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RESEARCH MEMORANDUM

INVESTIGATION TO DETERMINE EFFECTS OF RECTANGULAR VORTEX GENERATORS ON THE STATIC-PRESSURE DROP THROUGH A 90° CIRCULAR ELBOW

By E. Floyd Valentine and Martin R. Copp

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NATIONAL ADVISORY COMMITTEE
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INVESTIGATION TO DETERMINE EFFECTS OF RECTANGULAR VORTEX GENERATORS ON THE STATIC-PRESSURE DROP THROUGH A 90° CIRCULAR ELBOW

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SUMMARY

An investigation was made of a constant-area, circular 90° elbow of mean radius of curvature equal to its diameter with several arrangements of simple, nontwisted, rectangular vortex generators. The inlet flow had a boundary layer of about one-tenth the duct diameter. The vortex generators were located at stations in the inlet and at stations 15°, 30°, and 60° into the elbow. It was found that a one-third reduction in the static-pressure drop measured between the inlet and a station 4 diameters downstream of the elbow could be made by installing 12 vortex generators in the inlet. A similar reduction was also made by installing two vortex generators on the inner side at a station 60° into the elbow.

INTRODUCTION

In an aircraft induction system it is frequently required that air be turned through an angle as large as 90°. Nearly always losses in total pressure are to be avoided. In many cases it would be advantageous to have the air diffused at the same time but a compromise is usually made in which no diffusion is attempted in the elbow. Space limitations usually require the mean radius of the elbow to be as small as practicable

A basic discussion of the factors affecting flow in an elbow is given in reference 1. It is explained that for two-dimensional flow in a constant-area elbow with incompressible potential flow there would be a flow deceleration and consequent static-pressure increase along the first part of the outer boundary and along the last part of the inner boundary of the bend. In the actual case with a viscous fluid there is usually a separation of the flow in the last half of the inner boundary. Usually, no serious separation effects occur from the positive pressure gradient on the first part of the outer boundary because of the greater linear distance over which the pressure increase takes place and because this region is immediately followed by one with a favorable pressure gradient.

Because of the centrifugal forces of the main part of the flow, there is a greater static pressure on the outer boundary than on the inner boundary of the elbow. In the boundary layer, however, the centrifugal force of turning the slower-speed air is considerably less. Since the boundary layer has impressed on it the pressure gradient determined by the high-speed part of the flow, the result is an acceleration of boundary-layer air in the direction toward the inside of the elbow. This secondary flow may be one of the factors minimizing the separation effects on the outer boundary of the flow. Aside from this, however, it is, in general, an unfavorable effect because it is a factor in a reduction of the effective area at the elbow exit and contributes to distortion of the exit-velocity distribution.

Methods of improving the flow in elbows from references 2, 3, and 4 include the use of guide vanes, increasing the radius of curvature, and a reduction in area during the bend. The latter two often conflict with requirements already mentioned. The use of guide vanes may be objectionable from the standpoint of manufacturing complication and increased skin-friction losses. Also guide vanes which extend clear across the passage could result in completely plugging it in case of a severe icing condition. Any method, therefore, of improving the flow in an elbow having a small ratio of center-line radius to duct diameter without the use of extensive guide-vane arrangements would be of interest.

The use of boundary-layer removal to improve the flow in elbows is considered in reference 1. Another possibility for altering the boundary layer and secondary flow is provided by vortex generators which in reference 5 were shown to be effective in reducing the power requirement of a large wind tunnel. References 6, 7, and 8 give the results already obtained in increasing the pressure rise in conical and annular diffusers through the use of vortex generators. The present investigation is confined to the effects of simple arrangements of rectangular vortex generators in a constant-area, circular 90° elbow whose mean radius of curvature is equal to the cross-sectional diameter.

SYMBOLS

b	spanwise dimension of vortex generator
c	chord of vortex generator
d	duct diameter, in.

H	total pressure
n	number of vortex generators
p	static pressure
Δp	wall static-pressure drop, $\bar{p}_1 - \bar{p}$
q_c	impact pressure, $H - p$
r	mean radius of curvature of elbow
r/d	radius-diameter ratio of elbow
s	middle arc length between 0.3 chord stations of vortex generators
u	local velocity within boundary layer
U	local velocity at edge of boundary layer
x	distance upstream of elbow inlet
y	perpendicular distance from wall, in.
δ	boundary-layer thickness at $u = U$, in.
δ^*	two-dimensional boundary-layer displacement thickness, $\int_0^\delta \left(1 - \frac{u}{U}\right) dy$, in.

Nondimensional vortex-generator parameters:

b/c	aspect ratio
b/δ^*	span to average inlet-boundary-layer displacement thickness
s/b	spacing
α	angle of attack, deg
β	spacing angle between adjacent vortex generators, deg
θ	angular distance into elbow, deg
ϕ	angular extent of vortex-generator arrangement, deg

Subscripts:

0	reference conditions
1	inlet static-pressure measuring station
2	elbow exit conditions
4d	conditions 4 diameters downstream of elbow exit

A bar over a symbol indicates an average value.

APPARATUS AND METHODS

General arrangement.- The apparatus for this investigation is shown diagrammatically in figure 1. The elbow and a 1.5d length of duct downstream of it were of transparent plastic mounted to an external wooden framework. Tufts fastened to the duct inner surface could therefore be observed. Sufficient metal ducting downstream was incorporated to permit surveys and static-pressure measurements 4 diameters downstream of the elbow exit. Air was supplied from a 54-inch duct leading to an entrance bell which reduced to join a 21-inch-diameter duct 98 inches in length leading to the elbow entrance. This length was chosen to give a substantial boundary layer at the start of the elbow. A screen having a total-pressure drop of 1.24 times the dynamic pressure was installed 5 feet upstream of the entrance bell. A $1\frac{1}{2}$-inch band of cork particles was glued in the entrance bell to fix the transition point. Figure 2 is a photograph of the setup taken from the inner side of the elbow.

Vortex-generator arrangements.- The vortex generators were rectangular ones available from the previous investigations of references 6, 7, and 8. Although carefully made to NACA 0012 coordinates, there is no information as to whether this precision was essential to the results obtained.

Vortex generators were installed at the inlet vortex-generator station, figure 1. They were also installed 1/4 diameter upstream of this station and at three locations in the elbow itself as indicated in figure 3. In the locations in the elbow, the gap between the afterpart of the vortex generators and the surface was filled with modeling clay and faired to the airfoil contour.

A few runs were made with each vortex generator set at an angle of attack opposite to that of the one next to it. However, all arrangements for which curves are given were symmetrical as to number and angle of attack with respect to the plane of symmetry of the elbow. The angles of attack were in an opposite sense on either side of the plane of symmetry in such a direction (see fig. 4) as to oppose the secondary boundary-layer flow. In general, the vortex generators were grouped at the inner side of the elbow and did not extend around as far as the outer side. Figure 5 shows the meaning of ϕ, the angular extent of the vortex-generator arrangement, β, the spacing angle between adjacent vortex generators, and s, the linear spacing between vortex generators. In each case the two innermost vortex generators were spaced 12° apart. For the remaining vortex generators, the spacing angle β was given a value of 12°, 18°, or 24° to give a spacing variable.

Instrumentation.- Downstream static-pressure values were arithmetic averages from six radially distributed flush orifices for stations 2 and 4d of figure 1. For the inlet station, the average was used of two orifices in the plane of symmetry located 1/3 diameter upstream of the inlet vortex-generator station in order to place them outside the local pressure field. The total pressure measured at station 0 (fig. 1) was used with the inlet static pressure to provide the value of q_c. These pressures were recorded photographically on a multitube manometer.

The inlet velocity was varied between about 120 and 190 feet per second corresponding to a range of Reynolds number from 1.25×10^6 to about 2.00×10^6 based on inlet diameter. All comparisons were made at a speed of about 180 feet per second with a Reynolds number of about 1.85×10^6.

Remote-control pitot-static tubes were used to measure velocity distributions in the plane of symmetry. These measurements were made with the pitot-static element parallel to the axis at the station in question with no attempt at alinement with the local flow.

Tufts mounted on the inner surface of the elbow were photographed to obtain information on separation areas and on the secondary boundary-layer flow.

RESULTS AND DISCUSSION

Elbow With No Vortex Generators

The velocity distribution of the flow approaching the elbow was measured in the plane of symmetry 1 diameter upstream of the elbow. Figure 6 shows the boundary-layer thickness to be in the neighborhood of 1/10 the inlet diameter. The effect of the elbow is apparent in that the displacement thickness is less on the side approaching the inside of the bend than it is on the outer side.

The pressure drop through the elbow to a station 4 diameters downstream of the exit is shown in figure 7 for several flow rates. At the higher-speed part of the range the pressure drop is about 0.225 of the inlet center-line impact pressure.

Tuft photographs, figure 8, showed no separation in the outer boundary of the elbow. Although it is not discernible in figure 8(a), there was a separated area on the inner boundary starting half way around the bend and extending down the duct following the elbow. The secondary flow is seen in figure 8 to be qualitatively as would be predicted from consideration of the centrifugal pressure difference imposed on the lower-energy boundary layer. This is most clearly shown in figure 8(b).

Velocity profiles measured with no vortex generators are illustrated in figure 9 to give an over-all indication of what is occurring. The distribution before the elbow has already been discussed. The distribution at the exit is the reasonable result of a combination of the potential-flow distribution described in the introduction, the inner-surface separation on the inside of the elbow, and the secondary flow caused by the centrifugal forces. At 4 diameters downstream, the velocity distribution has become more uniform but is reversed in the sense of having the highest velocity at the outer wall. This is all in general agreement with reference 9 in which a more general consideration of the velocity distributions for elbows is given.

Elbow With Vortex Generators

Basic arrangement.- An arrangement on the basis of the diffuser investigation of reference 8 was selected as a starting point. Thirty vortex generators of aspect ratio 0.327 and $b/\delta^* = 4.85$ were installed at the entrance. They were set at an angle of attack of $\pm 15^\circ$; each vortex generator had an angle of attack opposite in sign to the one next to it. The pressure drop was 0.257 of the entrance impact pressure, higher than with no vortex generators. Changing the angles of attack so that, on one side of the plane of symmetry, each angle of attack was in the direction to oppose the secondary boundary-layer flow to be expected on that side resulted in a pressure drop slightly lower than with no vortex generators. Successive removal of pairs of vortex generators starting at the outside of the elbow resulted in decreases in the static-pressure drop until a minimum was reached at some number of vortex generators which depended on the span, chord, and spacing being considered. The procedure adopted, therefore, for a particular span, chord, and spacing was to vary the angle of attack with 14 or 16 vortex generators to find an effective value and then to try successive removal starting from the outer side of the elbow to determine the best number of vortex generators.

A check for the effect of alternating angles of attack when only part of the circumference was occupied was made with 10 vortex generators of $b/c = 0.654$ and $b/\delta^* = 9.7$. The static-pressure drop coefficient was reduced from 0.268 down to 0.150 by changing from alternating angles of attack to the arrangement in which the angles of attack were in the direction to oppose the secondary boundary-layer flow. No further arrangements were tried with each vortex generator having an opposite angle of attack to the ones on either side of it.

Effect of angle of attack.- Figure 10 shows the variation of pressure-drop coefficient with angle of attack for three vortex-generator arrangements at the inlet station. It is seen that an angle of attack of about 12° is most effective in all three cases. This result cuts down the running of different angles of attack. It is also noted that in one case the pressure-drop coefficient has been reduced to 34 percent less than the value for the no-vortex-generator condition.

Variation of circumferential extent of vortex generators.- The effect of varying the amount of the perimeter over which the vortex generators are disposed at the inlet vortex-generator station is shown in figure 11 for four different combinations of vortex-generator parameters. For the combinations incorporating a 12° spacing angle the minimum $\Delta p/q_c$ is in the neighborhood of 132°, 12 vortex generators; whereas for the 24° spacing angle the minimum is at 204°, 10 vortex generators.

Effect of span.- Variation of the pressure drop with span of the vortex generators in terms of the displacement thickness δ^* is shown in figure 12 for three arrangements. The minimum pressure drop comes at a span of about 8 times the inlet-boundary-layer displacement thickness in each case but departure from these values in the range from 7 to 11 does not cause a large change from the minimum pressure-drop value obtained.

Downstream velocity and pressure distributions.- The effect of the vortex generators on the velocity distribution in the plane of symmetry at the elbow exit is shown in figure 13 for one of the favorable arrangements. The vortex generators have increased the effective area at this station by reducing the extent of the reverse flow region at the inner side of the elbow. Also the peak-velocity value has been decreased. The effect on the velocity distribution in the plane of curvature 4 diameters downstream of the elbow exit is shown in figure 14 for an arrangement with a slightly greater span. In this case the velocities are, in general, decreased and the only evidence of improvement is that the values in the region of the peak have been reduced by the vortex generators.

The circumferential variation in static pressure at the exit and 4 diameters downstream with and without vortex generators is shown in figure 15. At the exit there is considerable variation around the circumference. At 4 diameters downstream, the static pressure is quite uniform both with and without the vortex generators.

Effect of upstream location of vortex generators.- The effect of moving the vortex generators 1/4 diameter upstream in the inlet duct is shown in figure 16 for several arrangements. The upstream pressure was of necessity obtained from taps far enough from the vortex generators in the upstream location to be outside the range of local pressure-field disturbances. The same taps were used for the vortex-generator arrangements at the inlet position for the data of this figure and the value plotted is the change in pressure drop caused by moving the vortex generators upstream. The change is seen to be small and is least unfavorable for the larger span value.

