second. The icing tolerance for the vent was 6 to 8 minutes and the air-flow losses were in the order of 21 percent for icing periods up to 60 minutes.

The flush-inlet-type vent with ramp-floor tube mounting gave satisfactory pressure differentials for the two inner tubes at all angles of attack investigated; whereas the pressure differentials observed for the outer tubes were satisfactory at angles of attack greater than 4°. The icing tolerance for this vent was 4 minutes and the vent-tube air-flow losses were 21 percent for a 45-minute icing period.

The recessed vent with rear-wall vent-tube mounting, reported in reference 1 and shown in figure 1(a), gave satsifactory pressure differentials at angles of attack greater than 8°. The icing tolerance for the vent was 2 to 3 minutes and air-flow losses were in the order of 23 percent for a 60-minute icing period.

The recessed vent with ramp-floor vent-tube mounting, reported in reference 2 and shown in figure 1(b), was unsatisfactory with respect to marginal vent-tube pressure differential at all angles of attack investigated. Because the pressure differentials were submarginal at the beginning of an icing period, there was no icing tolerance for the vent. The vent-tube air-flow losses were in the order of 15 percent for a 60-minute icing period.

SUMMARY OF RESULTS

From an aerodynamic and icing investigation conducted in the Cleveland icing research tunnel on several modifications of recessed vents and two NACA flush-inlet-type vents, the following results were obtained:

1. Fairing the original parallel wall recessed vent to approximate a flush inlet approximately doubled the vent-tube pressure differentials.

2. For the configurations investigated, the use of ram scoops did not improve the pressure characteristics of the vents.

3. In general, the aerodynamic characteristics of both NACA flush-inlet-type vents were satisfactory with respect to marginal vent-tube pressure-differential requirements for the conditions investigated. At a tunnel-air velocity of 220 feet per second, the vent with rear-wall tube mounting maintained the required pressure differential of 2 inches of water at angles of attack ranging from 0° to 12°. The vent with ramp-floor tube mounting maintained the required pressure differential in all tubes at angles of attack above 4°; whereas the inner two tubes were satisfactory at zero angle of attack.

4. The vent-tube pressure differentials for the flush-inlet-type vent with rear-wall tube mounting reached the marginal value after 6 to 8 minutes in an icing condition, compared with 2 to 3 minutes for the original vent, although the ice formations on the flush-inlet-type vent were more severe.

5. For the flush-inlet-type vent with ramp-floor tube mounting, the marginal-pressure differential was reached after 4 minutes in an icing condition.

6. Vent-tube air-flow losses for both NACA flush-inlet-type vents were approximately 21 percent for icing periods up to 60 minutes.

7. The rapid loss in vent-tube static-pressure differential observed during the first few minutes under icing conditions is

caused by the ice formations on the wing surface ahead of the vent ramp rather than icing of the vent itself.

8. Under the same aerodynamic and icing conditions, the flush-inlet-type vents were superior to the recessed-type vents previously reported with respect to marginal vent-tube pressure differentials and icing tolerance.

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National Advisory Committee for Aeronautics,
Cleveland, Ohio.

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1. Ruggeri, Robert S.: Investigation of the Aerodynamic and Icing Characteristics of a Recessed Fuel Cell Vent Assembly. I - Rear Wall Vent Tube Mounting. NACA RM No. E8A27b, 1948.

2. Ruggeri, Robert S.: Investigation of the Aerodynamic and Icing Characteristics of a Recessed Fuel Cell Vent Assembly. II - Ramp Floor Vent Tube Mounting. NACA RM No. E8B05a, 1948.

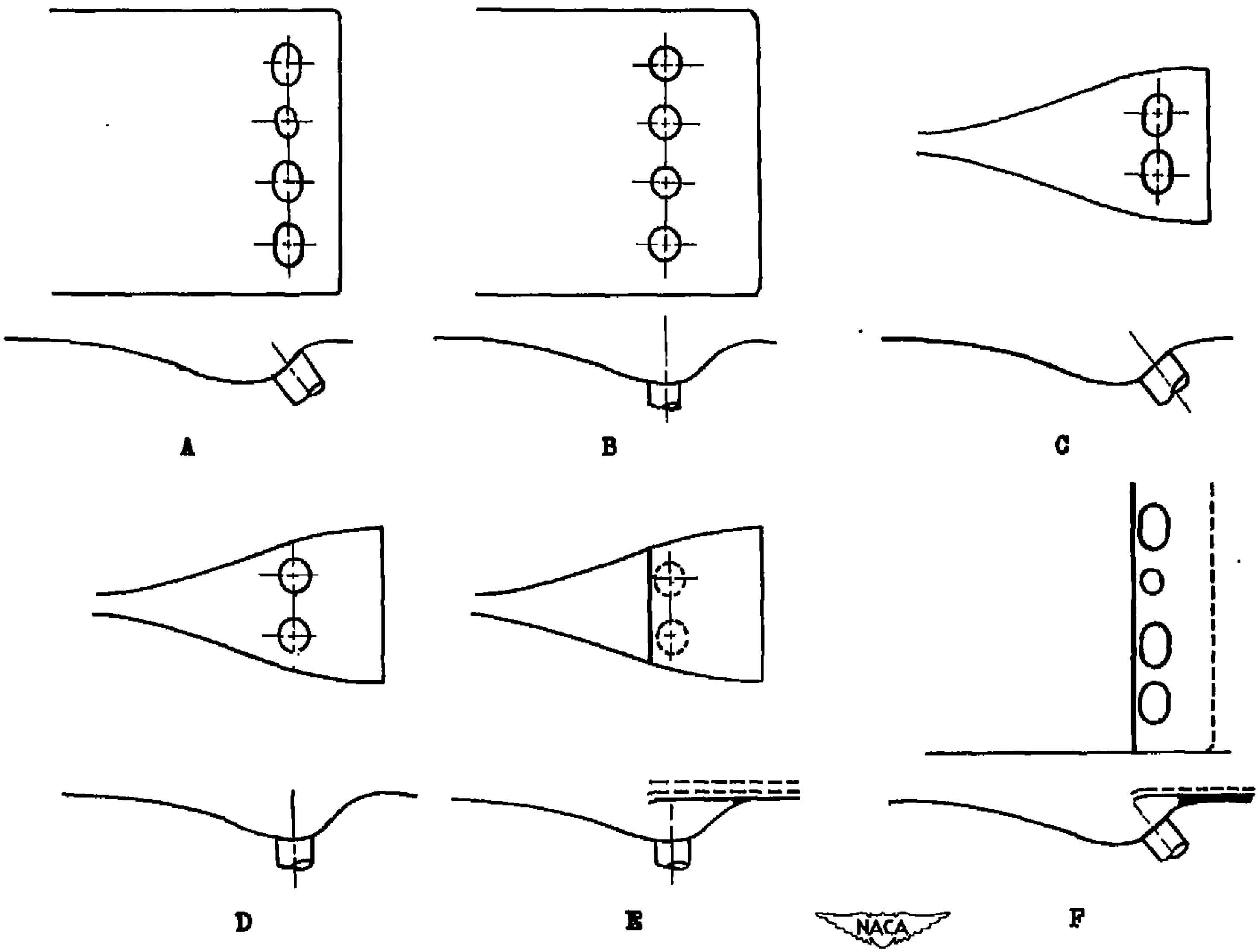

Figure 1. - Sketch of original vent installations A and B with several modifications.

