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RESEARCH MEMORANDUM

RAM-RECOVERY CHARACTERISTICS OF NACA SUBMERGED INLETS AT HIGH SUBSONIC SPEEDS

By Charles F. Hall and Joseph L. Frank

Ames Aeronautical Laboratory
Moffett Field, Calif.

NATIONAL ADVISORY COMMITTEE
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SUMMARY

Results are presented of an experimental investigation of the ram-recovery characteristics of NACA submerged inlets on a model of a fighter airplane at Mach numbers from 0.30 to 0.875. The effects on the entrance ram-recovery ratio of Mach number, angle of attack, entrance mass flow, boundary-layer thickness on the fuselage, inlet location, and boundary-layer deflectors are shown.

The data indicate only a slight decrease in ram-recovery ratio for the inlets ahead of or just behind the wing leading edge as Mach number increased, but show large decreases at high Mach numbers for the inlets aft of the point of maximum thickness of the wing. In general, the ram-recovery ratio decreased with increasing angle of attack. The ram-recovery ratio was a maximum at mass-flow ratios between 0.60 and 0.80. Artificially increasing the boundary-layer thickness or moving the inlets aft decreased the ram-recovery ratio. Boundary-layer deflectors increased the maximum ram-recovery ratio and the mass-flow ratio at which the maximum occurred.

INTRODUCTION

A research program was conducted in the Ames 16-foot high-speed wind tunnel which, in conjunction with work in an Ames 7- by 10-foot wind tunnel, continued the investigation of NACA submerged inlets developed during the tests discussed in references 1 and 2. Attention was concentrated on the inlet design found to have the most satisfactory pressure-recovery characteristics during the tests of reference 1. The effects of the following parameters on the pressure recovery at the inlets were investigated:

1. Aerodynamic parameters

   (a) Mach number

   (b) Angle of attack

   (c) Mass-flow ratio

   (d) Boundary-layer thickness

2. Model parameters

   (a) Inlet location with respect to wing and fuselage

   (b) Inlet lip angle

   (c) Boundary-layer deflectors

Data obtained during the present investigation of the model without inlets and with inlets 16.7 percent of the root chord ahead of the wing-root leading edge only were presented extensively in reference 3. To expedite the publication of the pressure-recovery characteristics for the inlets in other configurations, the present report was prepared.

SYMBOLS

The symbols used in this report and their definitions are as follows:

d	inlet depth, inches
H	average total pressure, pounds per square foot
$\frac{H_1-p_o}{H_o-p_o}$	ram-recovery ratio
h	the height of an area of unit width in which the complete loss of free-stream ram pressure is equivalent to the integrated loss of the total pressure in unit width of the boundary layer $\left[\int_o^\delta \left(\frac{H_o-H}{H_o-p_o}\right) dy\right]$, inches
M	Mach number

$\frac{m_1}{m_o}$ mass-flow ratio (the ratio of the mass flow through the inlet to the mass flow in the free stream through an area equal to the entrance area)

p static pressure, pounds per square foot

y increment of boundary-layer thickness, inches

α_u angle of attack uncorrected for tunnel-wall effects (measured relative to the fuselage reference line), degrees

δ boundary-layer thickness, inches

Subscripts

o free stream

1 duct entrance

APPARATUS

A complete description of the model was given in reference 3. Briefly, the model (shown in figs. 1 and 2) was patterned to represent a typical high-speed fighter airplane. Throughout the tests, a pair of identical inlets was used. They were disposed symmetrically on each side of the fuselage and connected to a common plenum chamber in the aft part of the fuselage. The four longitudinal inlet locations investigated (fig. 2) were at fuselage stations 34.25, 42.50, 50.75, and 59.00 and corresponded, respectively, to 16.7 percent of the root chord ahead of, and 8.3, 33.3, and 58.3 percent of the root chord behind the wing-root leading edge. Dimensions of the ramp, lip, and boundary-layer deflectors are shown in figure 3.

To determine the effect of boundary-layer thickness, the boundary layer along the fuselage surface was artificially increased from the natural thickness to medium and thick by roughening the fuselage 5 inches from the nose by means of small nails projecting from the surface. The boundary-layer thickness was measured with three small rakes, each consisting of 10 total-pressure tubes.

Pressure losses and flow rates at the intake were measured with a rake 2.1 inches behind the lip leading edge. The rake consisted of 30 total-pressure and 30 static-pressure tubes.

TESTS

During the tests the Mach number was varied from 0.30 to 0.875 and the Reynolds numbers per foot of length corresponding to these Mach numbers were 2.0×10^6 and 3.9×10^6, respectively. The principal angle-of-attack range of the tests was from -2° to 6°. At high Mach numbers, the strength of the model limited the maximum angle of attack to 1° at 0.875 Mach number. For some configurations, data were obtained from -3° to 12° angle of attack at low Mach numbers. The mass-flow ratio was varied from as low as zero to as high as 1.80, depending upon the effects of flow instability and Mach number. With the lowest total mass-flow rate of both inlets, the effect of flow instability was to force most of the air through one or the other of the inlets. Because most of the flow consistently entered the inlet in which the measurements were taken, for some angles of attack, data for low mass-flow ratios were not obtained. The highest mass-flow ratio depended upon the Mach number. At a Mach number of 0.875, a mass-flow ratio above approximately 0.90 could not be obtained, probably because of choking in the duct.

The boundary-layer thickness on the fuselage surface was measured without the inlets. Measurements were made simultaneously at three vertical locations (water lines 0 and ± 3.2) and separately at fuselage stations 20.0, 42.5, and 59.0. The effects of boundary-layer thickness were investigated only for the forward location of the inlets.

During the major portion of the investigation, the inlet lip angle (fig. 3) was -3°. With the inlets at the two forward locations, tests were also made with inlet lip angles of -1° and -5°.

The effects of boundary-layer deflectors were investigated for all inlet locations.

RESULTS AND DISCUSSION

Reduction of Data

<u>Data corrections</u>.- The Mach number calibration for the tests was derived from a survey of the wind tunnel without the model in place and corrected for constriction effects due to the presence of the model by the methods of reference 4. No other corrections were made to the data for tunnel-wall effects. Because of these effects, the uncorrected angle of attack of the model is approximately

10 percent smaller than it would be in free air for the same lift on the wing.

Total pressure and mass flow.– To expedite the publication of this report, the ram-recovery and mass-flow ratios have been computed from the average of the 30 total-pressure and 30 static-pressure readings rather than the more correct but time-consuming method used in reference 3. A comparison of the results from the two methods was made with the data from the inlets at station 34.25 with deflectors on the ramp and the differences are shown in figure 4. To indicate the possibility of adding these differences to correct the data of this report to agree with those which might be computed by the more correct method, calculations were made at random for data from tests of the inlets with deflectors on the ramps at the three other locations. The method using average-pressure values and the curves of figure 4 gave ram-recovery ratios which were in good agreement with the more exact method for mass-flow ratios above approximately 0.60 but which averaged approximately 0.02 lower at low mass-flow ratios.

Ram-Recovery Ratio

The ram-recovery data have been arranged to show first the effects of mass-flow ratio (fig. 5). Figure 6 presents values of the boundary-layer parameter on the fuselage and figures 7 to 9 show the effects of boundary-layer thickness, Mach number, angle of attack, inlet position, and boundary-layer deflectors on the ram-recovery ratio. Last, the original data from which the comparison plots were taken are shown in figures 10 to 18 as supplementary material with no formal discussion.

Effect of lip angle.– It was previously mentioned that the effects of lip angle were investigated during these tests. The data indicate no change in ram-recovery ratio for the range of lip angles tested. This result may be due to the fact that, with the rake at the entrance, it was impossible to obtain mass-flow ratios sufficiently large to exceed the critical Mach number of the inner surface of the lip at angles from -1° to -5°. Conditions under which lip angle might have a large effect on the ram-recovery ratio were not obtained, therefore. Because no effect of lip angle was evident in these tests, data in this report are presented for a lip angle of -3° only.

Effect of mass-flow ratio.– In general, the effect of mass-flow ratio on ram-recovery ratio was the same for all inlet positions. In figure 5 it is indicated that the effect of mass-flow ratio on ram-recovery ratio was large for the inlets at fuselage station 34.25. Increases in ram-recovery ratio of as much as 0.16 were obtained by increasing the mass-flow ratio from 0.40 to 0.60. Above 0.60 mass-flow ratio, the increase in ram-recovery ratio was, in general, small and a maximum value was usually reached between 0.60 and 0.80 mass-flow ratio. This latter fact indicates that these submerged inlets should be designed to operate near 0.60 mass-flow ratio, because the small increase in ram-recovery ratio with increasing mass-flow ratio above 0.60 would probably be offset by the increasing duct and diffuser losses.

The small quantity of data obtained at mass-flow ratios below 0.40 showed that the variation of ram-recovery ratio with mass-flow ratio was larger than that measured for higher mass-flow ratios. The data obtained at these low mass-flow ratios are believed to be somewhat questionable, however, due to the instability of flow which was observed during these tests, and also because those data for mass-flow ratios near zero indicate that the static pressure in the diffuser was as much as 10 percent of the free-stream ram pressure higher than the total pressure measured at the entrance.

Effect of boundary-layer thickness.- The boundary-layer parameter shown in figure 6 was selected to indicate concisely the boundary-layer thickness on the fuselage. The data show that, for the natural boundary layer, the parameter increased greatly on the forward part of the fuselage as the Mach number increased. This effect is attributed to the increase in Reynolds number associated with the Mach number increase, which probably caused a forward movement of the transition point. As the transition point for the medium and thick boundary layers was fixed at fuselage station 5.00 by the roughness, little or no increase in the boundary-layer parameter was noted as the Mach number increased. Between fuselage stations 20 and 40, the parameter for the medium and thick boundary layers decreased with increasing angle of attack. This characteristic is believed to be due to the manner in which the boundary-layer thickness was artificially increased. The increase in the flow inclination along the fuselage due to the increase in angle of attack of the fuselage and upwash ahead of the wing would tend to sweep the air coming in contact with the protruding nails above the rakes measuring the boundary-layer thickness. The boundary-layer parameter for the medium and thick boundary layers would therefore tend to conform to that of the natural boundary layer along the fuselage in the vicinity of the wing as the angle of attack increased.

The effect of boundary-layer thickness on ram-recovery ratio is shown in figure 7 for the inlets at fuselage station 34.25. The effects of boundary-layer thickness remained essentially constant at a given angle of attack and Mach number throughout the range of mass-flow ratios. The data are compared, therefore, at 0.70 mass-flow ratio only.

The data indicate that thickening the boundary layer reduced the ram-recovery ratio throughout the Mach number and angle-of-attack range of the tests. A general statement of the effect of Mach number on the ram-recovery ratio with the medium or thick boundary layers cannot be made because the effect is not consistent throughout the angle-of-attack range. For example, with the thick boundary layer the ram-recovery ratio increased slightly with Mach number for 0° and 2° angle of attack but decreased at -2° and 6° angle of attack. With the natural boundary layer, the ram-recovery ratio in general decreased with Mach number throughout the angle-of-attack range.

Effect of inlet position and Mach number.- The comparison of the ram-recovery ratio for mass-flow ratios of 0.60 and 0.80 for each inlet position (fig. 8) shows that throughout the Mach number and angle-of-attack ranges of the tests the highest ram-recovery ratios were obtained with the inlets in the forward location. This characteristic was expected because of the thinner boundary layer on the fuselage surface at this location. The variation of ram-recovery ratio as Mach number increased was smallest for the inlets in the forward location, being less than 0.02 within the range of data presented.

The ram-recovery ratio for the inlets in the second position (station 42.50) compared satisfactorily with that of the forward location, being within 0.03 at 0.30 Mach number. The decrease in ram-recovery ratio as Mach number increased was slightly greater for the inlets in the second location than in the forward location, resulting in the recovery ratio being as much as 0.05 less for the second location at high Mach numbers. It should be realized, however, that with a fixed engine location the shorter ducting system from the inlets to the compressor face for the second inlet location might result in an increase in the efficiency of the ducting sufficiently large to offset the higher entrance losses.

At 0.30 Mach number, the ram-recovery ratio for the inlets in the two aft locations was within 0.07 of that for the forward location in the angle-of-attack range of -2° to 6°. Except for the inlets at station 50.75 from -2° to 0° angle of attack, however, the ram-recovery ratio of the inlets in the two aft locations was poor at high Mach numbers. With the inlets in the aft location, a ram-recovery ratio of only 0.60 was obtained at a Mach number of 0.80 and 2° angle of attack.

The decrease in ram-recovery ratio as Mach number increased could be due to an increase in the boundary-layer thickness; separation; or to shock waves along the fuselage, in the wing-fuselage juncture, or on the ramps. In reference 3 it was indicated that separation occurred at approximately fuselage station 50 at 0.30 Mach number and 12.5° angle of attack and moved aft to fuselage station 60 at 1° angle of attack as Mach number increased to 0.875. At low Mach numbers, the separation was caused by poor flow in the wing-fuselage juncture at high angles of attack. At high Mach numbers the separation was due to the large increase in the boundary-layer thickness caused by the shock wave at the wing-fuselage juncture. With the inlets in the two forward locations, the decrease in ram-recovery ratio as Mach number increased is believed to be due primarily to the thickening boundary layer caused by a forward movement of the transition point with increasing Reynolds number. This effect was indicated in the section discussing the effects of boundary-layer thickness and also by the fact that the decrease of ram-recovery ratio as Mach number increased was fairly steady throughout the Mach number range. Reference 3 showed that critical speeds along the ramp were barely exceeded at 0.875 Mach number with the inlets in the forward location, thus indicating that shock waves on the fuselage or the ramp were not the cause of the decrease of ram-recovery ratio. Reference 3 also indicated that it was unlikely that critical speeds would be reached on the ramps of the inlets at station 42.50 because the speeds in that region without inlets were below those in the region of station 34.25.

With the inlets in the two aft locations, much of the pressure loss can be attributed to the influence of the boundary layer. For example, when the boundary layer became thick and separated from the surface, pressure losses greater than free-stream ram pressure were obtained at subcritical speeds with the inlets in the aft location. (See fig. 18 for results at 12° angle of attack and a Mach number of 0.60 for which conditions reference 3 indicated subcritical speeds and a thick, possibly separated, boundary layer on the fuselage surface without inlets.) For conditions having a similar boundary-layer growth at supercritical speeds, it is believed that large losses also would be caused primarily by the thick boundary layer. (See figs. 6 and 8 for results at the highest angles of attack at Mach numbers of 0.70 and 0.80.) When the boundary layer on the fuselage did not thicken, as indicated by the boundary-layer data obtained without inlets (fig. 6), some of the losses might be attributed to boundary-layer and shock-wave interaction on the ramp. For example, in figure 8 the results show that the increase in losses with angle of attack at high Mach numbers was larger at 0.60 than 0.80 mass-flow ratio. This characteristic was probably due to the interaction of the shock wave and the thicker boundary layer on the ramp caused by the more adverse pressure gradient at 0.60 mass-flow ratio because the shock waves on the ramp were probably weaker at 0.60 mass-flow ratio. Reference 3 showed that along the ramps of the inlets in the forward location the increase in static pressure from the point of minimum pressure to the inlets was larger and the maximum airspeeds were lower at 0.60 than 0.80 mass-flow ratio. The effect of the boundary layer in the presence of shock waves would be less severe with a thinner boundary layer at the beginning of the ramp. This effect, together with the fact that for some conditions the losses are caused primarily by the extremely thick boundary layer, suggests that the characteristics of submerged inlets in regions of airspeeds as high as those obtained in the aft location would be much better in the absence of the thick boundary layer.

Effect of angle of attack.- The effect of angle of attack on the ram-recovery ratio also is shown in figure 8 for the four inlet locations. The data indicate that throughout the Mach number range at both 0.60 and 0.80 mass-flow ratio, the ram-recovery ratio decreased with increasing angle of attack. This decrease was probably caused by the increase in the boundary-layer parameter with angle of attack, as generally indicated in figure 6. Also for inlets in the two aft locations, this effect would be combined with that of the greater shock-wave intensity caused by the increase in airspeed along the fuselage induced by the wing at high Mach numbers.

Effect of deflectors.- The effect of deflectors on the ram-recovery ratio was essentially constant throughout the Mach number range. A comparison of the data obtained with and without deflectors at each of the four locations is shown, therefore, only for 0.70 Mach number in figure 9. The apparent extrapolation of some of the data for the inlets with deflectors at low mass-flow ratios is due to the fact that some of the end points for such data were beyond the limits of the plots of figure 9. Such curves were traced from the more complete curves of figures 15 to 18.

The data of figure 9 show that the effect of the deflectors was to increase the maximum ram-recovery ratio for all inlet locations.