Location of vortex generators in the elbow.- Several arrangements were tried at stations inside the elbow. For the 12-vortex-generator arrangement of figures 17 and 18, moving the vortex generators farther into the elbow increased the value of the most favorable angle of attack until it was about 18° at a station 30° into the elbow. At a station 60° into the elbow, (fig. 19), however, the most favorable angle of attack for the 12-vortex-generator arrangement has decreased to around 10° and the pressure drop has increased to a value greater than with no vortex generators. When the number of vortex generators was systematically reduced, however, it was found that the pressure drop was not materially changed at stations 15° and 30° into the elbow. At 60° into the elbow, however, (fig. 19) the lowest pressure drop was with only two vortex generators and was comparable with the results obtained with the better arrangements at the inlet station (figs. 11 and 12). The best angle of attack was increased by 8° over the value for the inlet station. A downstream circumferential static-pressure distribution for two vortex generators set at an angle of attack of 20° at a station 15° into the elbow is shown in figure 20. The main difference between this arrangement and one for vortex generators at the inlet is in the pressure at the inner part of the elbow at the exit. This pressure orifice is immediately downstream of the two vortex generators.

The effect of location definitely depends on the arrangement being considered. The two arrangements in figure 17 which give essentially the same low value of pressure drop at a station 15° into the elbow can be seen in figure 21 to be less effective when moved to the inlet vortex-generator station. When moved in farther than the 15° station, the arrangement with 12 vortex generators becomes increasingly less effective. The arrangement with two vortex generators set at an angle of attack of 20°, however, gives a decreasing pressure drop as it is moved to 30° and then to 60° into the elbow. It should be noted that figure 21 is not useable to decide the best station at which to put vortex generators. Although this investigation was not extended to determine the absolute optimum arrangement for each location, consideration of the best arrangement from those investigated should show the general trend. Figure 22 shows this variation for the angle of attack and for the span in terms of the inlet displacement boundary-layer thickness.

Comparison of best results at three vortex-generator stations.- Figure 23 provides a means of comparing results from several vortex-generator stations over a speed range. The variation over this speed range is seen to be small for a given arrangement. There is also seen to be very little difference between the results with 12 vortex generators of aspect ratio 0.500, span of $7.3\delta^*$, and spaced 1.33 spans in the inlet and those with two vortex generators of aspect ratio 0.235, span of $2.29\delta^*$, and spaced 4.29 spans at a station 60° into the elbow. The advantage at the higher speed appears slightly in favor of the arrangement with 12 vortex generators at the inlet. Since any application of these results would in all probability be to an elbow having inlet flow conditions and elbow geometry which differ in some degree from those covered in this investigation, it is considered that the final choice of vortex-generator station should be made after determining the results of installing them successively in at least two stations in the elbow in which they are to be used.

SUMMARY OF RESULTS

The following statements apply to simple, nontwisted, rectangular vortex generators used with a constant-area, circular 90° elbow of mean radius of curvature equal to the diameter. They apply for an inlet speed of 180 feet per second and an inlet flow condition in which the boundary-layer thickness is about 1/10 the inlet diameter. Comparisons are based on measurements of the static-pressure drop between the inlet and a station 4 diameters downstream of the elbow:

1. The static-pressure drop around the elbow can be reduced one-third by a simple vortex-generator arrangement.

2. The effective arrangements were symmetrical about the plane of symmetry with the vortex generators starting at the inside of the elbow but not extending around to the outside. The angles of attack were all in the same direction on one side of the plane of symmetry and in a direction to oppose the secondary boundary-layer flow.

3. The lowest pressure drop was obtained with 12 vortex generators of aspect ratio 0.500, set at an angle of attack of 12° at a station just upstream of the inlet. The span was 7.3 times the inlet-boundary-layer displacement thickness and the vortex generators were spaced 1.33 spans apart. The separated cross-sectional area at the exit was appreciably reduced. An arrangement giving essentially the same low static-pressure drop consisted of two vortex generators set at an angle of attack of 20°

at a station 60° into the elbow with aspect ratio 0.235. The span was 2.29 times the inlet-boundary-layer displacement thickness and they were spaced 4.29 spans apart.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., June 25, 1953.

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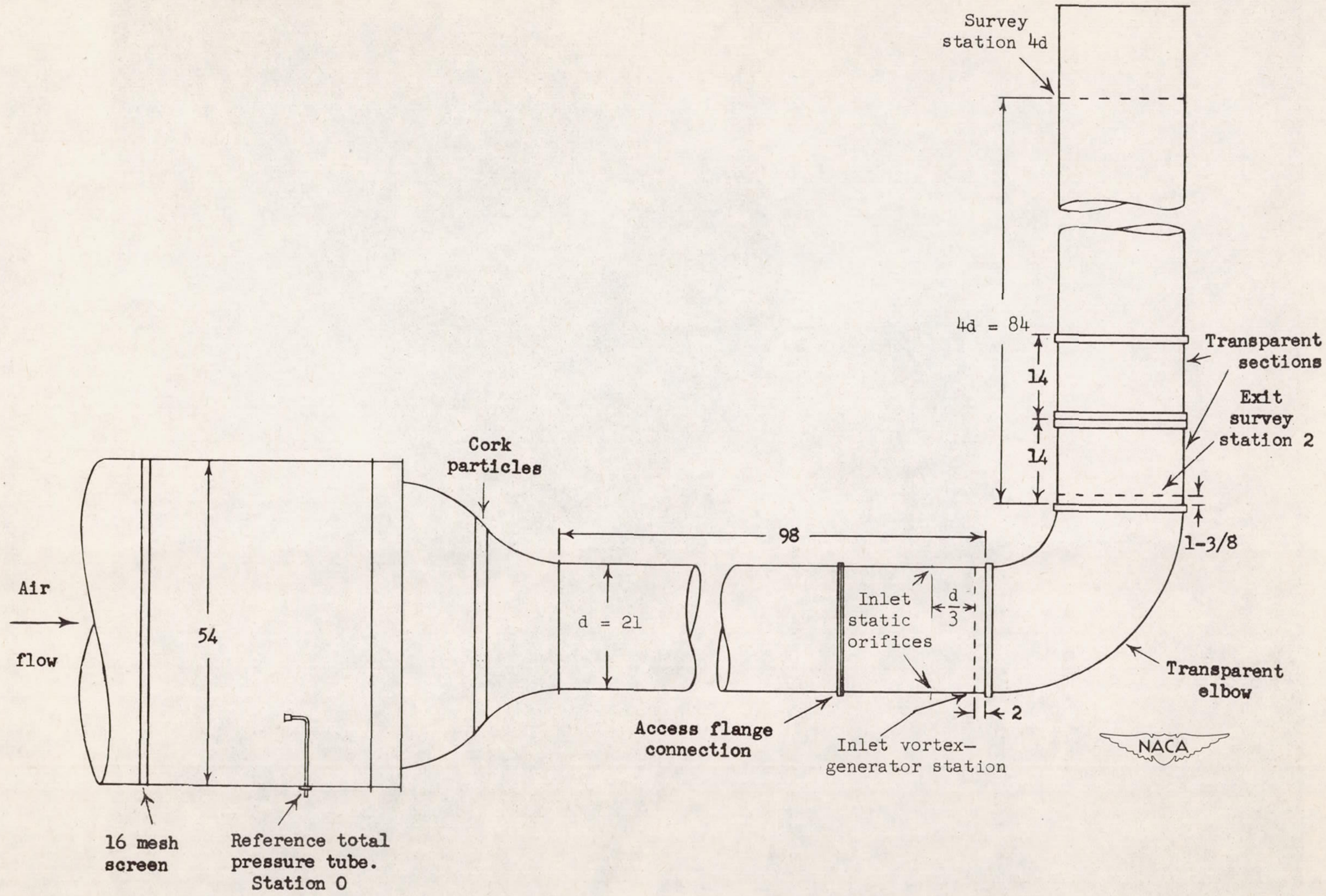

Figure 1.- General arrangement of apparatus and instrumentation. All dimensions are in inches.

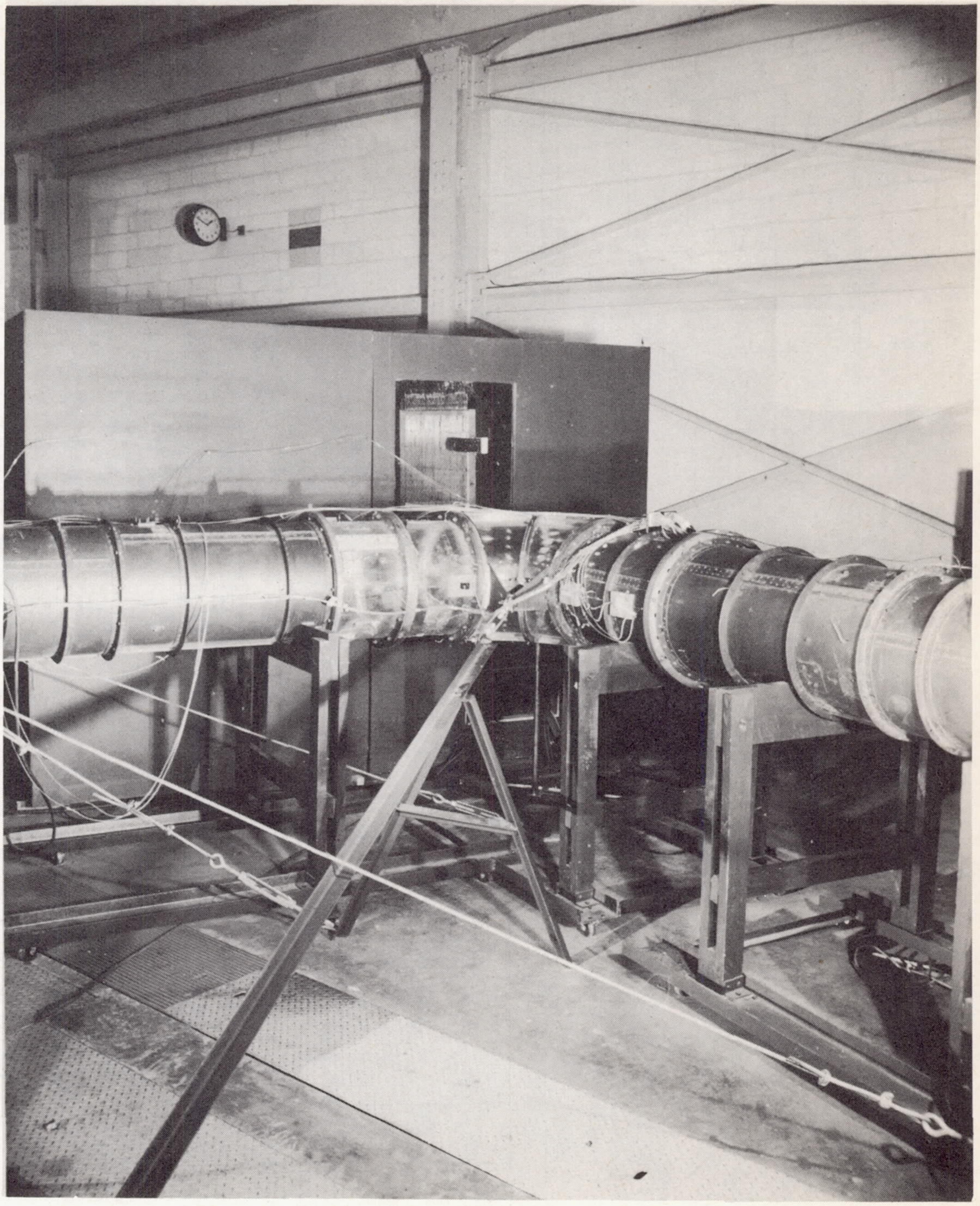

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Figure 2.- General arrangement of test apparatus.

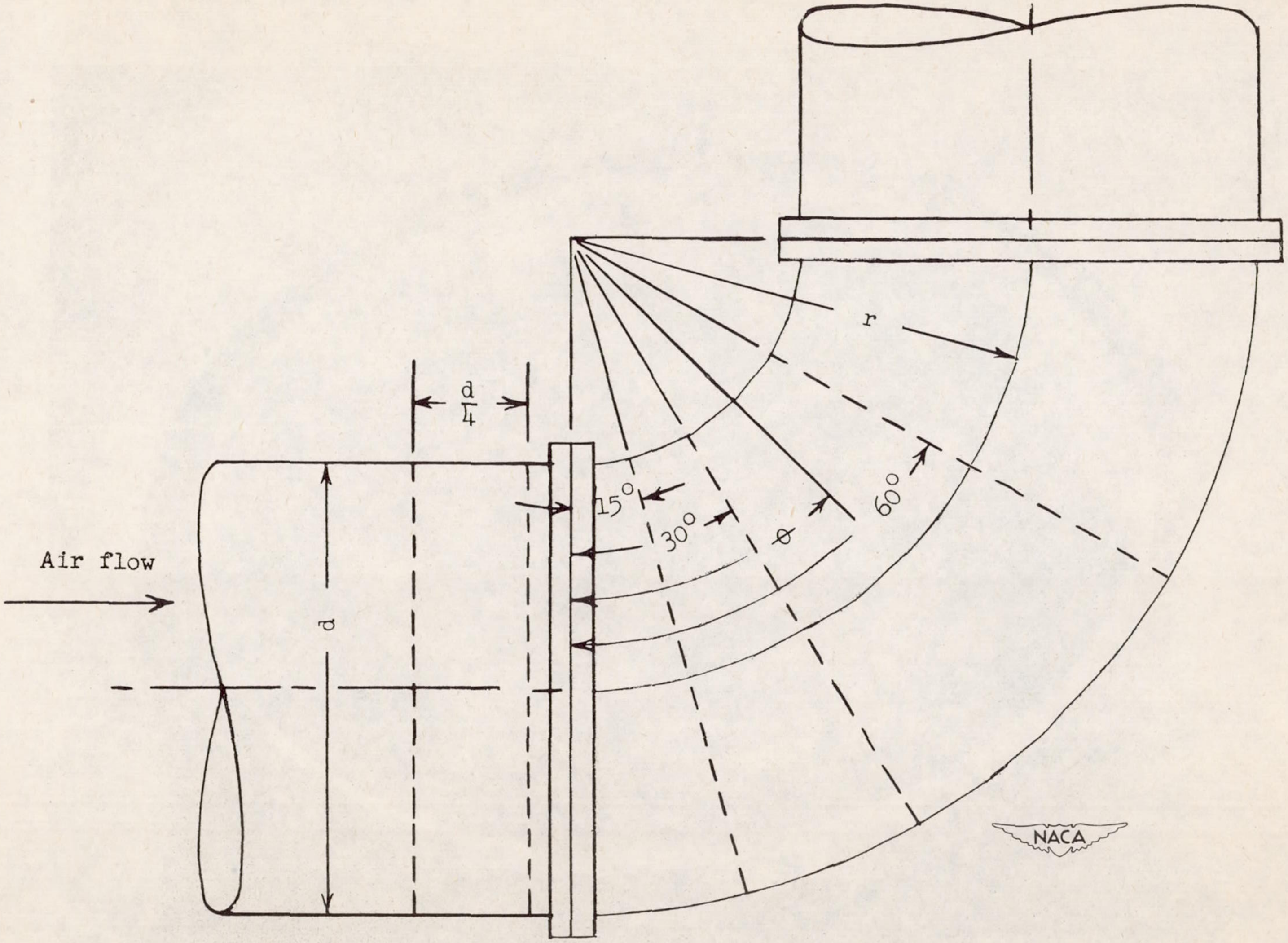

Figure 3.- Location of vortex-generator stations.

