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RESEARCH MEMORANDUM

THE USE OF SUCTION TO PREVENT SHOCK-INDUCED SEPARATION IN A NOZZLE

By James R. Sterrett, Robert W. Dunning,
and Maurice J. Brevoort

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Langley Field, Va.

NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

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THE USE OF SUCTION TO PREVENT SHOCK-INDUCED SEPARATION IN A NOZZLE

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SUMMARY

An investigation was made of the use of suction to prevent shock-induced flow separation in a nozzle formed by a 7.5-percent-thick bump on a wall of a channel. Various transverse and longitudinal suction-slot arrangements and suction through porous surfaces were tested. All these devices were effective in preventing separation, and certain suction-slot arrangements reduced the total power loss, including the power lost in the suction process.

INTRODUCTION

The rapid rise in drag of a wing or body in the high-subsonic speed range with local supersonic flow is associated with wave drag and drag caused by the separation of flow behind the shock wave. Several investigators have considered the problem of flow separation behind the shock. Stack (reference 1) showed that the sharp drag increase at transonic speeds was due in a large measure to flow separation and suggested that this drag could be avoided by boundary-layer removal.

Regenscheit (reference 2) made drag and schlieren measurements on an airfoil with several suction-slot arrangements. Fage and Sargent (reference 3) also tested an airfoil (NACA 0020) having one suction-slot arrangement located at the 30-percent-chord station. The drag in both cases was measured by wake surveys, and in the case of reference 3 the drag associated with suction power was estimated. In both of these investigations the use of suction was effective in reducing shock-induced separation and the results indicated that a more detailed study of techniques for applying suction was needed.

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The present investigation was undertaken to determine the relative effectiveness of various methods of applying suction, including multiple transverse slots with controlled flow through each slot, porous material, and longitudinal slots. The emphasis in the tests was put on finding the optimum location and arrangement of the devices for controlling the flow separation with a minimum of suction power. Because of the small size of the available equipment, it was decided to make the tests on the curved wall of a two-dimensional nozzle. Thus, the results apply quantitatively to a nozzle and can serve only as a guide in the application of suction to a wing.

Donaldson (reference 4) used the same nozzle and associated test equipment in a study of the use of vortex generators as a means for reducing the flow separation. His results are, therefore, directly comparable with those of the present investigation, and they show that the effectiveness of the vortex-generator action was about the same as that of boundary-layer suction.

SYMBOLS

M maximum Mach number

m mass flow per inch width

p static pressure

H total pressure

Subscripts:

a slot

c suction chamber

l bump surface

o ahead of nozzle

r rake

t total of all slots

TEST SETUP AND METHODS

A photograph of the test section is shown in figure 1. The air flow through this nozzle was induced by an aircraft engine supercharger driven by an electric motor. The current to drive the motor was furnished by a variable-frequency generator, and with this arrangement any compression ratio up to 2 could be obtained and held constant. The pressure in the large duct just ahead of the nozzle was approximately atmospheric. An air exchange system located in the return passage was used to maintain a sufficiently high air temperature to avoid condensation.

The test nozzle was formed by a bump on one wall of the 4- by 4-inch channel. (See fig. 1.) The bump was 8 inches long and had a height of 7.5 percent of the length. The contour of the bump is shown in figure 2 and the ordinates are given in table I. Static-pressure orifices were located on the downstream portion of the bump where the various suction devices were installed. All the slots were formed by saw cuts normal to the surface. No effort was made to give the slots a good aerodynamic shape. The air entering the suction slots passed into a suction compartment which was piped to a vacuum tank. For some of the configurations, individual compartments were provided for each slot. The piping was designed to permit regulation of the pressure in the suction compartment, as well as to allow measurement of the mass flow, stagnation temperature, and pressure of the removed air. A survey rake was placed 3 inches downstream from the bump (fig. 1). The rake spanned the nozzle vertically and was located midway between the side walls.

The pressures in the suction compartments were adjusted for each test run to obtain the approximate suction power needed to prevent flow separation. The flow conditions were examined by a schlieren system, surface static pressures, and wake total pressures. After the conditions had been visually adjusted, the data were photographically recorded.

Several experiments, not included in this paper, were made in which the boundary layer was removed on the floor of the test section in front of the curved nozzle block. No appreciable changes were noticed in the nozzle-flow phenomena by so removing the boundary layer, but the suction power necessary to prevent separation was slightly reduced. Also, it was determined by velocity profile measurements that the boundary layer was turbulent over the test surface.

The various suction devices tested were as follows:

Arrangement I was the basic arrangement before any suction slots or porous material had been added to the expansion surface of the arrangement. A sketch of this arrangement is given in figure 2(a).

Arrangement II had five 0.030-inch slots located at 51, 61, 71, 80, and 86 percent of the arrangement length. The flow through these slots entered into a common suction chamber without any method of controlling the flow through the individual slots. A sketch of this arrangement is given in figure 2(b).

Arrangement III had four 0.030-inch slots located at 68, 76, 82, and 88 percent of the arrangement length. Each of these slots was provided with a separate suction compartment. On the basis of experience gained with arrangement II, only four slots were used. A sketch of this arrangement is given in figure 2(c).

Arrangement IV had slots placed parallel to the flow located from 40 to 100 percent of the arrangement length. These slots were spaced approximately 1/8 inch apart and had an average width of 0.005 inch. The flow through these slots entered four compartments, equally spaced in the direction of flow. A sketch of this arrangement is given in figure 2(d).

Arrangement V had a porous material located from 47 percent to 90 percent of the arrangement length. This porous material was sintered bronze with a porosity of approximately 5 percent. No attempt was made to smooth the surface of this material, which was quite rough. The flow passing through this material entered a common suction chamber. A sketch of this arrangement is given in figure 2(e).

Arrangement VI had two slots located at 71 and 79 percent of the arrangement length. The flow through these slots entered individual suction compartments. A sketch of this arrangement is given in figure 2(f).

RESULTS

The figures presenting the test results for the basic nozzle and the four nozzles using various suction devices are given in the following table:

Arrangement	Schlieren photographs	Pressure distributions	Wake surveys	Flow data
I	Figure 3	Figure 4	Figure 5	-----------
II	Figure 6	Figure 7	Figure 8	Table II(a)
III	Figure 9	Figure 10	Figure 11	Table II(b)
IV	Figure 12	Figure 13	Figure 14	Table II(c)
V	Figure 15	Figure 16	Figure 17	Table II(d)
VI	Figure 18	Figure 19	Figure 20	Table II(e)

Representative power curves are presented in figures 21, 22, and 23.

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The maximum local Mach number, as indicated by static-pressure measurements along the bump surface, was considered as the independent parameter throughout this paper.

In evaluating the total power loss, extraneous losses due to separation on the straight-wall surface opposite the bump were avoided by extending the integrations only over 85 percent of the height of the channel. To determine the power loss due to separation, an arbitrary boundary line was drawn between the region of large losses near the surface and the region of small (shock) losses extending out into the stream as shown by the dashed line in figure 8. The separation loss so defined also contains some losses due to friction and to the passage of a part of the air involved through the base of the shock. The suction power was calculated as the power necessary to reintroduce into the stream the removed air at the total pressure of the free stream ahead of the nozzle.

In preliminary work not included in this paper, it was determined that the disturbances evident behind the shocks in the schlieren photographs, in cases where suction had been applied to prevent separation, were associated with boundary-layer separations from the side walls. The important feature to be noted in the schlieren photographs with suction applied is that the boundary layer adheres to the surface.

DISCUSSION

The schlieren photographs (fig. 3), pressure distributions (fig. 4), and wake surveys (fig. 5), show that for the basic shape the greatest shock-induced separation occurred at maximum local Mach numbers in the range of approximately 1.25 to 1.35. It will be noted that very little separation occurred when the local supersonic region extended to the end of the nozzle ($M_l = 1.40$).

Results of slot arrangement II (figs. 6 to 8 and table II(a)) show that separation was essentially eliminated when suction was applied. Analysis of these data indicated that there is probably an optimum location of the active slots relative to the shock position; accordingly, arrangement III, having four slots with individual controllable flow, was tested. Results of this arrangement (figs. 9 to 11 and table II(b)) show that separation was eliminated as before, but with fewer active slots; for example, the first slot was not used at $M_l = 1.31$.

Arrangement IV employed longitudinal slots similar to those tested in reference 3 with four individual controllable suction compartments under the slots. Separation was also prevented by this arrangement, as shown by the results given in figures 12 to 14 and table II(c).

Arrangement V was tested in order to obtain the effects of removing the boundary layer through porous material. This arrangement controlled the separated flow similar to the other arrangements tested (as shown in figs. 15 to 17 and table II(d)).

From the tests on arrangement III, it appeared that the most effective location of a suction slot was close to the base of the shock. Accordingly, arrangement VI was tested at a Mach number of 1.33 with two slots so located that one slot was ahead of and one behind the base of the shock and the results are given in figures 18 to 21 and table II(e). Preliminary tests showed that suction applied only ahead of the shock did not prevent large-scale separation. The effectiveness of the two slots as compared with the rear slot alone is apparent in figure 21. It will be noted that one slot operating behind the shock is as effective as both slots. The suction quantity required to control flow separation was relatively small, being 0.75 percent of the channel flow for this particular nozzle, or the equivalent of removal of approximately 70 percent of the boundary-layer flow for the example given in figures 18, 19, and 20.

Each of the arrangements tested proved effective in controlling the separation but varied in the suction power required. The results of arrangement III are compared with the results of arrangement I in figures 22 and 23. An analysis of these figures shows that the prevention of shock-induced separation by suction resulted in a large net power saving. For example, from figure 22 at a Mach number of 1.33, a suction power of 280 foot-pounds per second would result in a net separation power saving of 560 foot-pounds per second. With arrangement VI it can be seen, from an examination of figure 21, that an optimum suction power of 140 foot-pounds per second resulted in a net separation power saving of approximately 600 foot-pounds per second. This indicates that arrangement VI is more efficient than arrangement III; however, part of the difference between these two arrangements may be explained by a lack of exactly optimum suction for arrangement III. From other data not included in this paper it was determined that arrangements II, IV, and V did not result in any appreciable net power saving when separation was prevented. Thus, of all devices tried for boundary-layer removal, the transverse slots of arrangements III and VI were the most efficient.

CONCLUDING REMARKS

An investigation was made of the use of suction to prevent shock-induced flow separation in a nozzle formed by a 7.5-percent-thick bump on a wall of a channel. Various transverse and longitudinal suction-slot arrangements and suction through porous surfaces were tested. All these devices were effective in preventing separation, and certain suction-slot arrangements reduced the total power loss, including the power lost in the suction process.

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1. Stack, John: Compressible Flows in Aeronautics. Jour. Aero. Sci., vol. 12, no. 2, April 1945, pp. 127-143.

2. Regenscheit, B.: Drag Reduction by Suction of the Boundary Layer Separated behind Shock Wave Formation at High Mach Numbers. NACA TM 1168, 1947.

3. Fage, A., and Sargent, R. F.: Effect on Aerofoil Drag of Boundary-Layer Suction behind a Shock Wave. R. & M. No. 1913, British A.R.C., 1943.

4. Donaldson, Coleman duP.: Investigation of a Simple Device for Preventing Separation Due to Shock and Boundary-Layer Interaction. NACA RM L50B02a, 1950.

TABLE I

ORDINATES OF CURVED SURFACE

Station (percent chord)	Ordinate (percent chord)
0	0
.5	.563
1.0	1.000
5.0	3.125
10.0	4.500
15.0	5.438
20.0	6.063
25.0	6.438
30.0	6.813
35.0	7.188
40.0	7.375
45.0	7.500
50.0	7.438
55.0	7.313
60.0	6.938
65.0	6.438
70.0	5.813
75.0	5.063
80.0	4.188
85.0	3.250
90.0	2.313
95.0	1.250
100.0	0

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TABLE II

SUCTION DATA

[m_o = 1.01 lb/sec/in. width]

(a) Arrangement II

M_l	Figure	H_c/H_o	m_t/m_o (percent)
0.85	7(a), 8(a)	0.47	2.58
1.14	7(b), 8(b)	.28	1.99
1.29	7(c), 8(c)	.32	1.49
1.35	7(d), 8(d)	.16	1.39
1.41	7(e), 8(e)	.18	1.19

(b) Arrangement III

M_l	Figure	Slots								m_t/m_o (percent)
		1		2		3		4		
		H_c/H_o	m_a/m_t (percent)	H_c/H_o	m_a/m_t (percent)	H_c/H_o	m_a/m_t (percent)	H_c/H_o	m_a/m_t (percent)	
0.90	10(a), 11(a)	0.61	53.5	0.68	46.5	----	0	----	0	0.43
1.15	10(b), 11(b)	.55	48.6	.63	51.4	----	0	----	0	.35
1.31	10(c), 11(c)	----	0	.45	26.0	0.51	25.0	0.55	49.0	1.00
1.35	10(d), 11(d)	----	0	.38	21.0	.39	39.5	.46	39.5	.81
1.43	10(e), 11(e)	----	0	----	0	.34	44.3	.45	55.7	.70

(c) Arrangement IV

M_l	Figure	Compartment								m_t/m_o (percent)
		1		2		3		4		
		H_c/H_o	m_a/m_t (percent)	H_c/H_o	m_a/m_t (percent)	H_c/H_o	m_a/m_t (percent)	H_c/H_o	m_a/m_t (percent)	
1.28	13, 14	0.42	11.4	0.36	39.4	0.47	26.4	0.53	22.8	1.91

(d) Arrangement V

M_l	Figure	H_c/H_o	m_t/m_o (percent)
1.28	16, 17	0.34	1.99

(e) Arrangement VI

M_l	Figure	Slots				m_t/m_o (percent)
		1		2		
		H_c/H_o	m_a/m_t (percent)	H_c/H_o	m_a/m_t (percent)	
1.33	19, 20	0.29	41.2	0.43	58.8	0.75