The mass-flow ratio at which the maximum ram-recovery ratio was obtained increased as much as 0.30 with deflectors on the ramps. The effects of this latter characteristic are twofold. To take advantage of the higher maximum recovery ratios, characteristic of the inlets with deflectors, they must be operated at mass-flow ratios higher than required by the inlets without deflectors. The higher mass-flow ratios will increase the internal duct losses due to both the higher speeds in the duct and the higher rate of diffusion necessary to reduce the speed of the air to that required by the engine. The larger internal duct losses will therefore reduce part of the gain in ram-recovery ratio at the entrance due to the deflectors. On the other hand, because of the higher inlet velocities it would be possible to use a smaller inlet if deflectors were on the ramp. The increment of external drag attributed to the deflectors on the ramps would therefore be smaller than was indicated in reference 5 in which the inlets with and without deflectors were the same size. Reference 5 showed that the drag of deflectors like those used during the present investigation was large, but could be reduced somewhat by reshaping the aft part. It is believed, however, that the drag of even the better-shaped deflectors is too large to be compensated for by the increase in thrust possible with the higher ram-pressure recoveries.

The data of figure 9 also show that the deflectors reduced the effect of angle of attack on the ram-recovery ratio for the inlets in the two forward locations, but had little or no such effect for the inlets in the two aft locations. In the range of mass-flow ratios from roughly 0.40 to 0.70, the deflectors reduced the ram-recovery ratio.

CONCLUSIONS

A wind-tunnel investigation up to 0.875 Mach number of NACA submerged inlets on a model of a fighter airplane to determine the ram-recovery characteristics at the entrance indicated the following:

1. The ram-recovery ratio for the inlets in the forward locations (16.7 percent of the root chord ahead and 8.3 percent of the root chord aft of the wing-root leading edge) varied only slightly as Mach number increased. For the two aft locations (33.3 and 58.3 percent of the root chord aft of the wing-root leading edge) large decreases in ram-recovery ratio occurred at high Mach numbers and angles of attack above 2°.

2. The highest ram-recovery ratios were obtained with the

inlets in the forward location.

3. Increasing the boundary-layer thickness decreased the ram-recovery ratio.

4. In general, the ram-recovery ratio decreased with increasing angle of attack.

5. With no deflectors on the ramp the ram-recovery ratio increased greatly as mass-flow ratio increased to approximately 0.60, reached a maximum between 0.60 and 0.80 mass-flow ratio, and slowly decreased for greater flow rates.

6. The boundary-layer deflectors increased the maximum ram-recovery ratio and the mass-flow ratio at which it occurred. They reduced the ram-recovery ratio between approximately 0.40 and 0.70 mass-flow ratio and also reduced the change in ram-recovery ratio with angle of attack for inlets in the two forward locations.

Ames Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Moffett Field, Calif.

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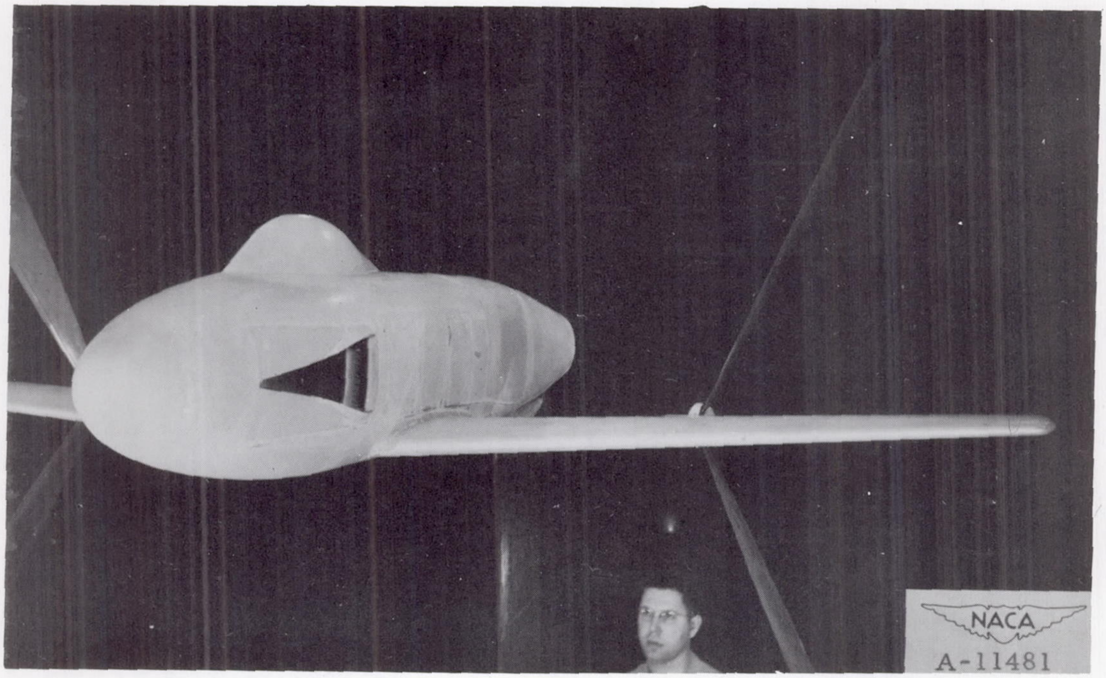
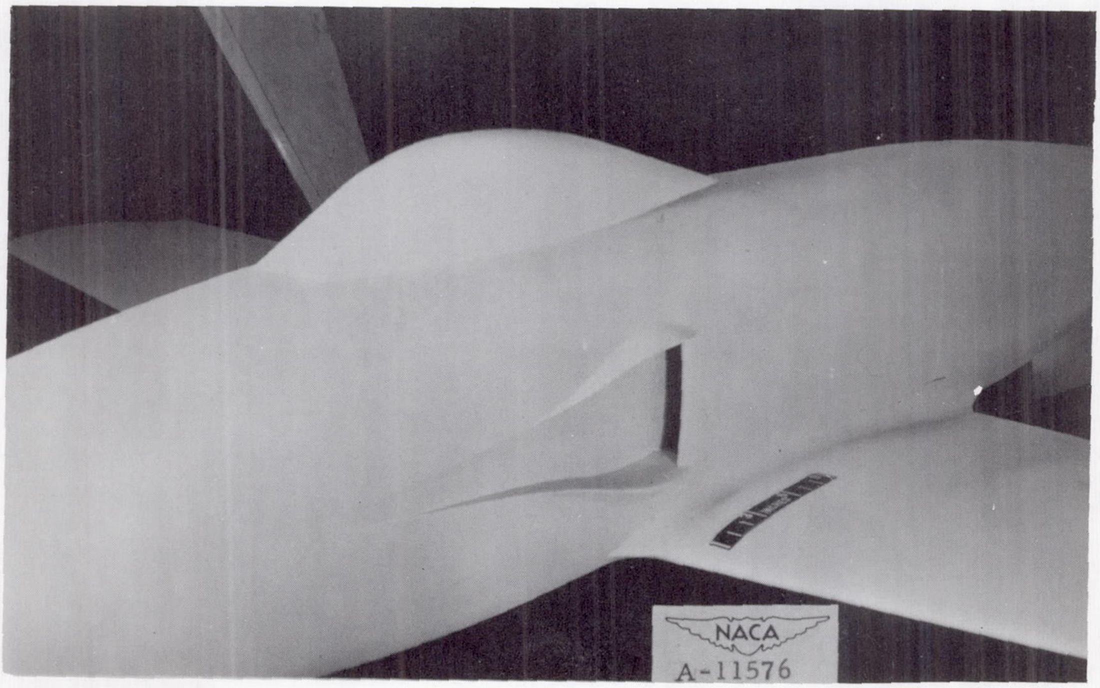
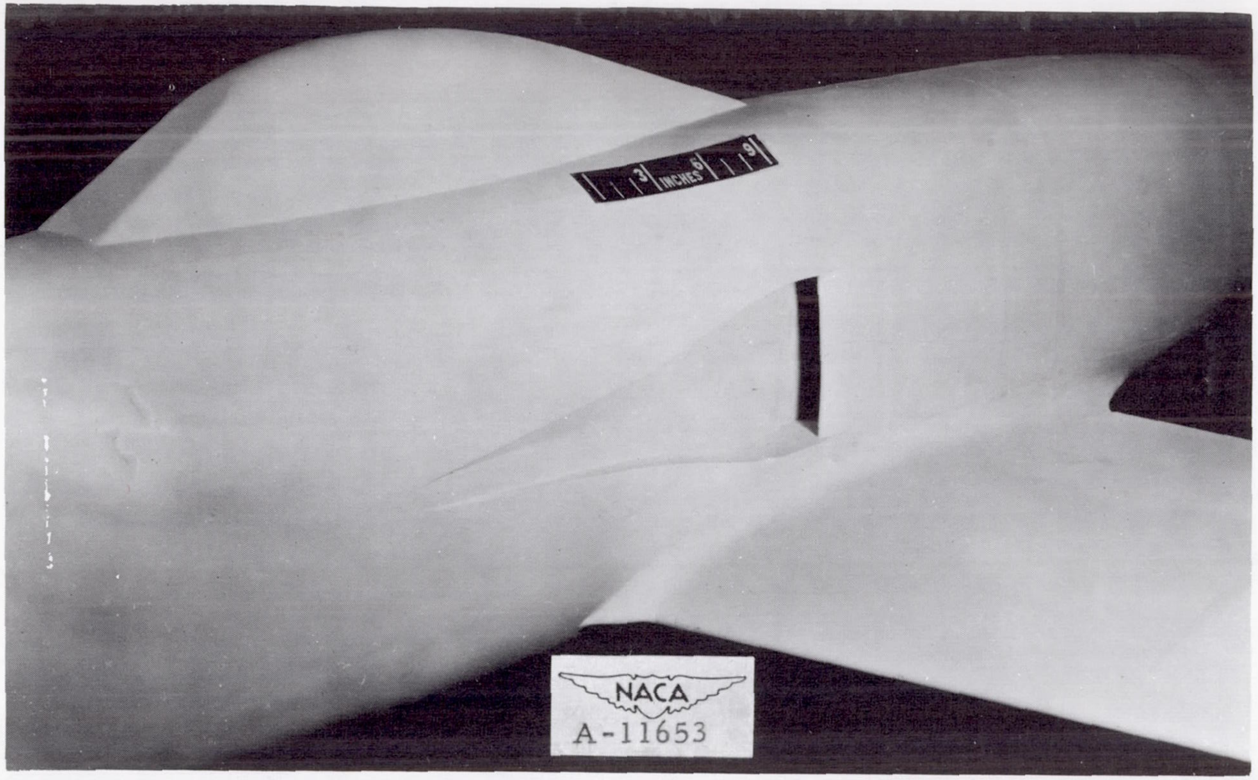


(a) Inlet with deflectors at fuselage station 34.25.



(b) Inlet with deflectors at fuselage station 42.50.

Figure 1.– Submerged inlet model in 16–foot wind tunnel.



(c) Inlet without deflectors at fuselage station 50.75.

Figure 1.– Concluded.

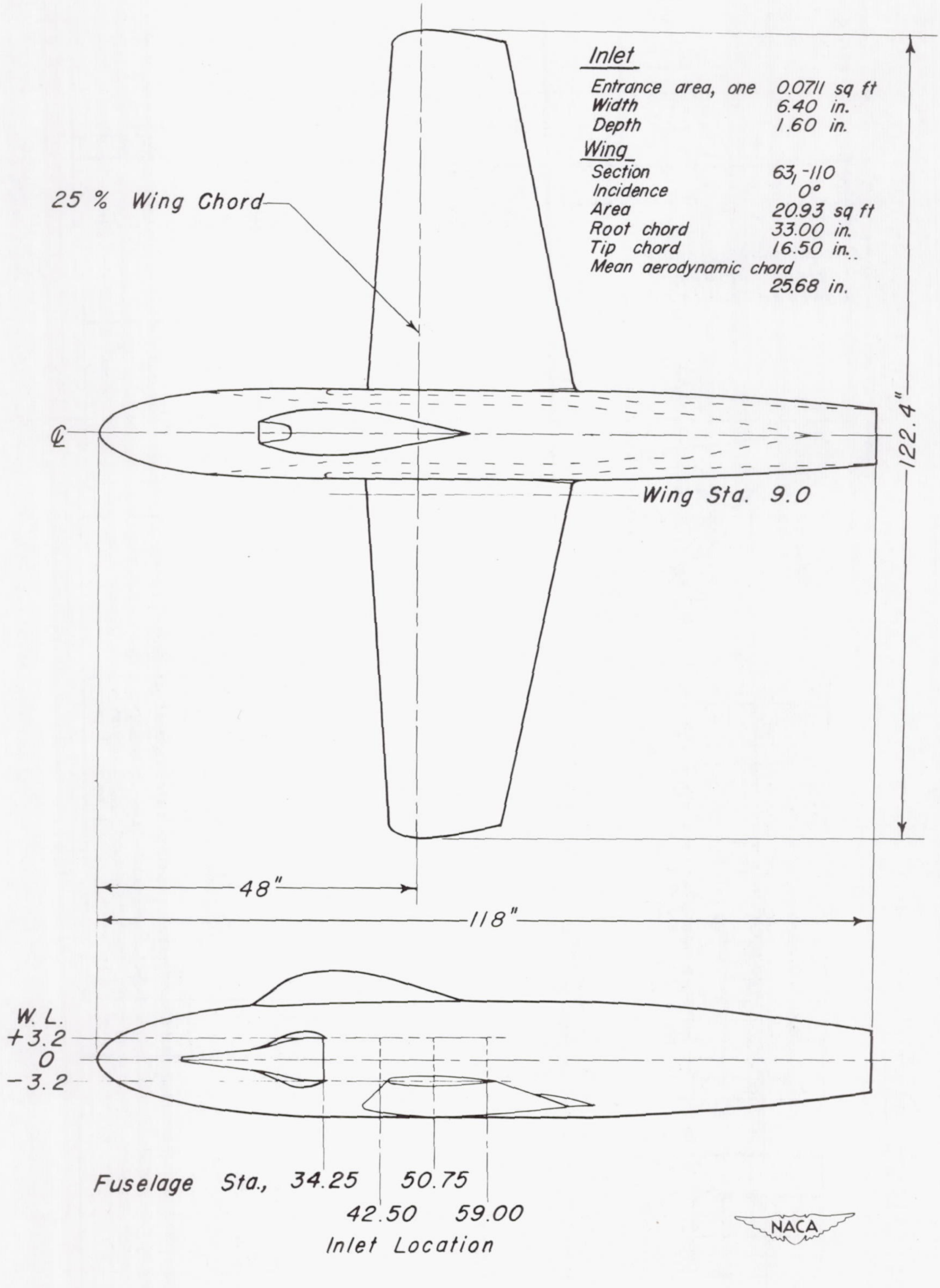
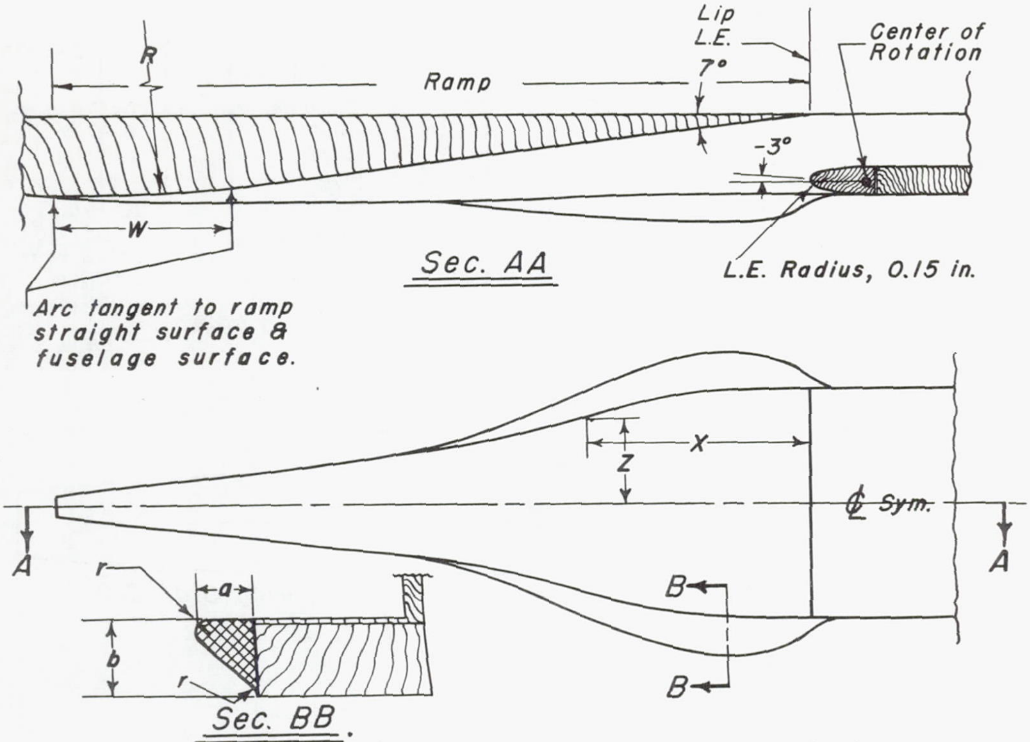


Figure 2.— Submerged-inlet model.