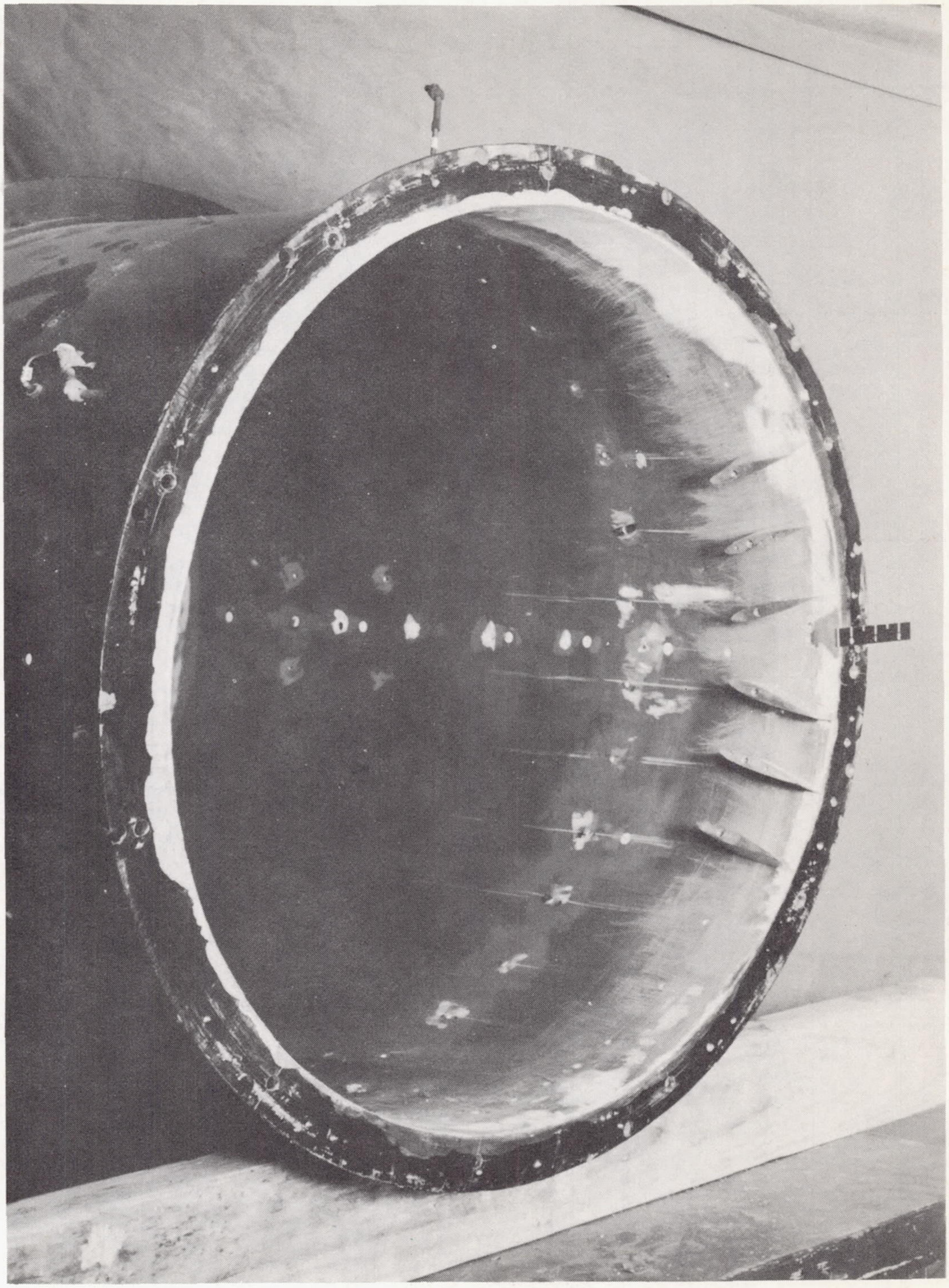

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Figure 4.- Typical arrangement at inlet vortex-generator station. Six vortex generators upstream of inner side of elbow.

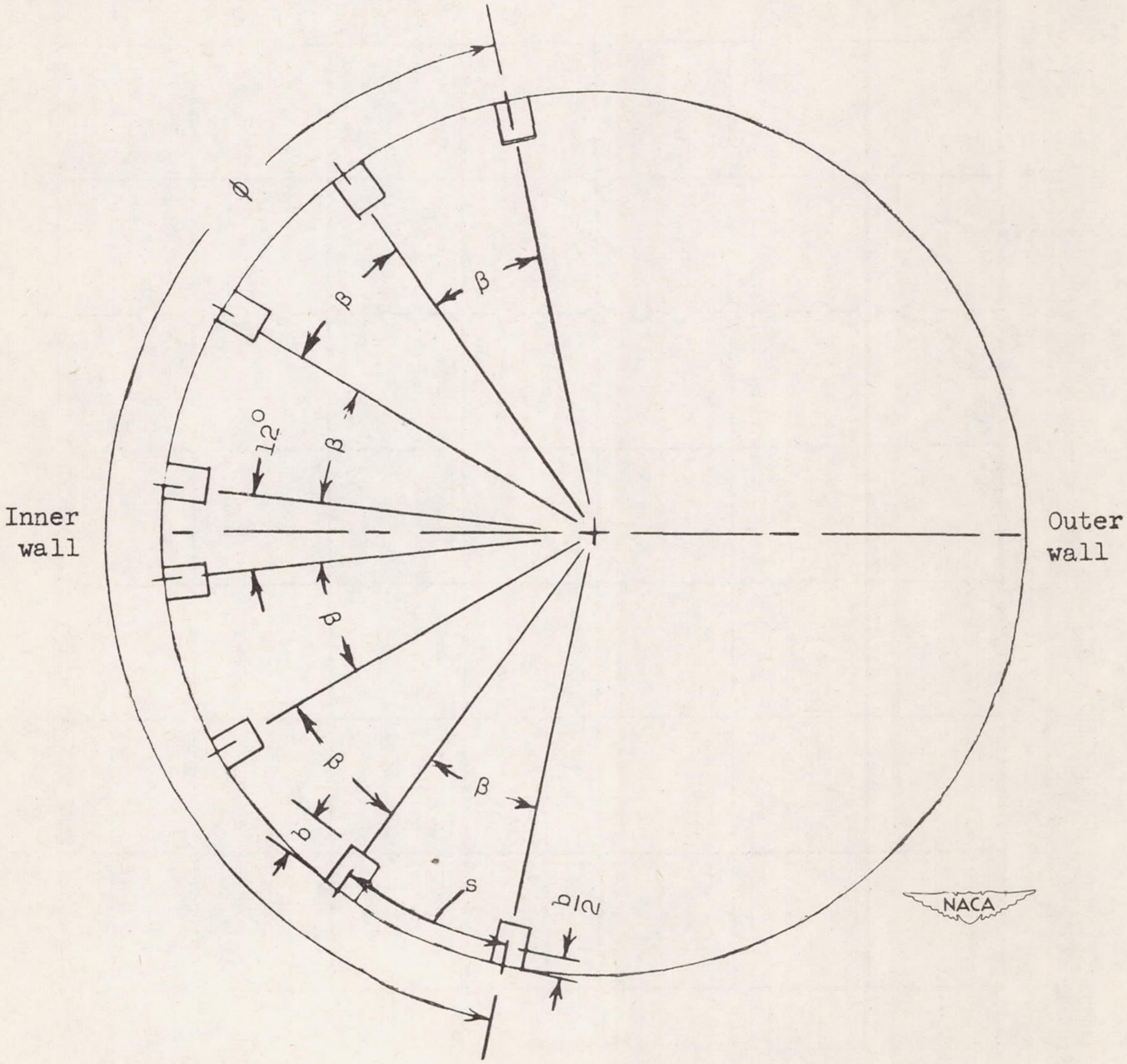


Figure 5.- Vortex-generator spacing.

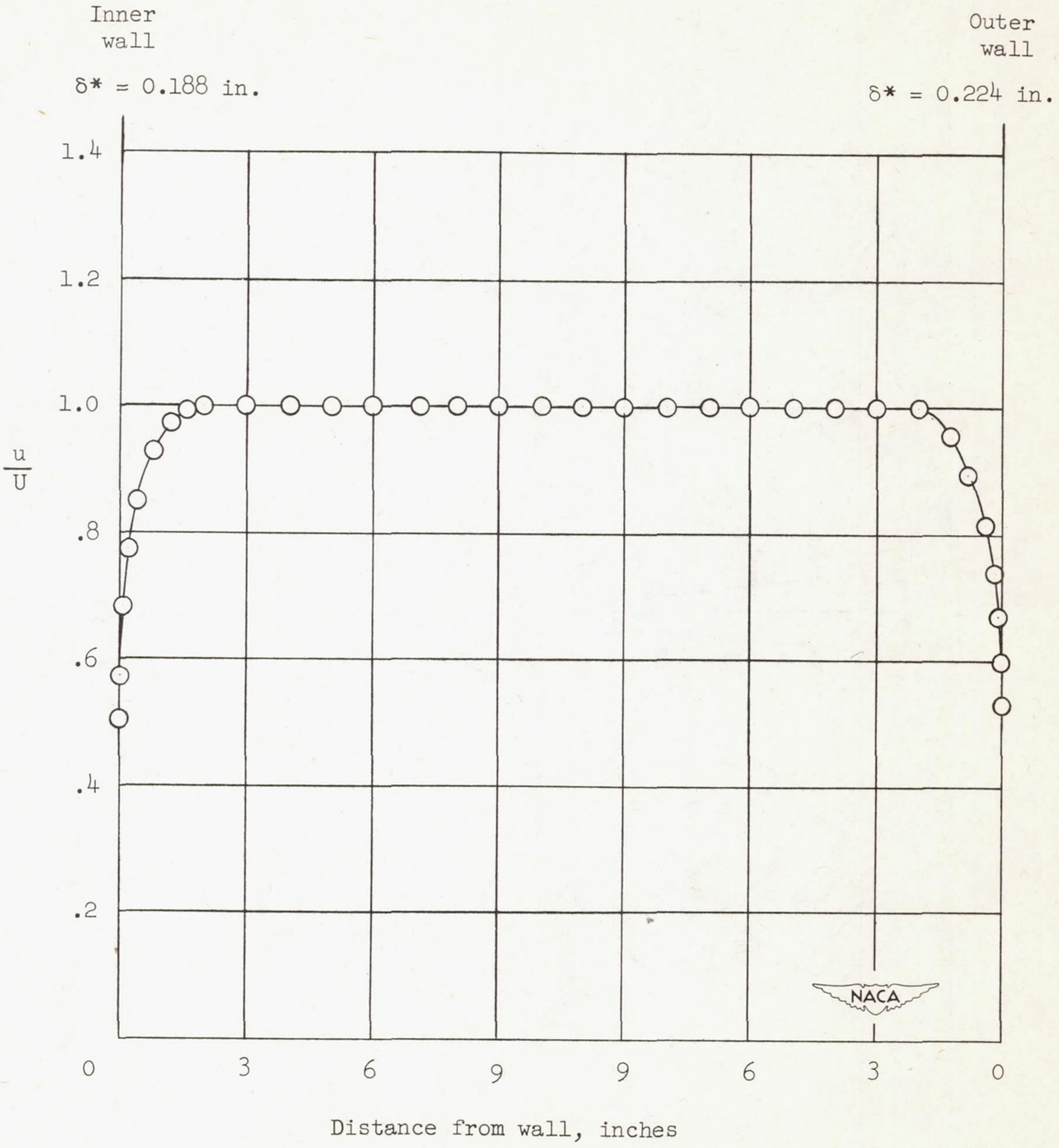


Figure 6.- Velocity profile 1 diameter upstream of elbow.