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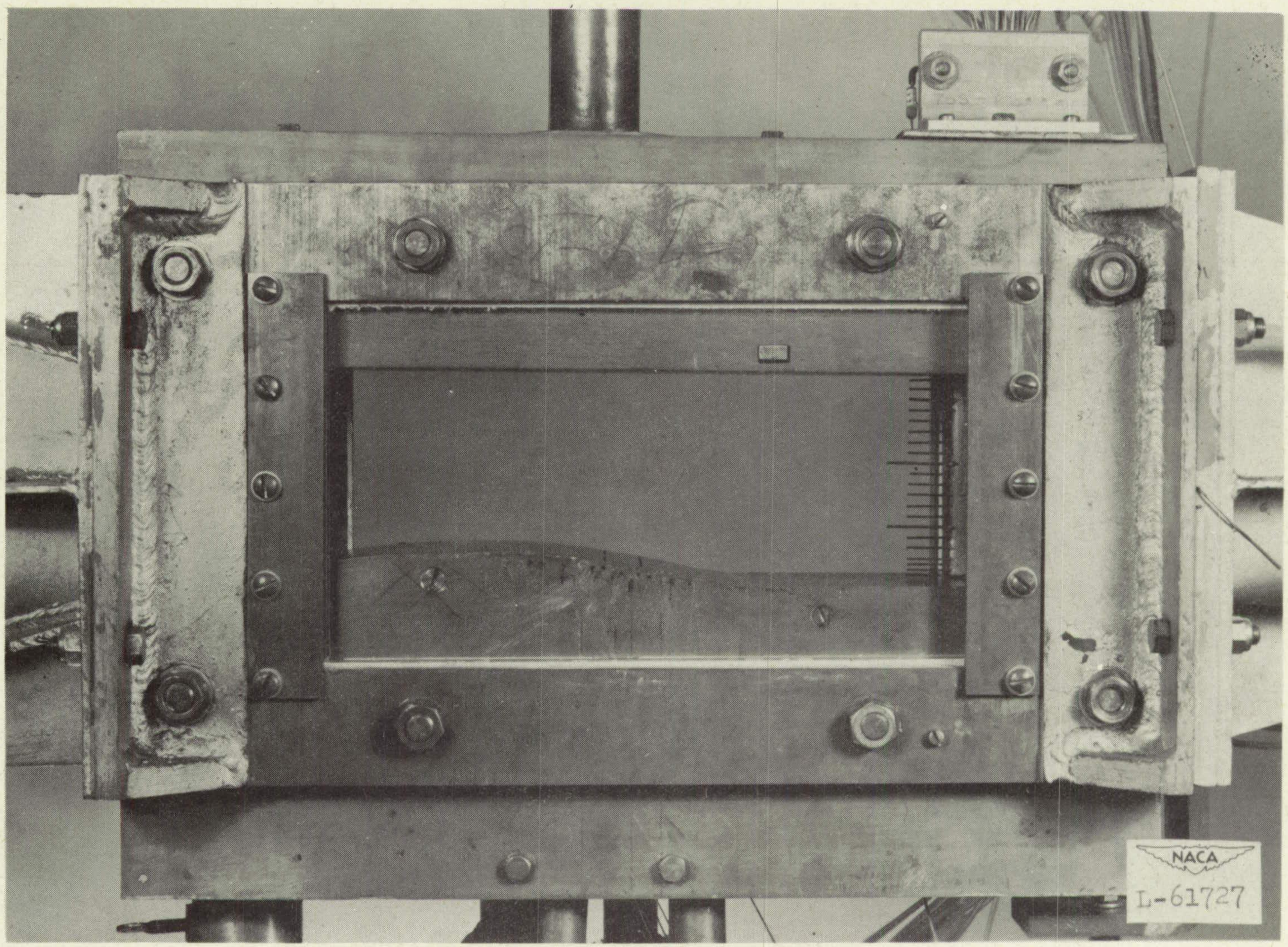
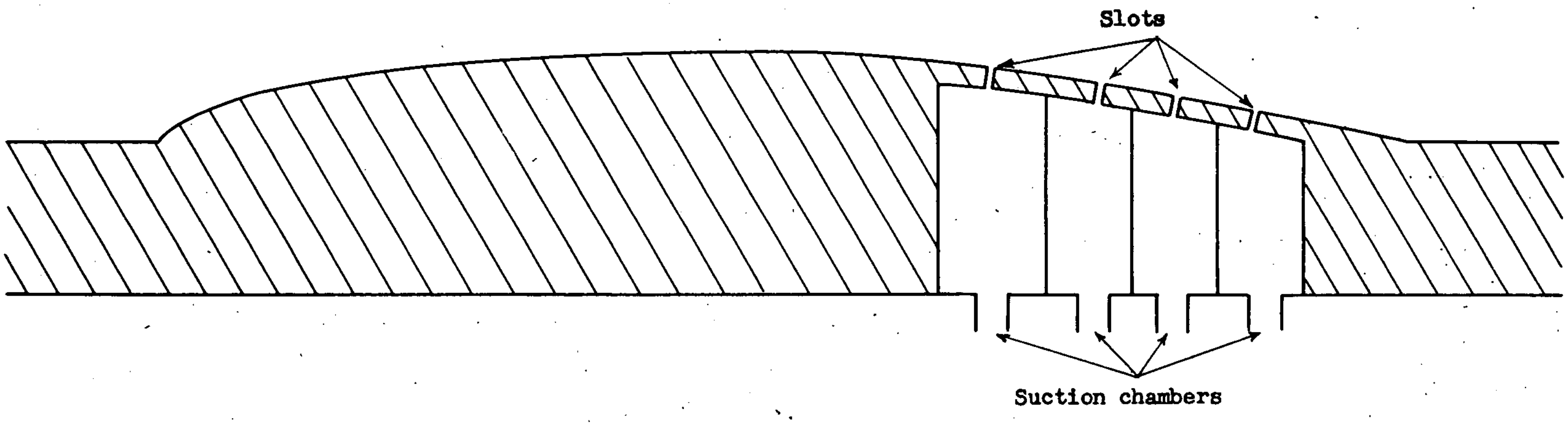
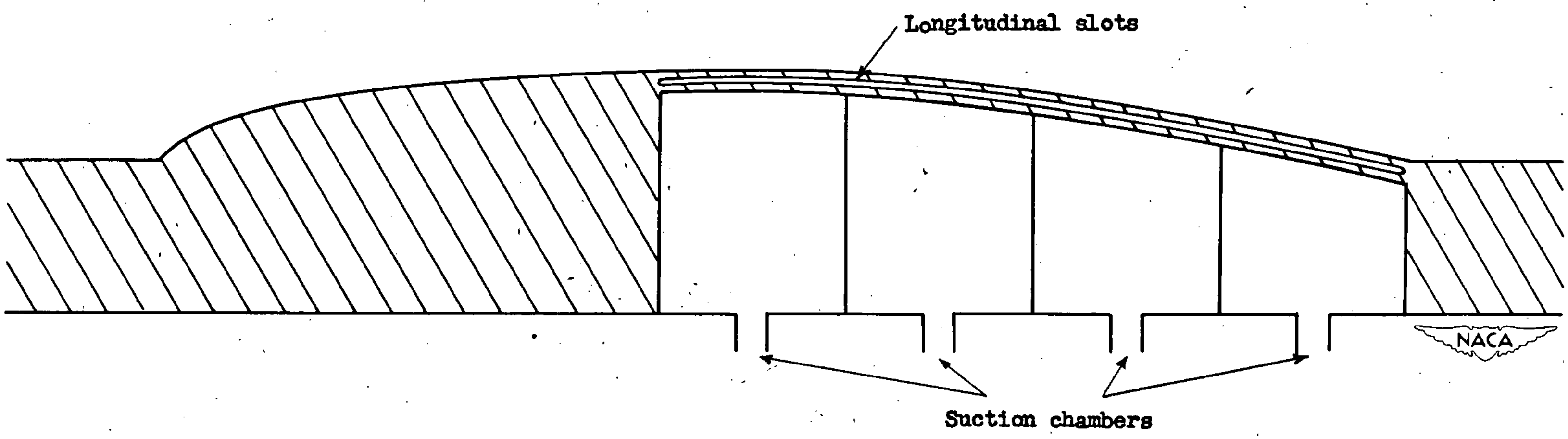


Figure 1.- Photograph of test section.

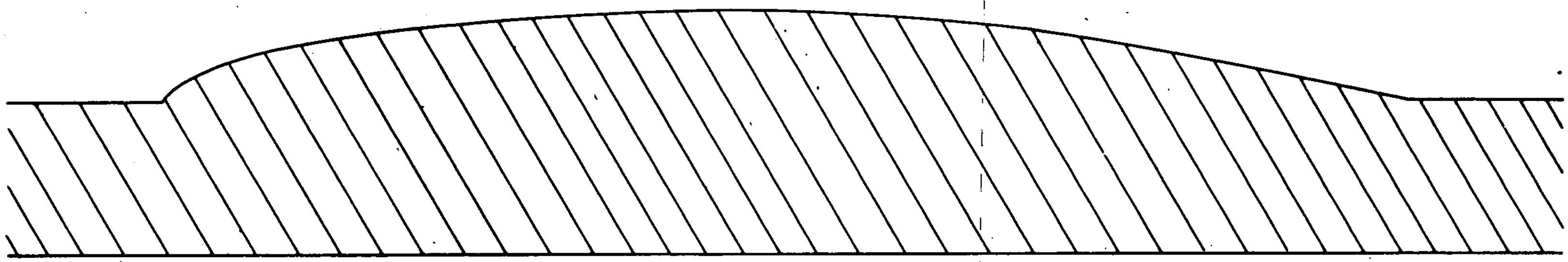


(c) Arrangement III.

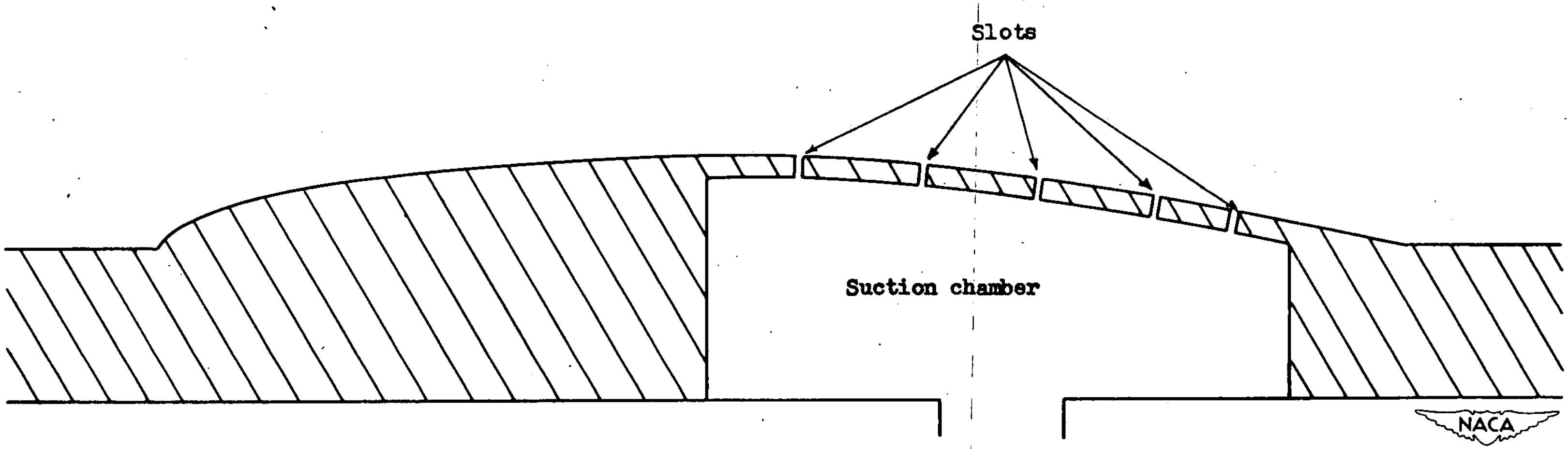


(d) Arrangement IV.

Figure 2.- Continued.

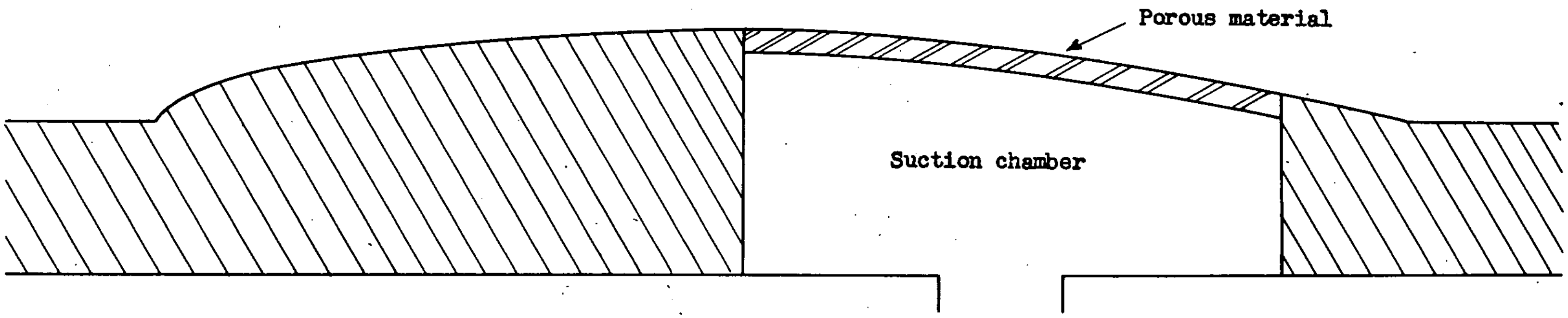


(a) Arrangement I.

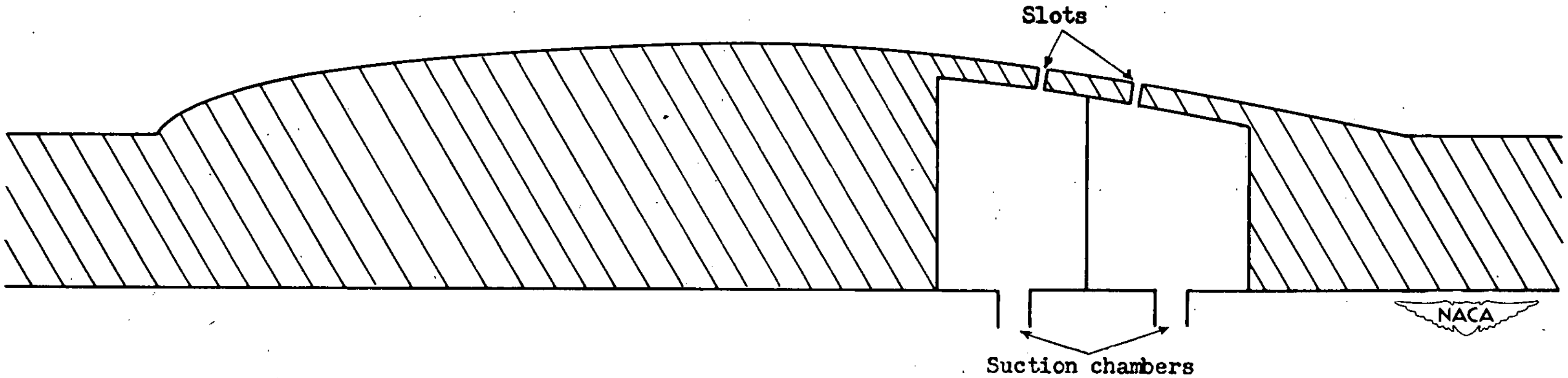


(b) Arrangement II.