Deflector Coordinates

X- (in.)	a- (in.)	b- (in.)	r- (in.)
-0.63	0	0	0
-.32	.069	.099	.014
0	.224	.323	.047
.63	.446	.642	.094
1.27	.630	.907	.132
1.90	.721	1.038	.151
2.53	.745	1.073	.156
3.17	.741	1.067	.156
3.80	.723	1.041	.152
4.43	.694	.999	.146
5.06	.648	.933	.136
5.70	.588	.847	.123
6.33	.522	.752	.110
6.96	.452	.651	.095
7.60	.370	.533	.078
8.23	.284	.409	.060
8.86	.200	.288	.042
9.50	.122	.176	.026
10.13	.058	.084	.012
10.76	0	0	0

Lip Coordinates at -3° Lip Angle

Station	Outer Surface	Inner Surface
Inches From Nose	Inches From Fuselage Surface	Inches From Fuselage Surface
0	0.372	0.372
.2	.193	.568
.4	.131	.638
.6	.085	.691
.8	.055	.725
1.0	.032	.747
1.2	.015	.759
1.4	.004	.761
1.6	0	.762
1.8	0	.762

Ramp Wall Coordinates

X- (in.)	Z- (in.)
0	3.20
2.11	3.18
4.22	2.93
6.33	2.45
8.44	1.94
10.55	1.55
12.66	1.25
14.77	.99
16.88	.75
18.99	.51
21.10	.27

Ramp Coordinates

No.	Inlet Location	W- (in.)	R- (in.)
1	34.25	8.60	32.40
2	42.50	5.02	29.70
3	50.75	3.75	28.85
4	59.00	3.75	30.70

Figure 3.— Dimensional data for inlets.

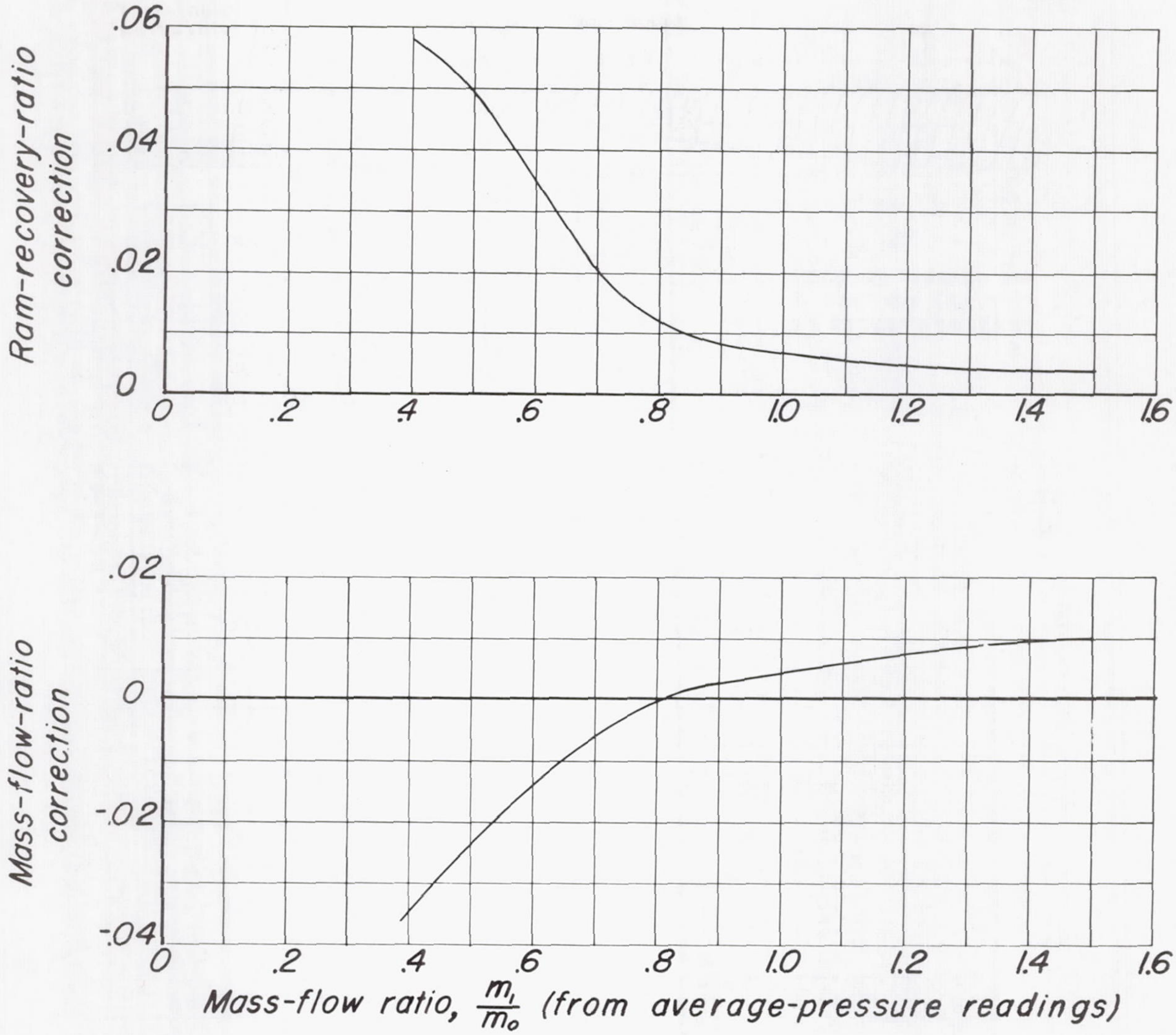


Figure 4. — Ram-recovery-ratio and mass-flow-ratio correction.

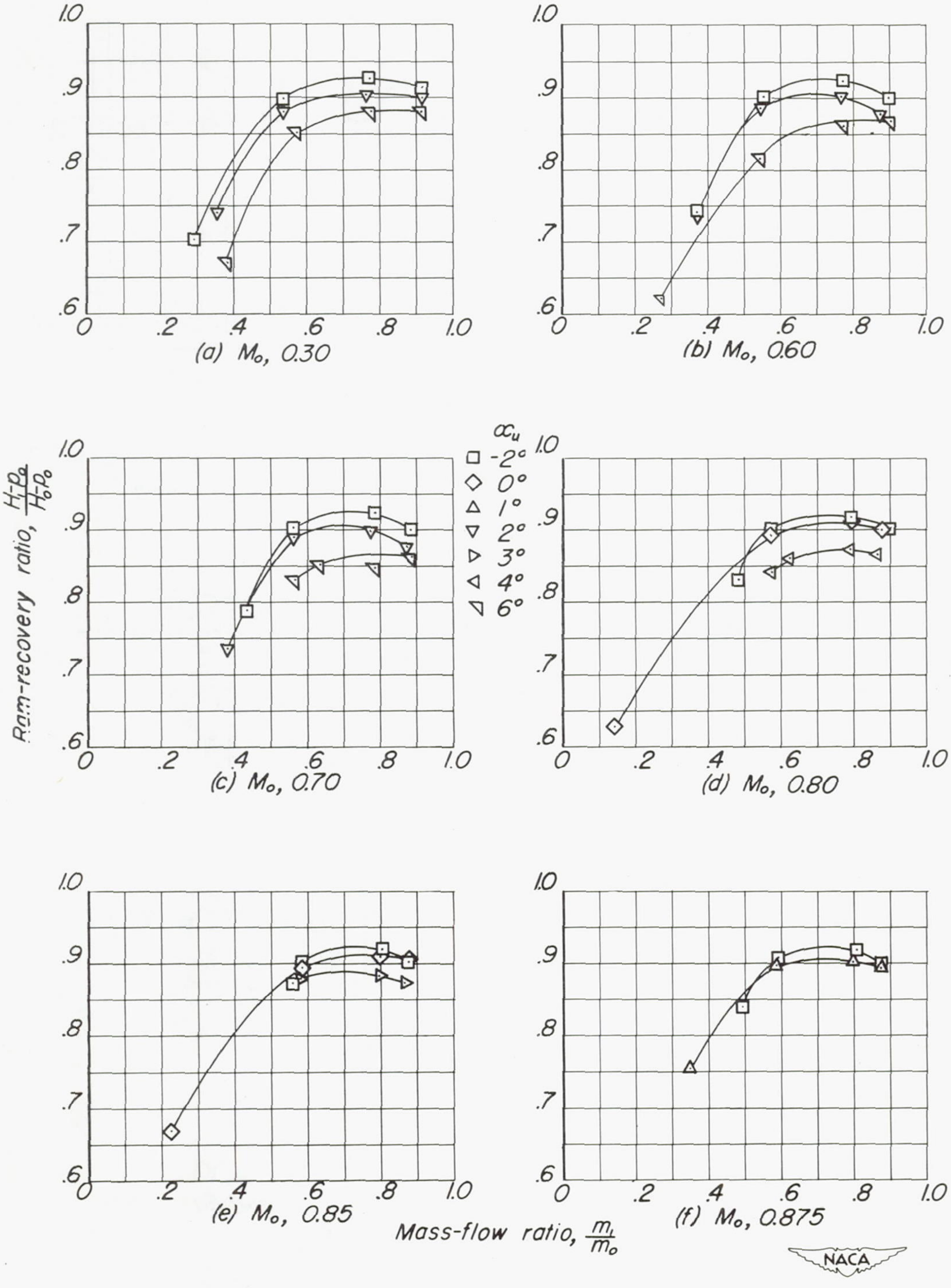


Figure 5. — Ram-recovery ratio at entrance of inlet at fuselage station 34.25. No deflectors on ramp; natural boundary layer.

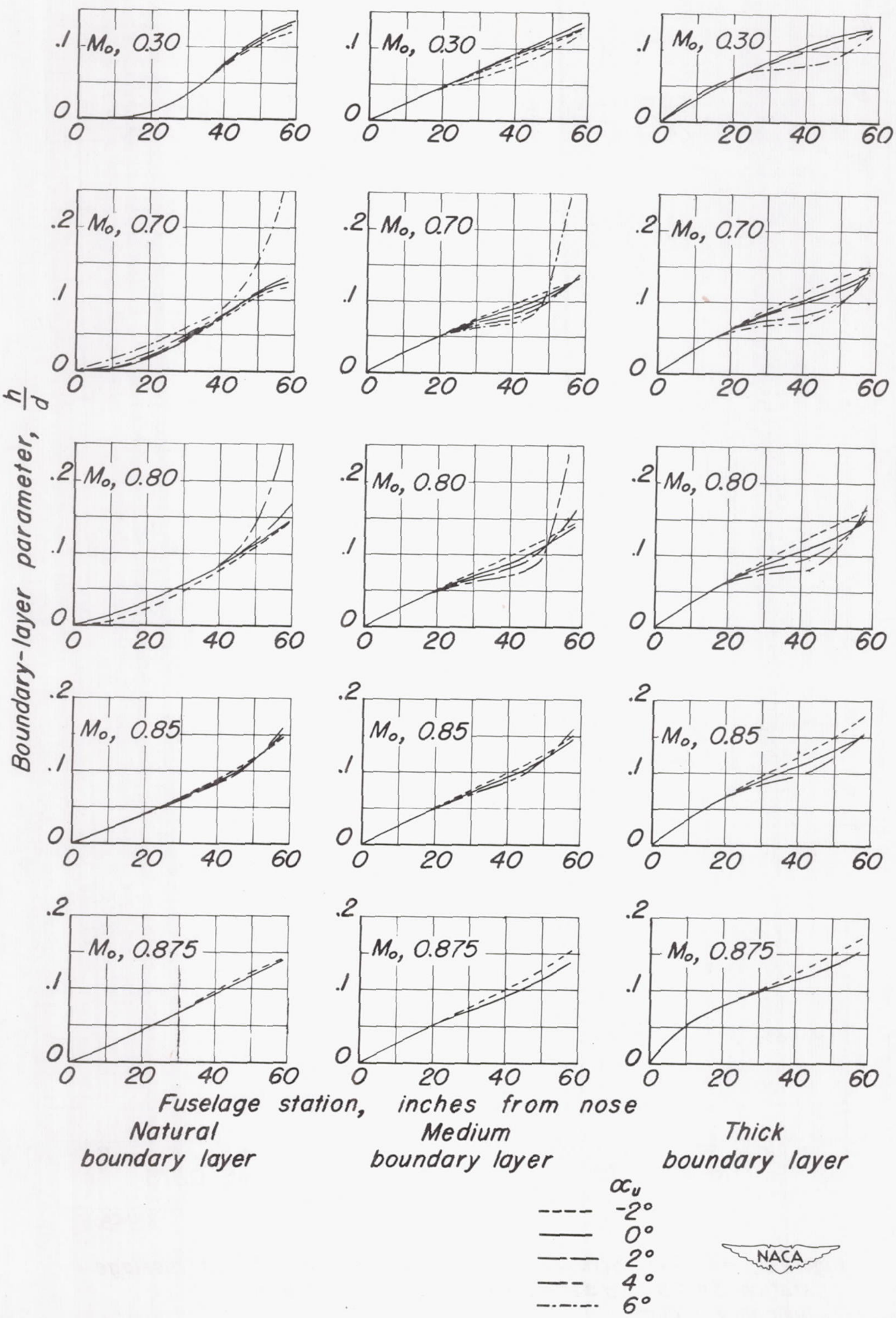


Figure 6. — Boundary-layer parameter.