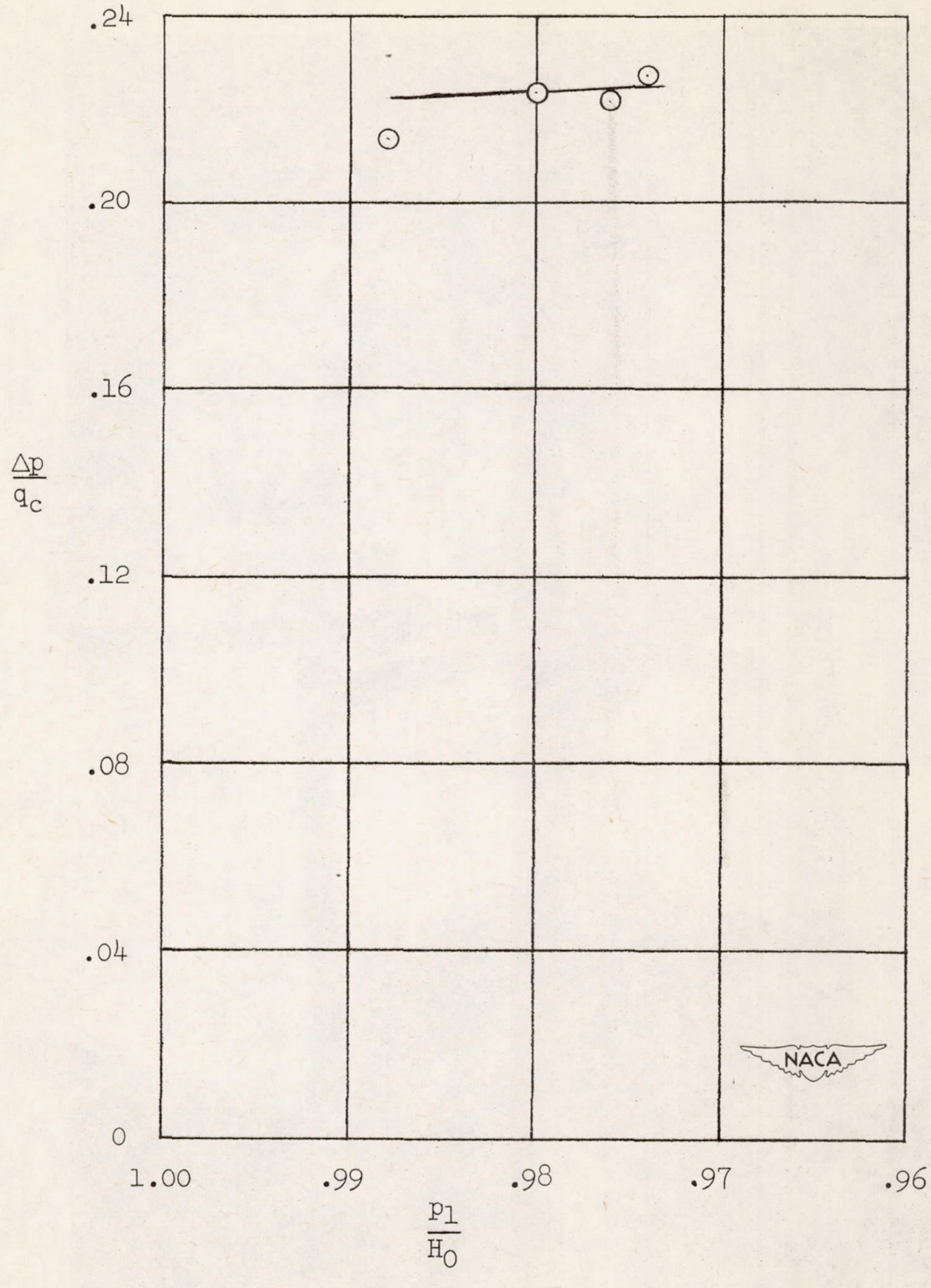
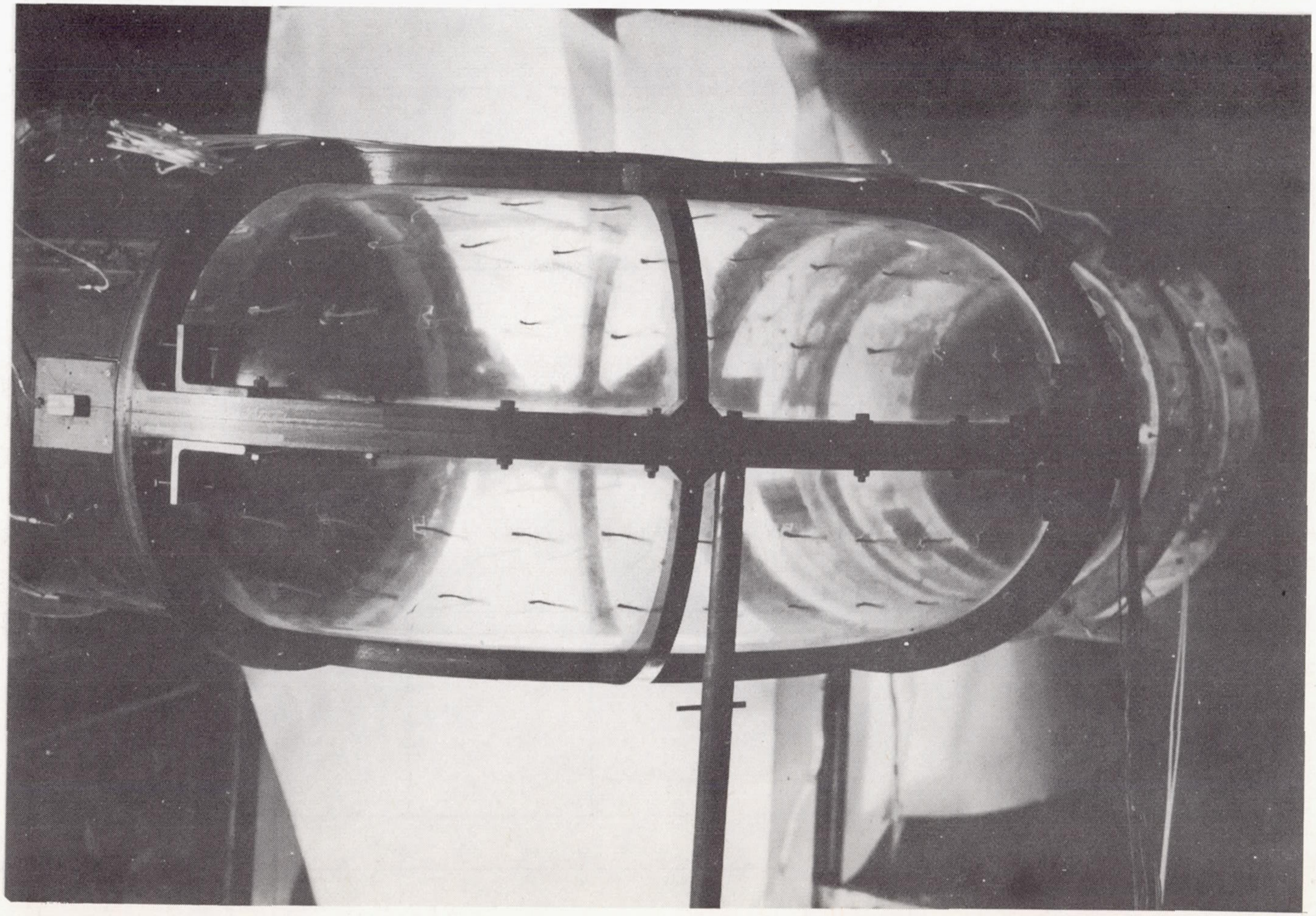


Figure 7.- Pressure drop at several flow rates. No vortex generators.



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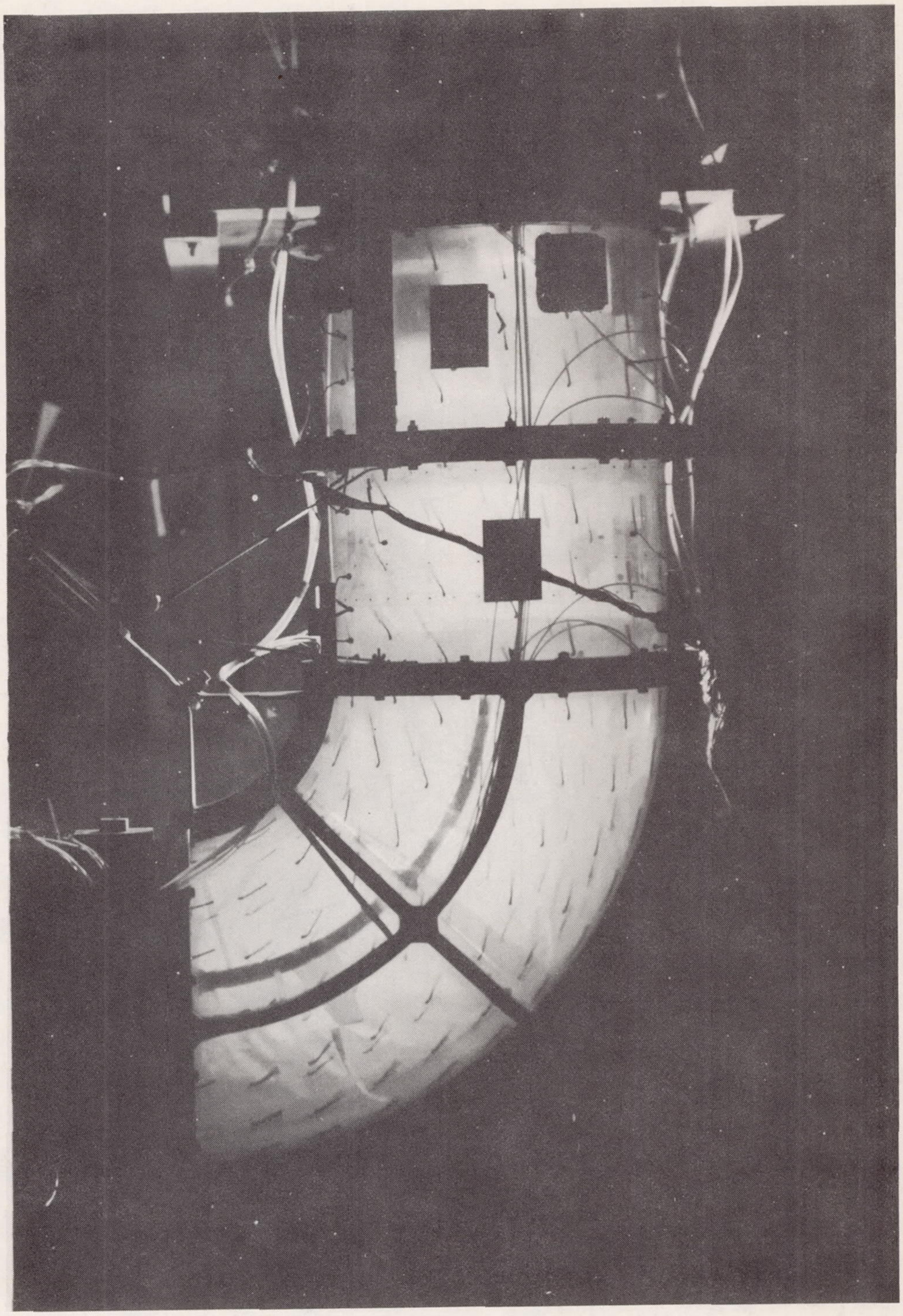
(a) Outer wall.

Figure 8.- Tuft pattern. No vortex generators.



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(b) Side walls.