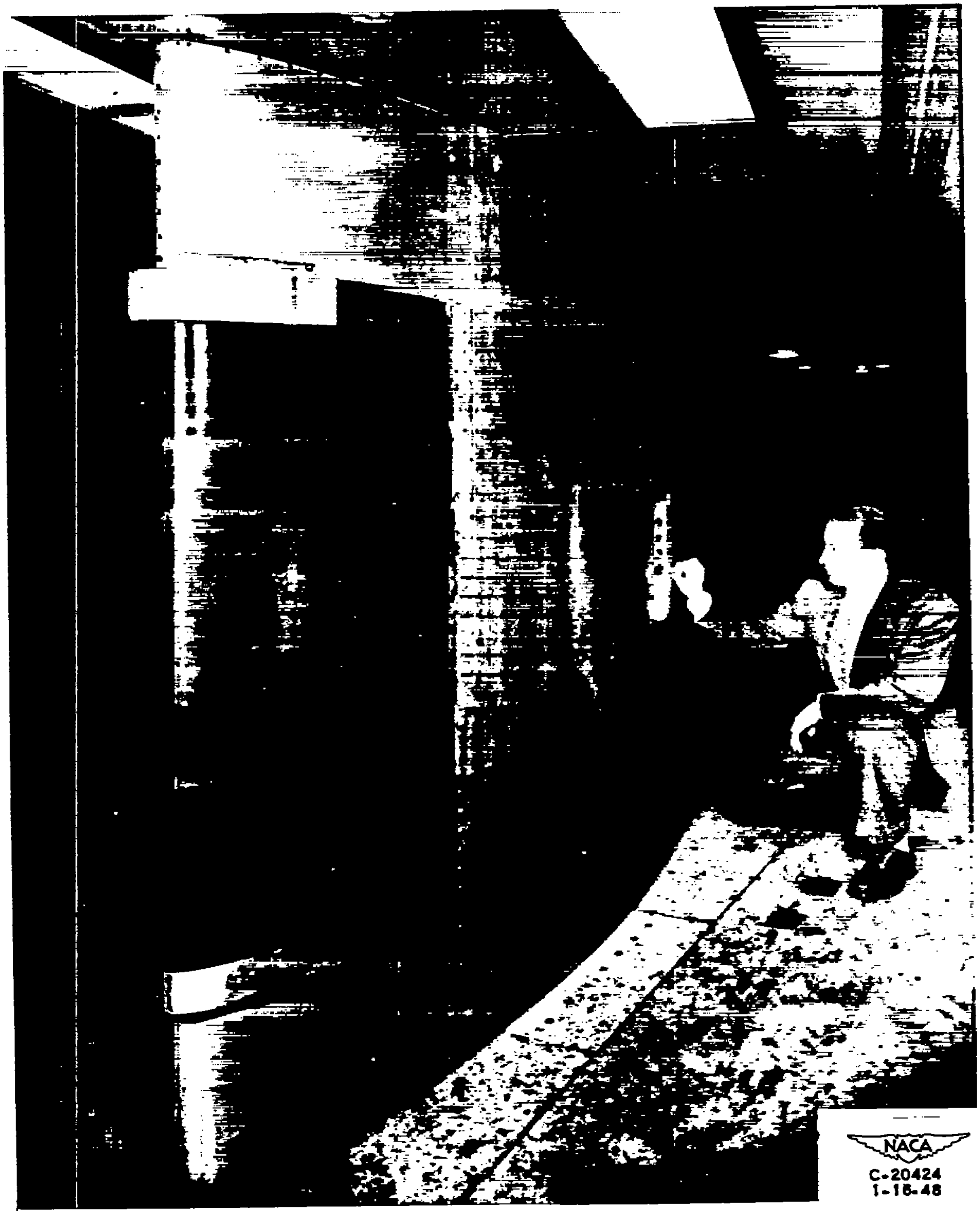

Figure 2. - Typical fuel-cell-vent installation mounted on NACA 65,2-216 airfoil section in test section of icing research tunnel.