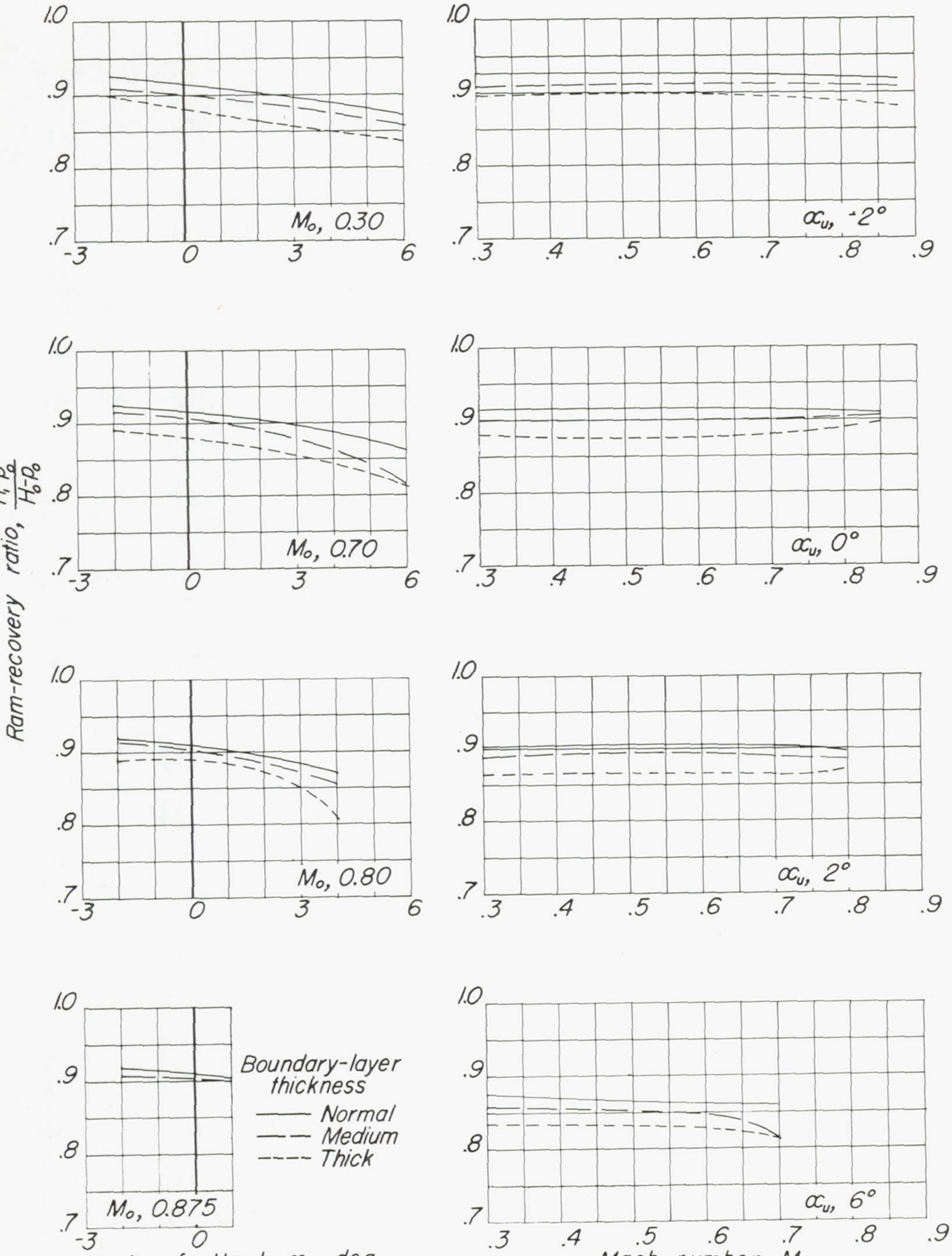
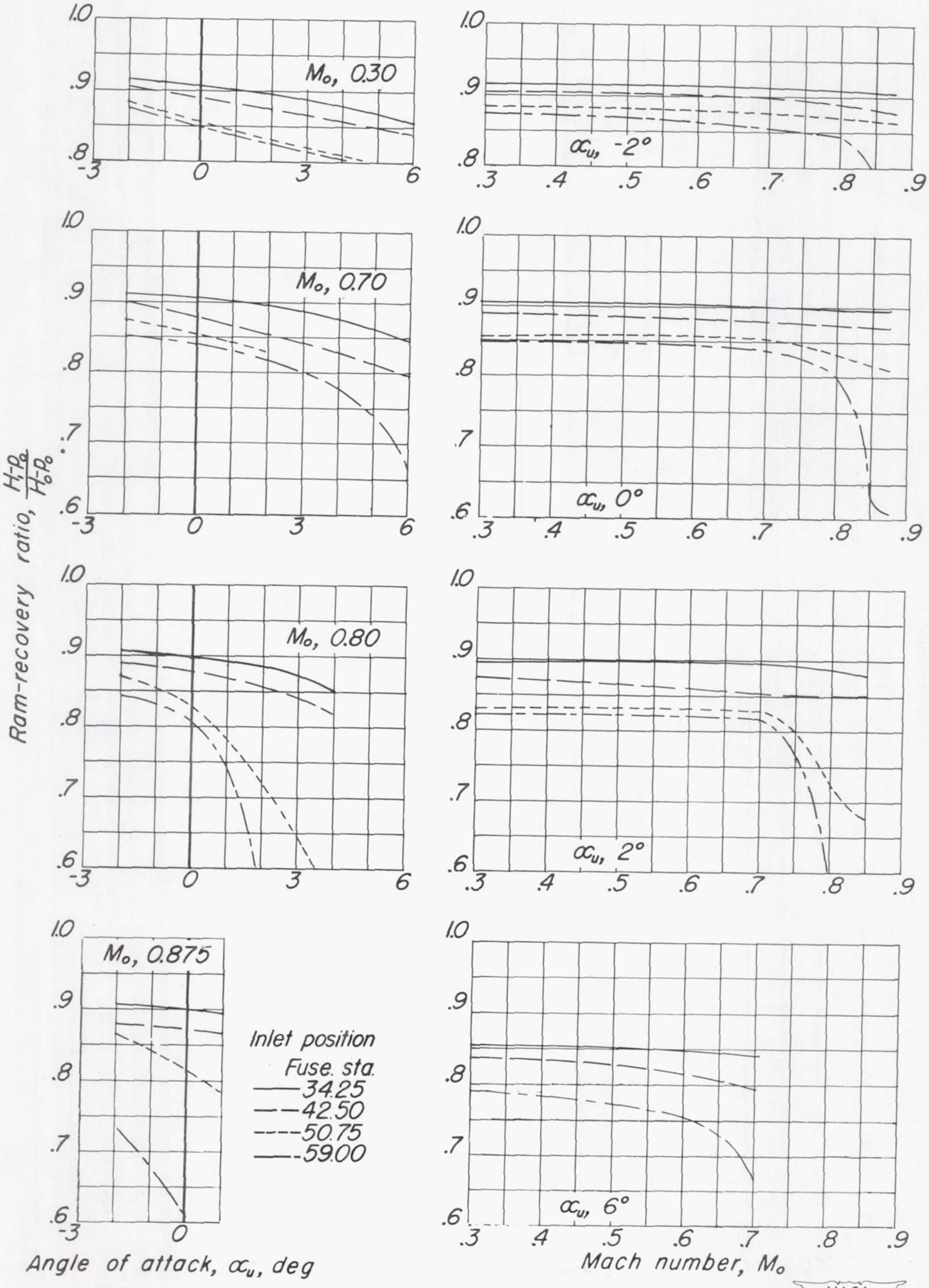
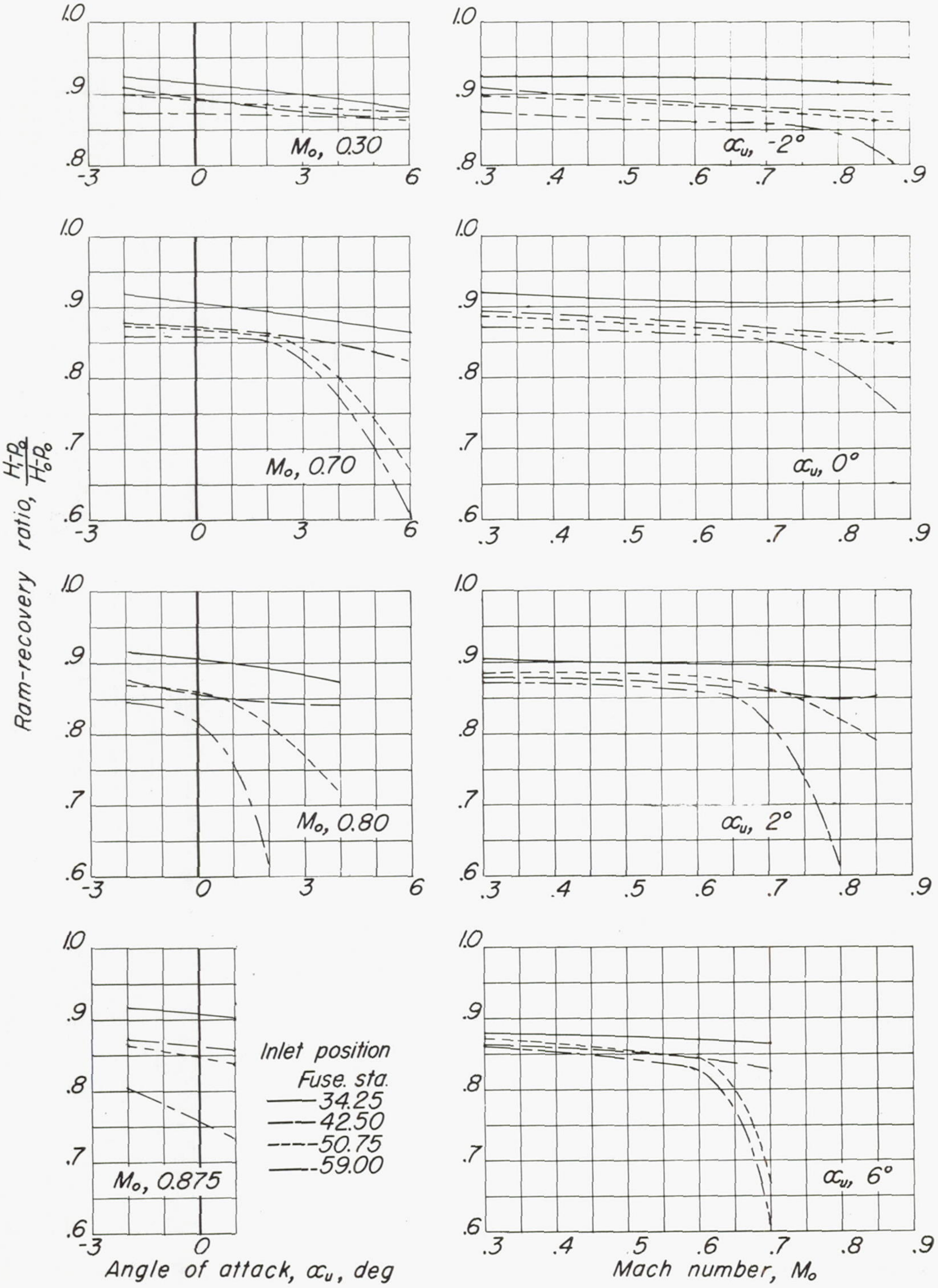


Figure 7. — Effect of boundary-layer thickness on ram-recovery ratio for 0.70 mass-flow ratio. Inlet at fuselage station 34.25; no deflectors on ramp.



(a) m_1/m_0 , 0.60

Figure 8 — Effect of inlet location on ram-recovery ratio. No deflectors on ramp; natural boundary layer.



(b) m_1/m_o, 0.80

Figure 8. — Concluded.

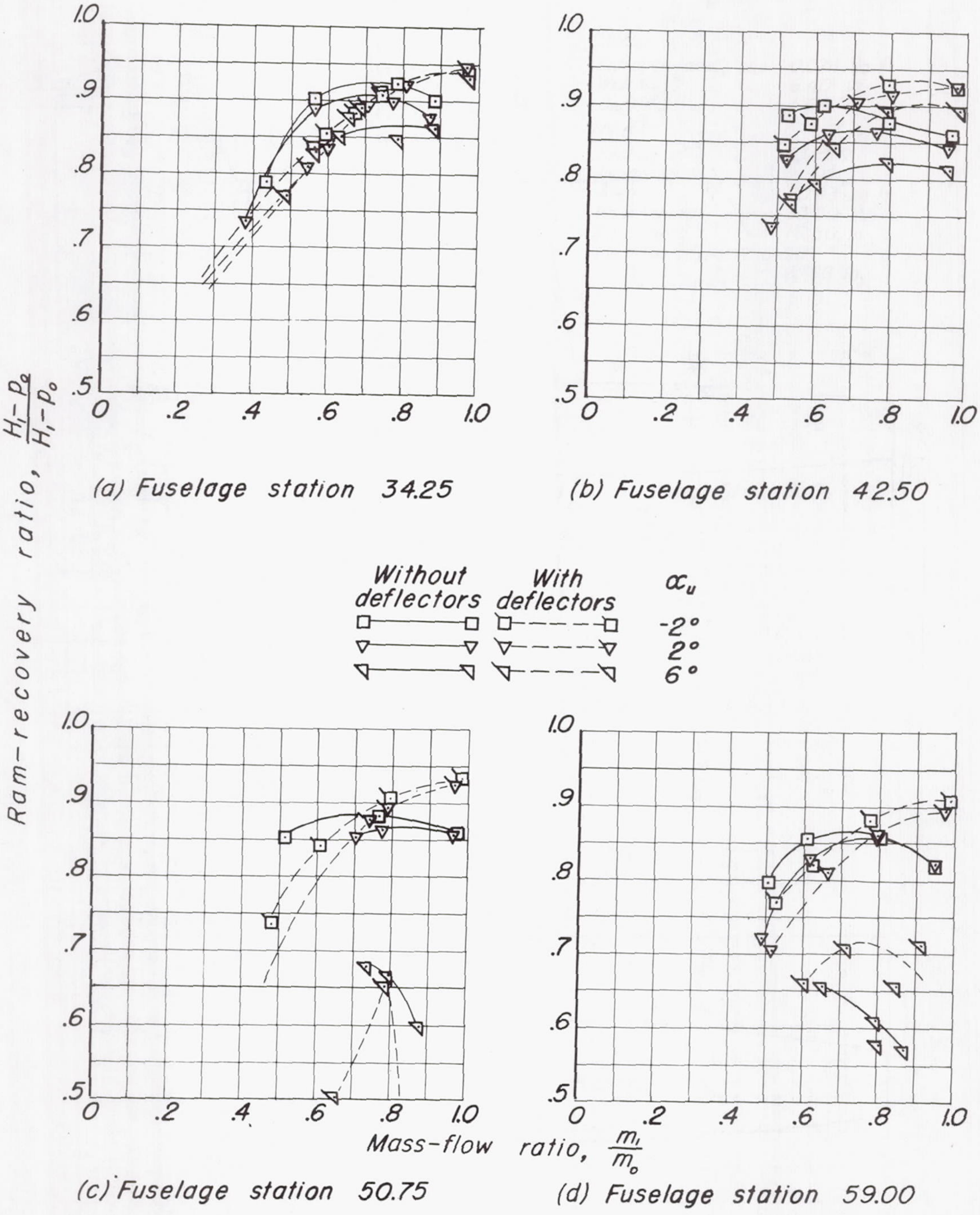


Figure 9. — Effect of boundary-layer deflectors on ram-recovery ratio for 0.70 Mach number.

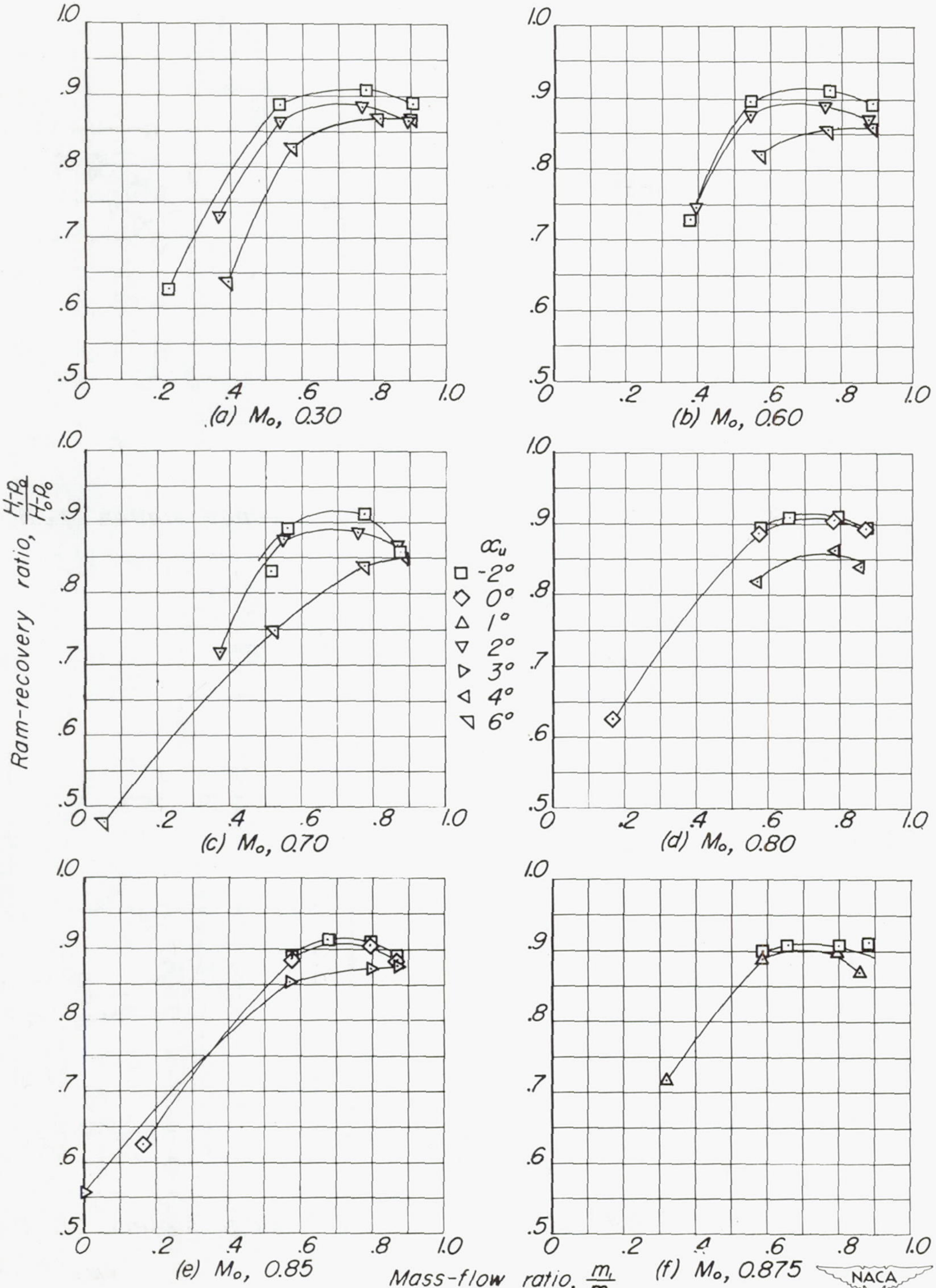


Figure 10. — Ram-recovery ratio at entrance of inlet at fuselage station 34.25. No deflectors on ramp; medium boundary layer.