Figure 2.- Test arrangements.



(e) Arrangement V.



(f) Arrangement VI.

Figure 2.- Concluded.

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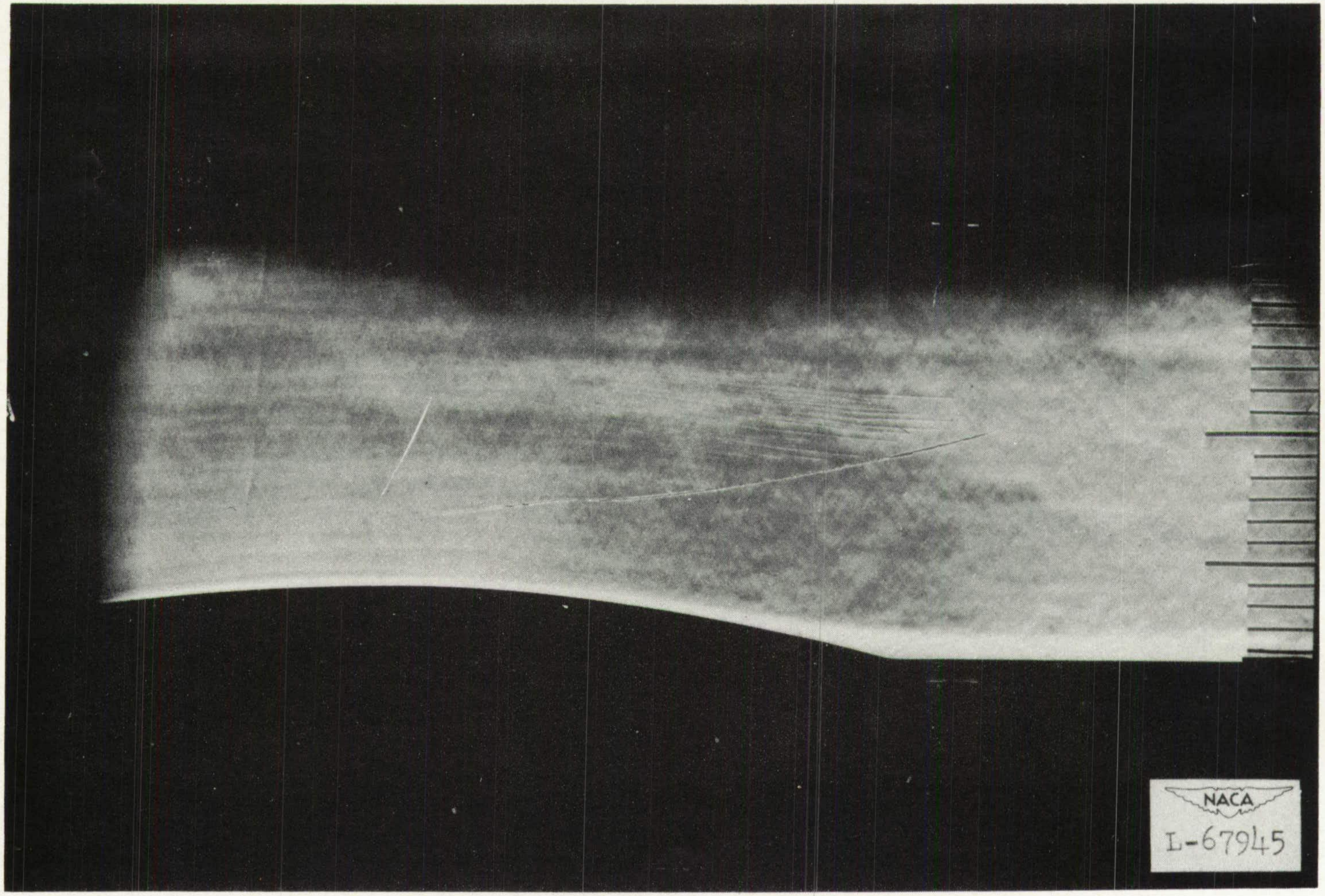

(a) $M_l = 0.79$.

Figure 3.- Flow through arrangement I.

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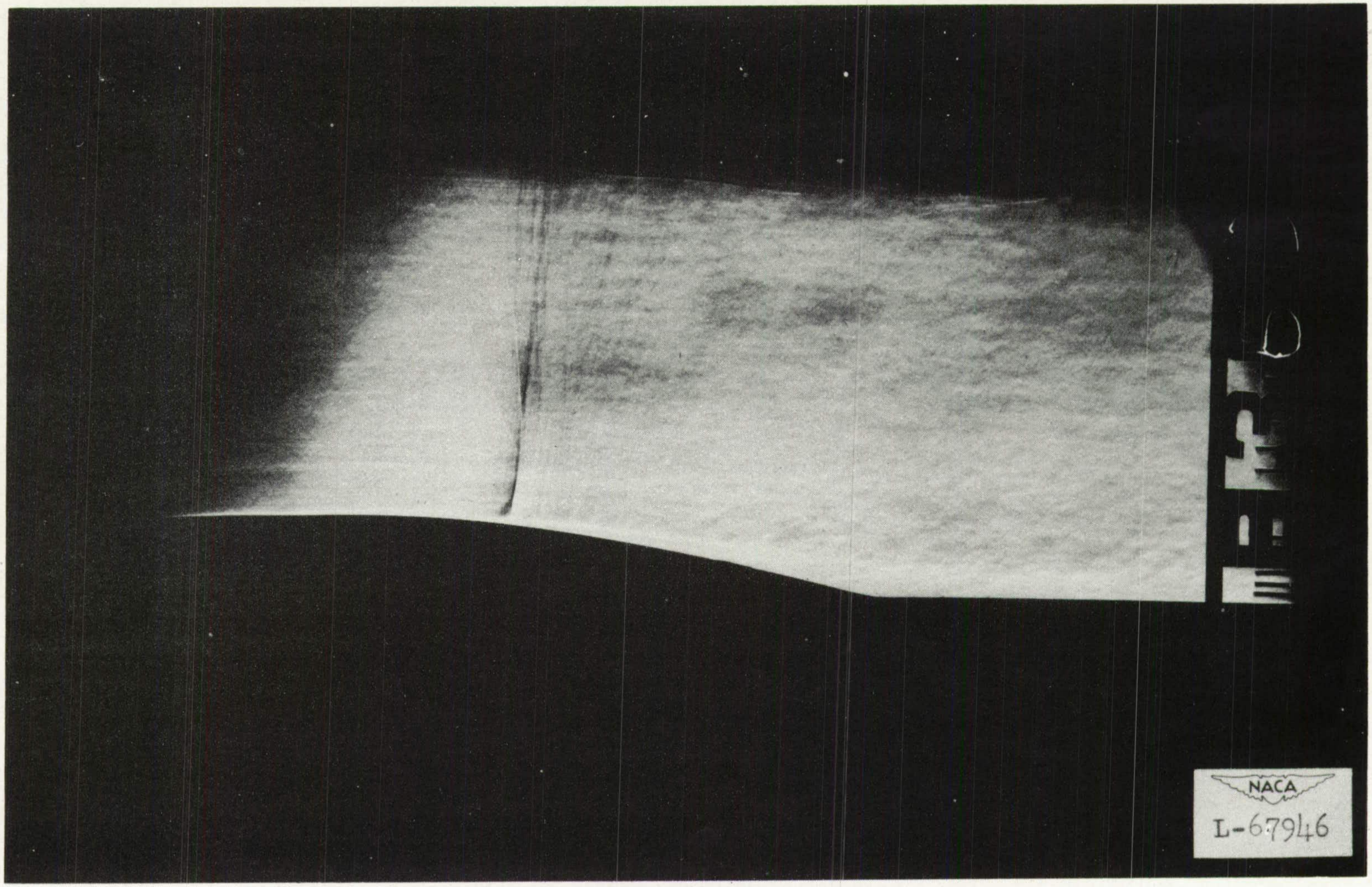

(b) $M_l = 1.18$.

Figure 3.- Continued.

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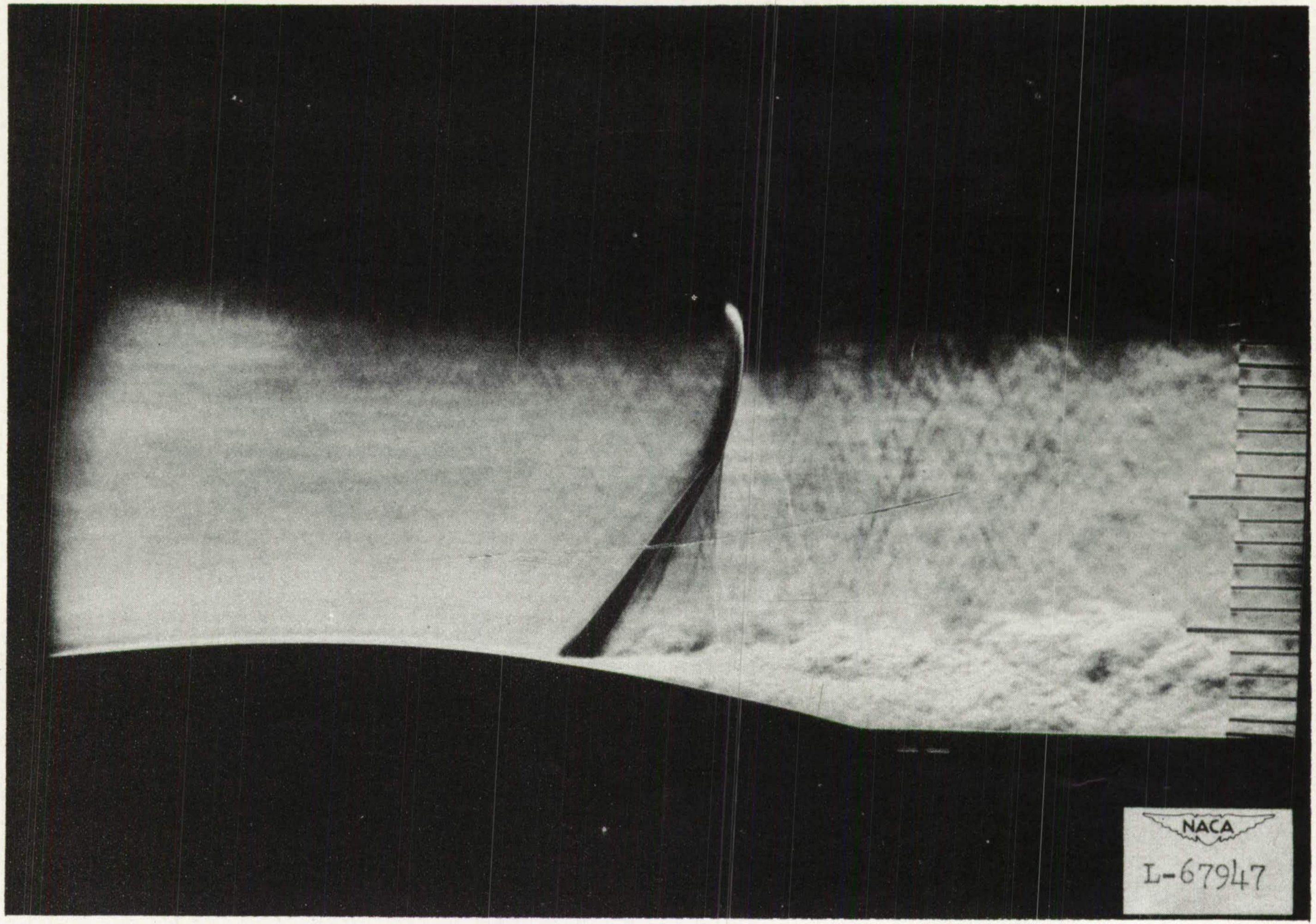

(c) $M_l = 1.30$.

Figure 3.- Continued.