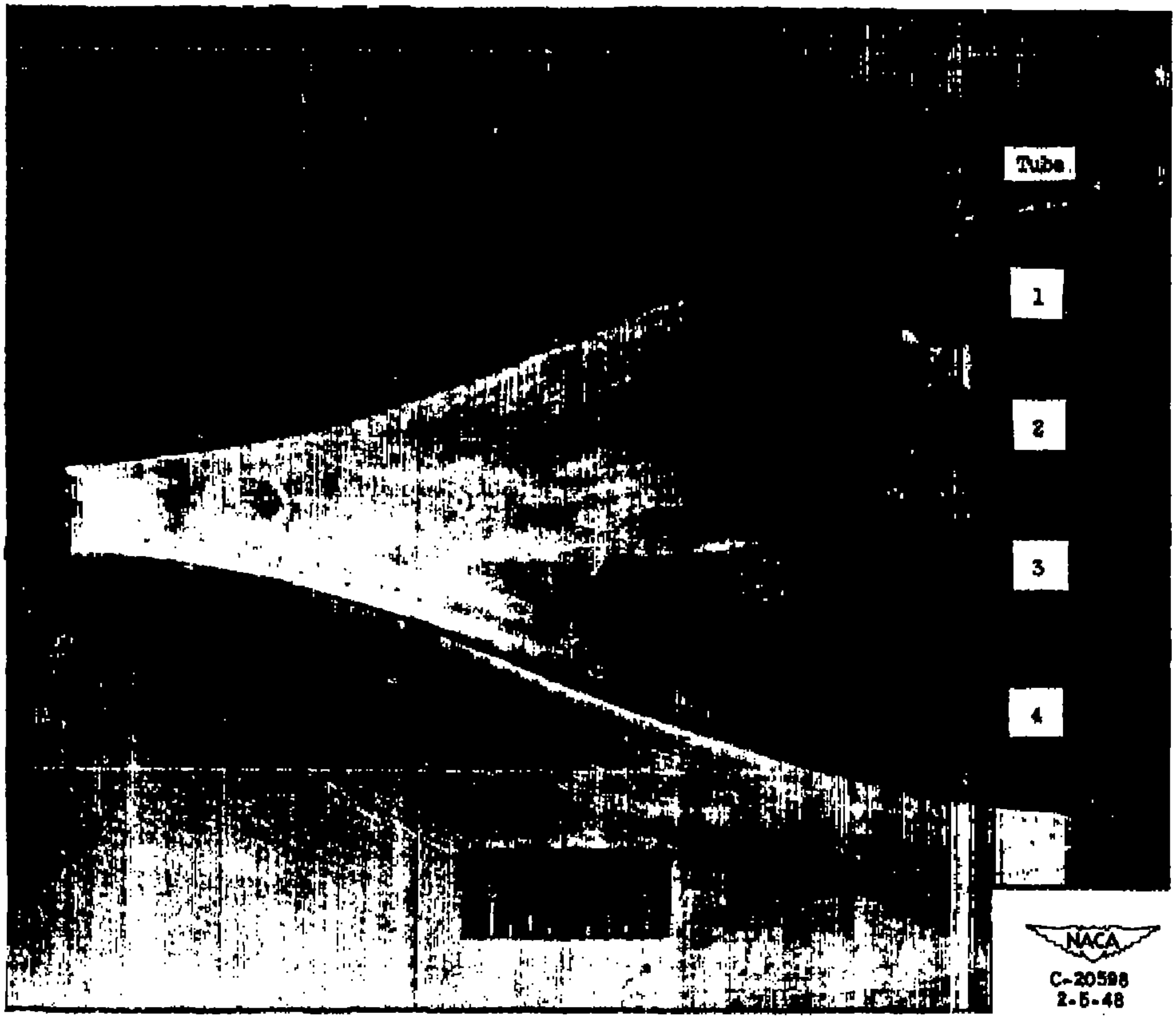

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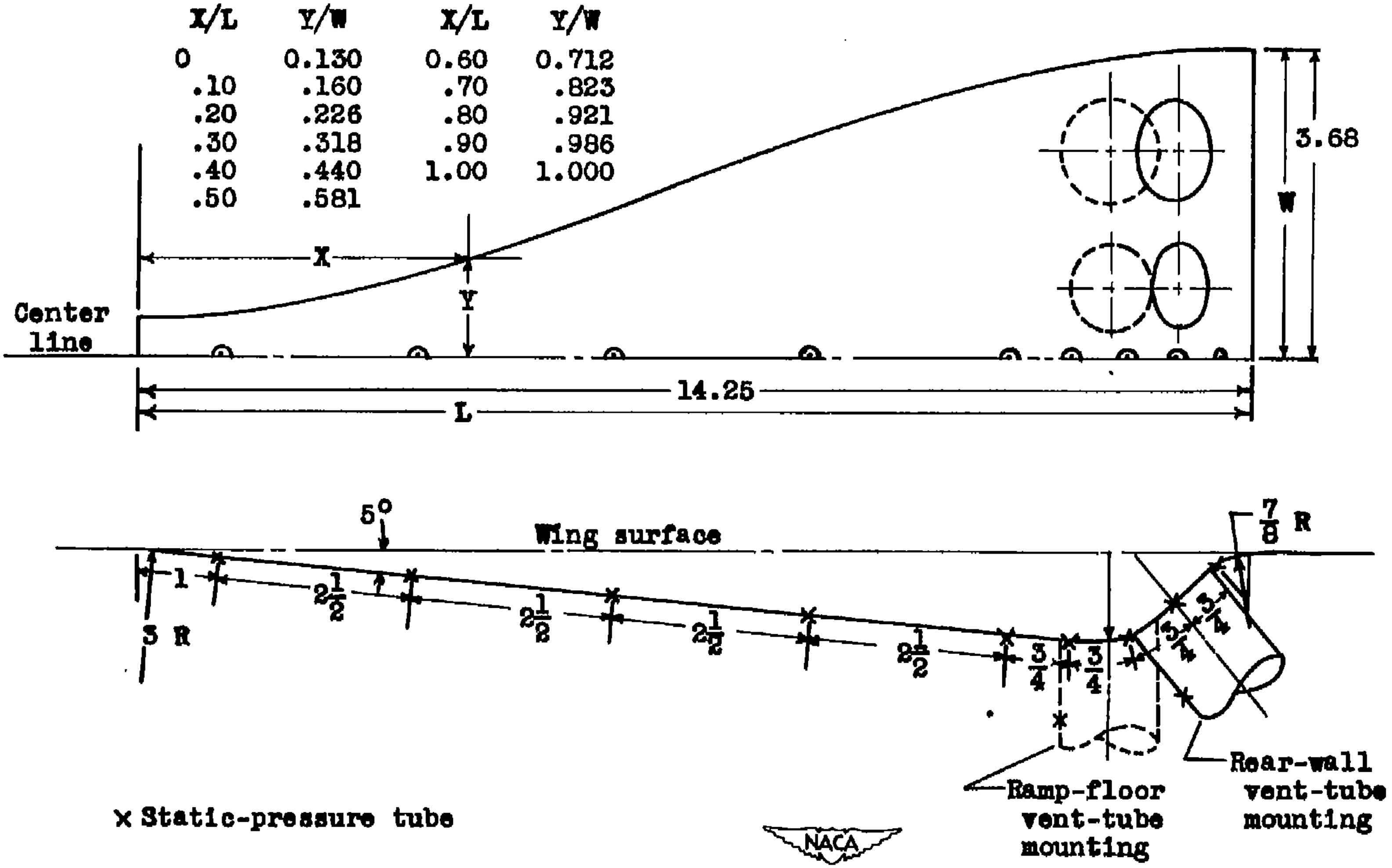
Figure 5. - Typical flush-inlet-type vent with tubes mounted in ramp floor.



X/L	Y/W	X/L	Y/W
0	0.130	0.60	0.712
.10	.160	.70	.823
.20	.226	.80	.921
.30	.318	.90	.986
.40	.440	1.00	1.000
.50	.581		

Figure 4. - Schematic diagram of flush-inlet-type vent showing location of static-pressure tubes. (All dimensions in inches.)

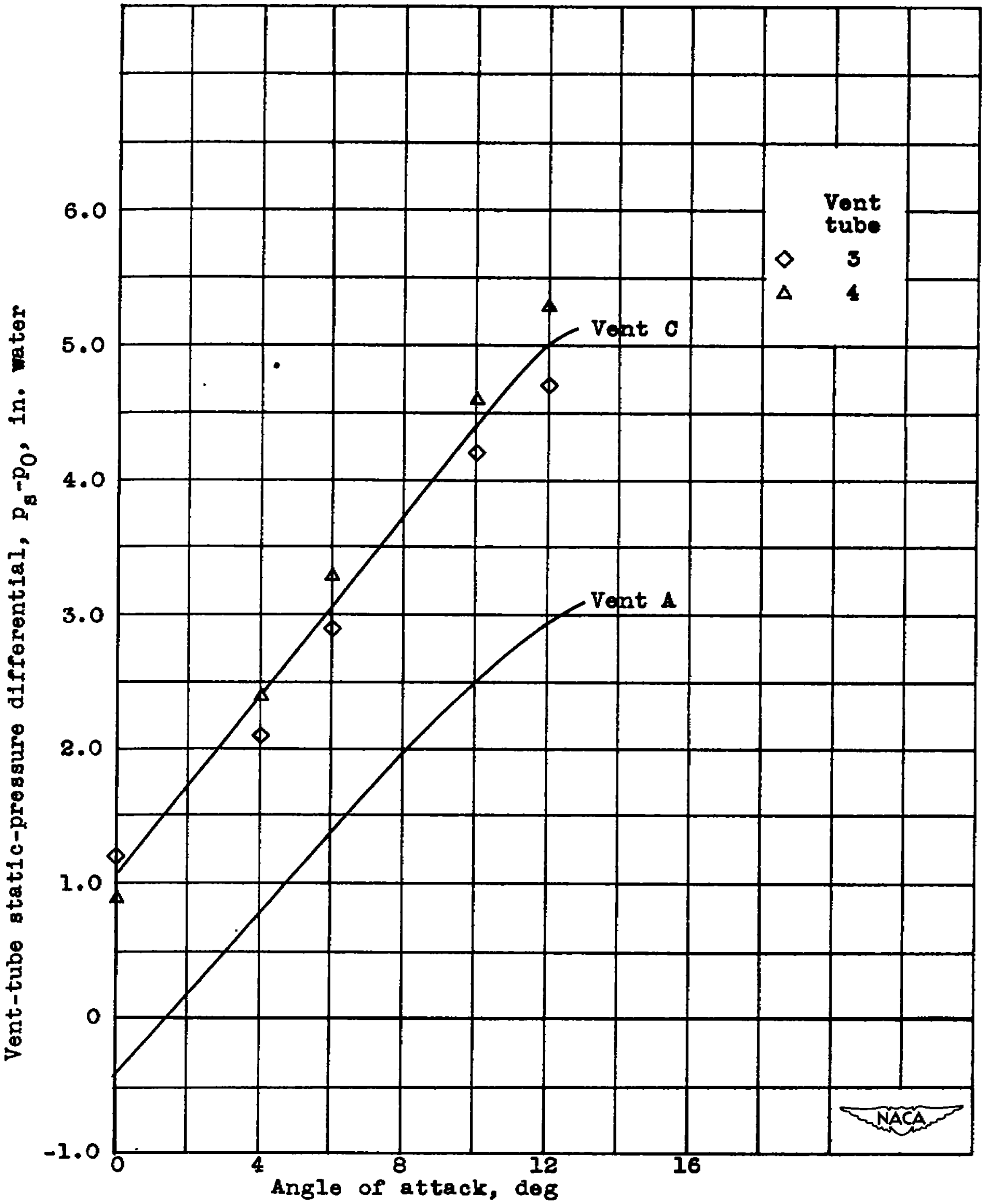


Figure 5. - Variation of vent-tube static-pressure differential with angle of attack for vents A and C. Tunnel-air velocity, 220 feet per second.