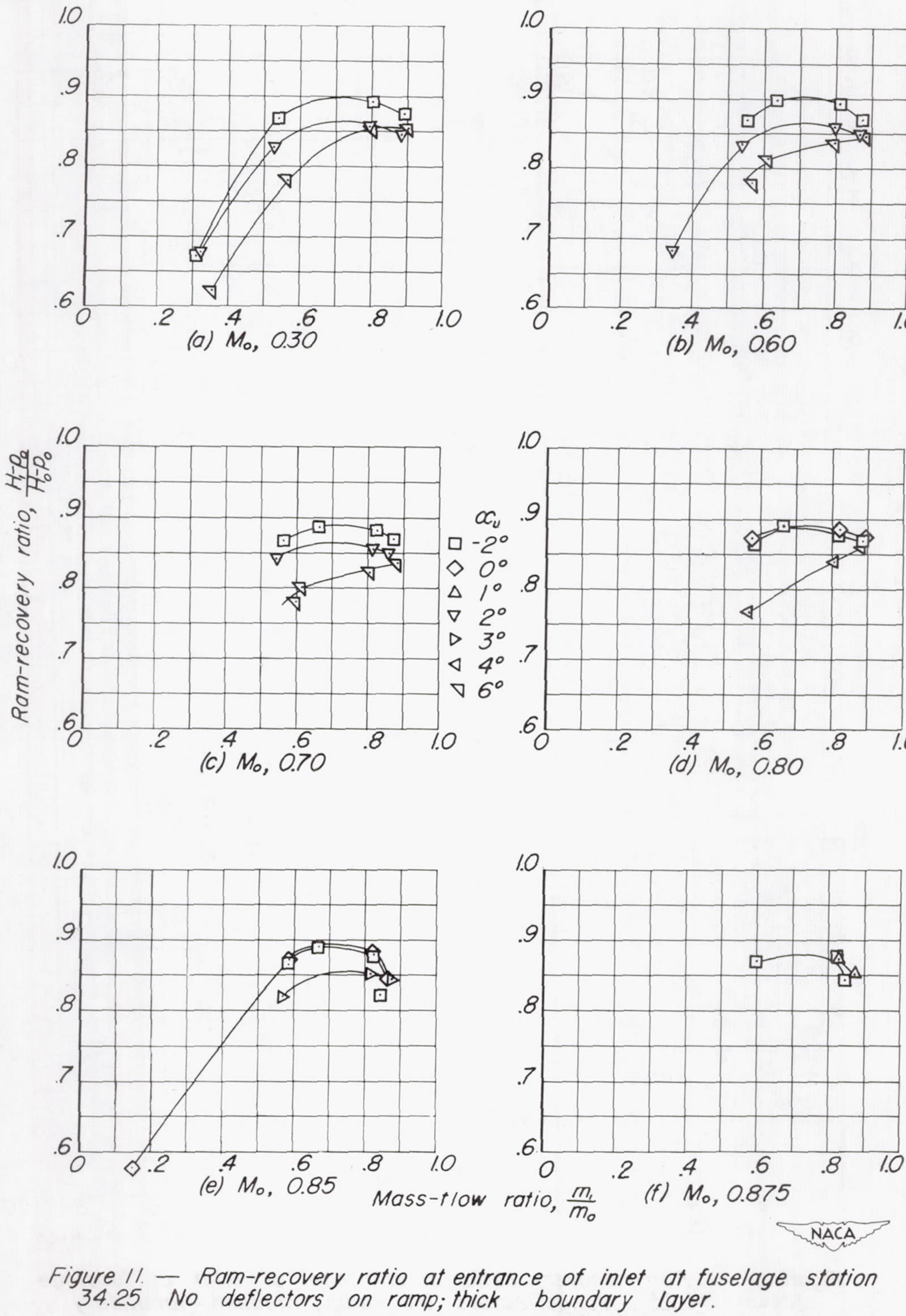


Figure 11. — Ram-recovery ratio at entrance of inlet at fuselage station 34.25 No deflectors on ramp; thick boundary layer.

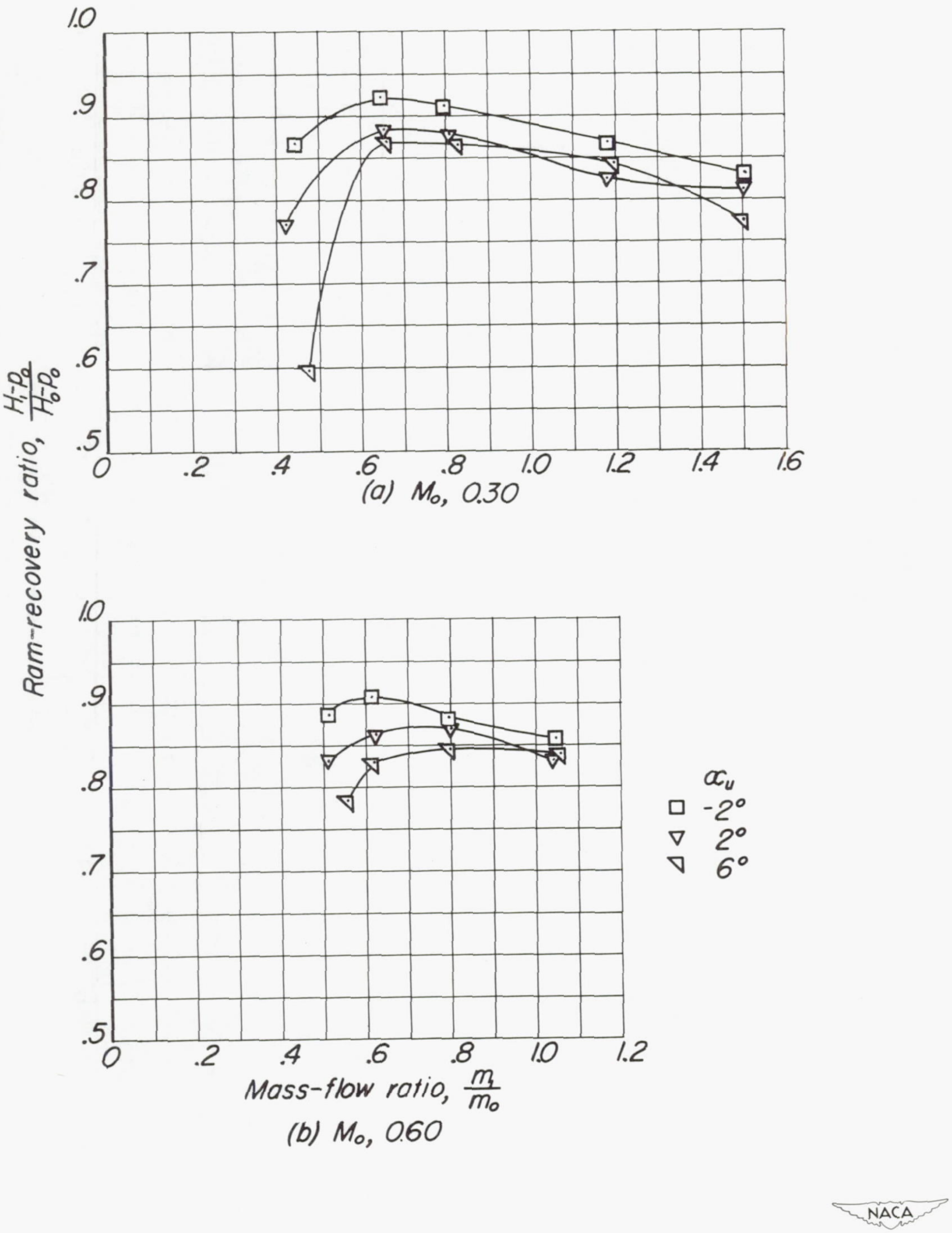


Figure 12.— Ram-recovery ratio at entrance of inlet at fuselage station 42.50. No deflectors on ramp; natural boundary layer.

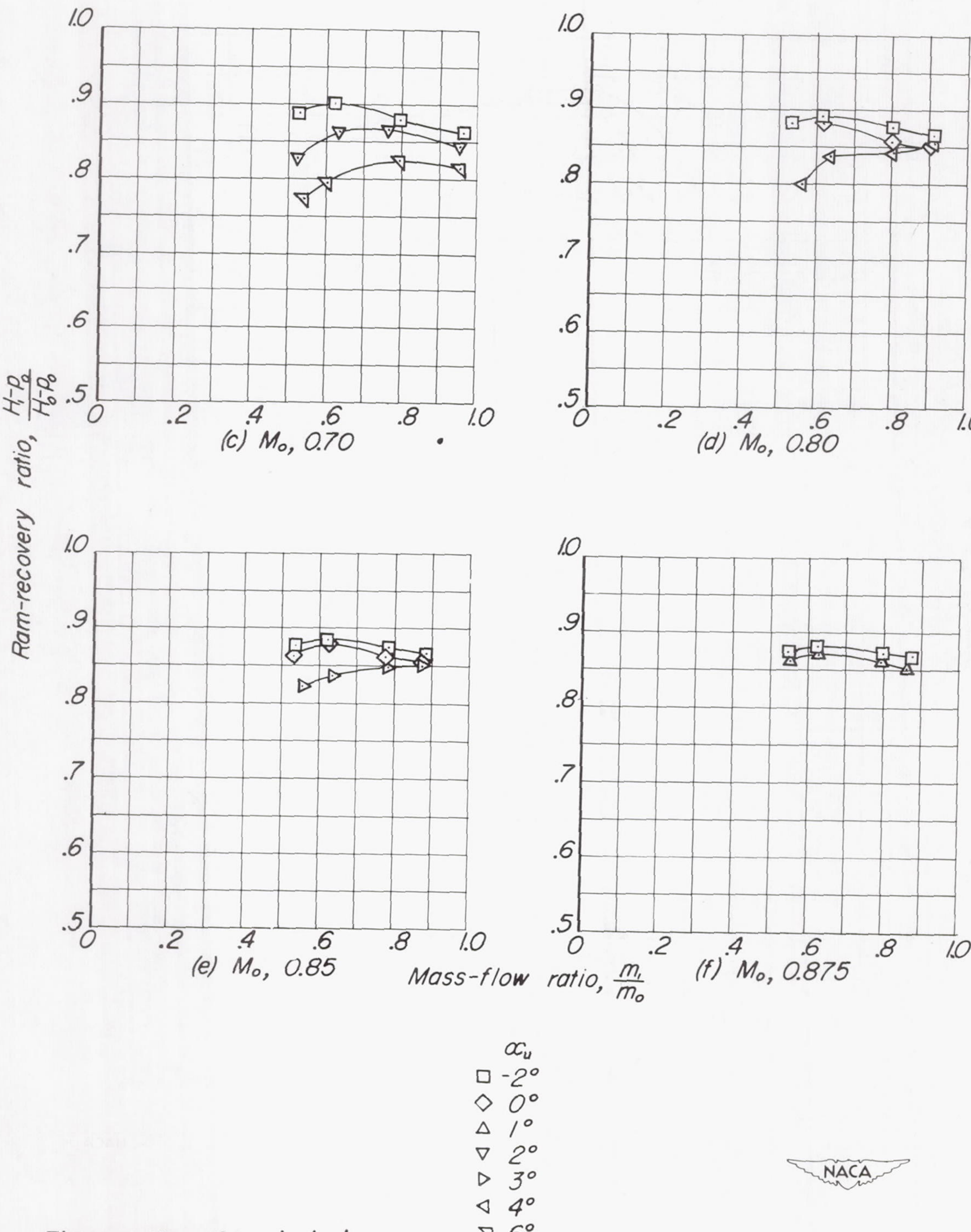


Figure 12. - Concluded.

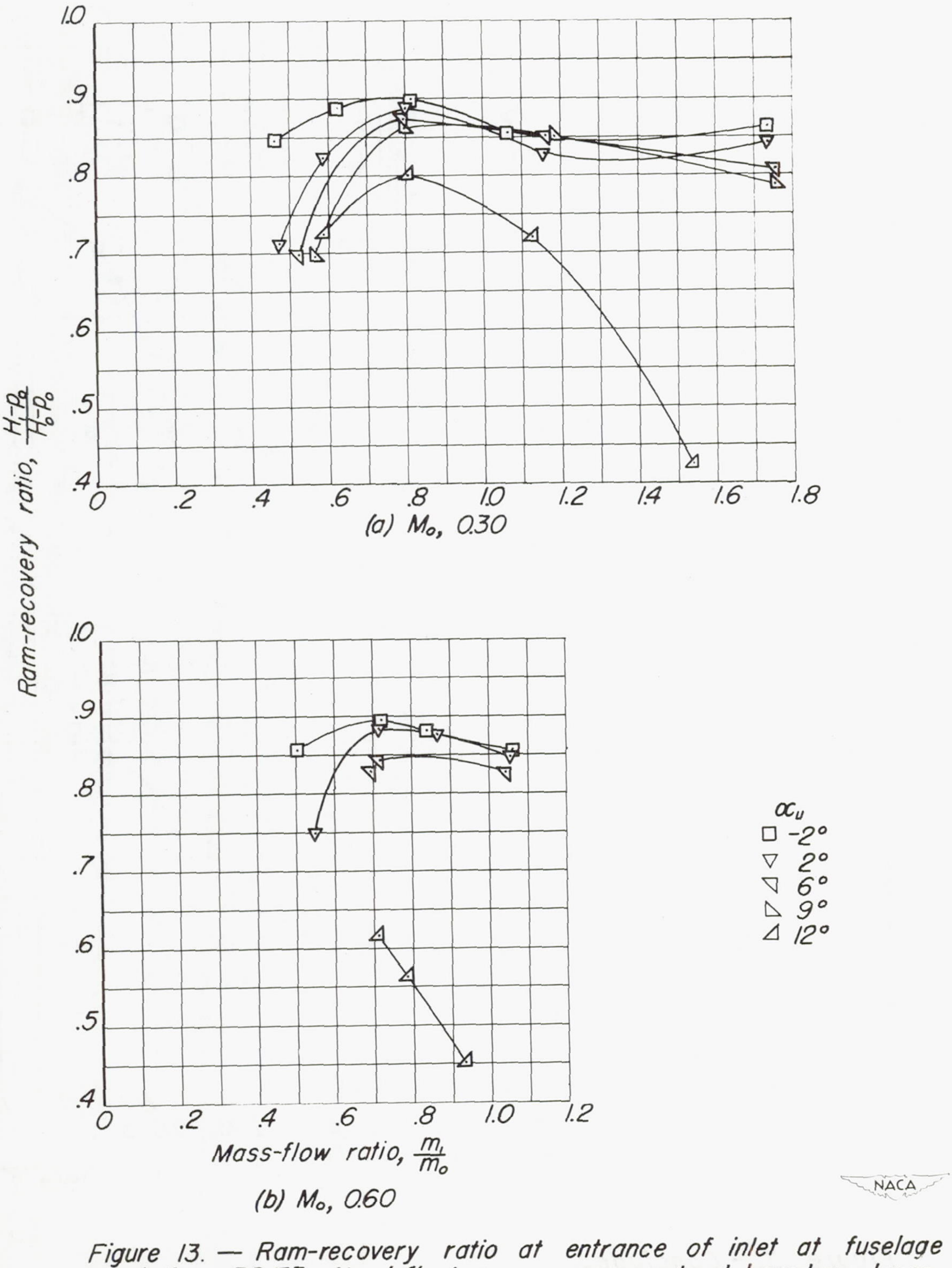


Figure 13. — Ram-recovery ratio at entrance of inlet at fuselage station 50.75. No deflectors on ramp; natural boundary layer.

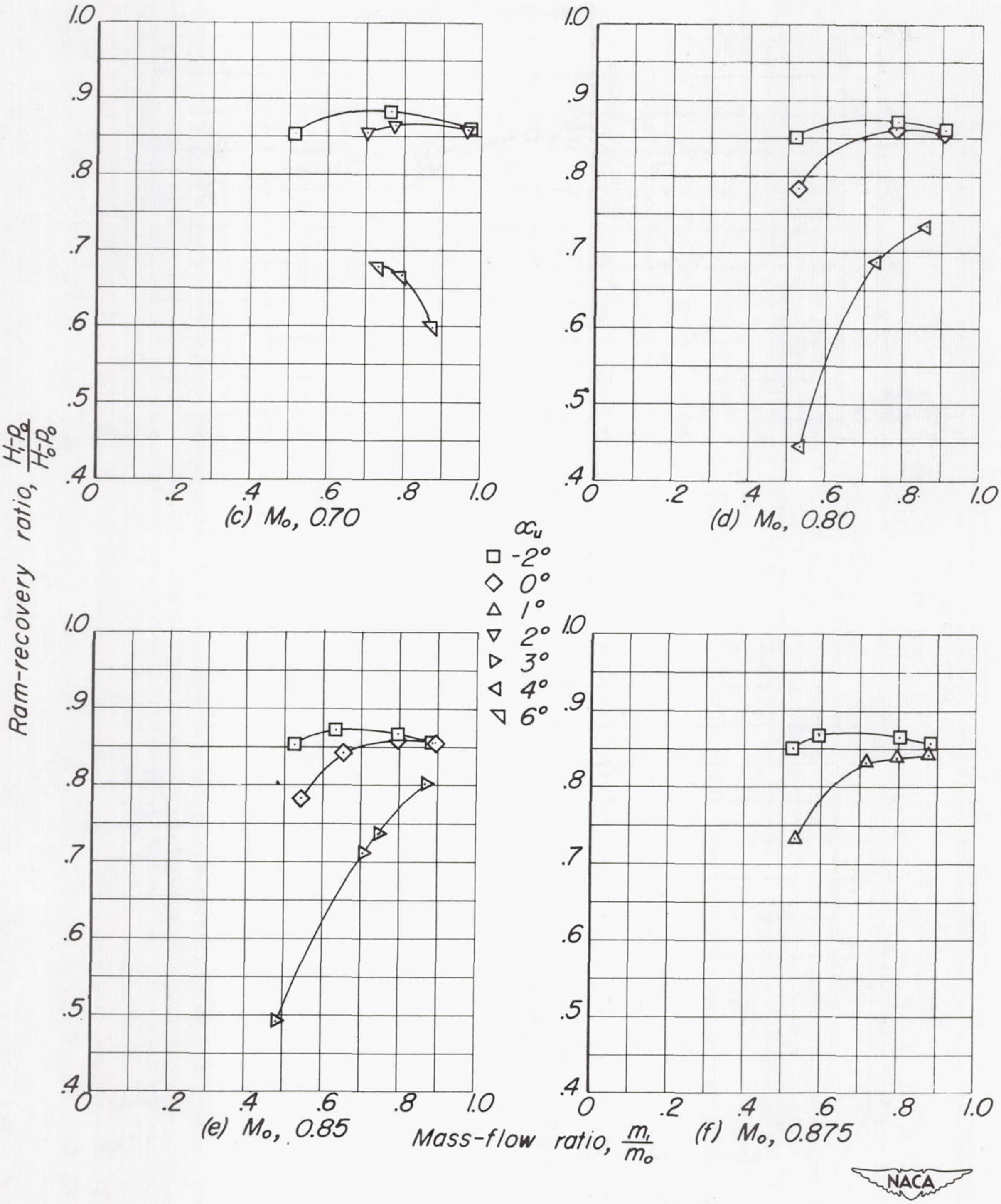


Figure 13. – Concluded.