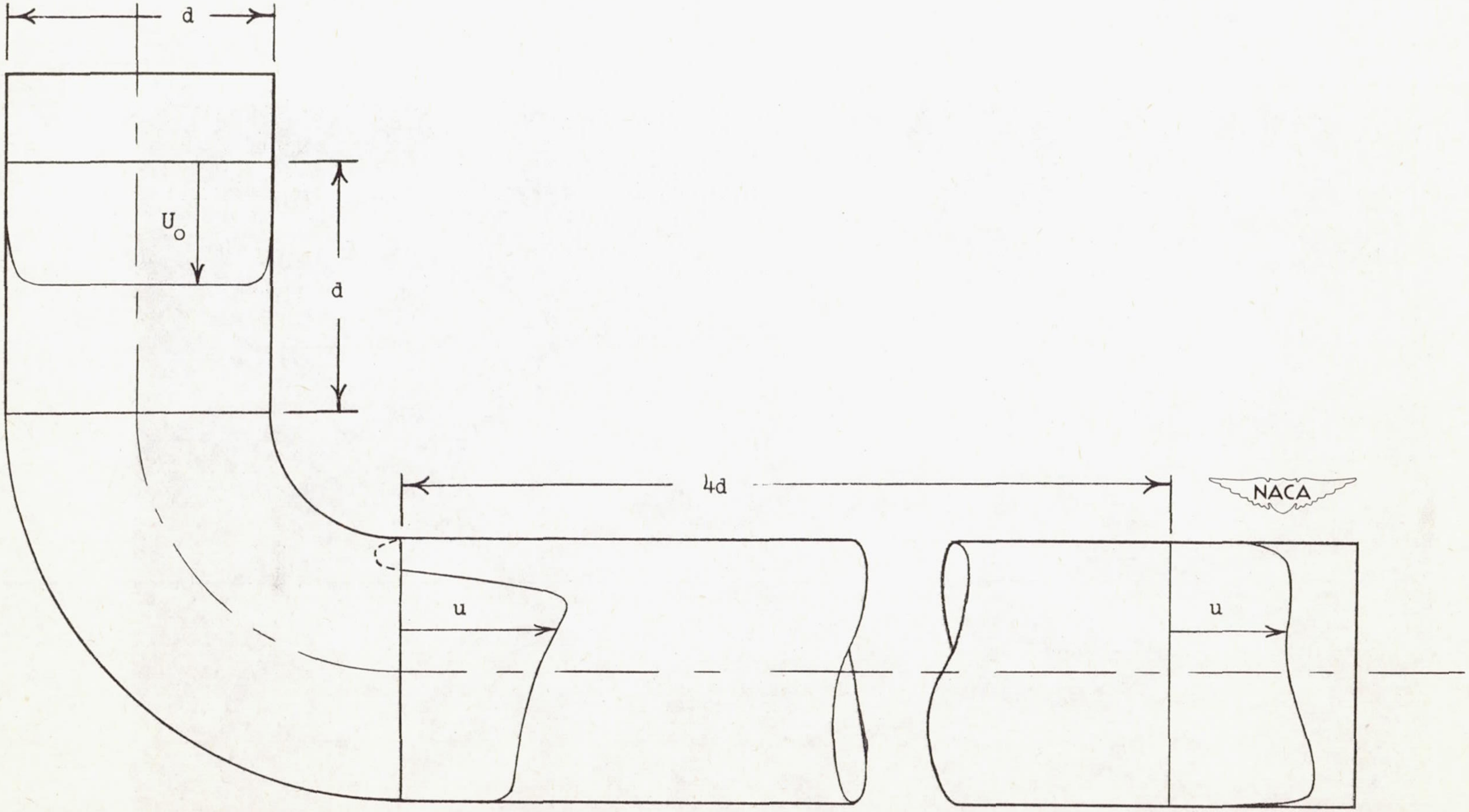
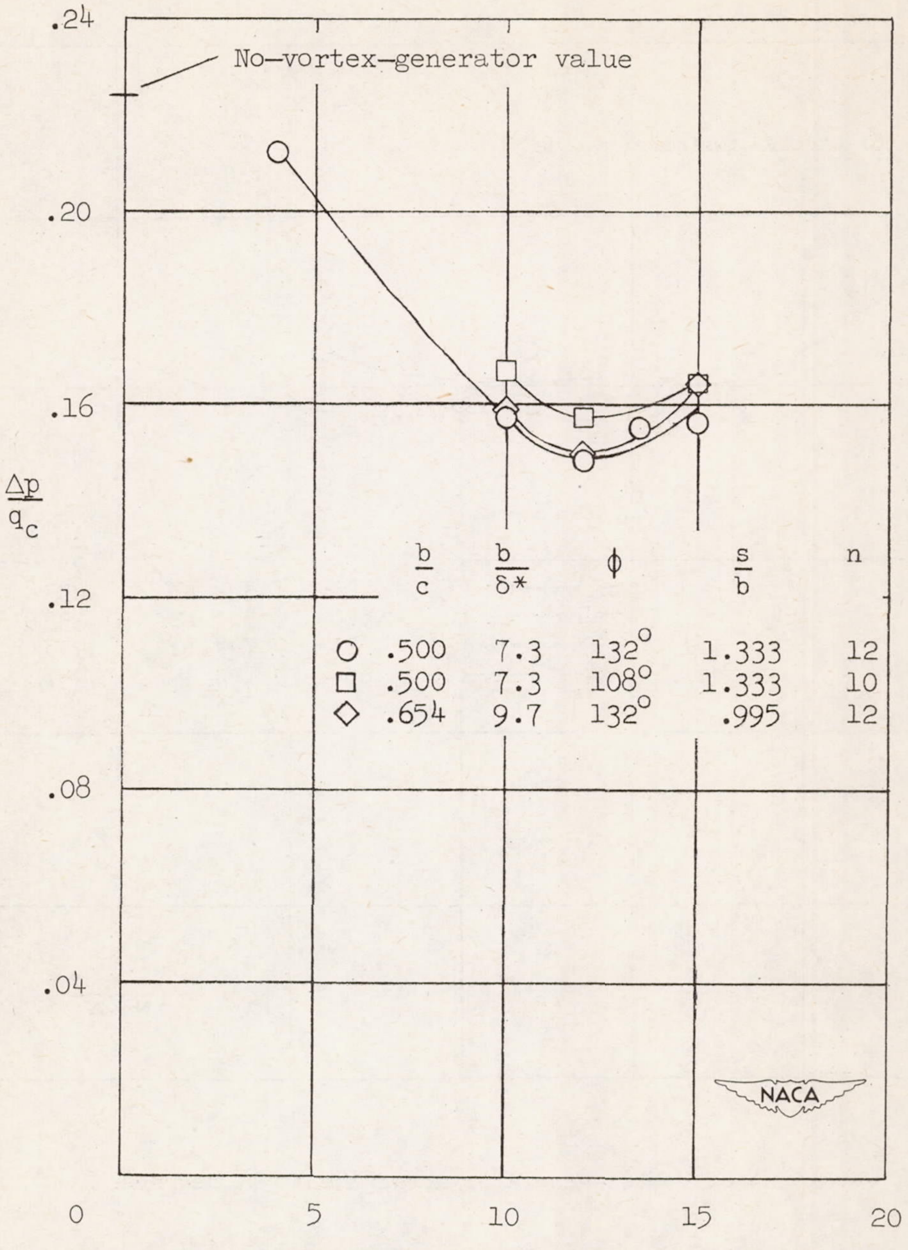


Figure 9.- Velocity profiles in the plane of symmetry. No vortex generators.



	$\frac{b}{c}$	$\frac{b}{\delta *}$	ϕ	$\frac{s}{b}$	n
○	.500	7.3	132°	1.333	12
□	.500	7.3	108°	1.333	10
◇	.654	9.7	132°	.995	12

Figure 10.- Effect of angle of attack of vortex generators located at the inlet station. $\beta = 12^{\circ}$.

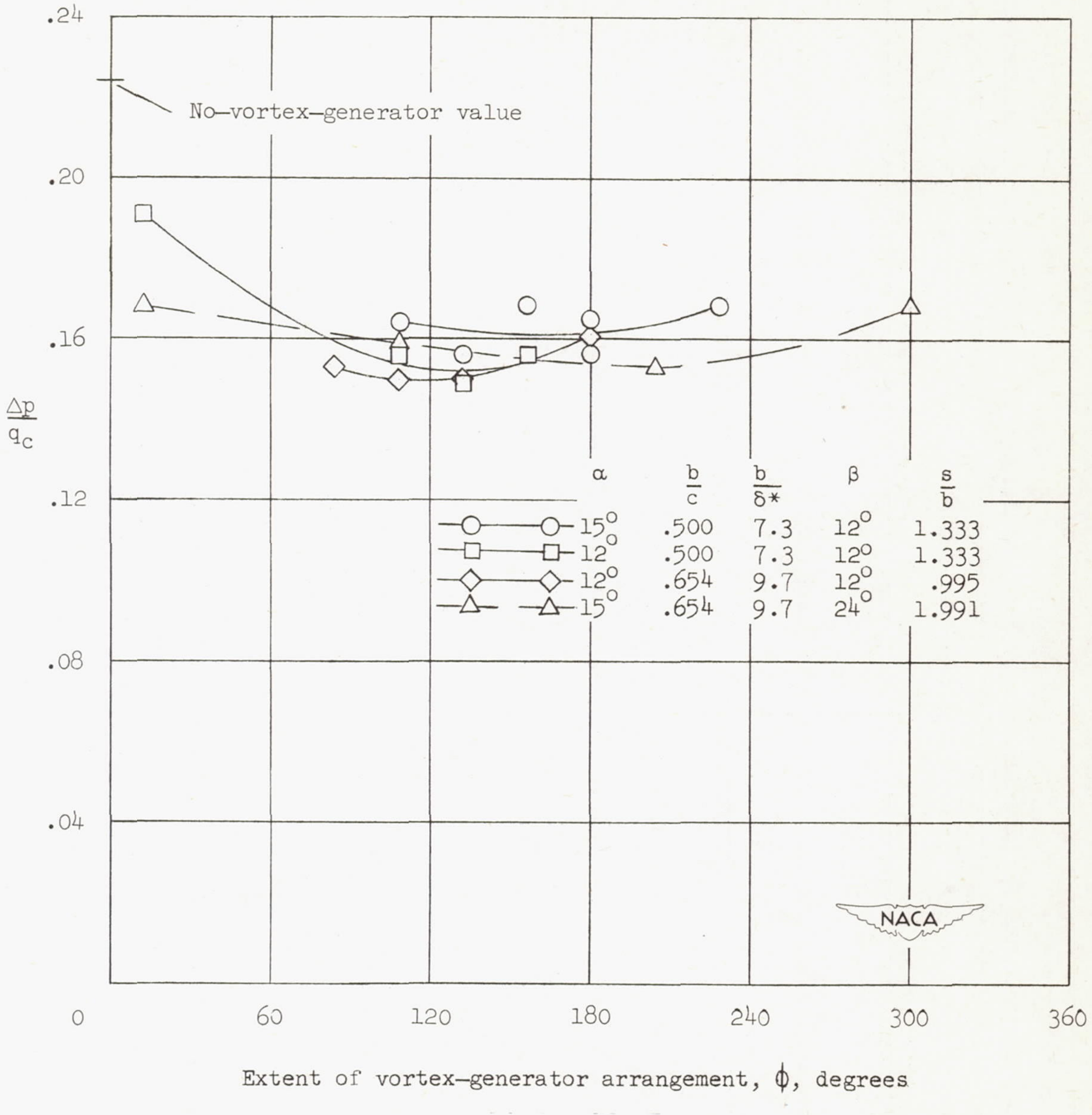


Figure 11.- Effect of circumferential extent of vortex generators. Inlet station.

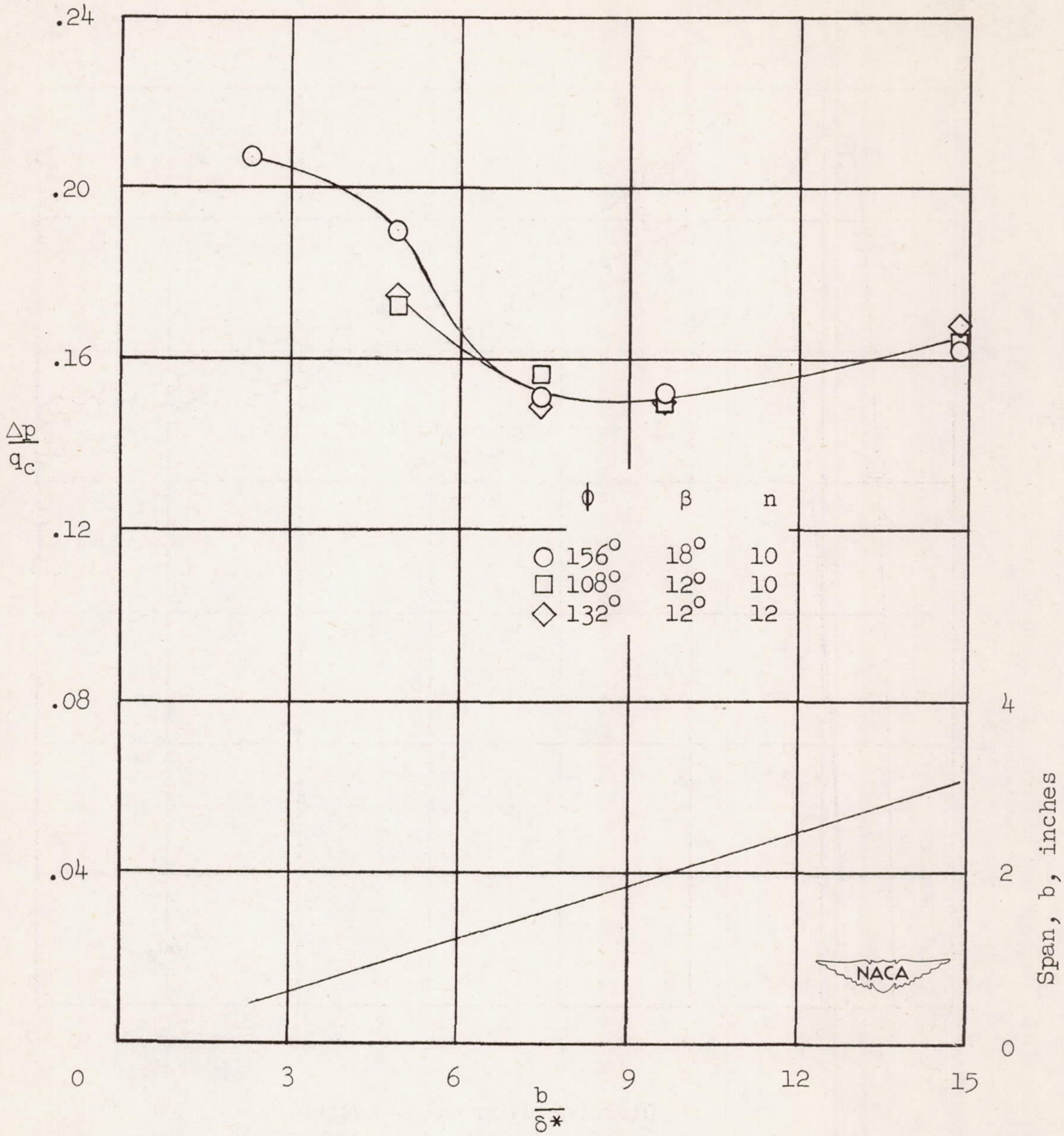


Figure 12.- Effect of vortex-generator span. Inlet station. $\alpha = 12^\circ$; $c/\delta^* = 14.9$.