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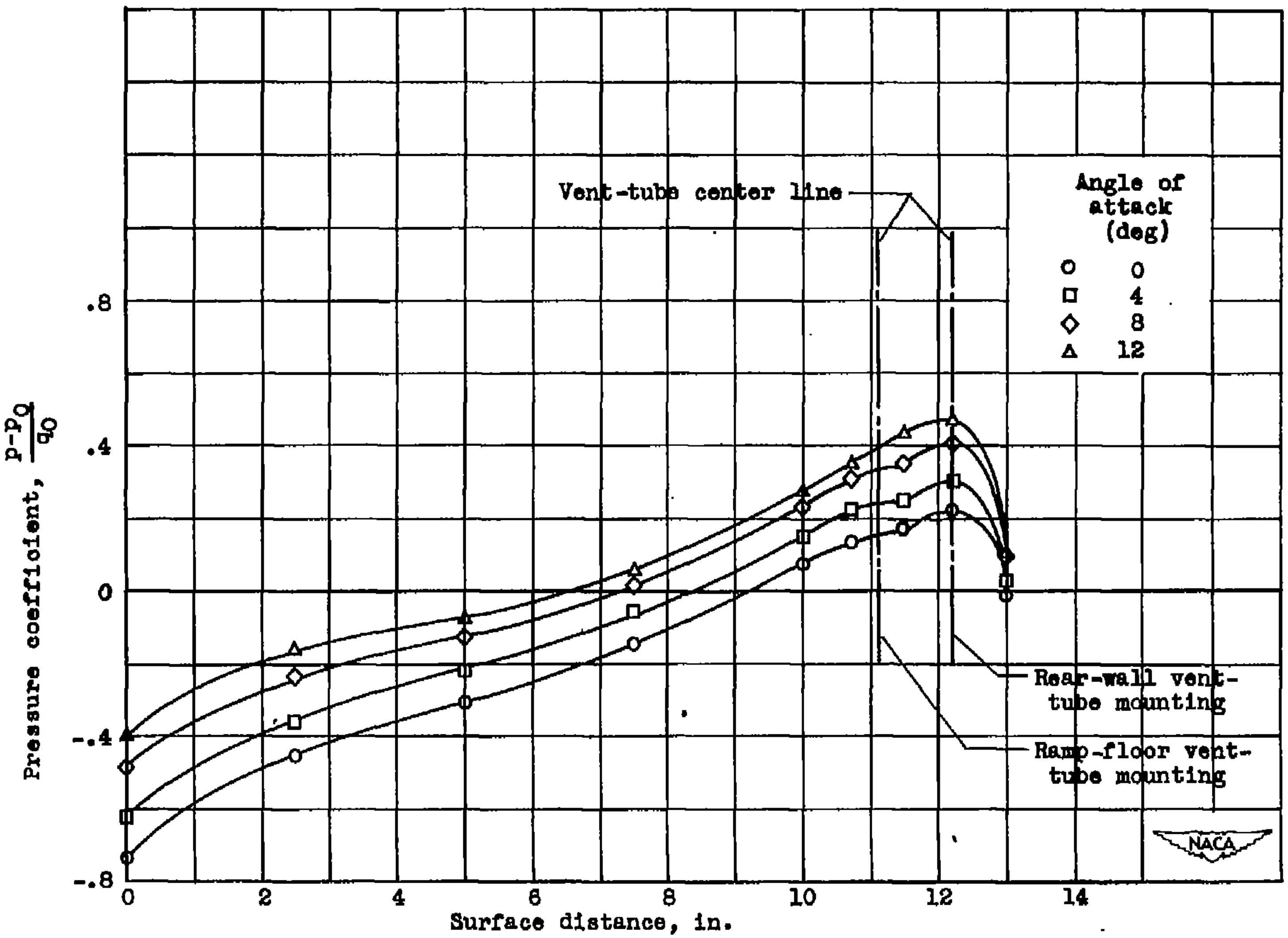

Figure 6. - Effect of angle of attack on pressure distribution over ramp surface. No vent air flow; tunnel-air velocity, 220 feet per second.