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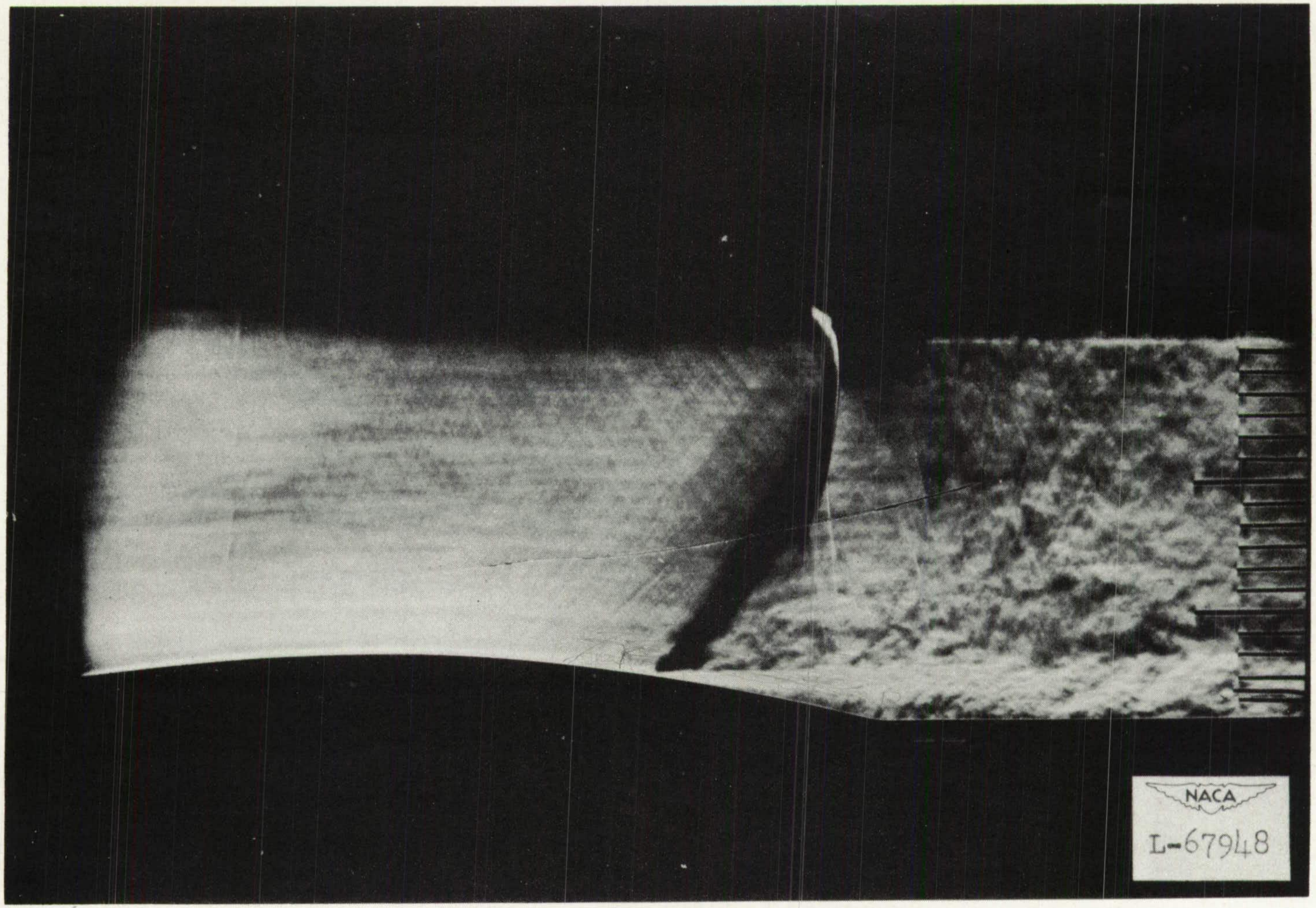

(d) $M_l = 1.36$.

Figure 3.- Continued.

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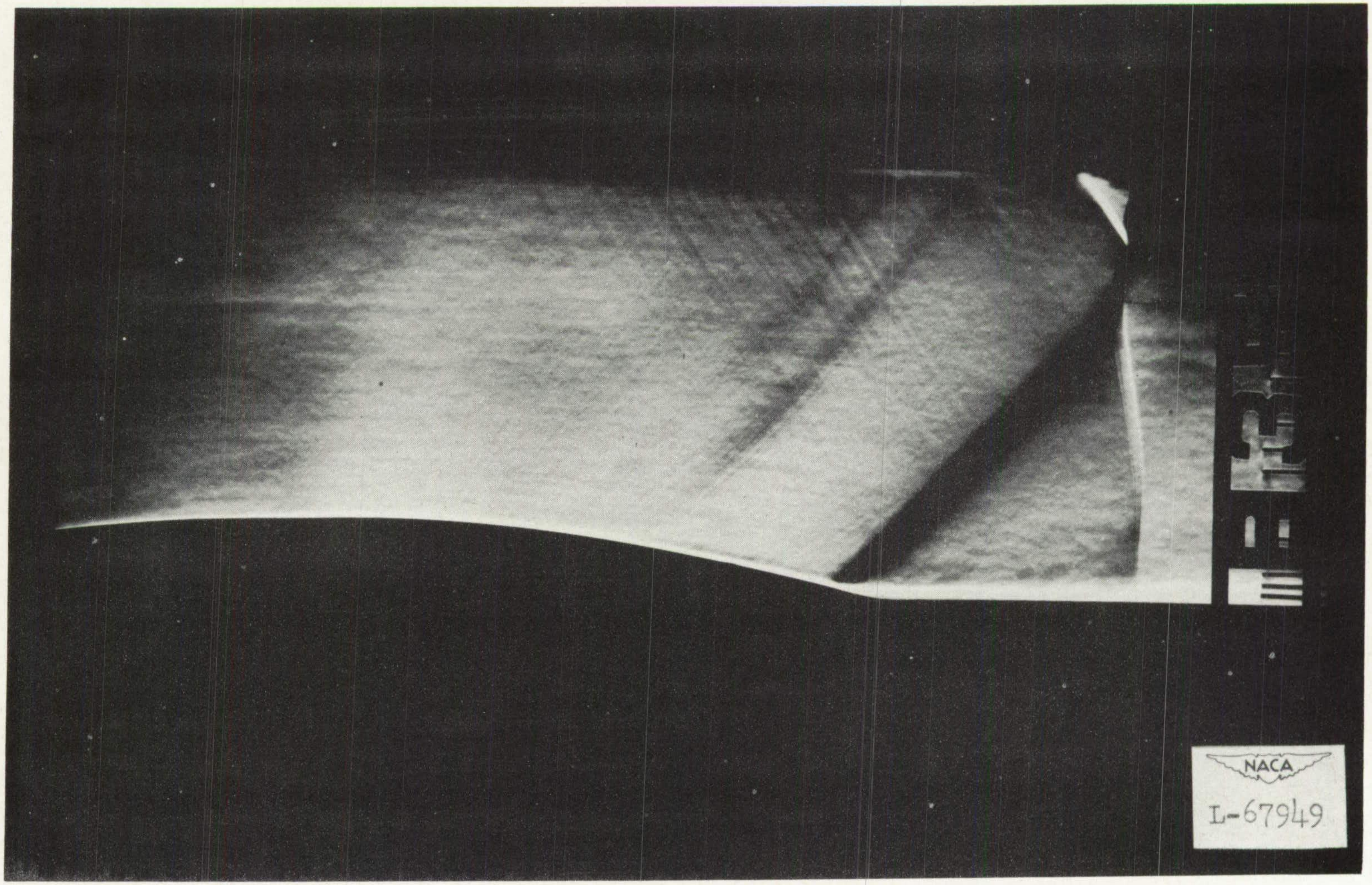

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(e) $M_l = 1.40$.

Figure 3.- Concluded.

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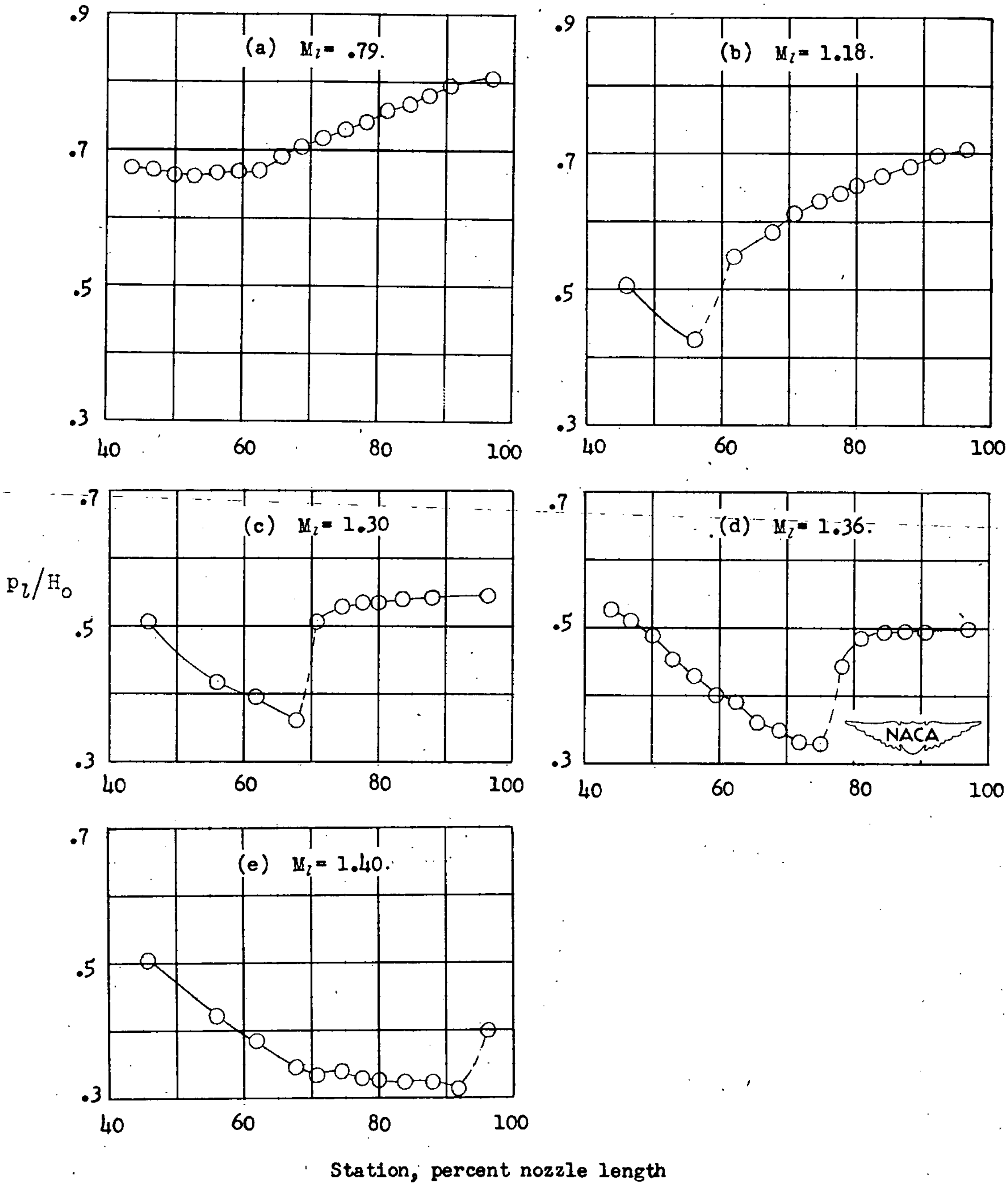
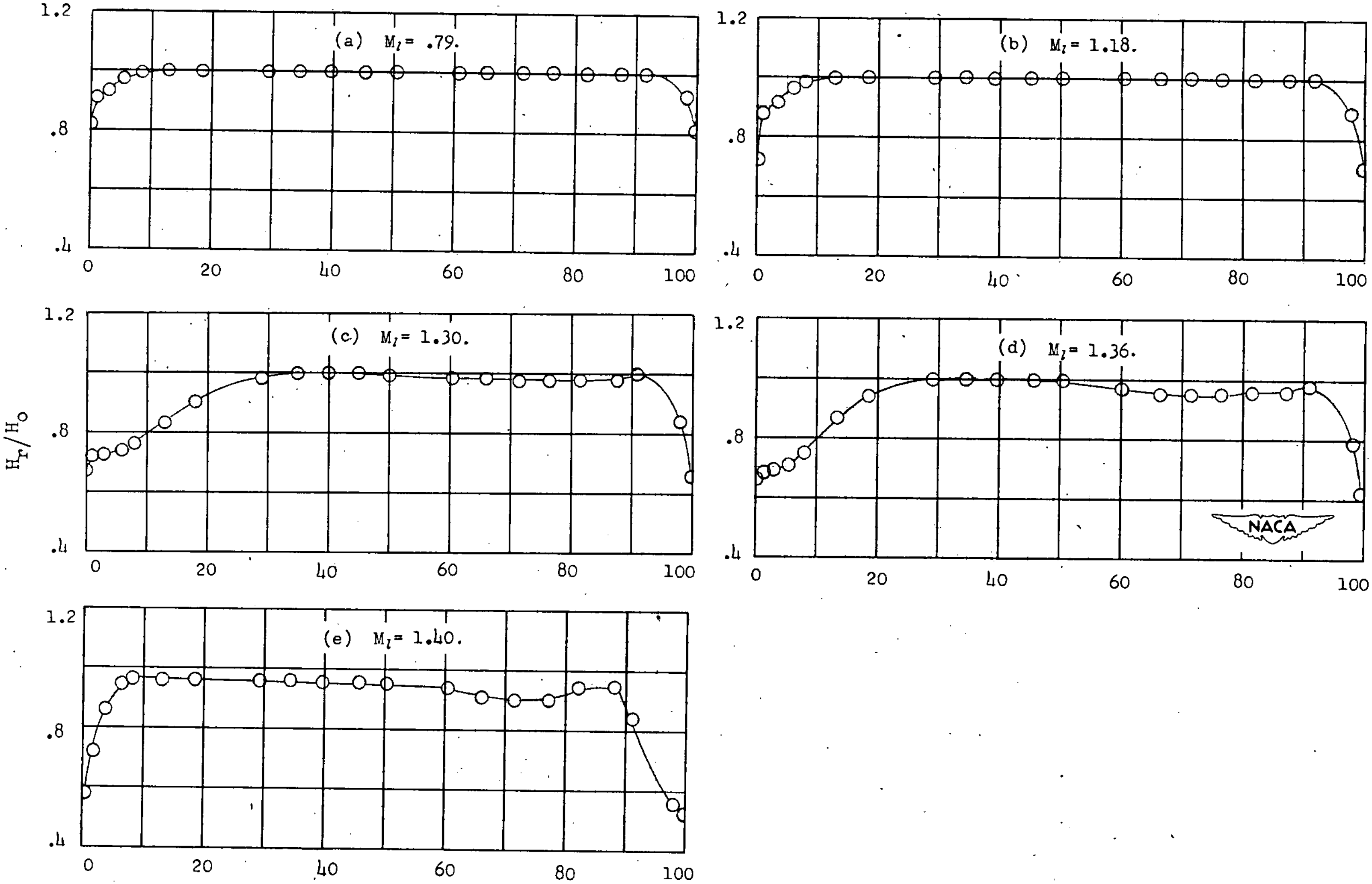
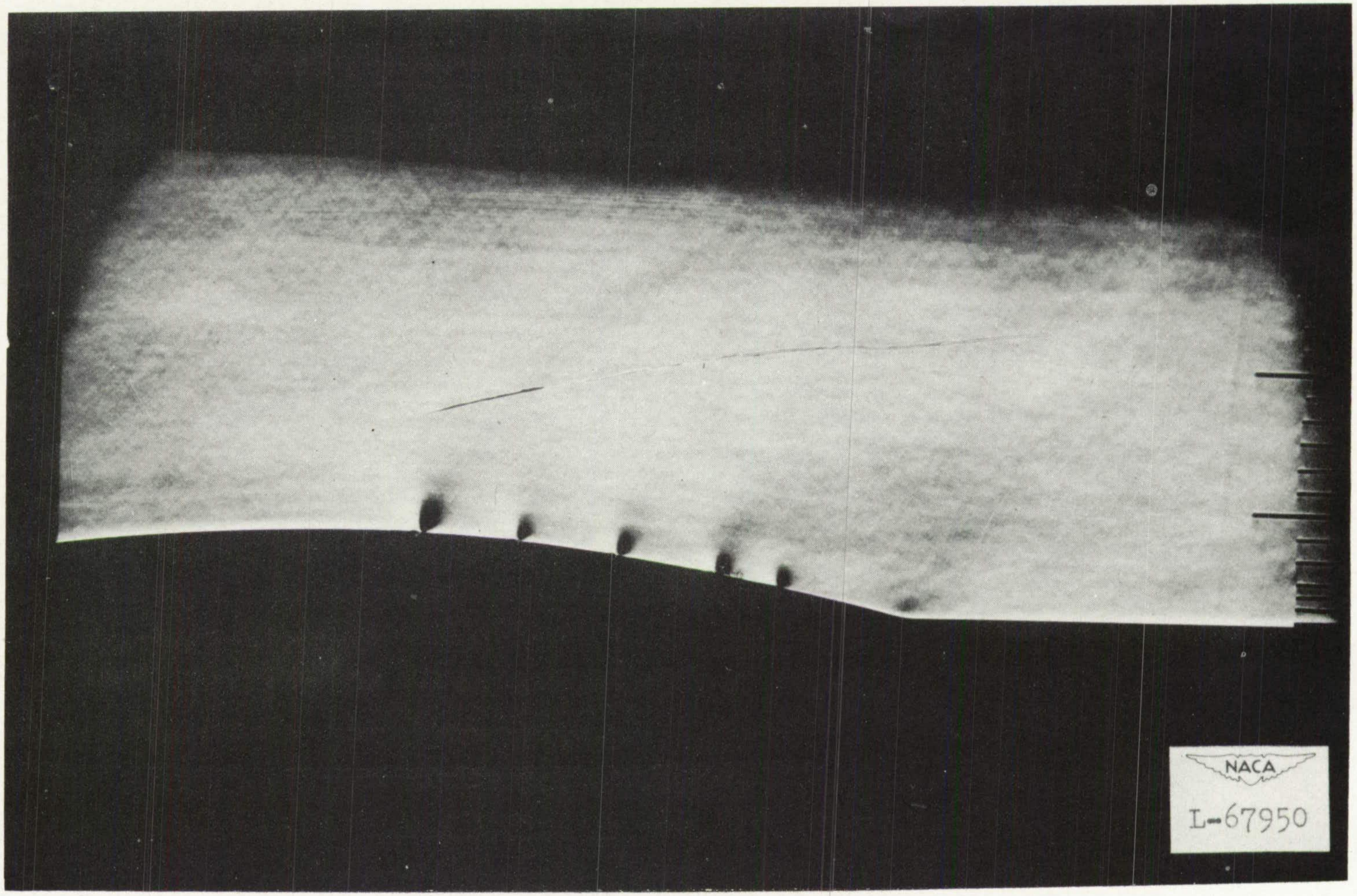