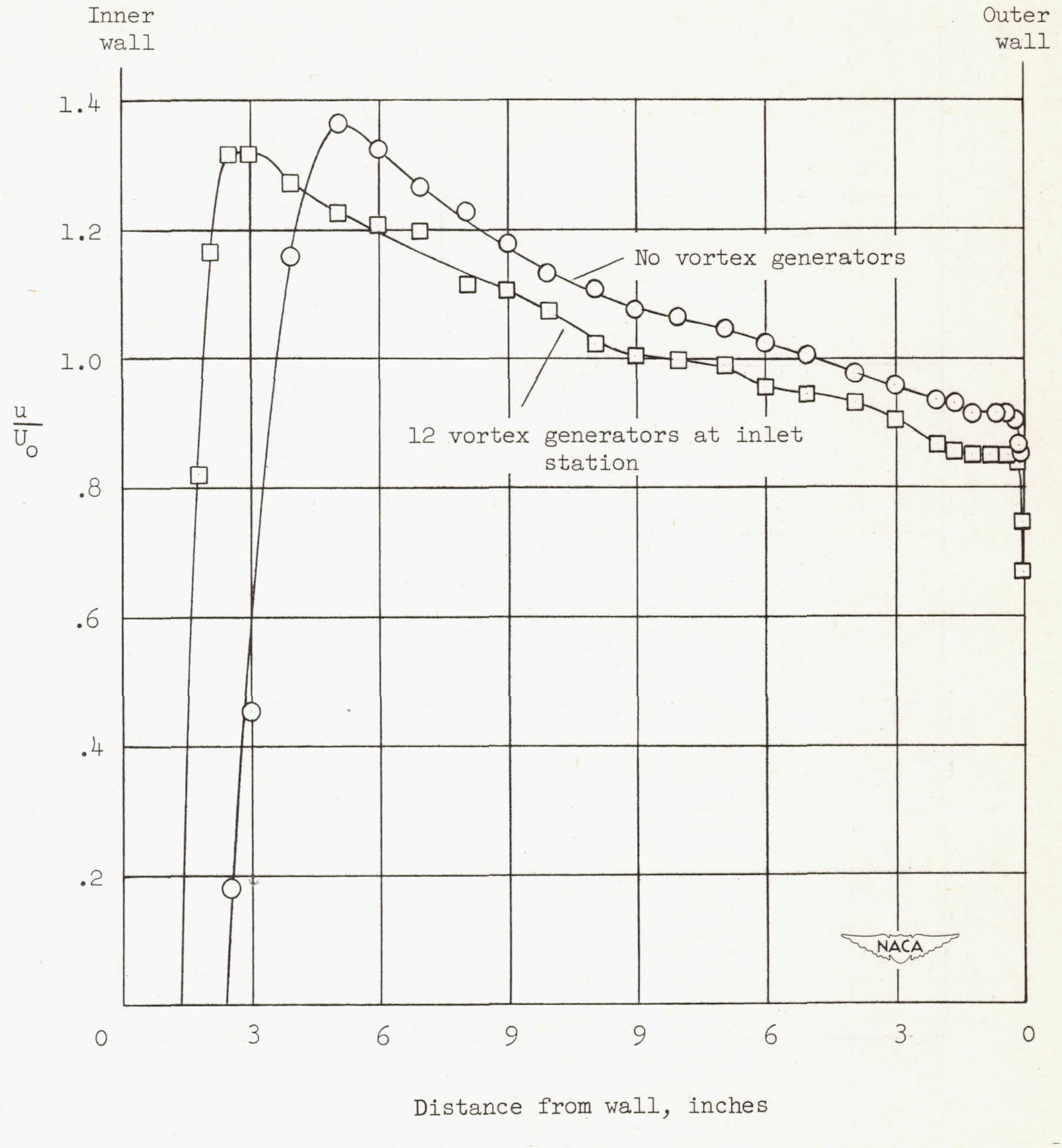


Figure 13.- Velocity distributions in plane of symmetry at elbow outlet. $\alpha = 12^\circ$; $b/\delta^* = 7.3$; $b/c = 0.500$; $\phi = 132^\circ$; $\beta = 12^\circ$; $s/b = 1.333$.

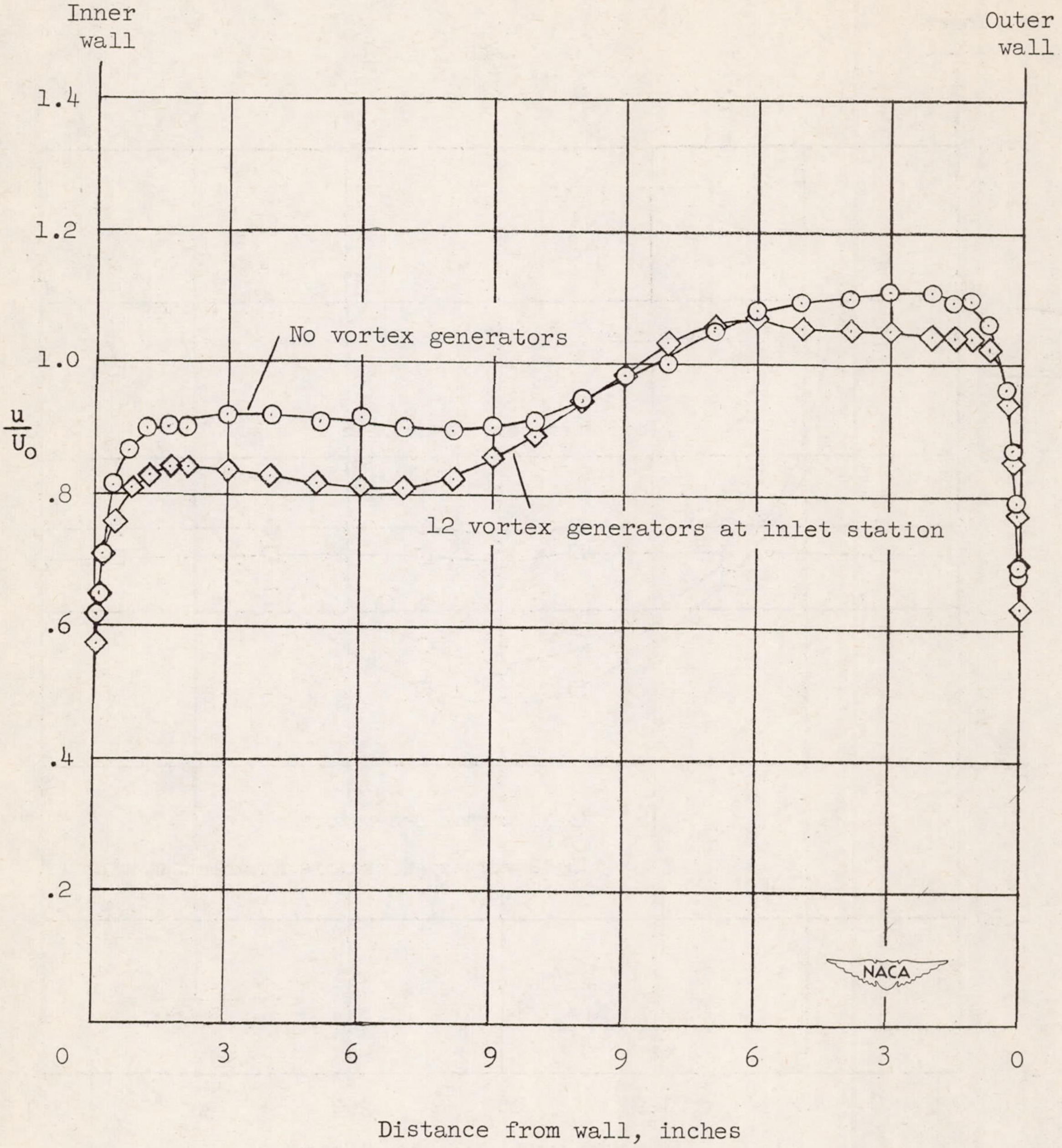


Figure 14.- Velocity distribution in plane of symmetry 4 diameters downstream of elbow outlet. $\alpha = 12^\circ$; $b/\delta^* = 9.7$; $b/c = 0.654$; $\phi = 132^\circ$; $\beta = 12^\circ$; $s/b = 0.995$.

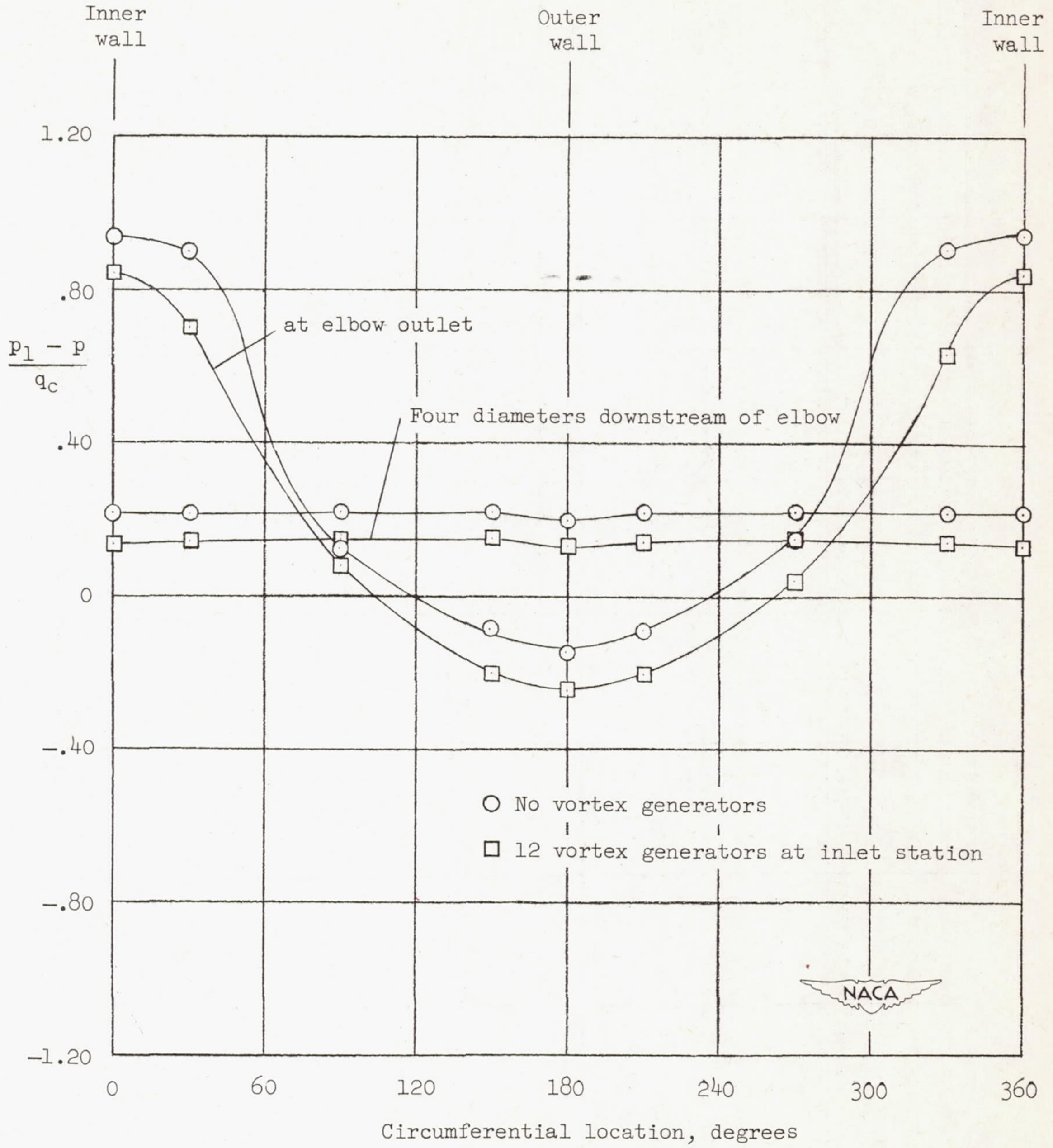


Figure 15.- Circumferential variation of static pressure downstream of elbow. $\alpha = 12^{\circ}$; $b/c = 0.500$; $b/\delta^* = 7.3$; $\phi = 132^{\circ}$; $\beta = 12^{\circ}$; $s/b = 1.333$.

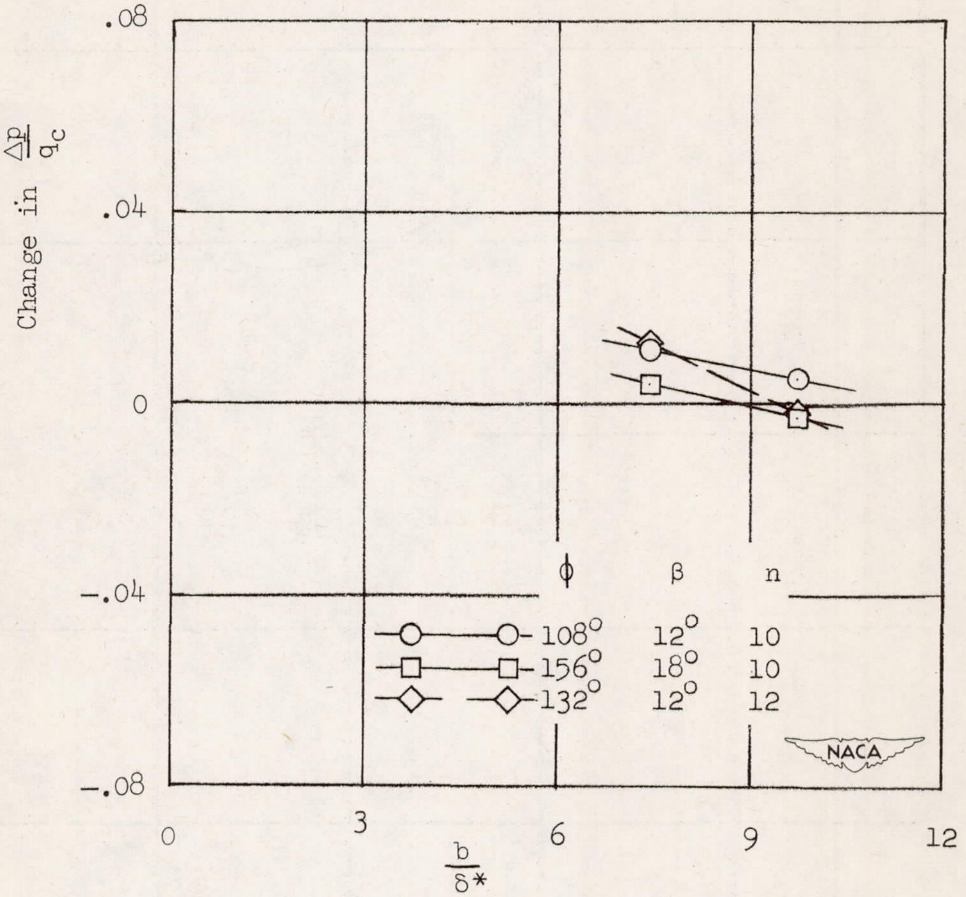


Figure 16.- Effect of moving vortex generators 1/4 diameter upstream. $\alpha = 12^\circ$; $c/\delta^* = 14.9$.