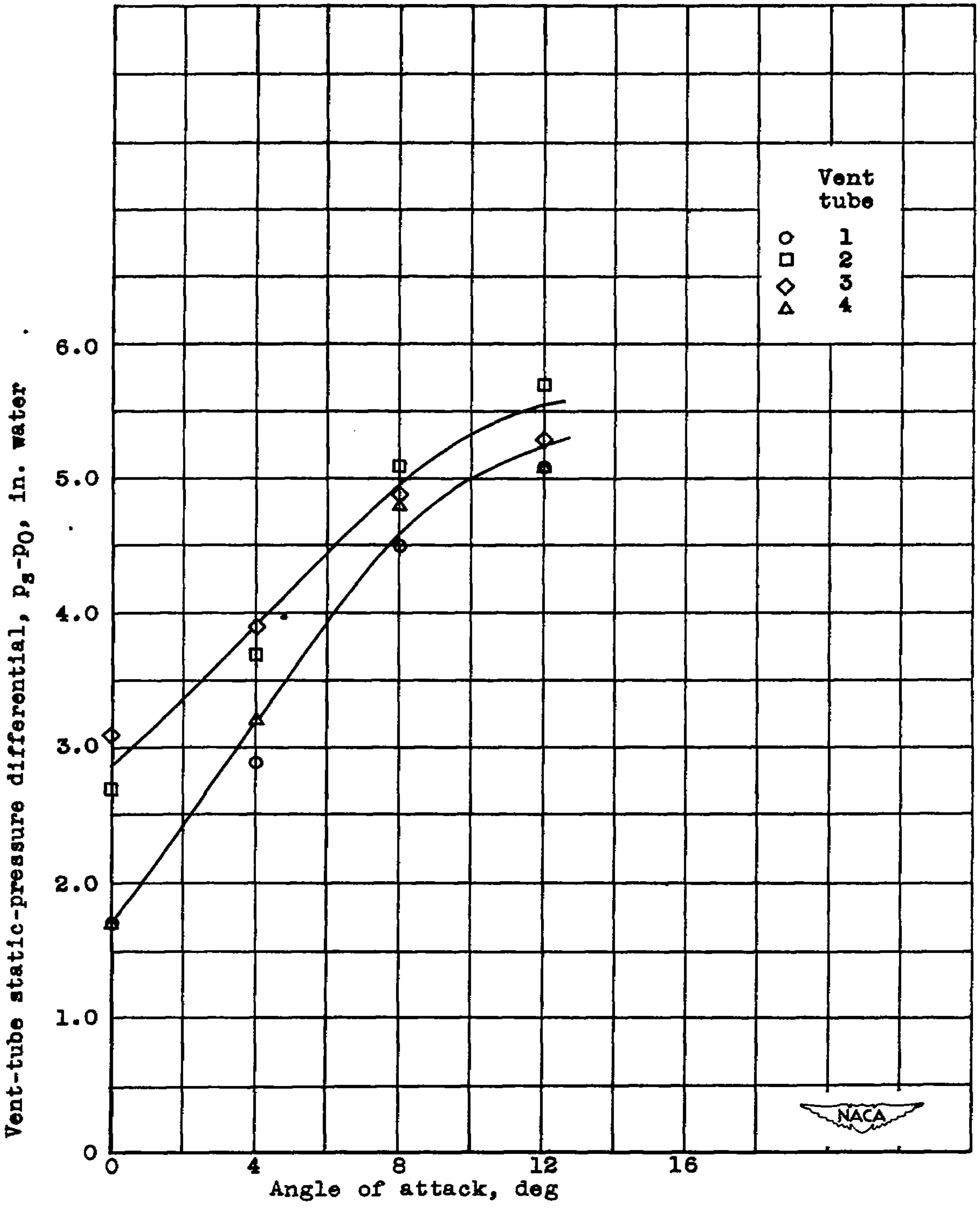

Figure 7. - Variation of vent-tube static-pressure differential with angle of attack for flush-inlet-type vent with tubes mounted in rear wall. No vent air flow; tunnel-air velocity, 220 feet per second.

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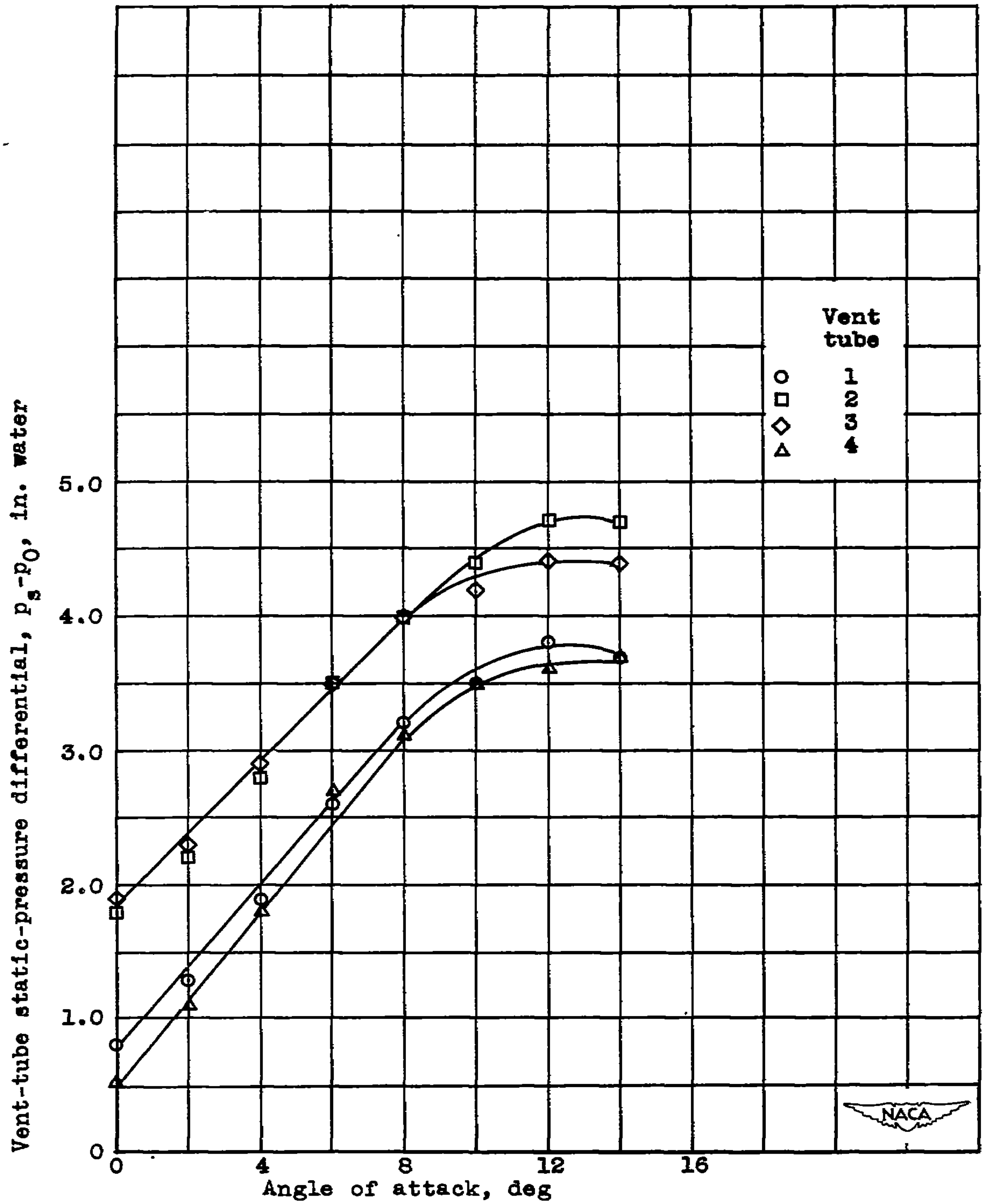

Figure 8. - Variation of vent-tube static-pressure differential with angle of attack for flush-inlet-type vent with tubes mounted in ramp floor. No vent air flow; tunnel-air velocity, 220 feet per second.

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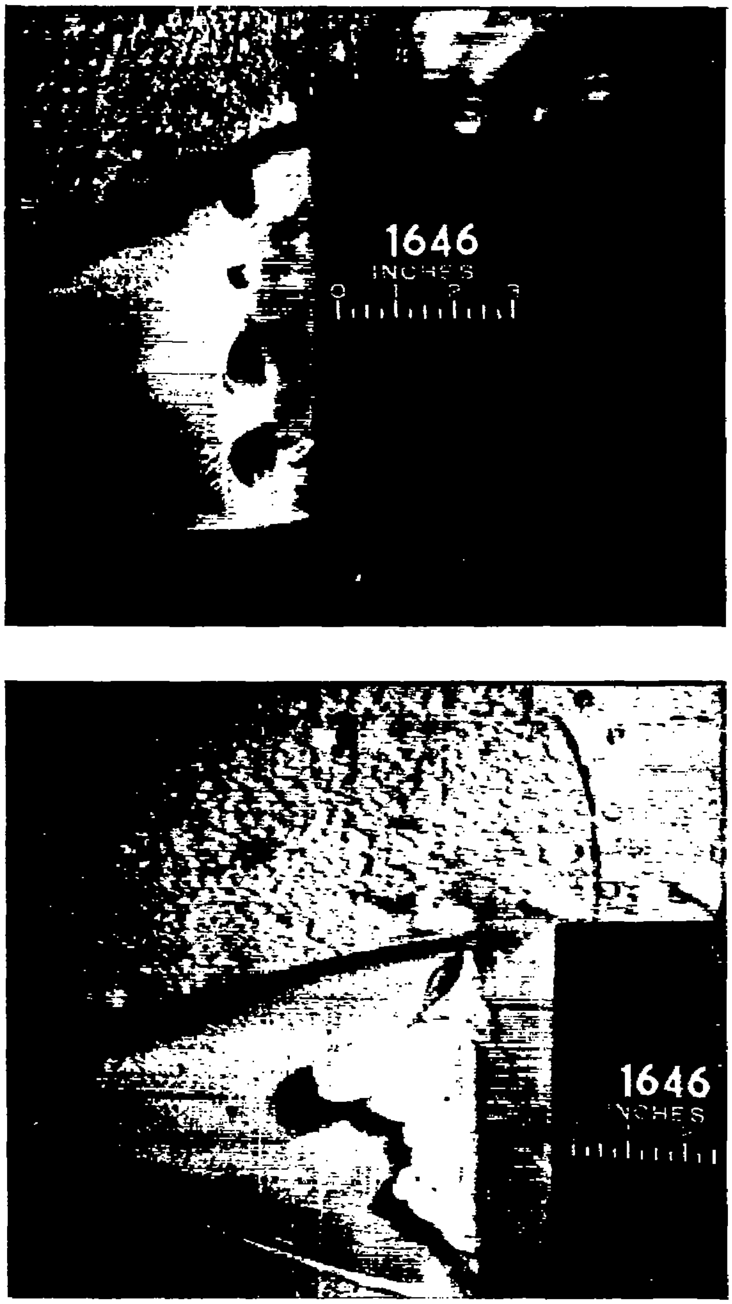