Figure 4.- Pressure distributions over expansion surface of arrangement I.



Vertical station, percent channel height

Figure 5.- Wake surveys, arrangement I.



(a) $M_l = 0.85$.

Figure 6.- Flow through arrangement II.

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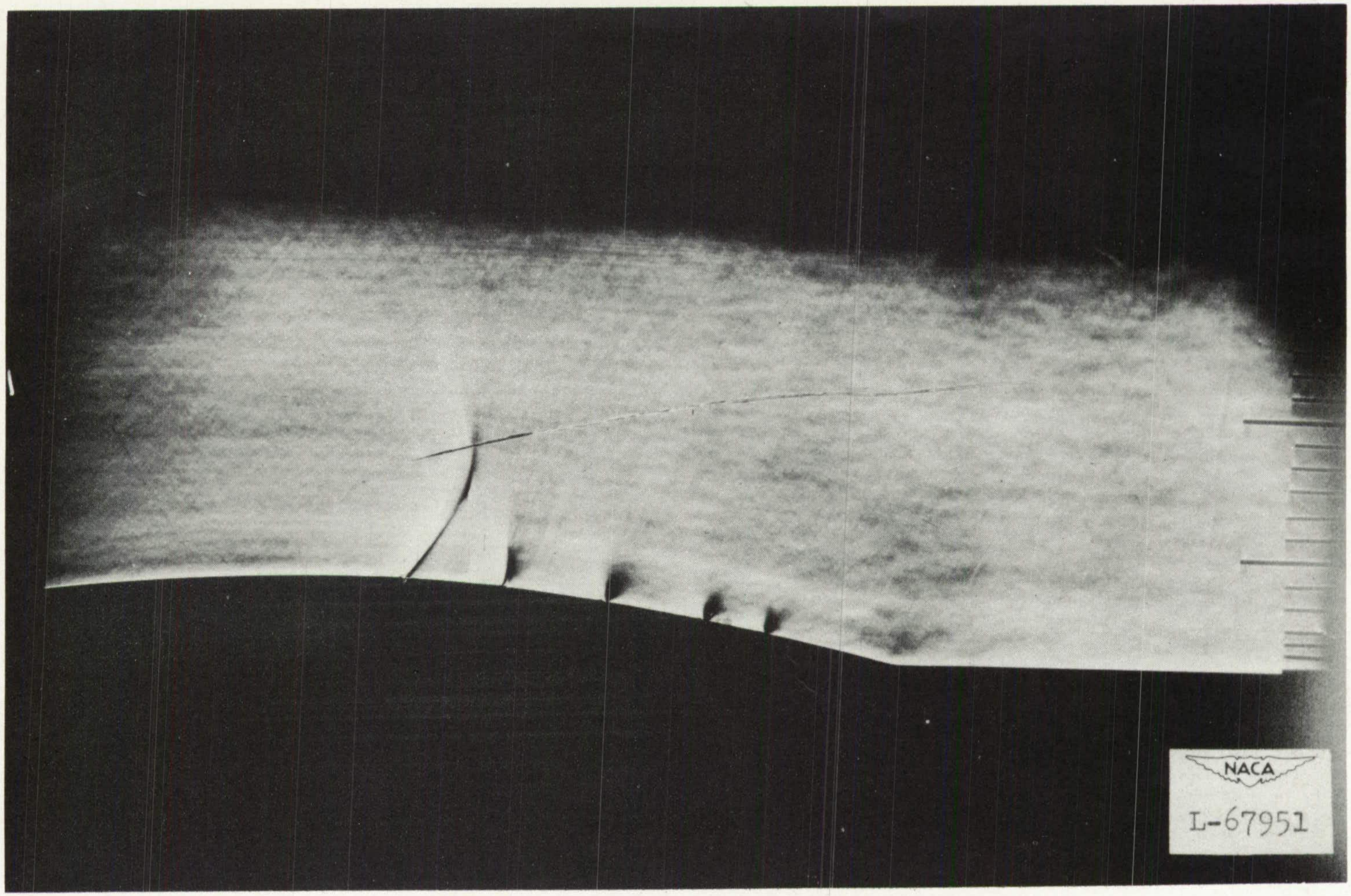

(b) $M_l = 1.14$.

Figure 6.- Continued.

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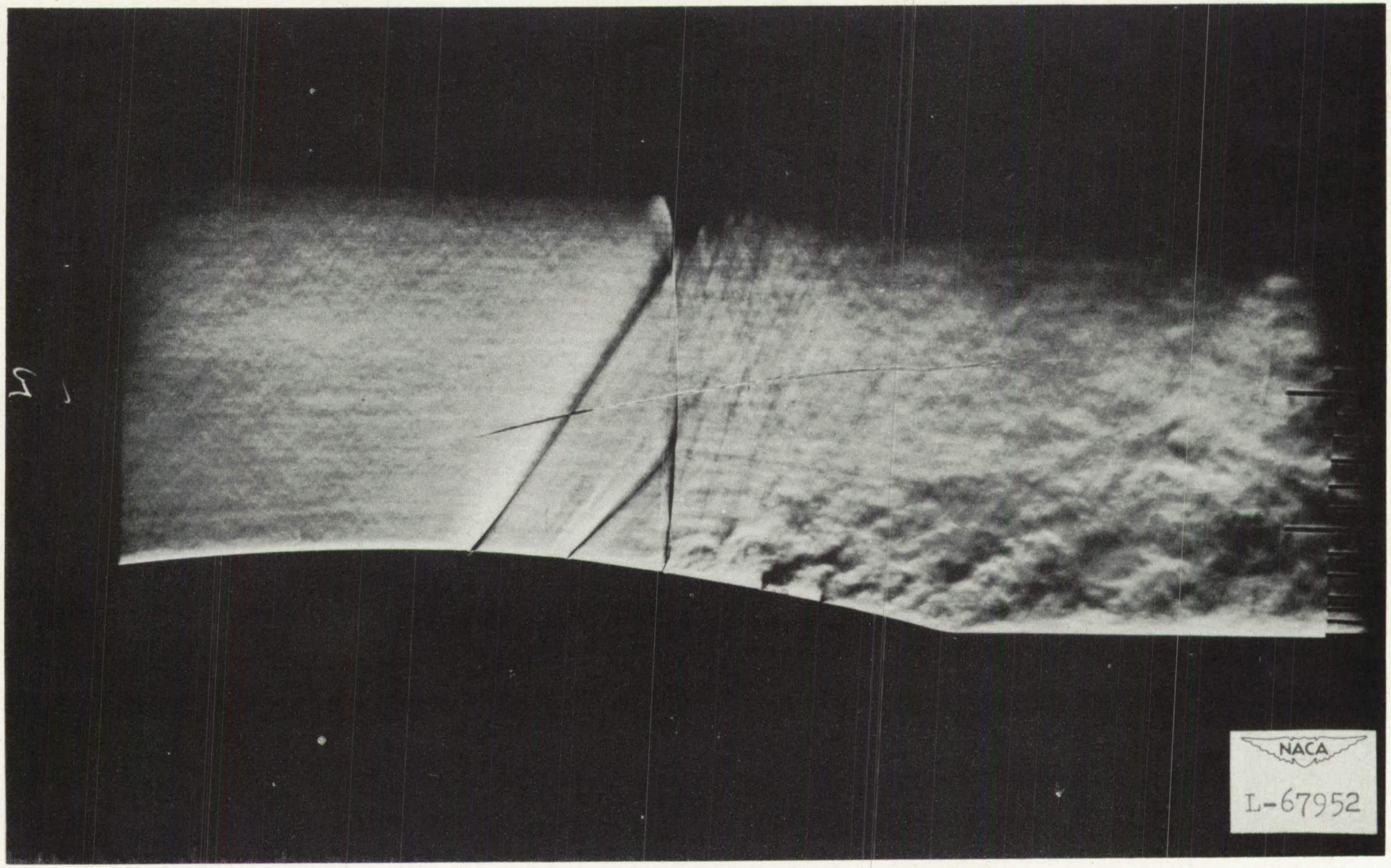

(c) $M_l = 1.29$.

Figure 6.- Continued.

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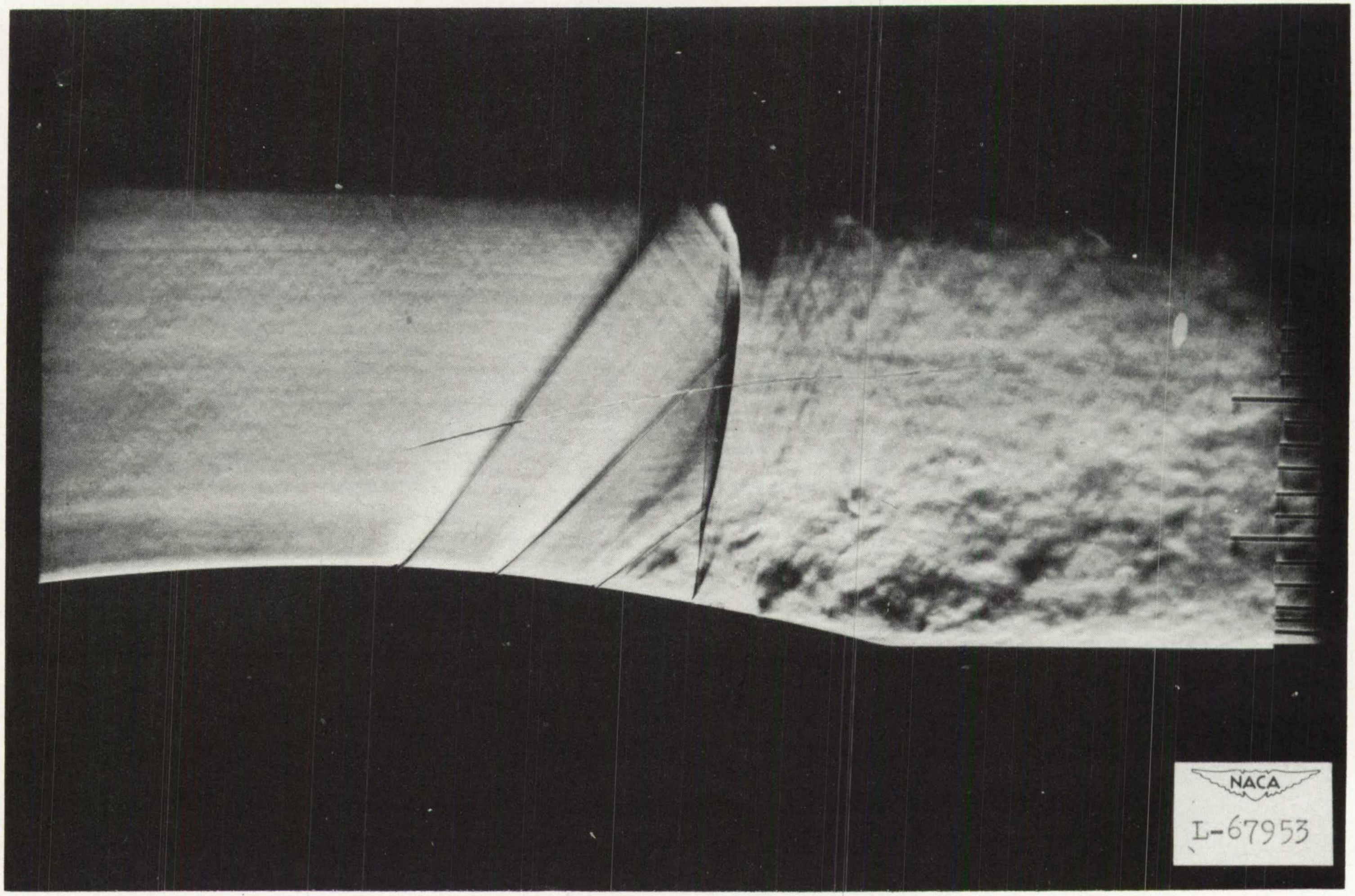

(d) $M_l = 1.35$.