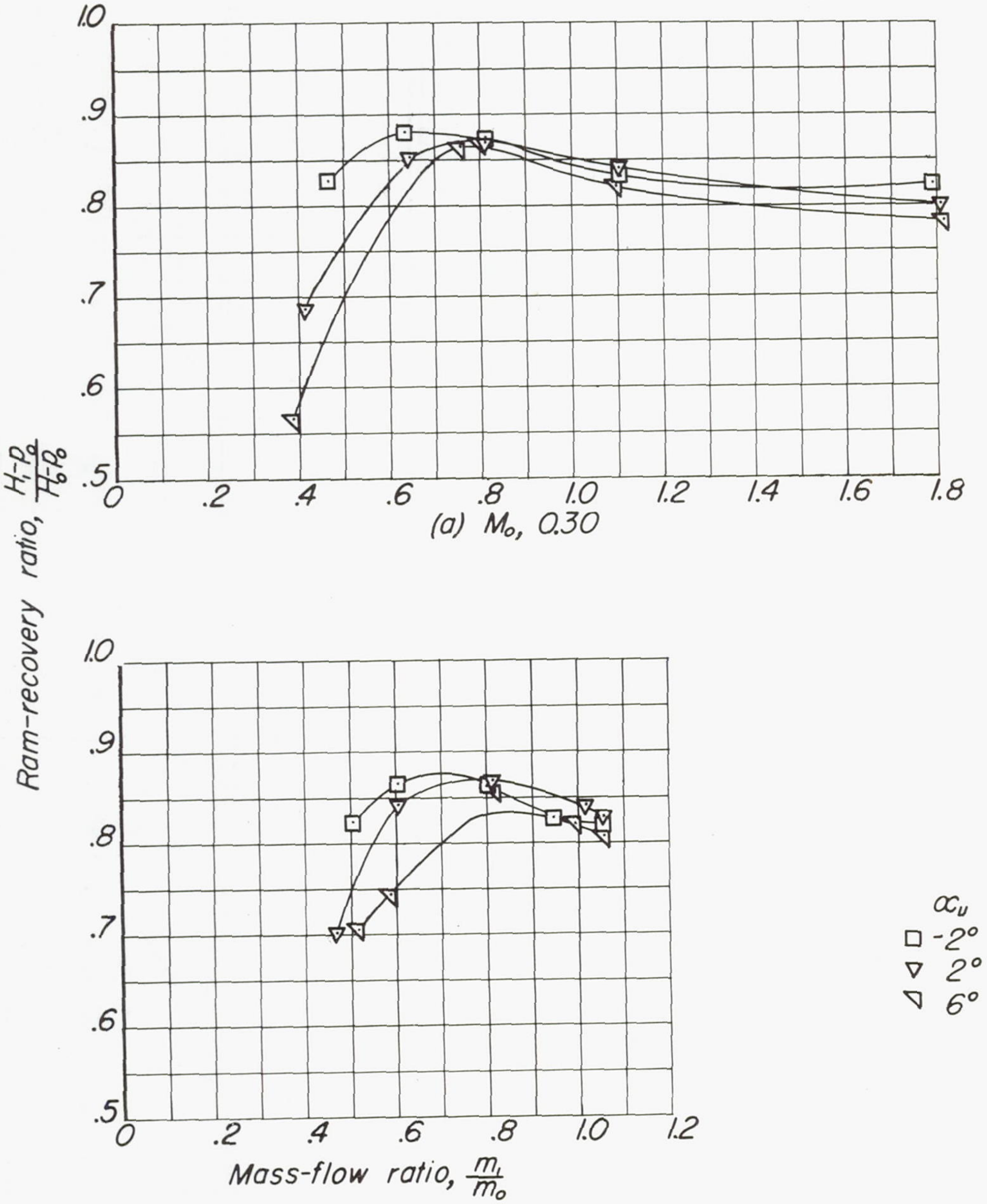


Figure 14.— Ram-recovery ratio at entrance of inlet at fuselage station 59.00. No deflectors on ramp; natural boundary layer.

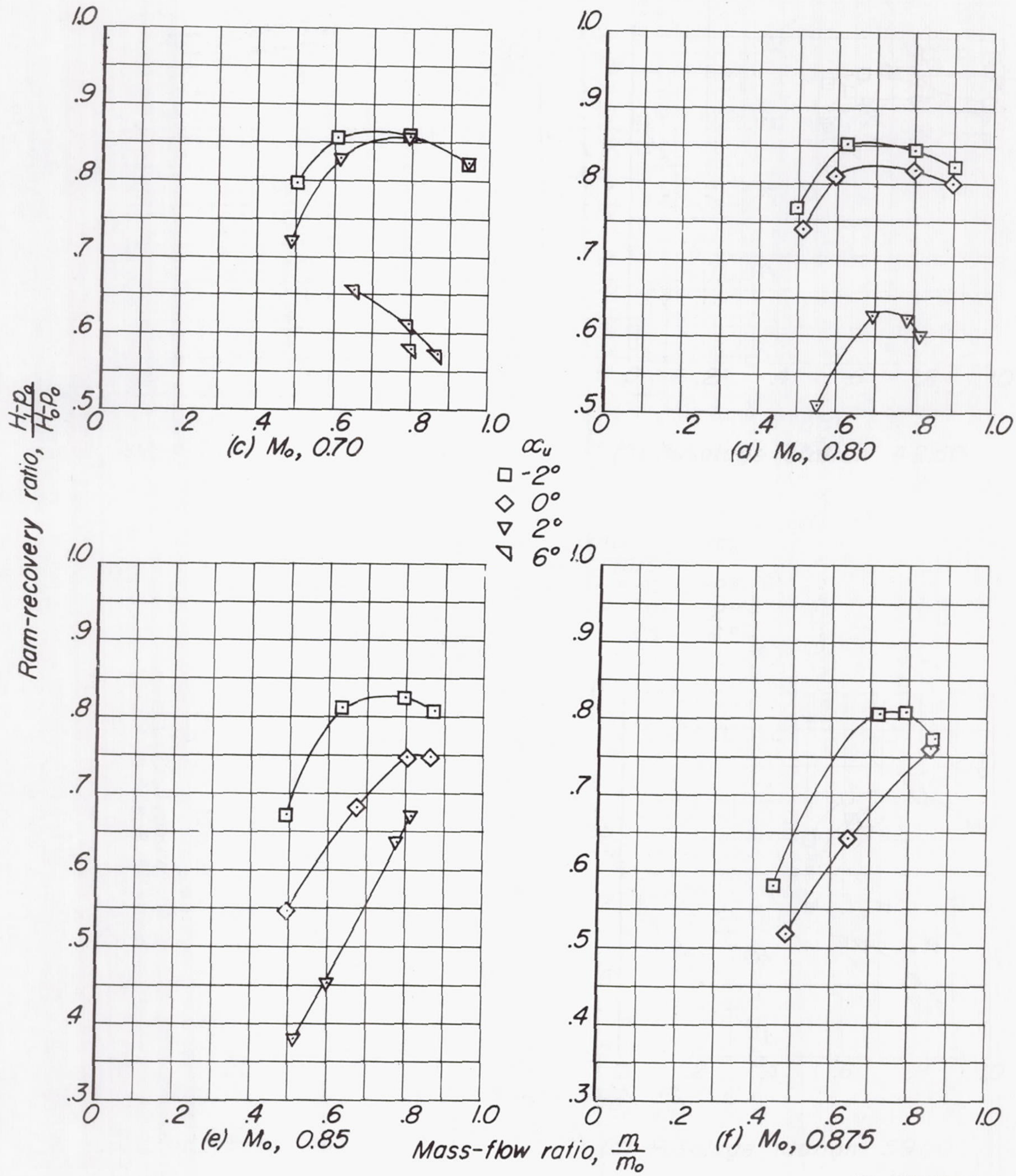


Figure 14. – Concluded.

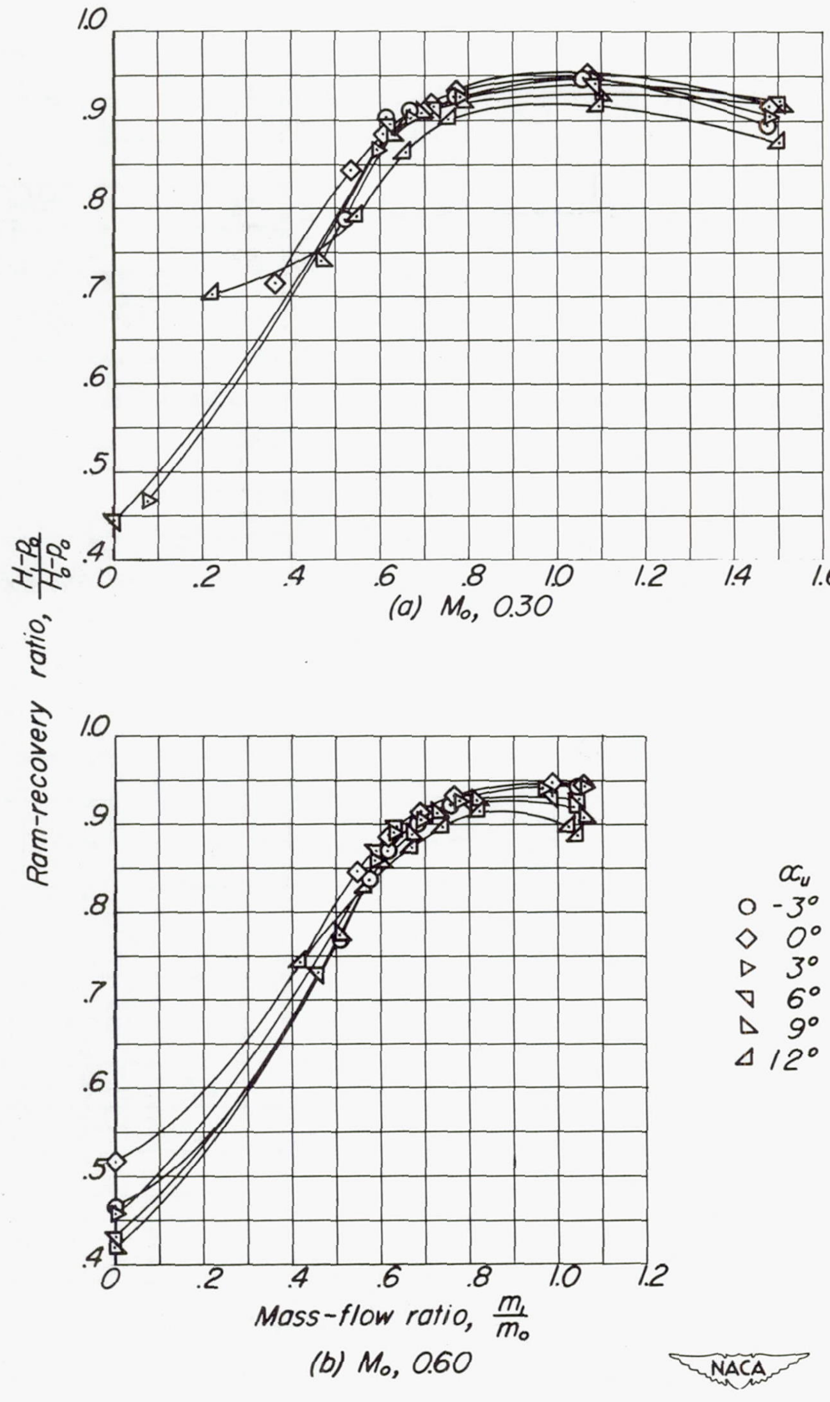


Figure 15.— Ram-recovery ratio at entrance of inlet at fuselage station 34.25. Deflectors on ramp; natural boundary layer.

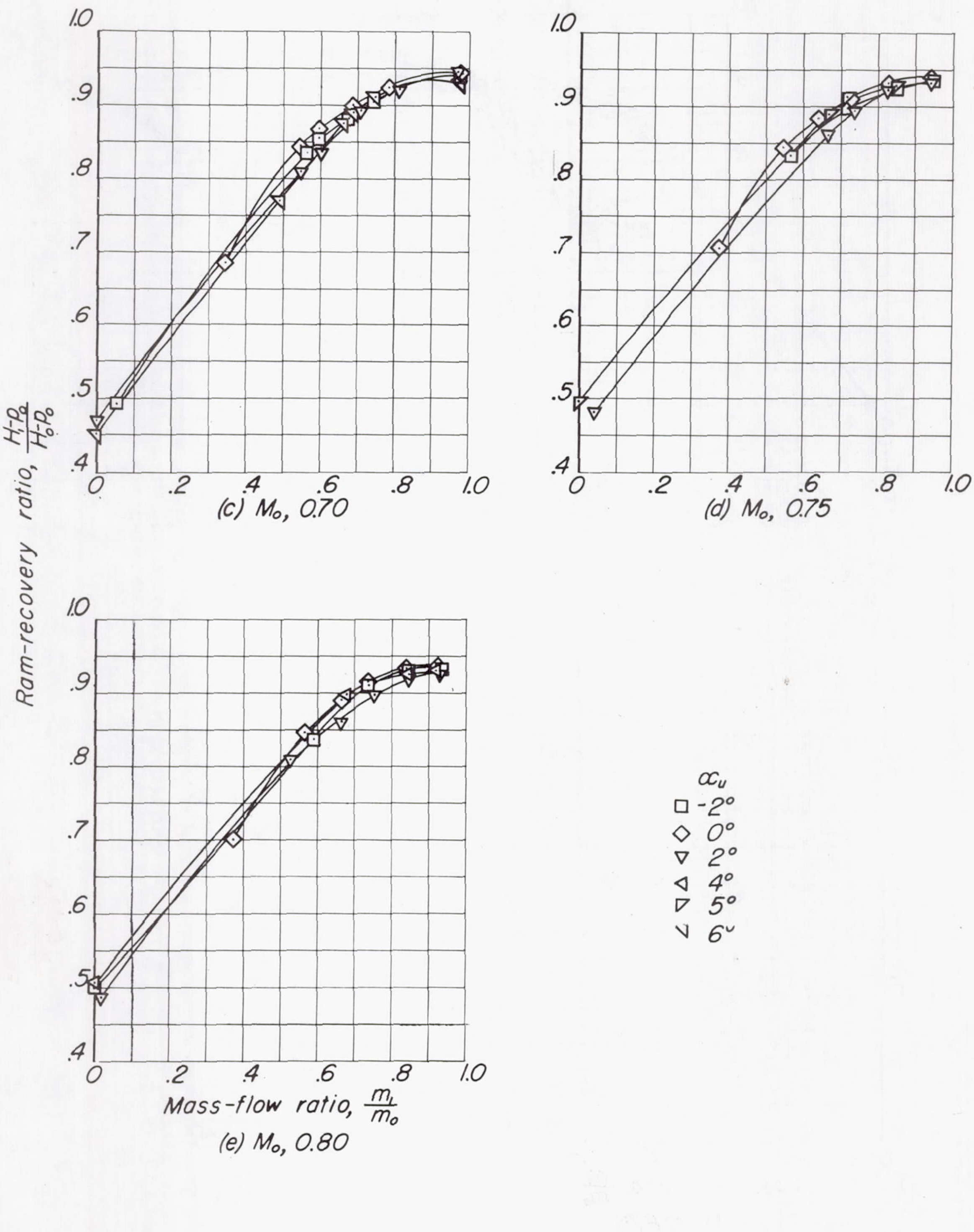


Figure 15. - Continued.