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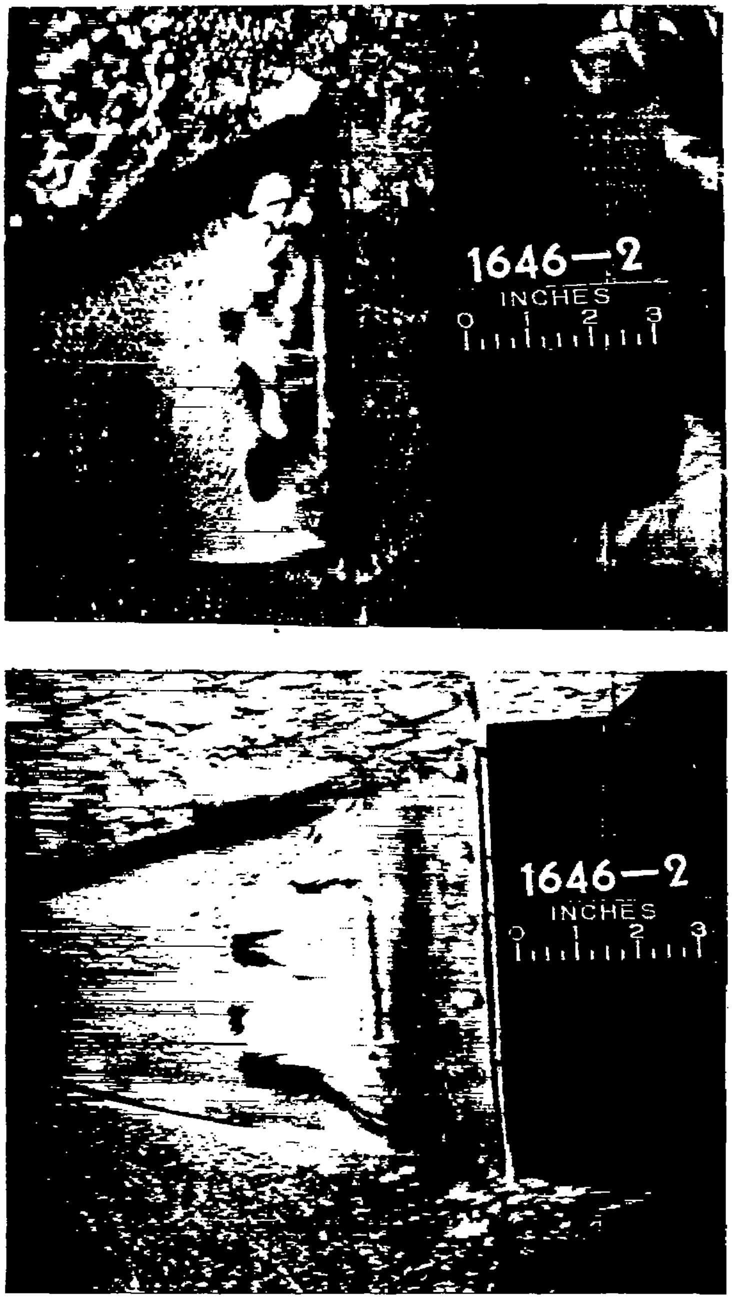
(a) Ice accretions following 30-minute icing period.

Figure 9. Ice formations on flush-inlet-type vent with tubes mounted in rear wall. Tunnel-air velocity, 220 feet per second; angle of attack, 12°; ambient-air temperature, 20° F; liquid-water content, 1.5 grams per cubic meter.



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(b) Ice accretions following 60-minute icing period.

Figure 9. - Concluded. Ice formations on flush-inlet-type vent with tubes mounted in rear wall. Tunnel-air velocity, 220 feet per second; angle of attack, 12°; ambient-air temperature, 20° F; liquid-water content, 1.5 grams per cubic meter.