Figure 6.- Continued.

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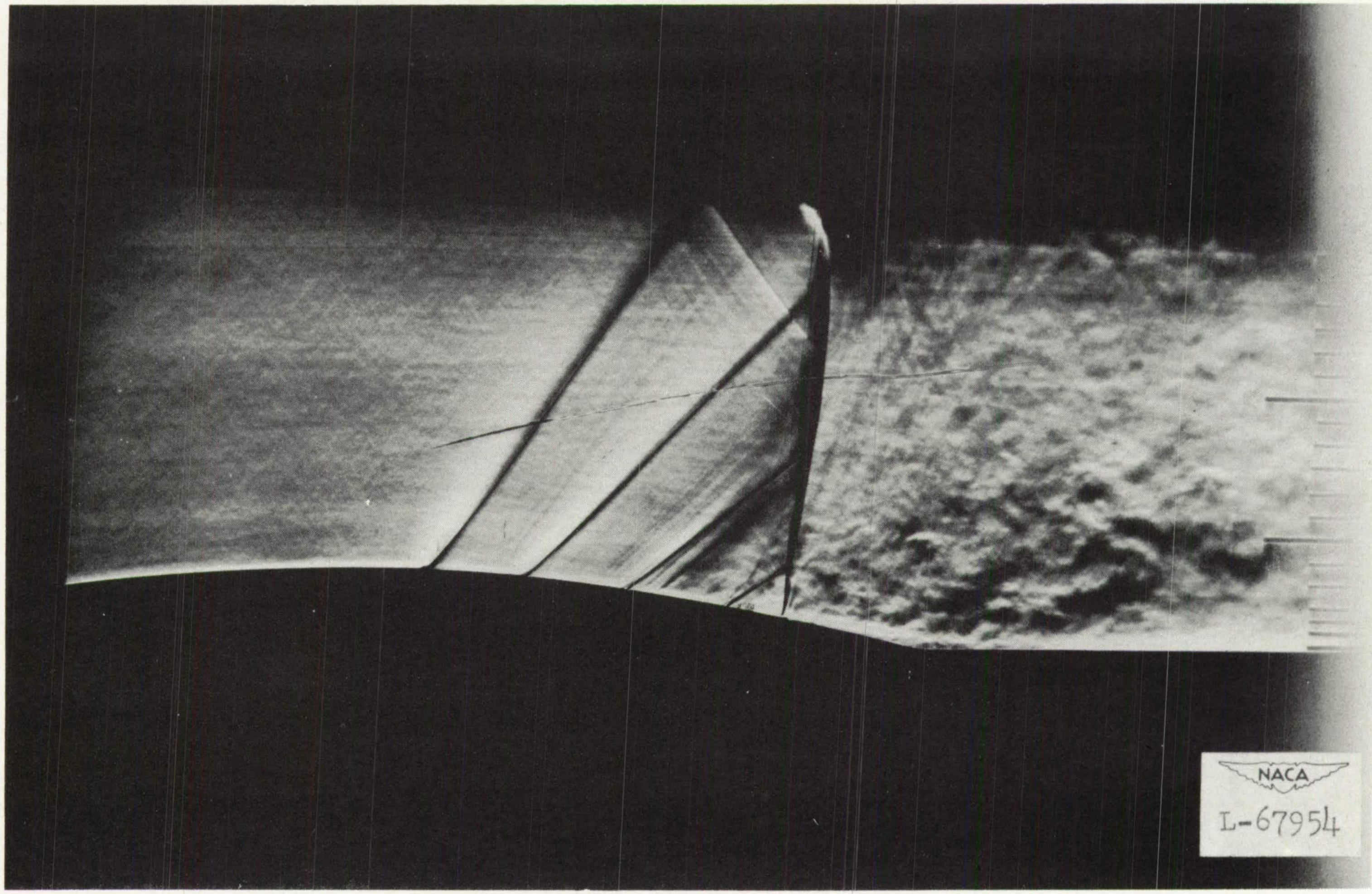

(e) $M_l = 1.41$.

Figure 6.- Concluded.

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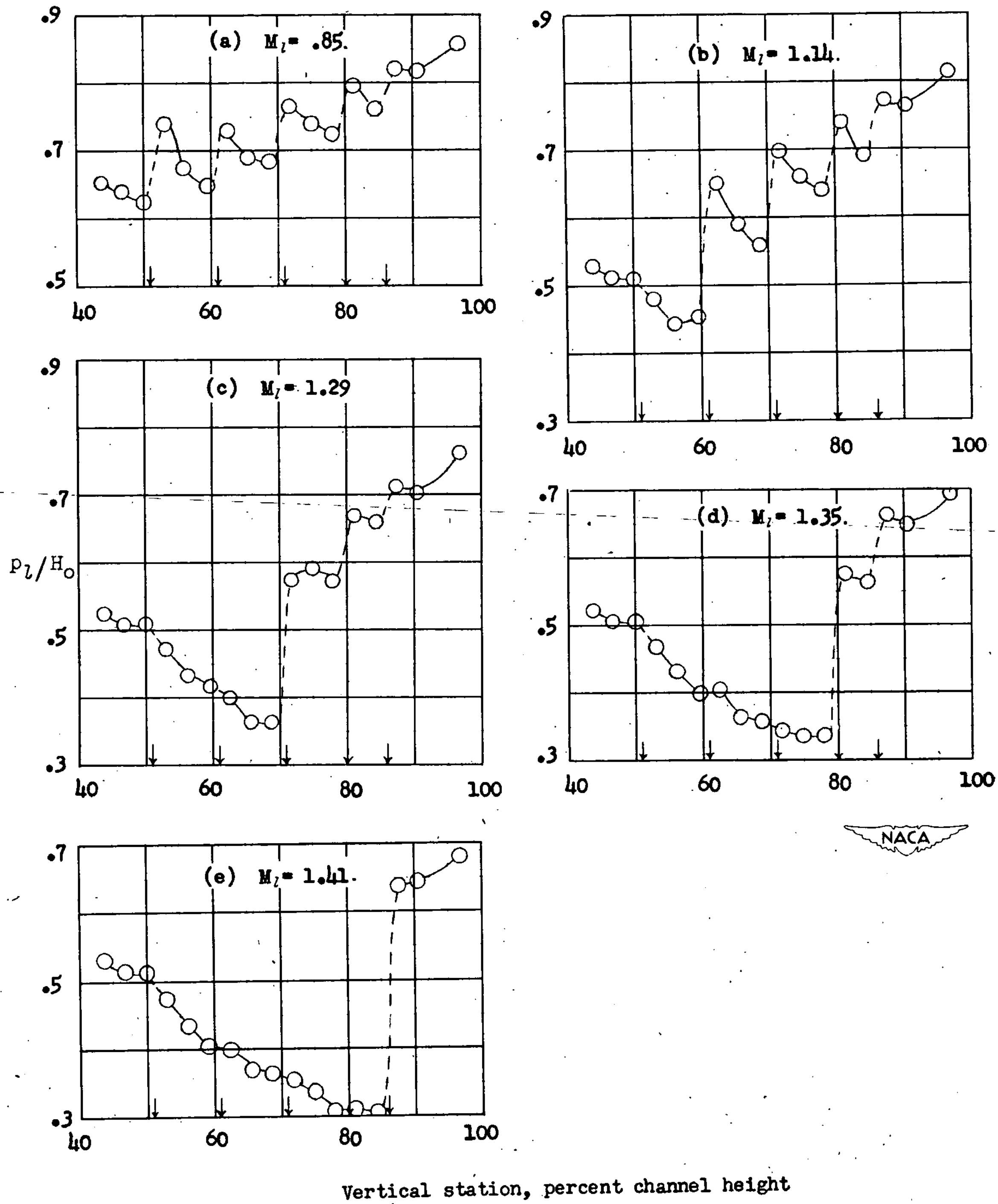


Figure 7.- Pressure distributions over expansion surface of arrangement II. (Arrows represent active slot location.)

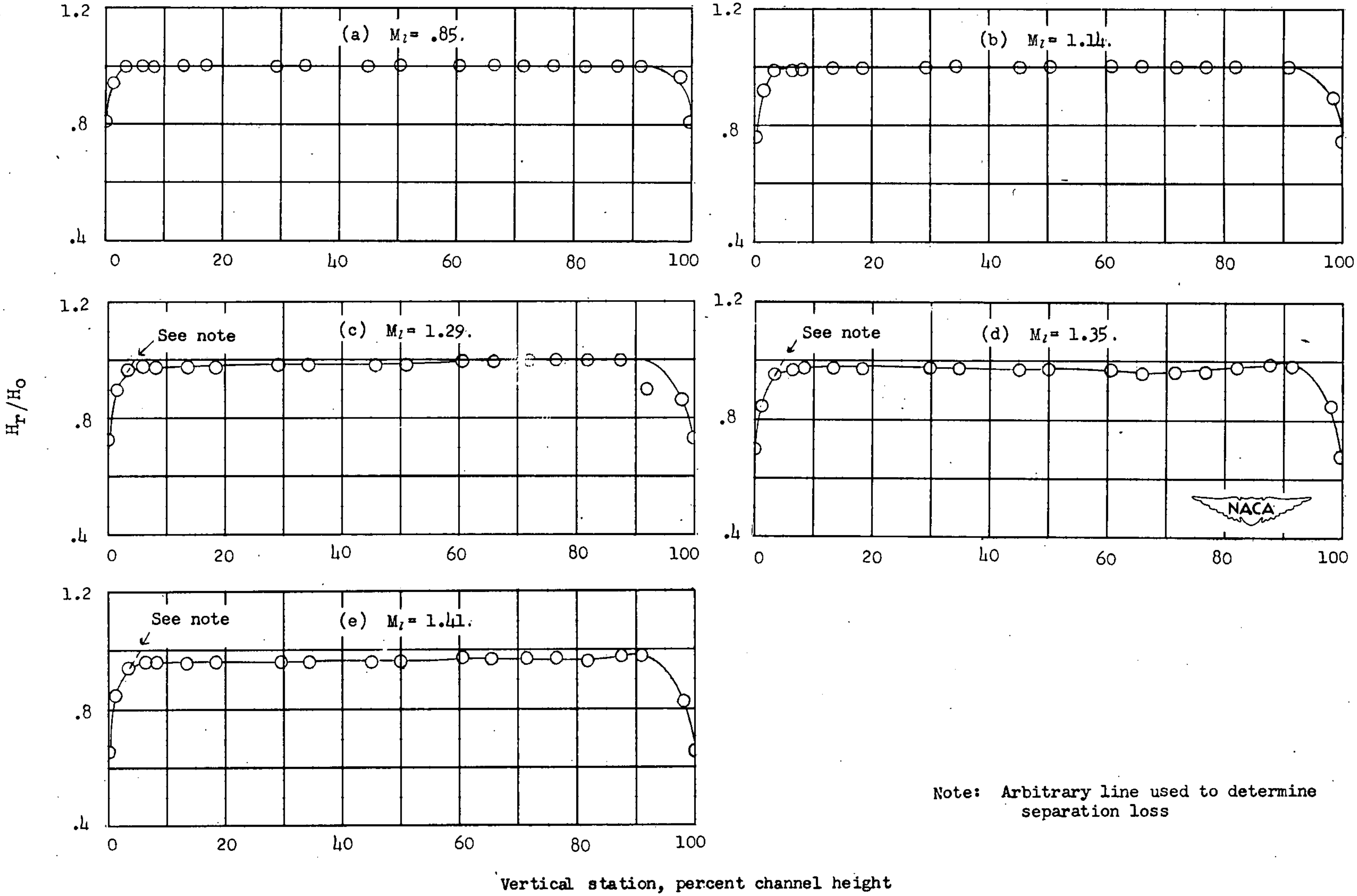
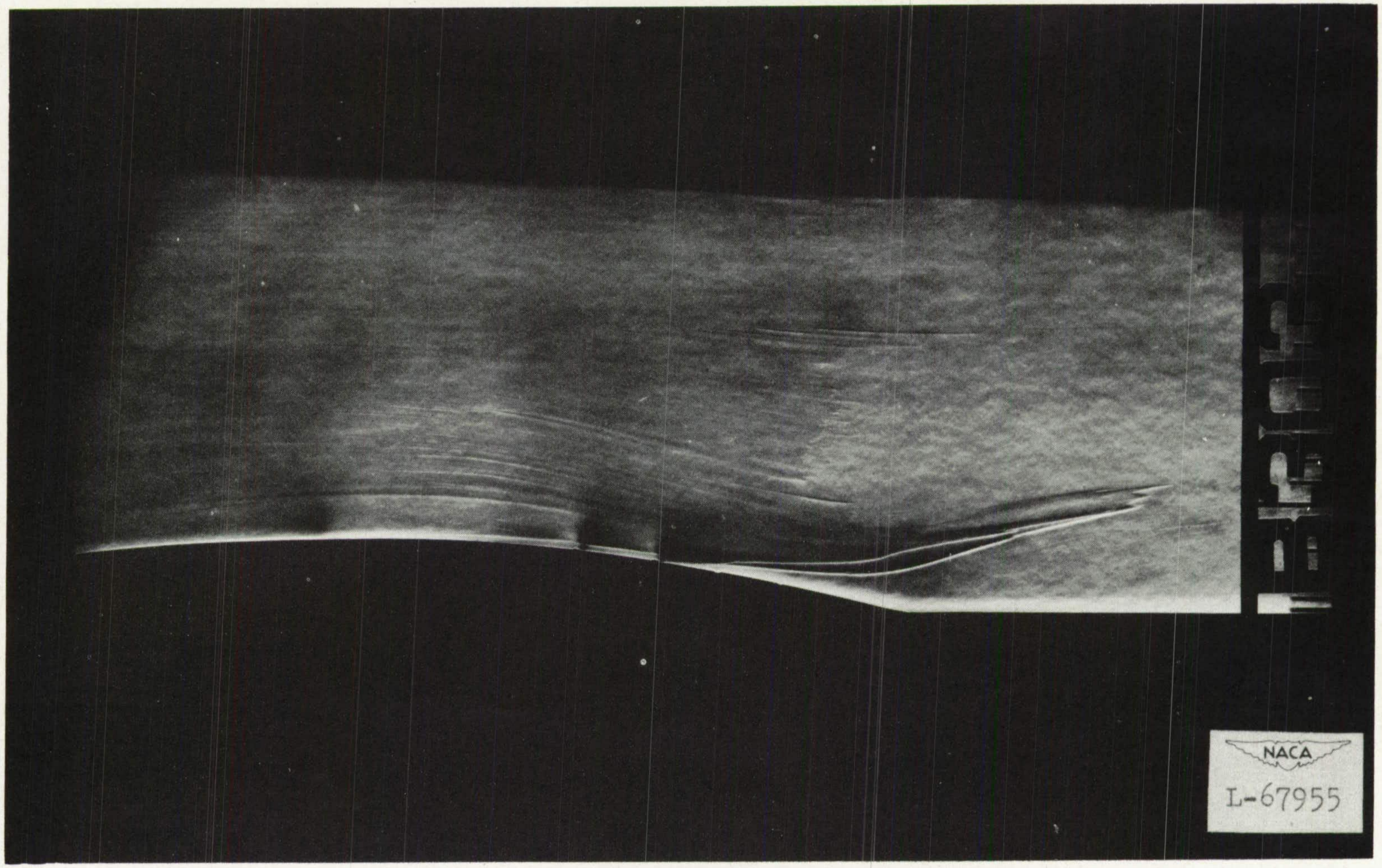


Figure 8.- Wake surveys, arrangement II.