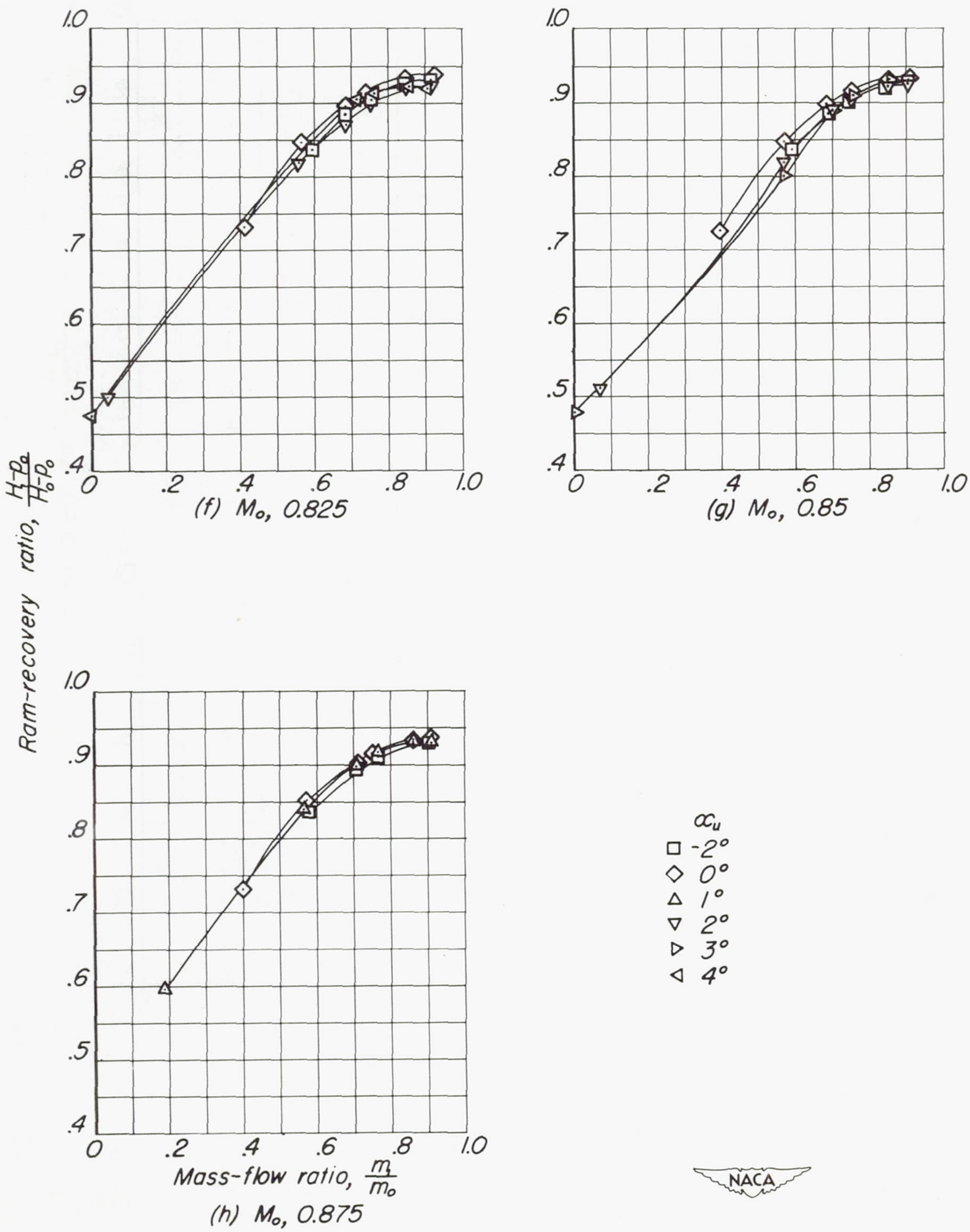


Figure 15. - Concluded.

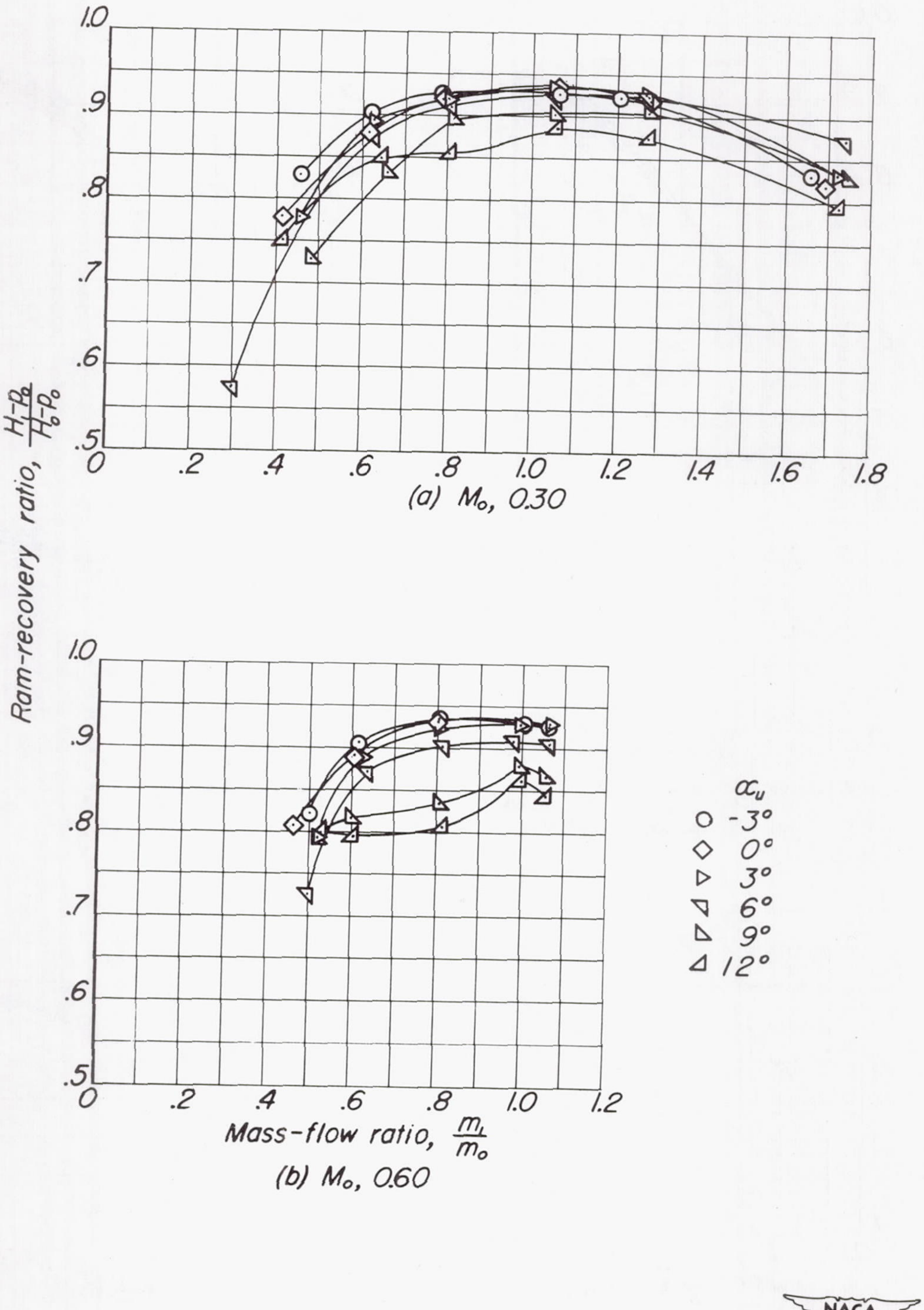


Figure 16. — Ram-recovery ratio at entrance of inlet at fuselage station 42.50 Deflectors on ramp; natural boundary layer.

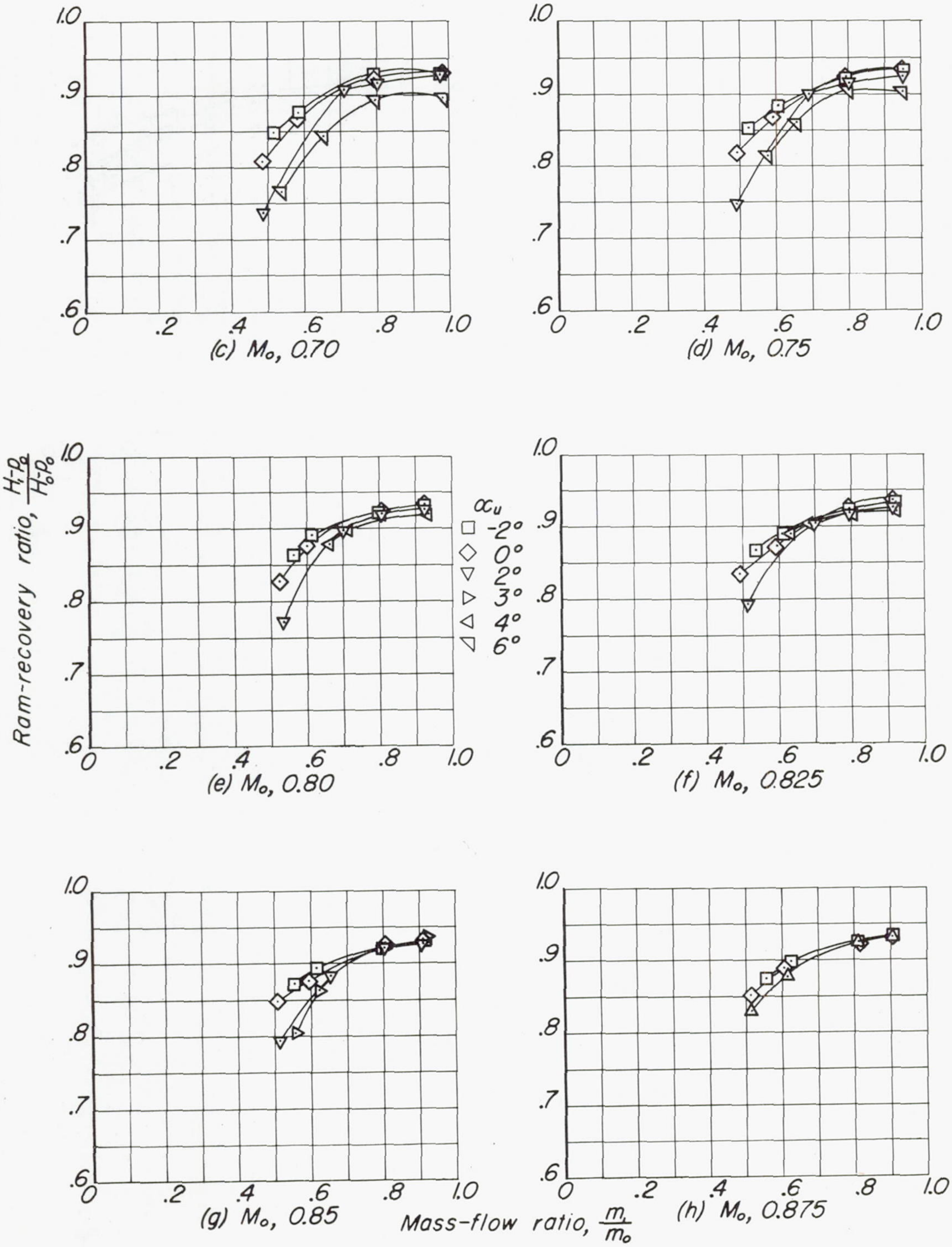


Figure 16. – Concluded.

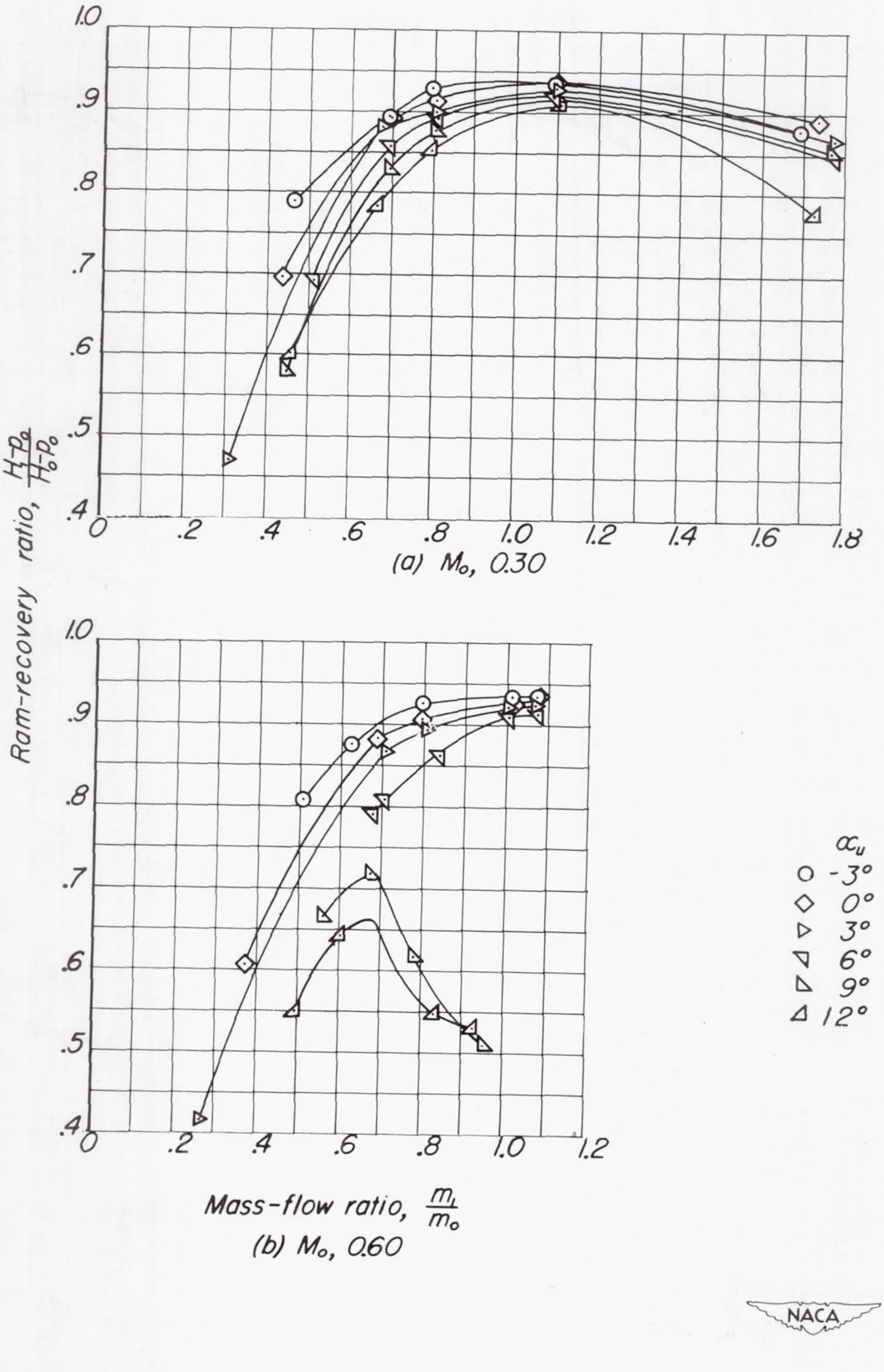


Figure 17. — Ram-recovery ratio at entrance of inlet at fuselage station 50.75. Deflectors on ramp; natural boundary layer.

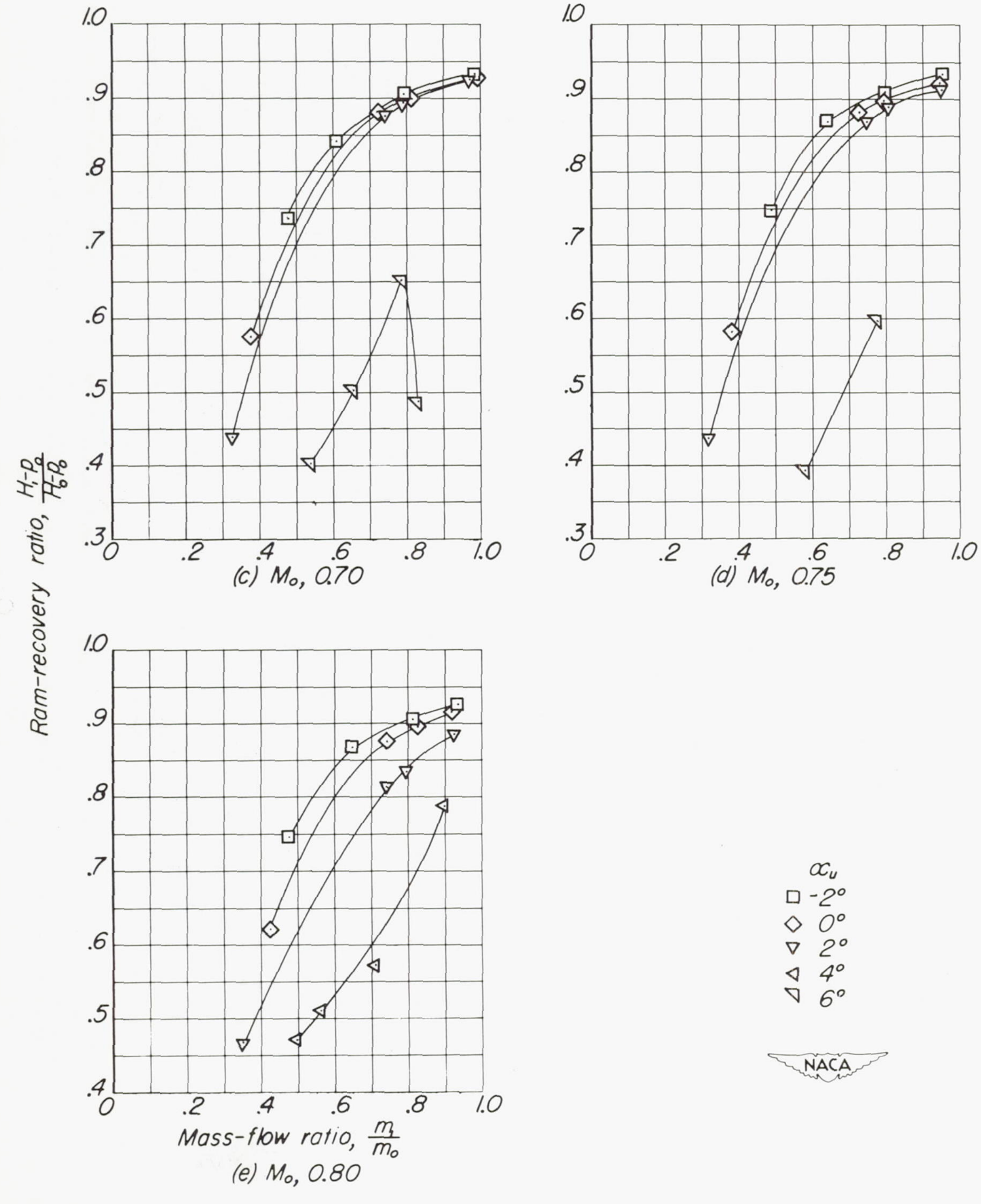


Figure 17. - Continued.