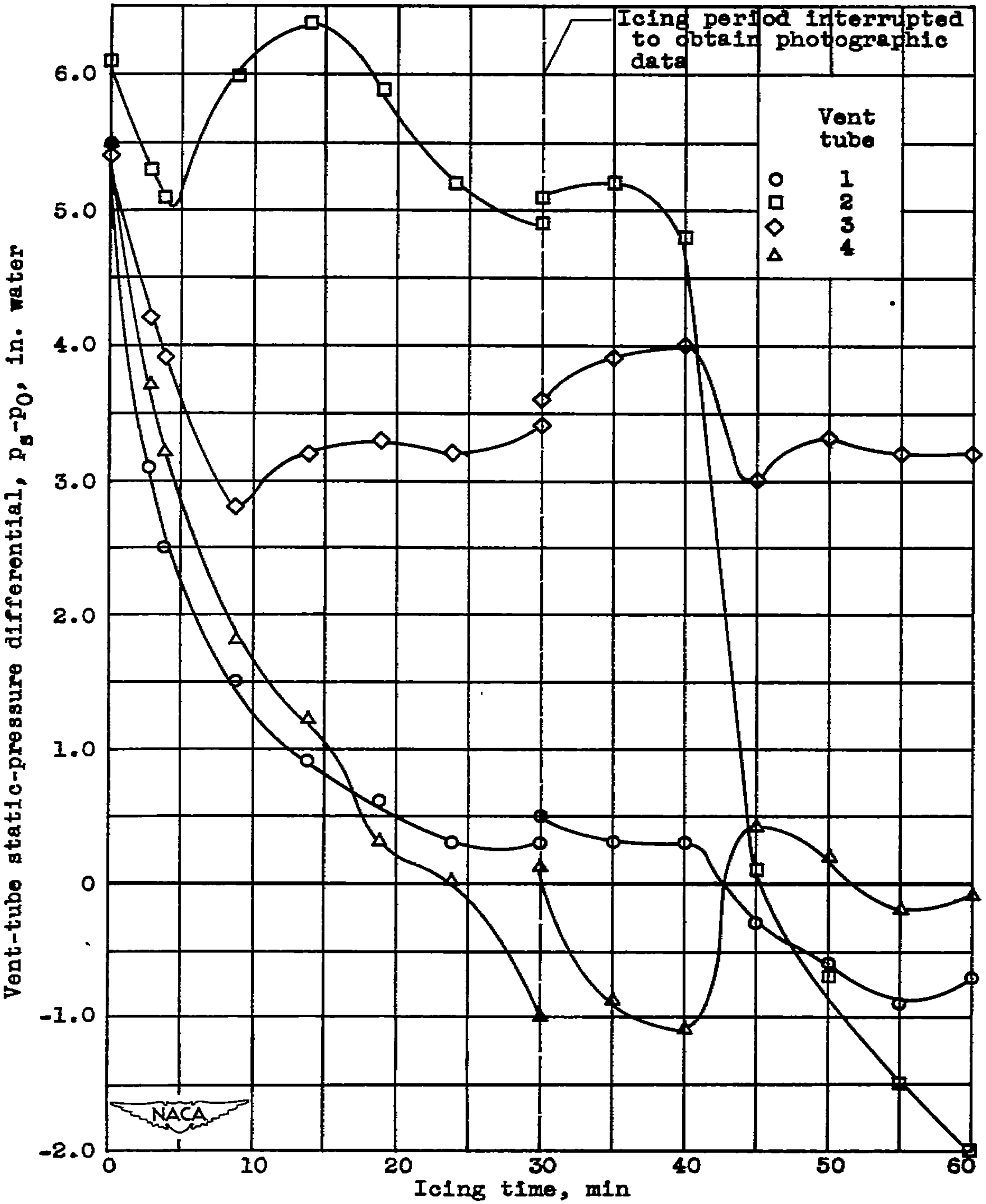


Figure 10. - Variation of vent-tube static-pressure differential with icing time for flush-inlet-type vent with tubes mounted in rear wall. Tunnel-air velocity, 220 feet per second; angle of attack, 12°; ambient-air temperature, 20° F; liquid-water content, 1.5 grams per cubic meter.

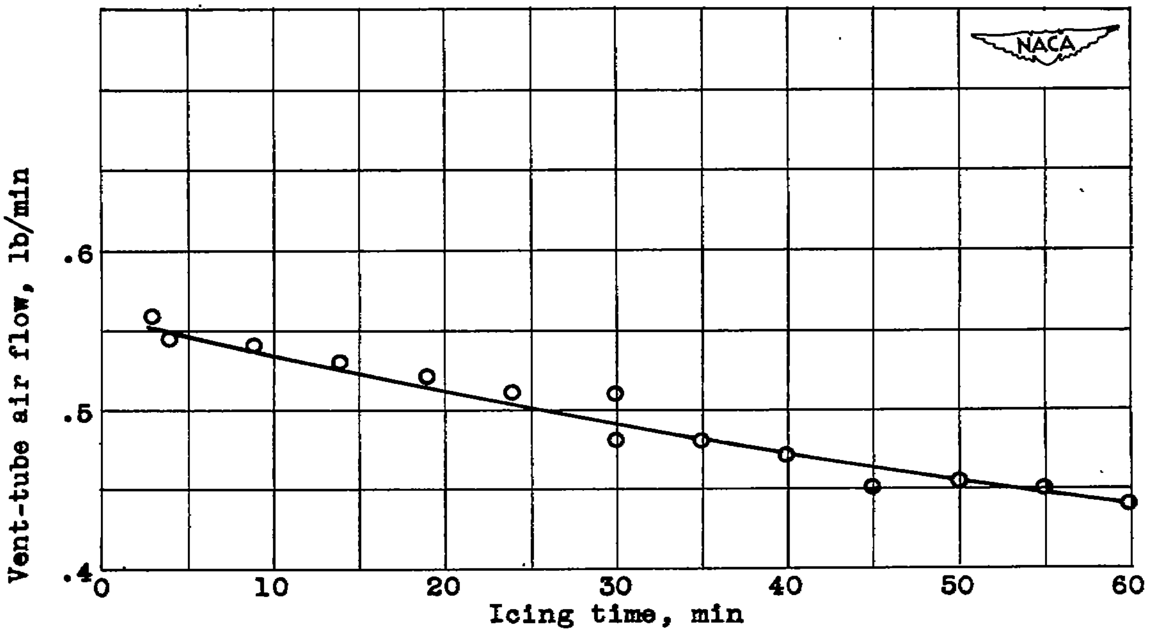
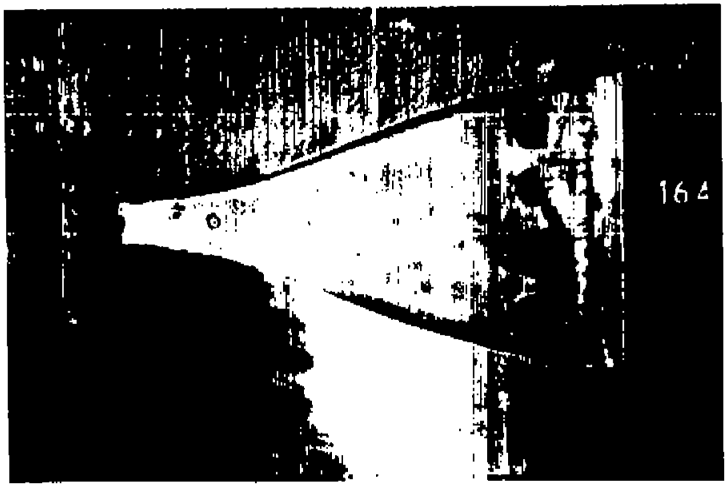


Figure 11. - Typical variation of vent-tube air flow with icing time for flush-inlet-type vent with tubes mounted in rear wall. Tunnel-air velocity, 220 feet per second; angle of attack, 12°; ambient-air temperature, 20° F; liquid-water content, 1.5 grams per cubic meter.



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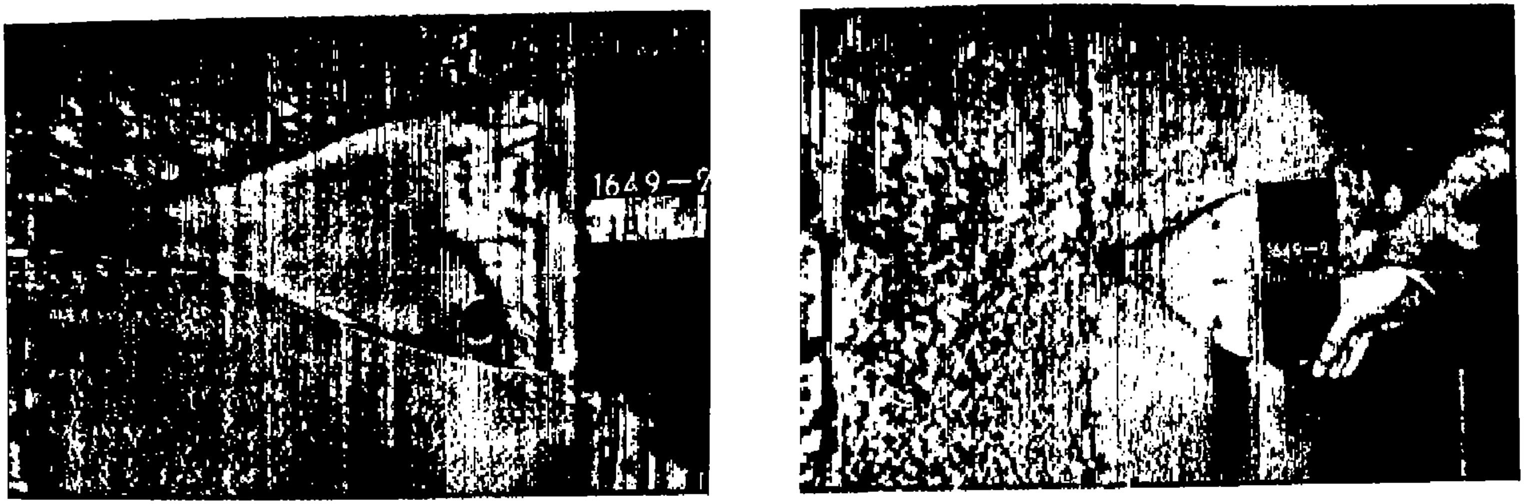
(a) Ice accretions following 15-minute icing period.