(a) $M_l = 0.83$.

Figure 9.- Flow through arrangement III.

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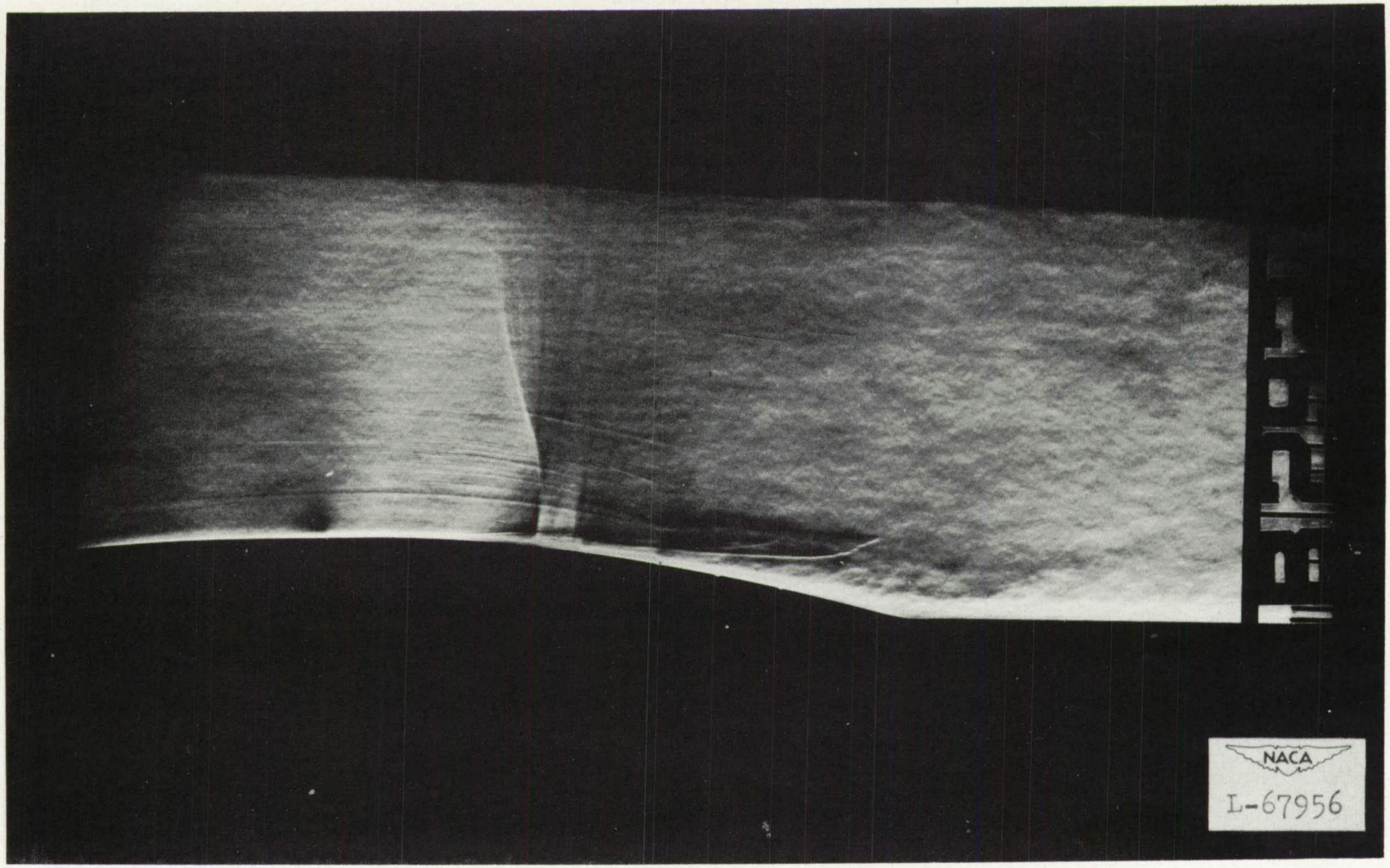

(b) $M_l = 1.16$.

Figure 9.- Continued.

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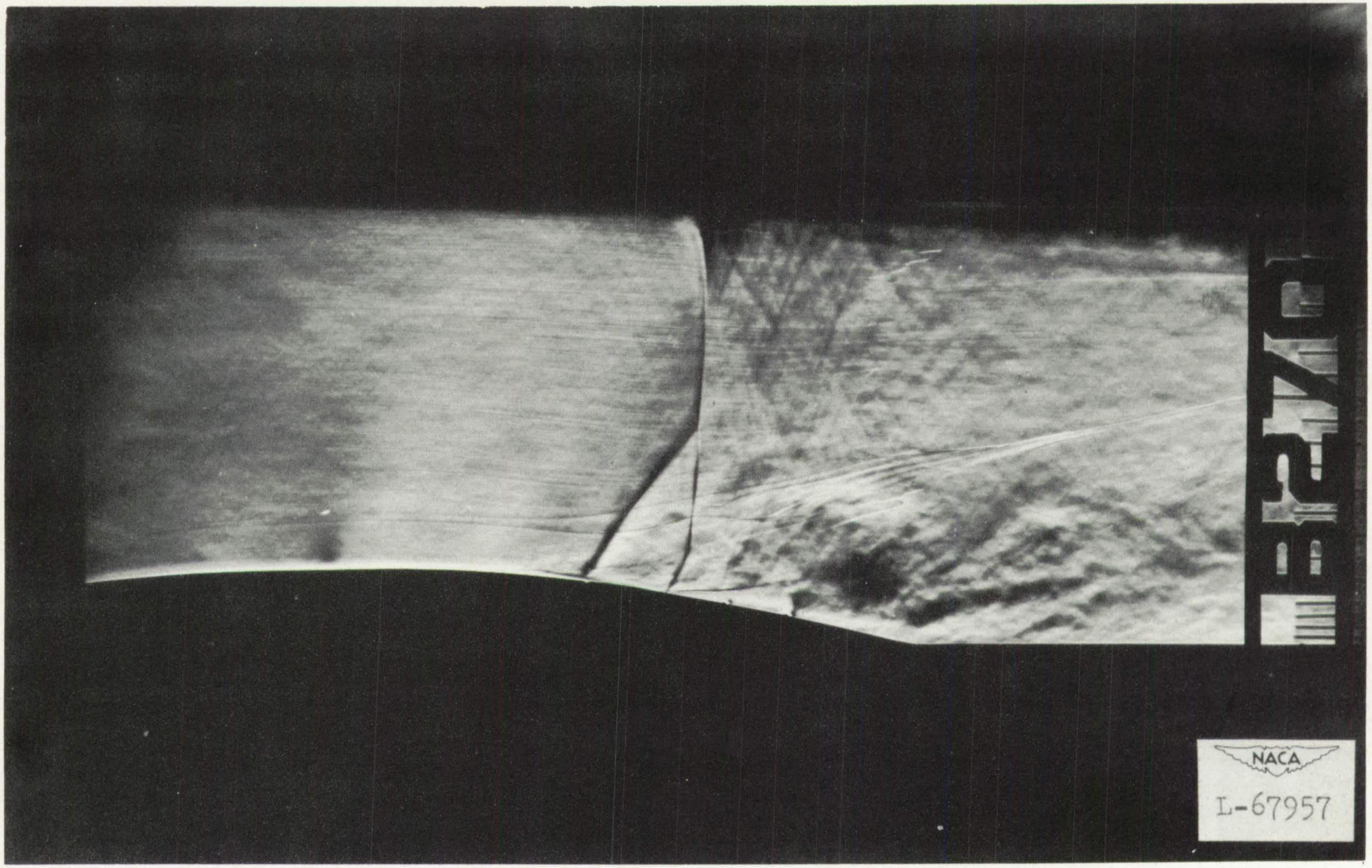

(c) $M_l = 1.31$.

Figure 9.- Continued.

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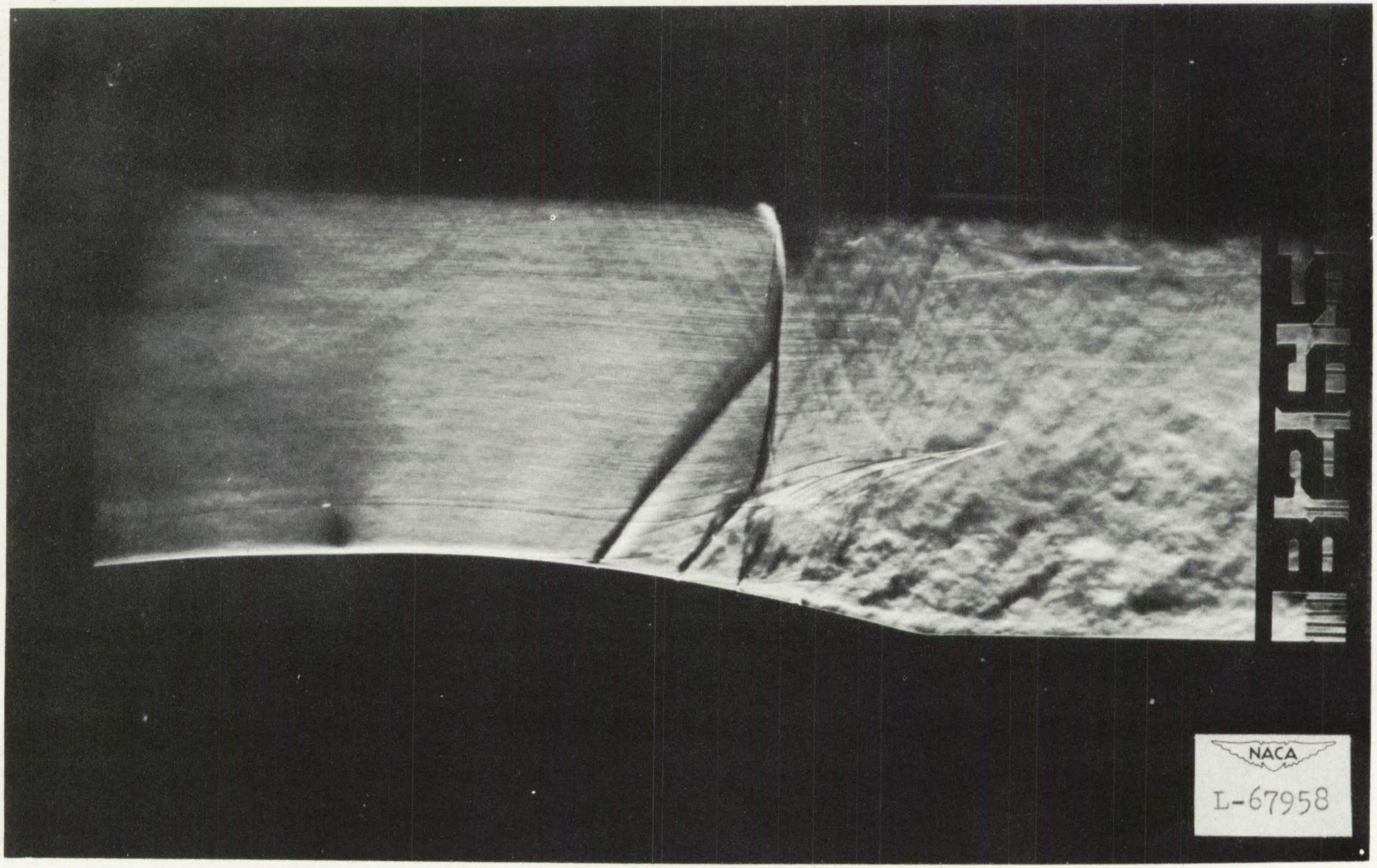

(d) $M_l = 1.35$.

Figure 9.- Continued.