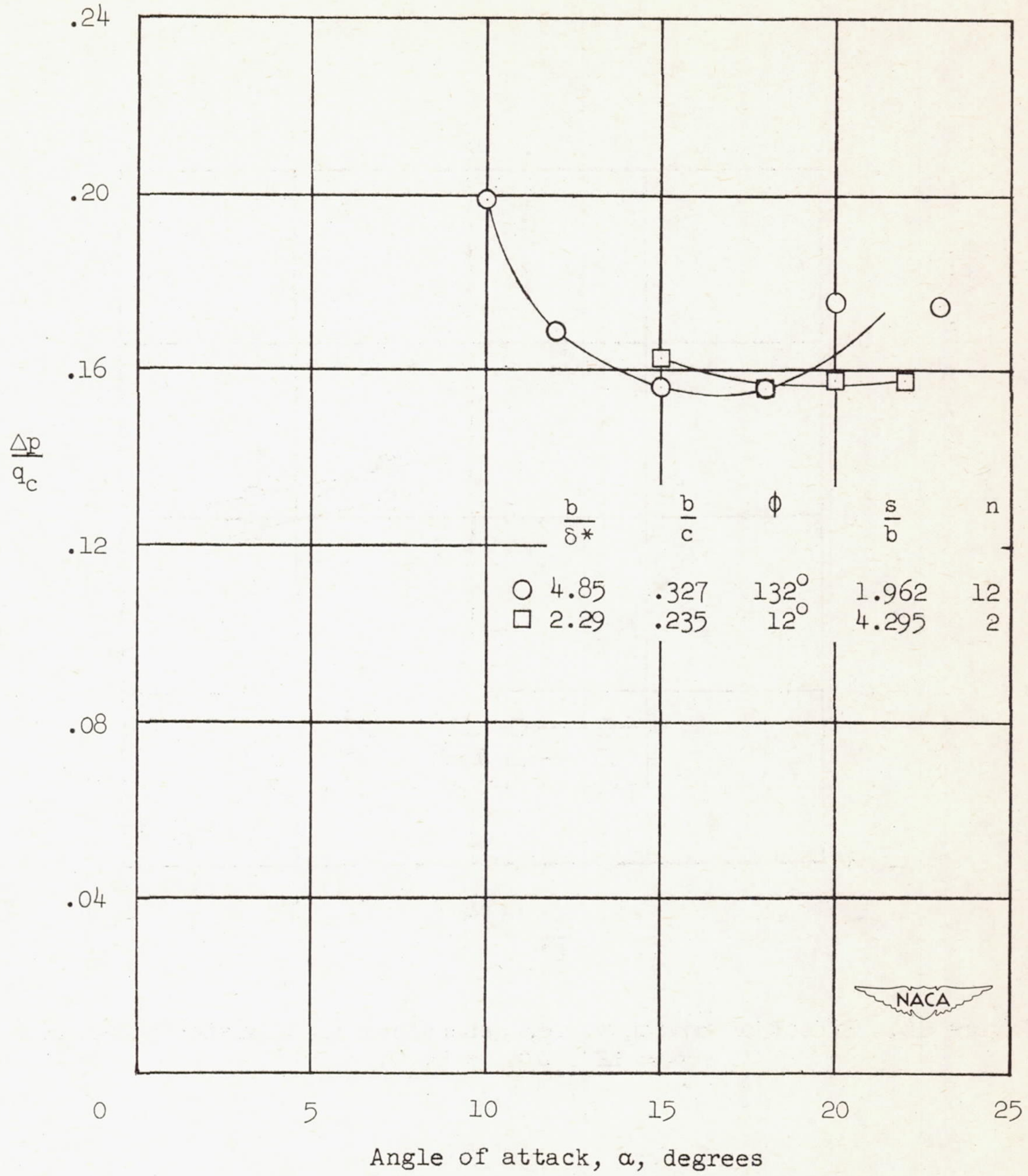


Figure 17.- Effect of angle of attack of vortex generators located 15° into the elbow. $\beta = 12°$.

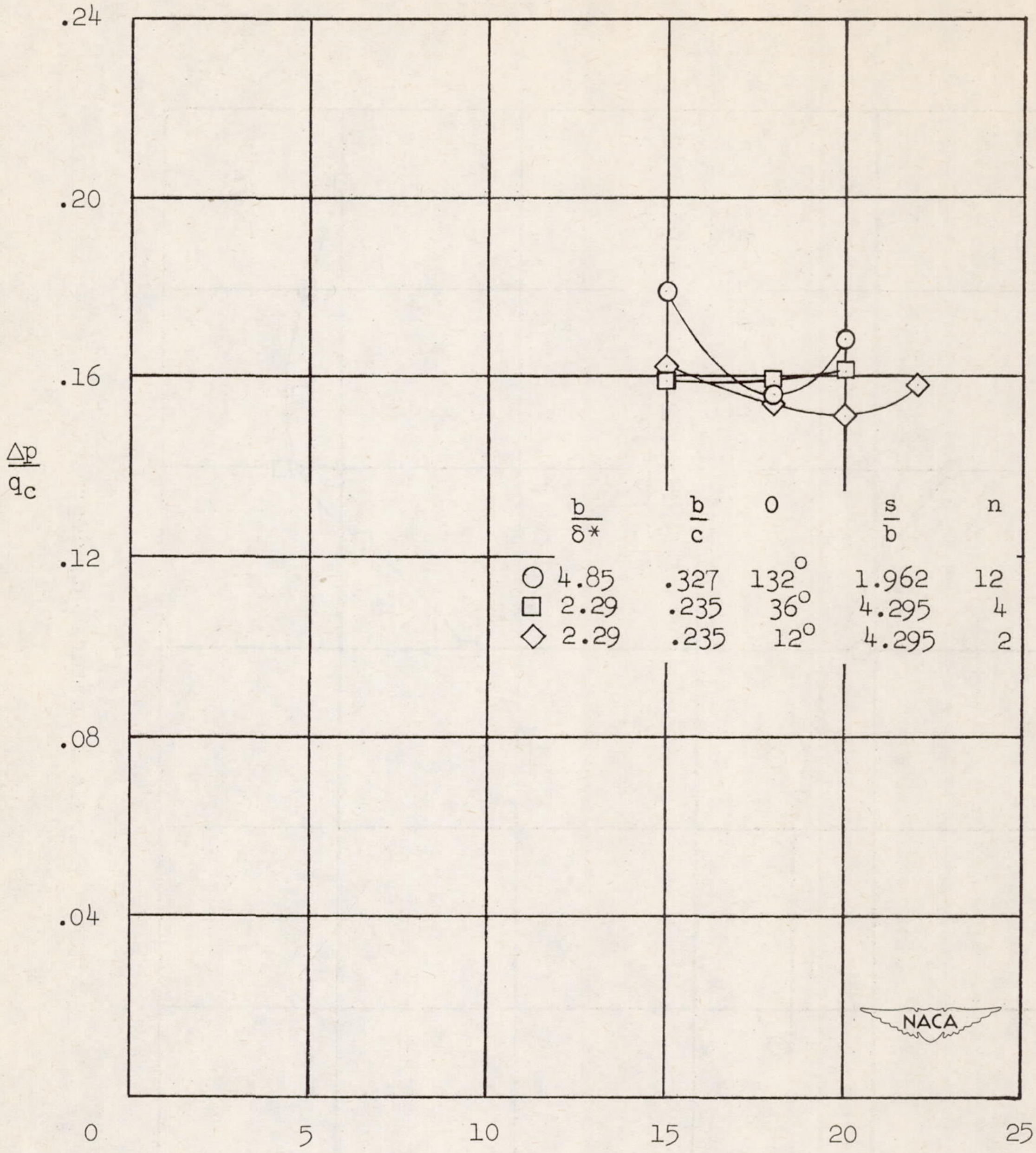


Figure 18.- Effect of angle of attack of vortex generators located 30° into the elbow. β = 12°.

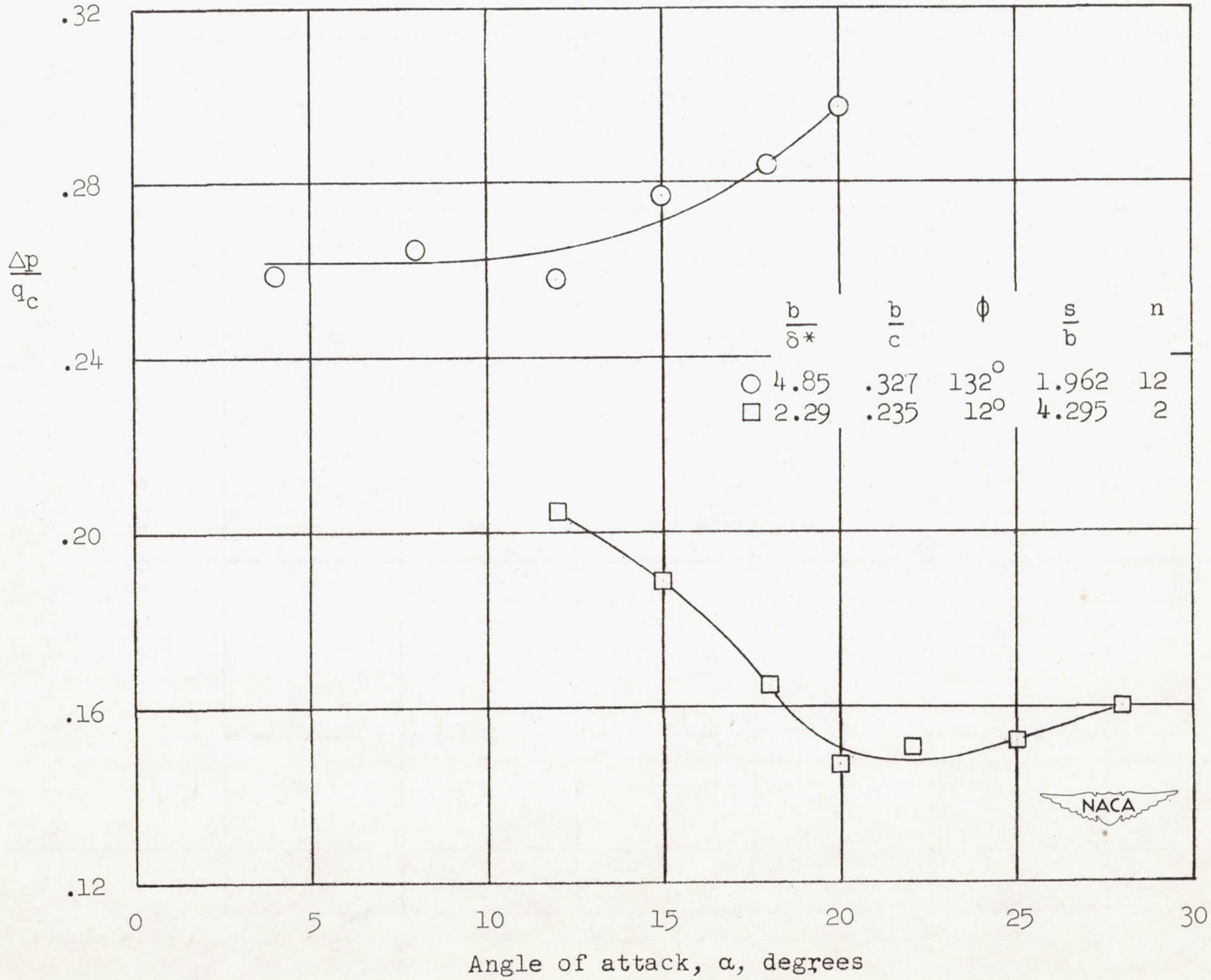


Figure 19.- Effect of angle of attack of vortex generators located 60° into the elbow. β = 12°.

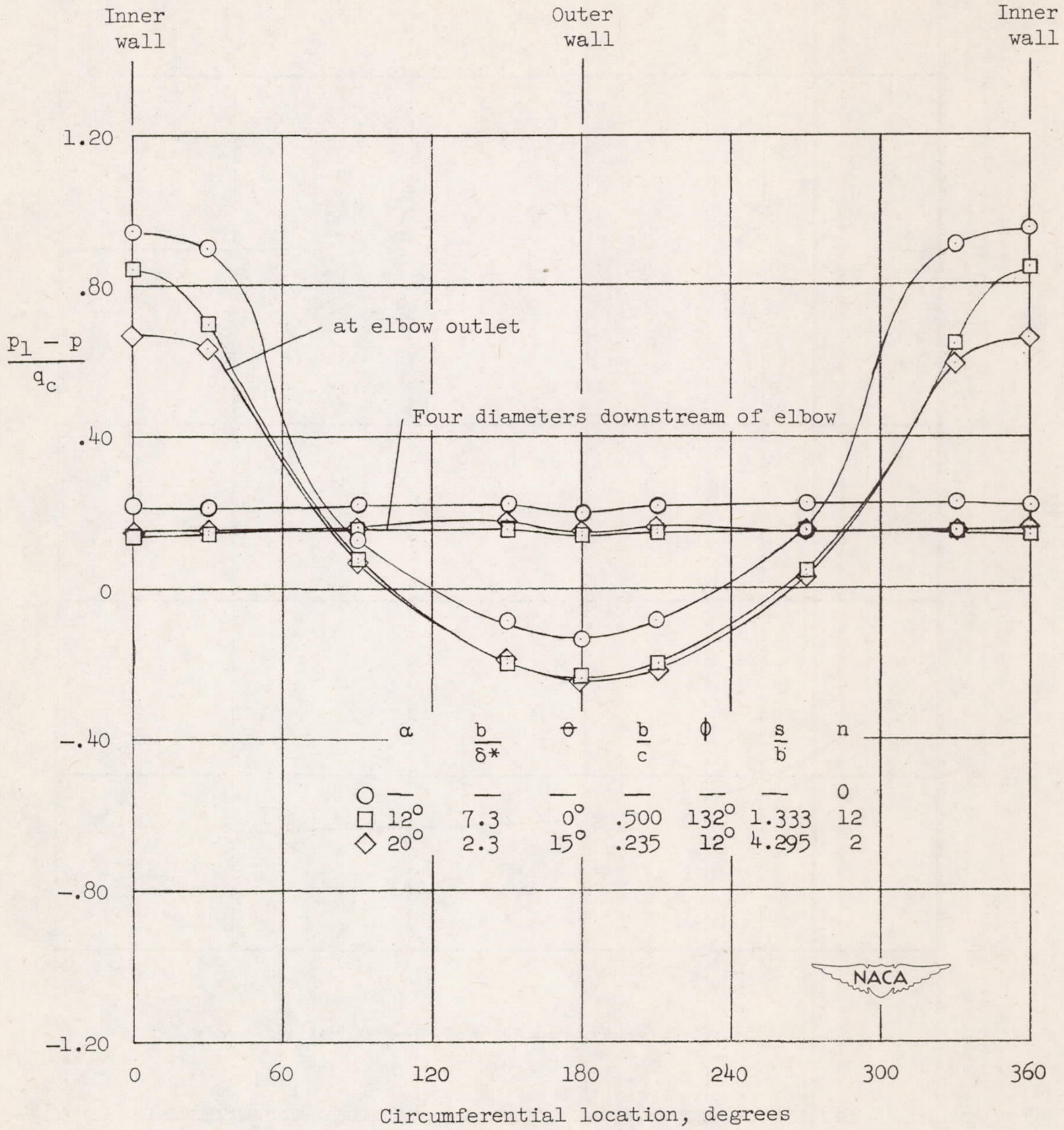


Figure 20.- Circumferential variation of static pressure downstream of elbow. $\beta = 12^{\circ}$.