(b) Ice accretions following 45-minute icing period.

Figure 12. - Ice formations on flush-inlet-type vent with tubes mounted in ramp floor. Tunnel-air velocity, 220 feet per second; angle of attack, 12°; ambient-air temperature, 20° F; liquid-water content, 1.5 grams per cubic meter.

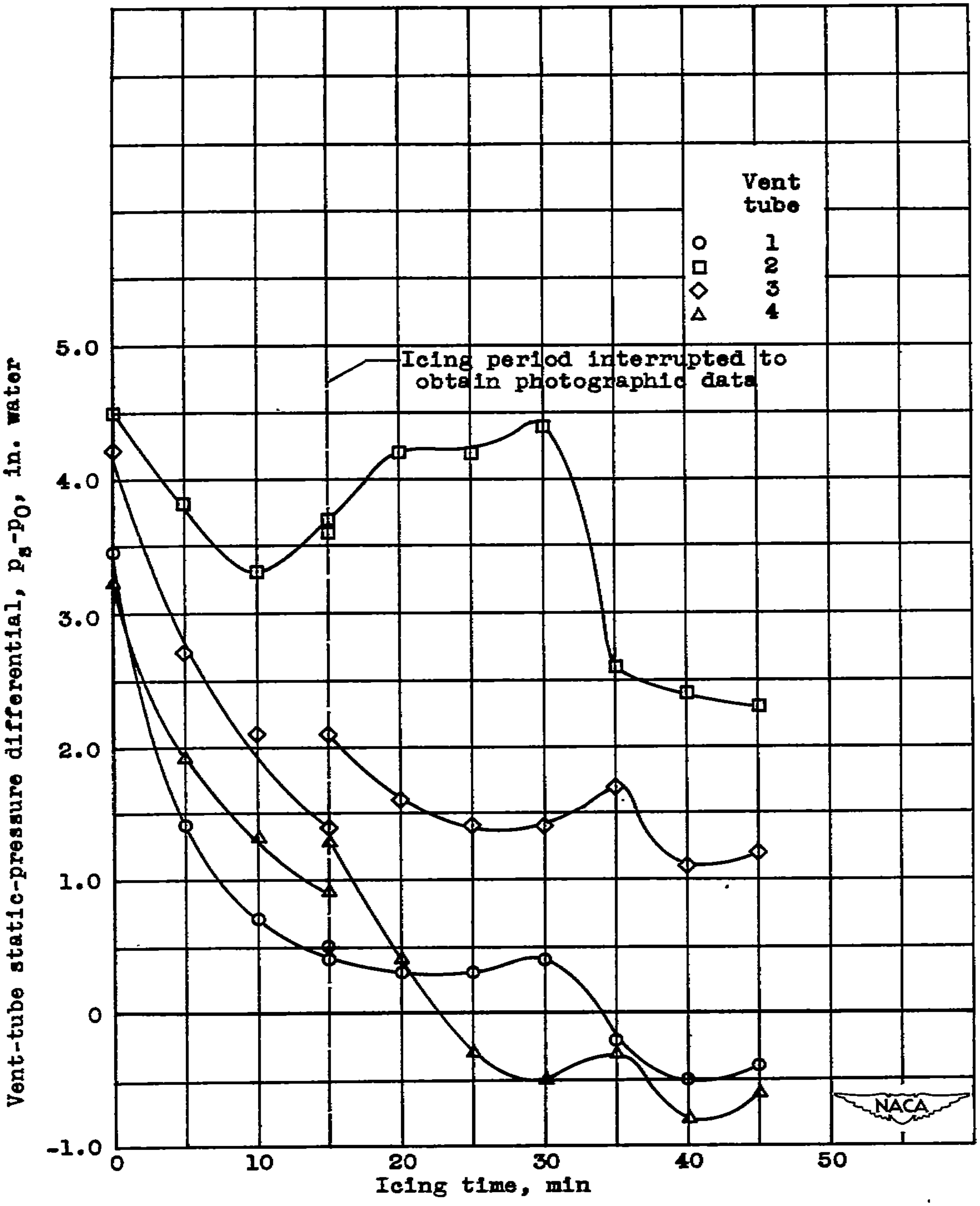


Figure 13. - Variation of vent-tube static-pressure differential with icing time for flush-inlet-type vent with tubes mounted in ramp floor. Tunnel-air velocity, 220 feet per second; angle of attack, 12°; ambient-air temperature, 20° F; liquid-water content, 1.5 grams per cubic meter.

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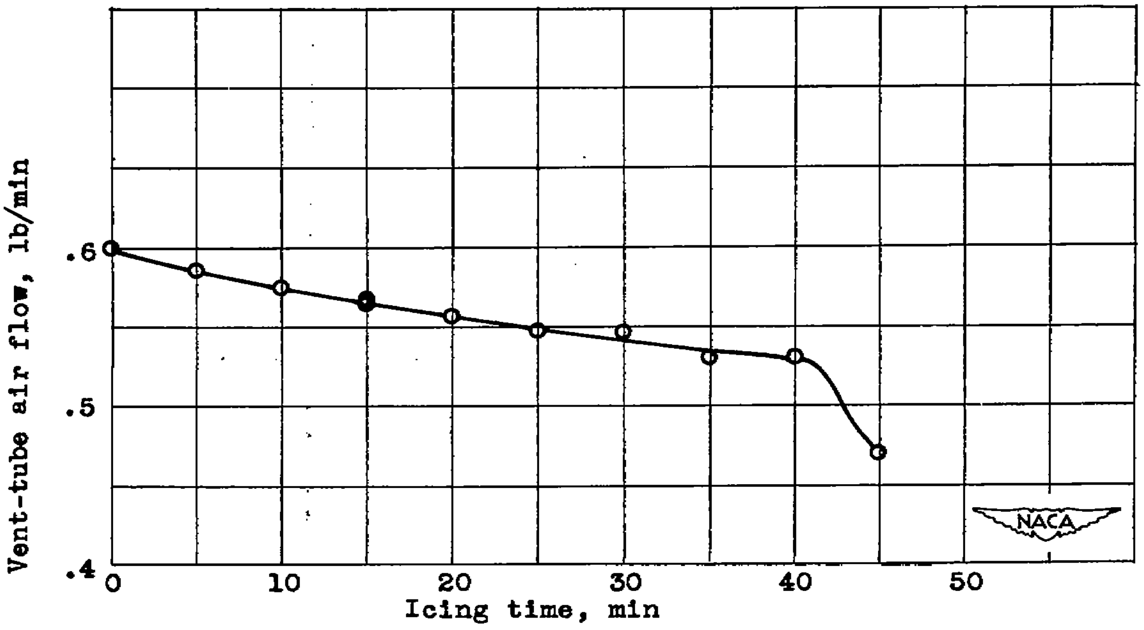

Figure 14. - Typical variation of vent-tube air flow with icing time for flush-inlet-type vent with tubes mounted in ramp floor. Tunnel-air velocity, 220 feet per second; angle of attack, 12°; ambient-air temperature, 20° F; liquid-water content, 1.5 grams per cubic meter.