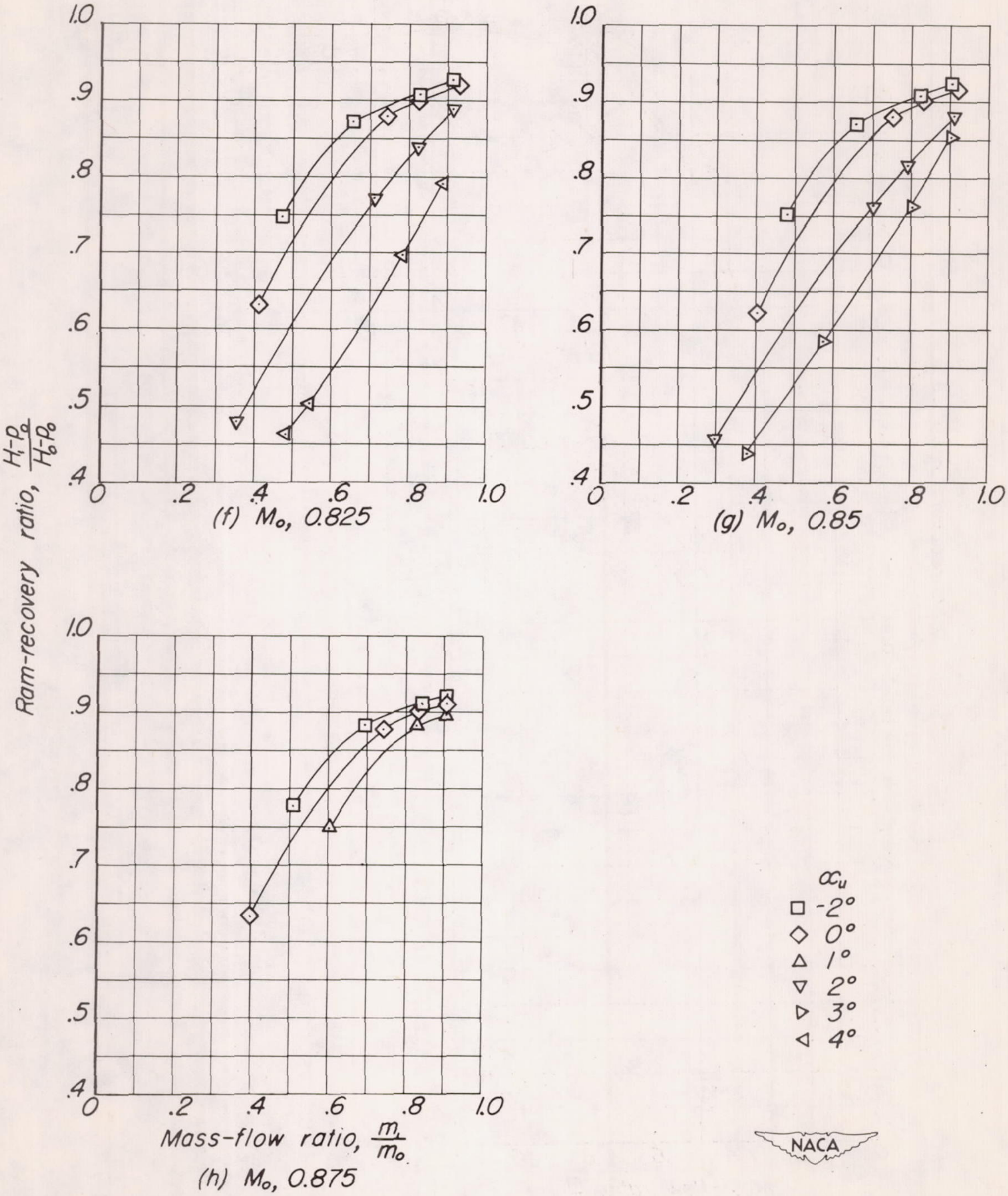


Figure 17.— Concluded.

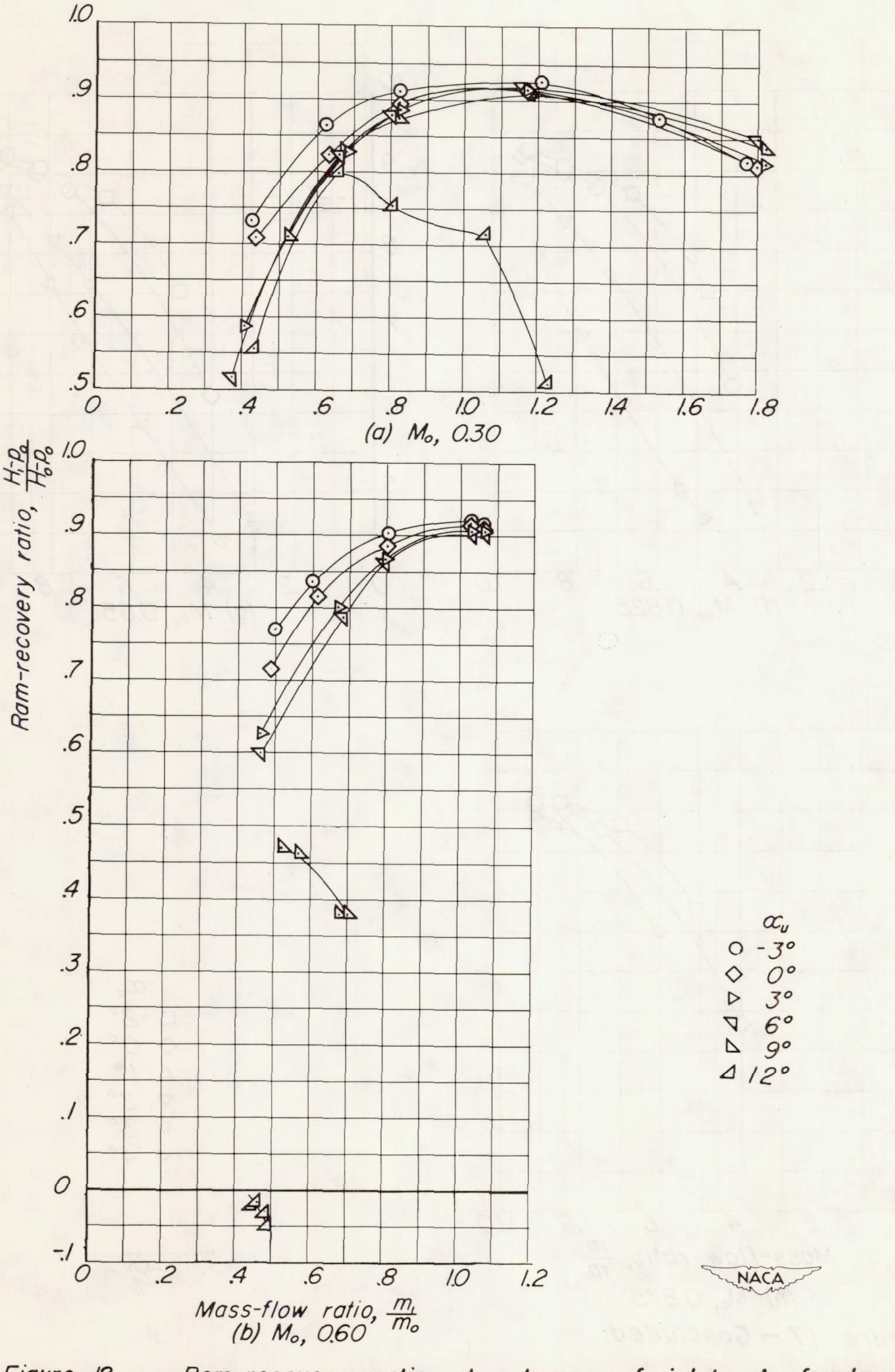


Figure 18. — Ram-recovery ratio at entrance of inlet at fuselage station 59.00 Deflectors on ramp; natural boundary layer.

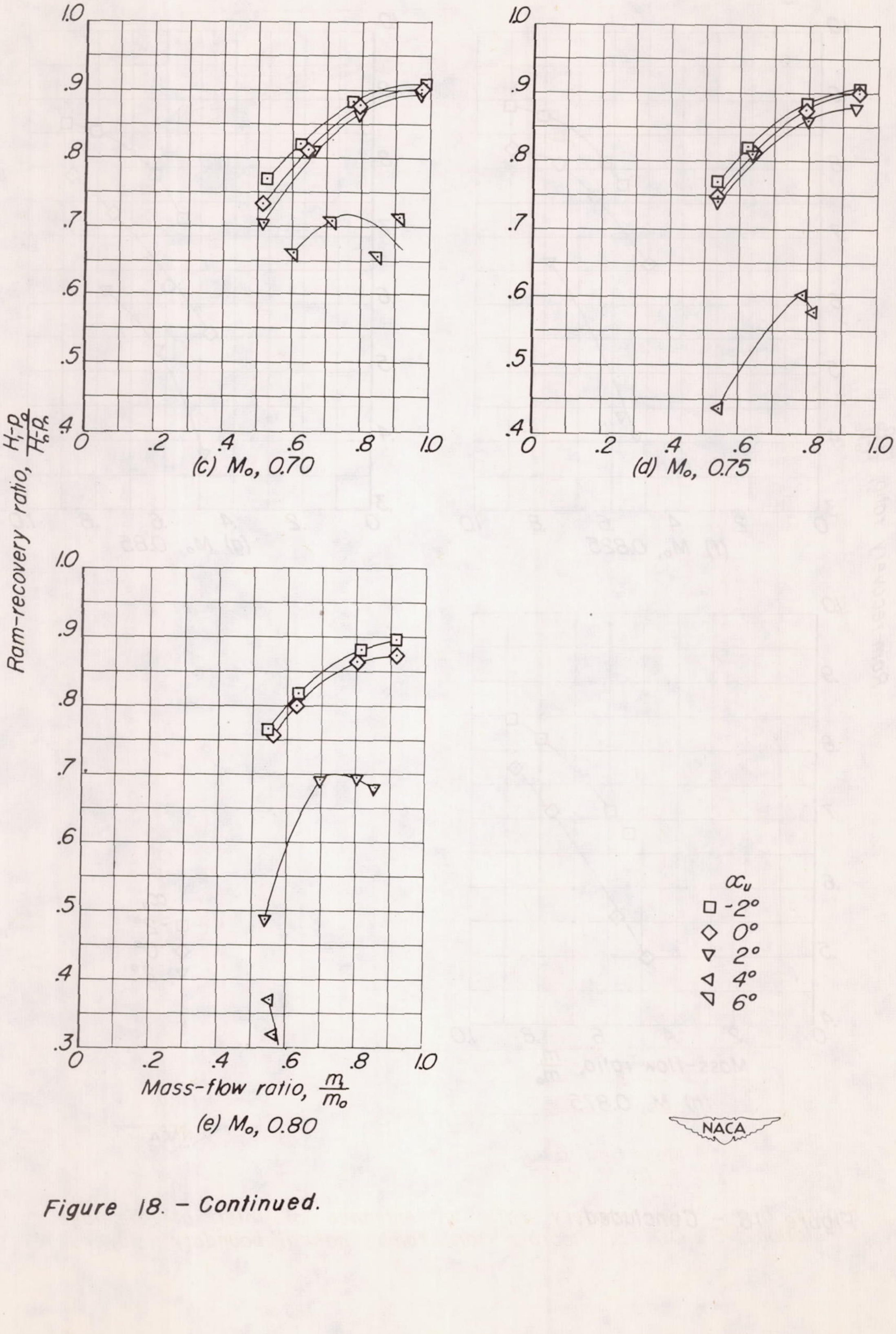


Figure 18. - Continued.

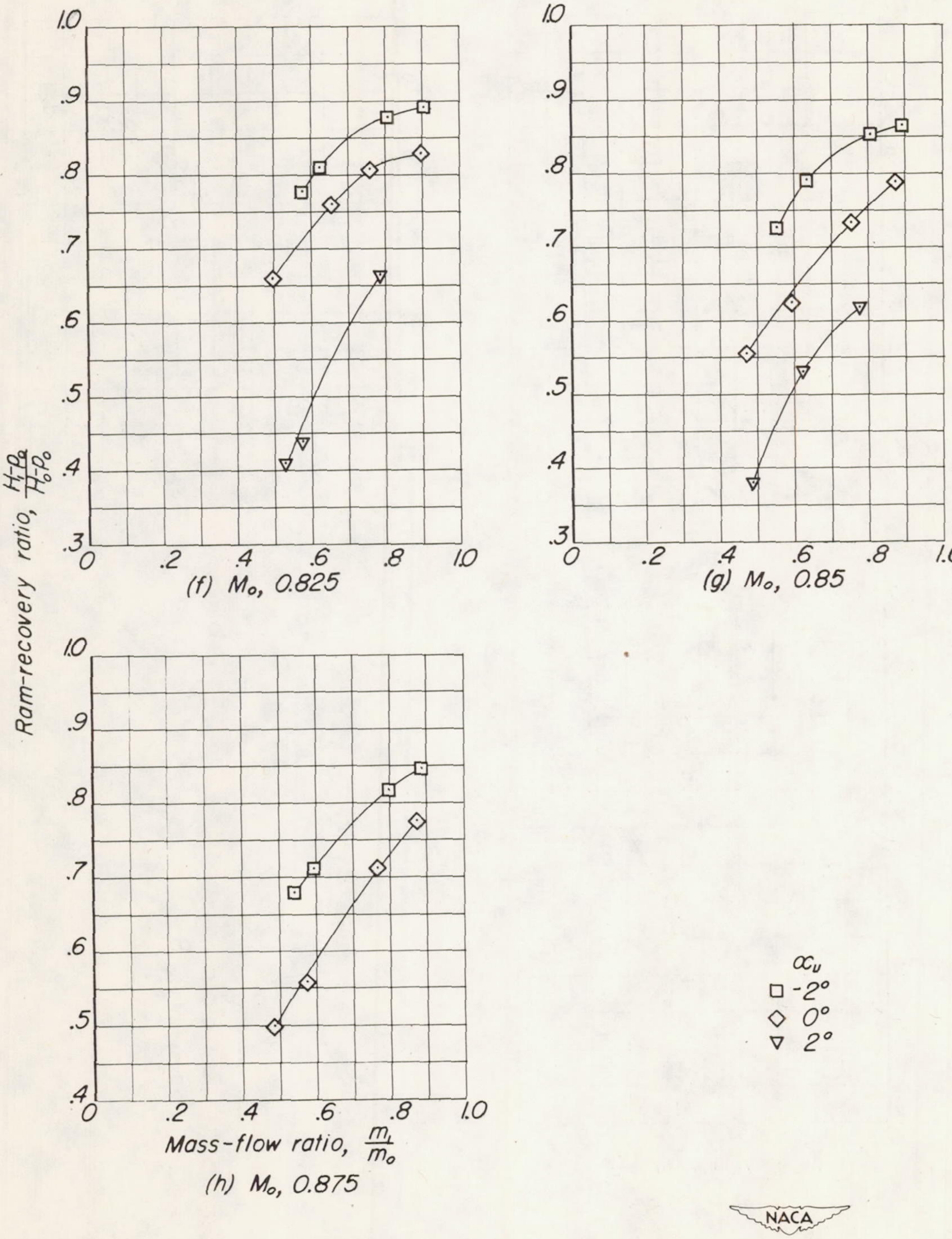


Figure 18. - Concluded.