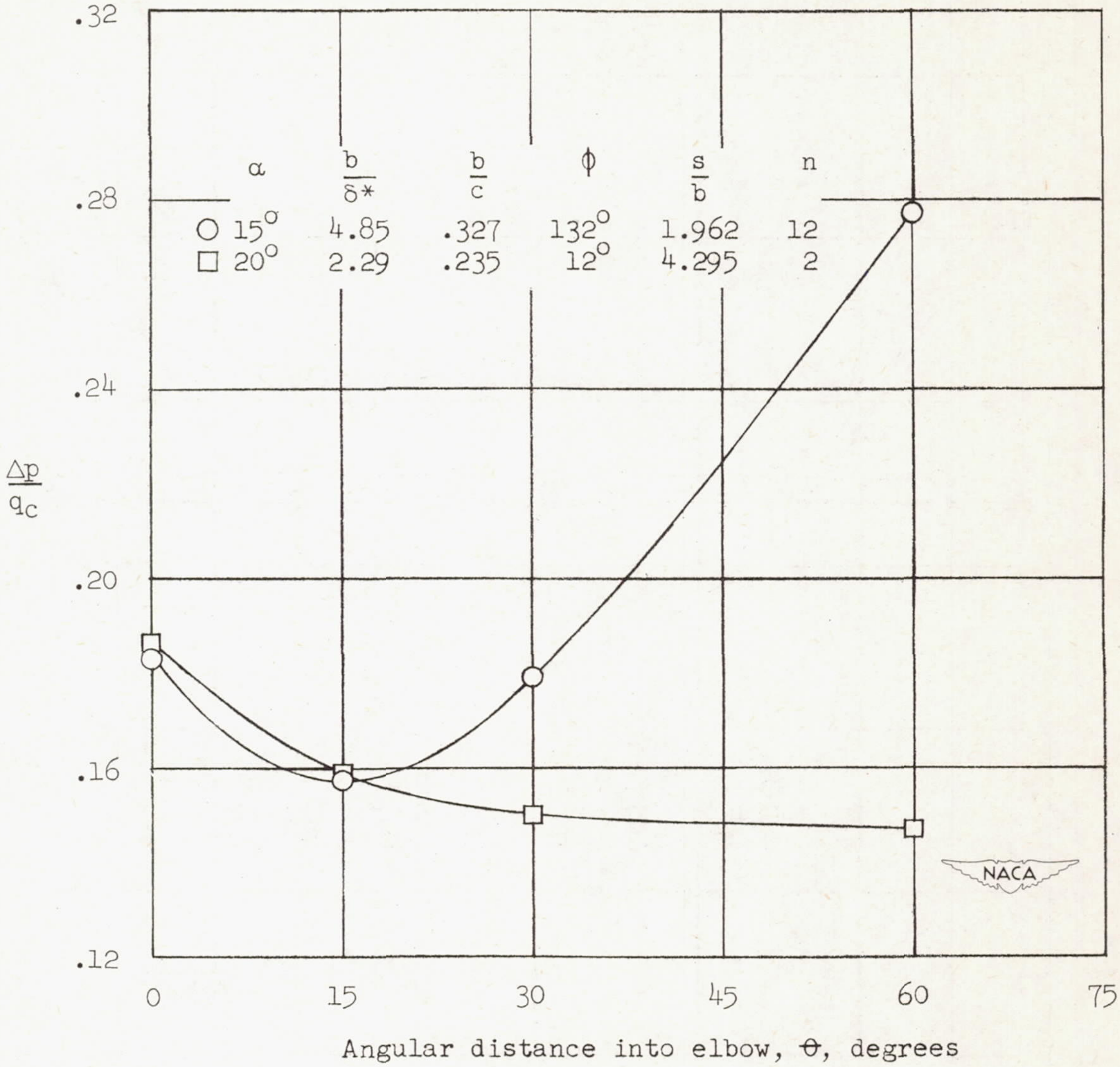


Figure 21.- Effect of moving two vortex-generator arrangements to different locations in the elbow. $\beta = 12^{\circ}$.

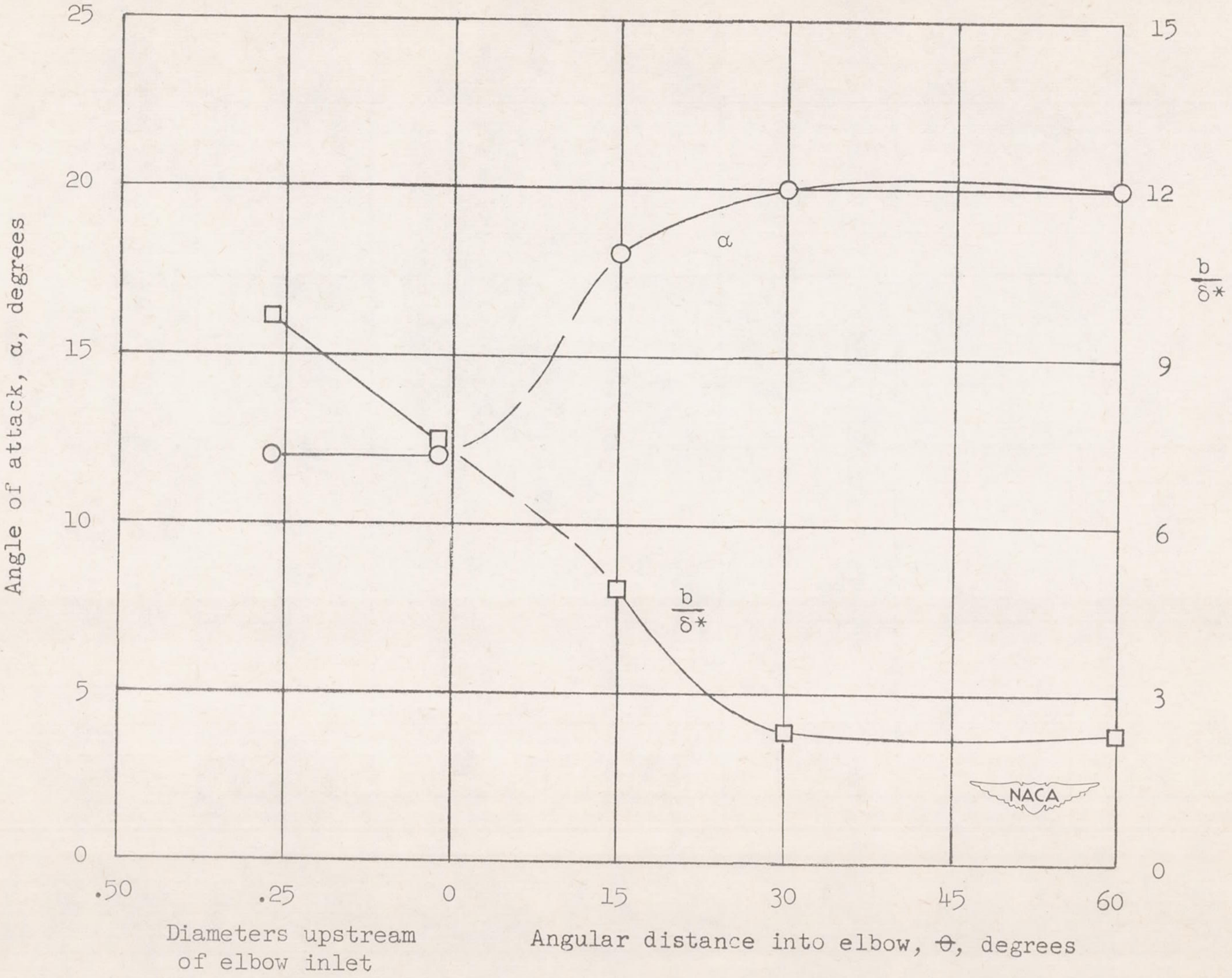
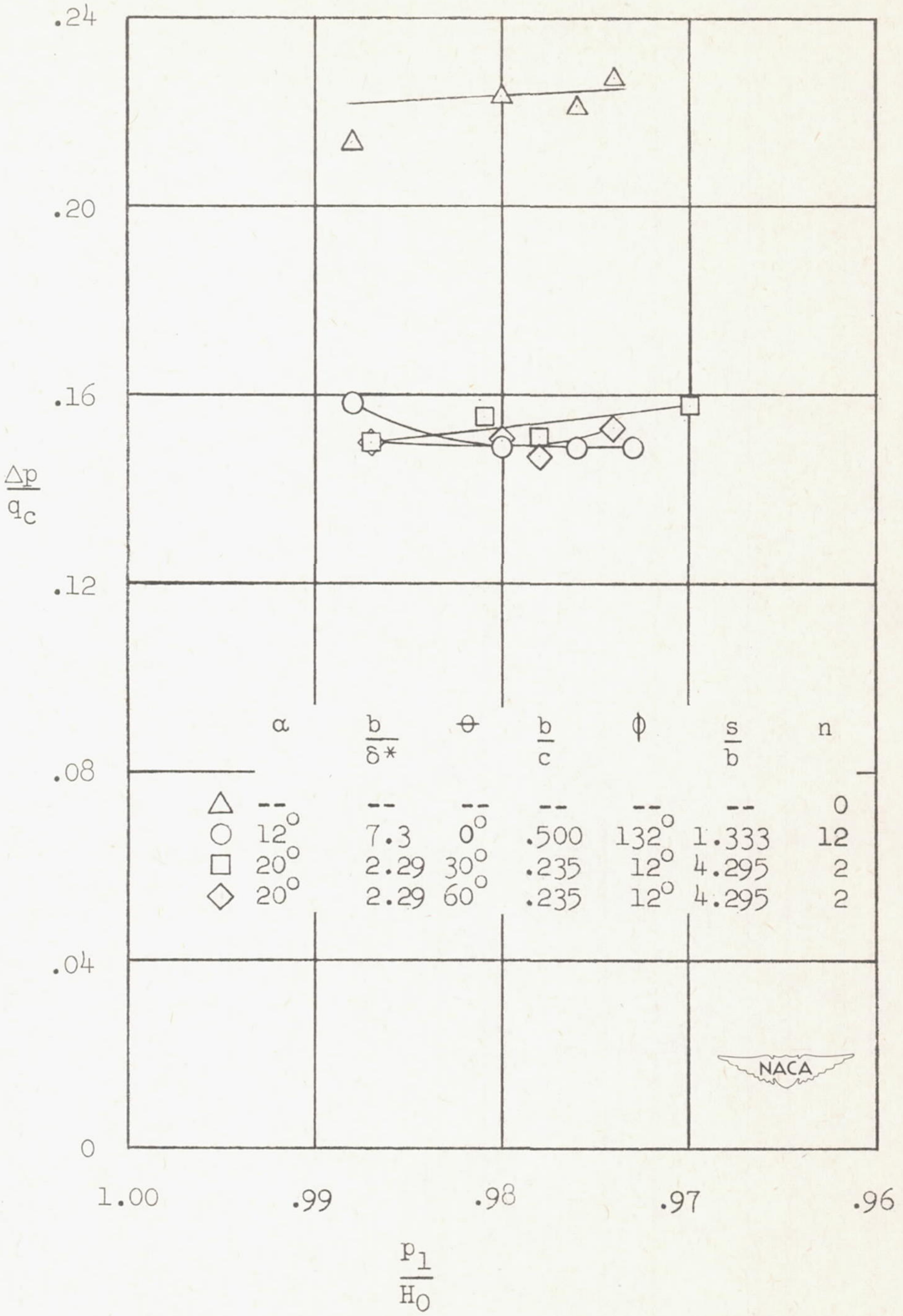


Figure 22.- Best values found for span and angle of attack.



	α	$\frac{b}{\delta *}$	θ	$\frac{b}{c}$	ϕ	$\frac{s}{b}$	n
△	--	--	--	--	--	--	0
○	12°	7.3	0°	.500	132°	1.333	12
□	20°	2.29	30°	.235	12°	4.295	2
◇	20°	2.29	60°	.235	12°	4.295	2

Figure 23.- Pressure drop obtained over a range of flow rate with vortex generators at inlet and at 30° and 60° into the elbow.