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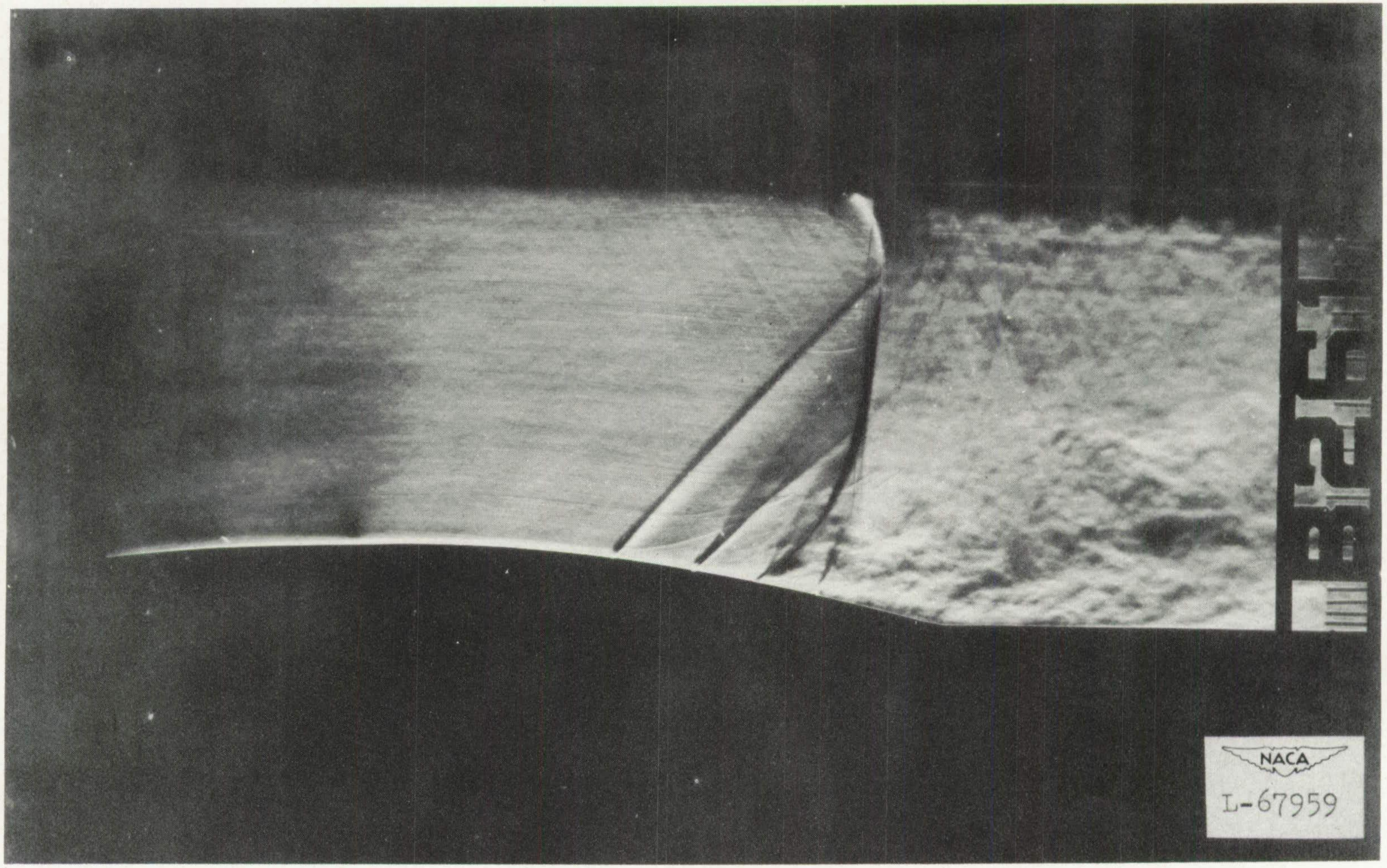

(e) $M_l = 1.42$.

Figure 9.- Concluded.

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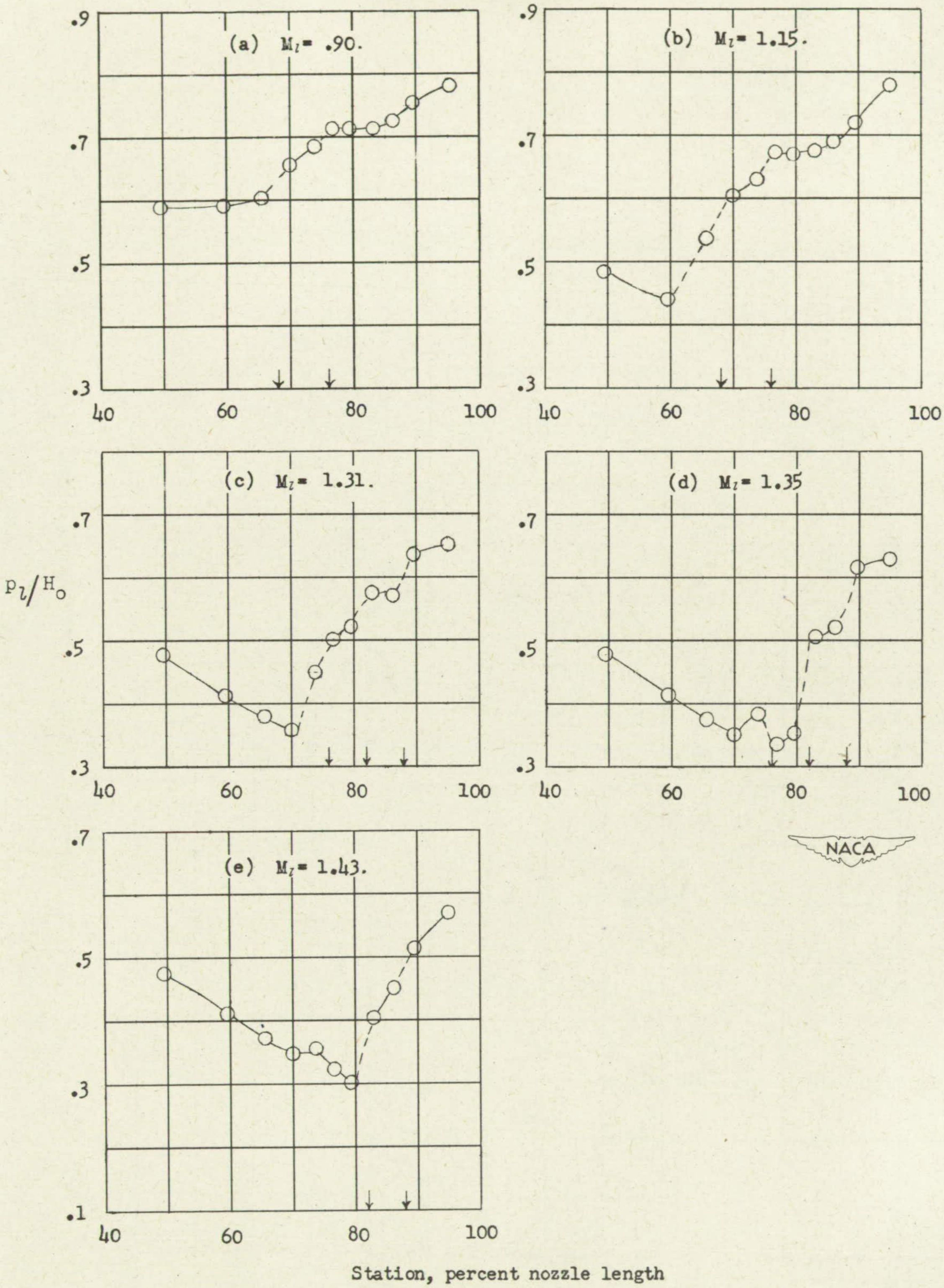

Figure 10.- Pressure distributions over expansion surface of arrangement III. (Arrows represent active slot location.)

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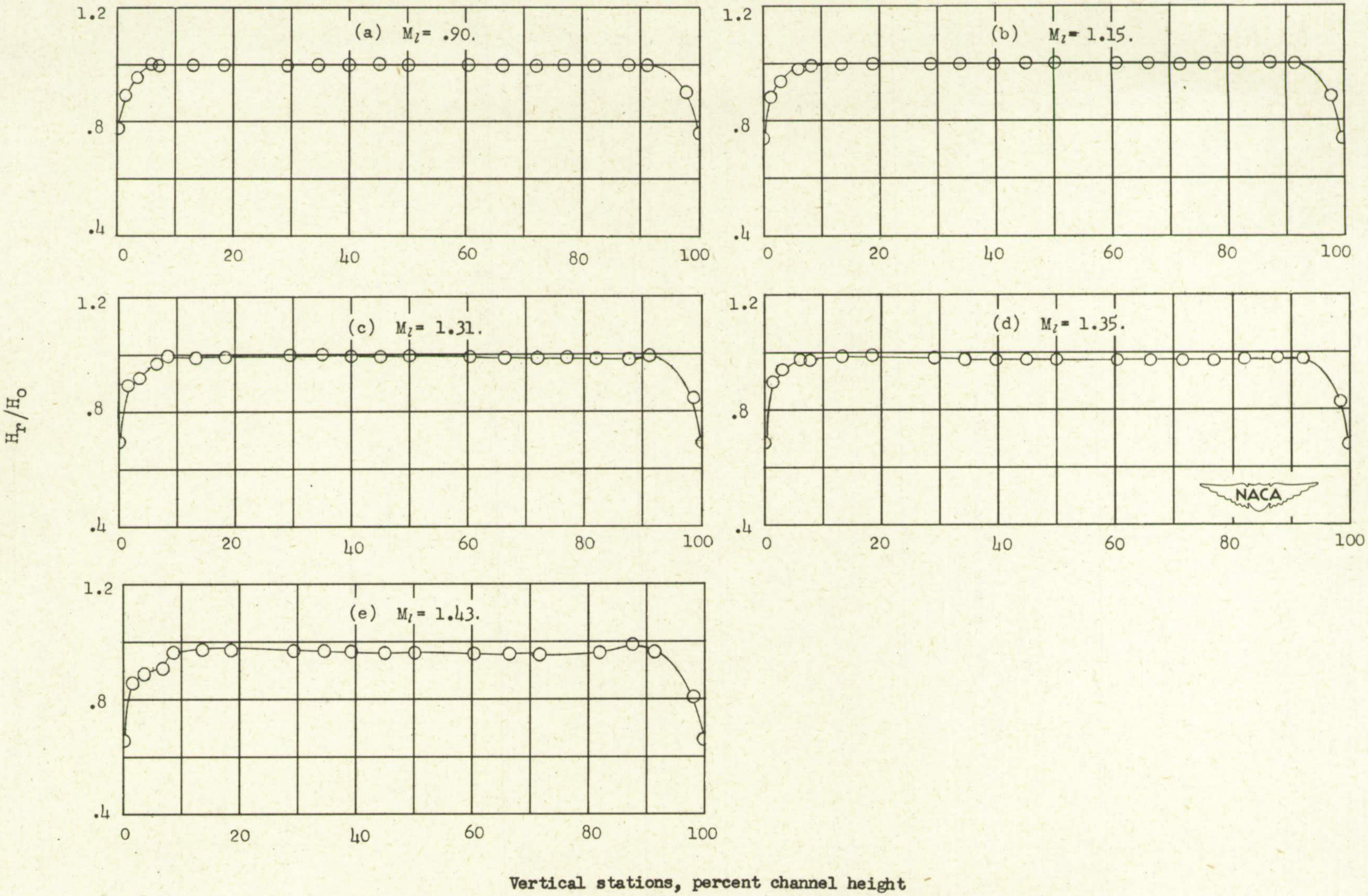

Figure 11.- Wake surveys, arrangement III.

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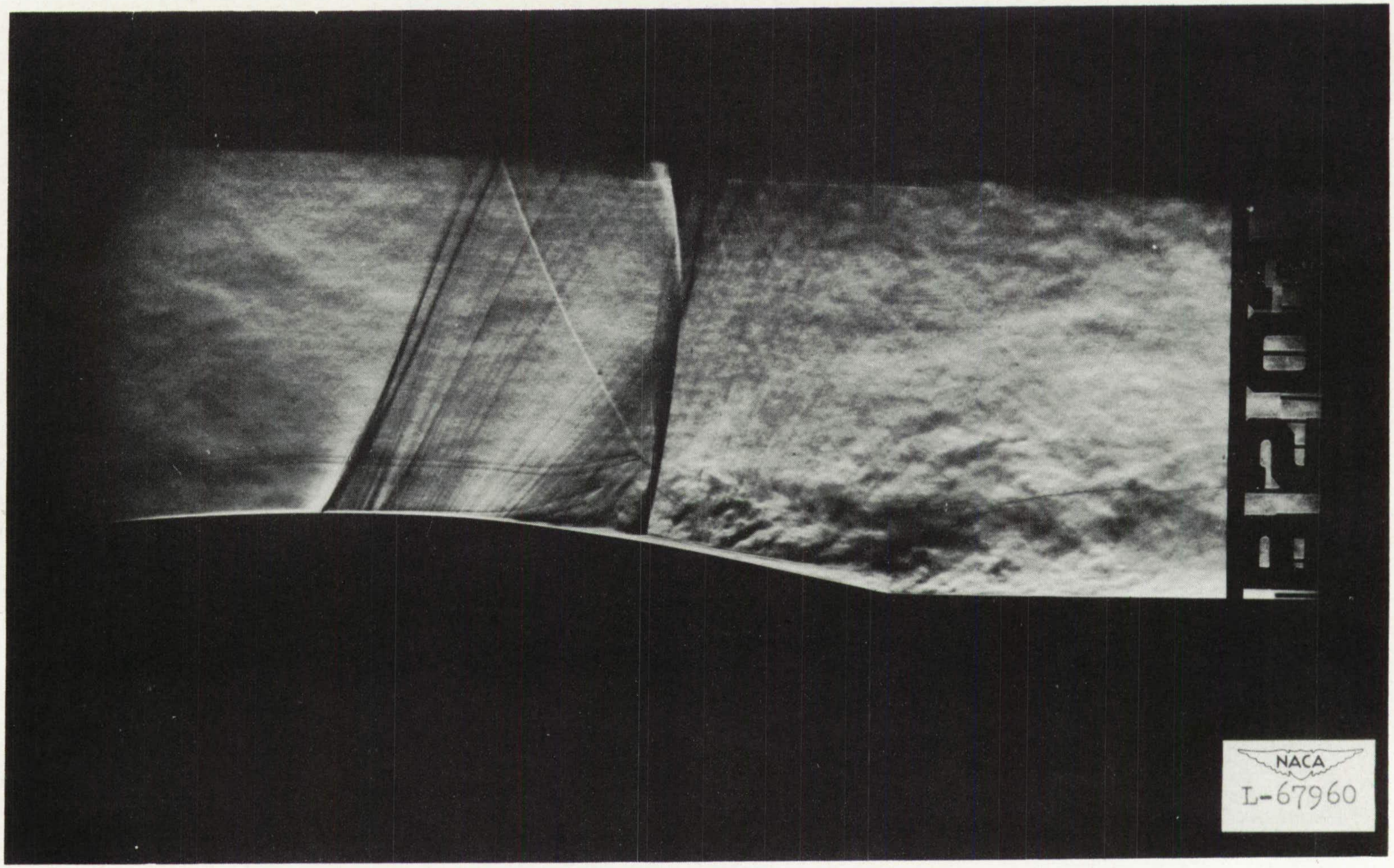

Figure 12.- Flow through arrangement IV. $M_l = 1.32$.

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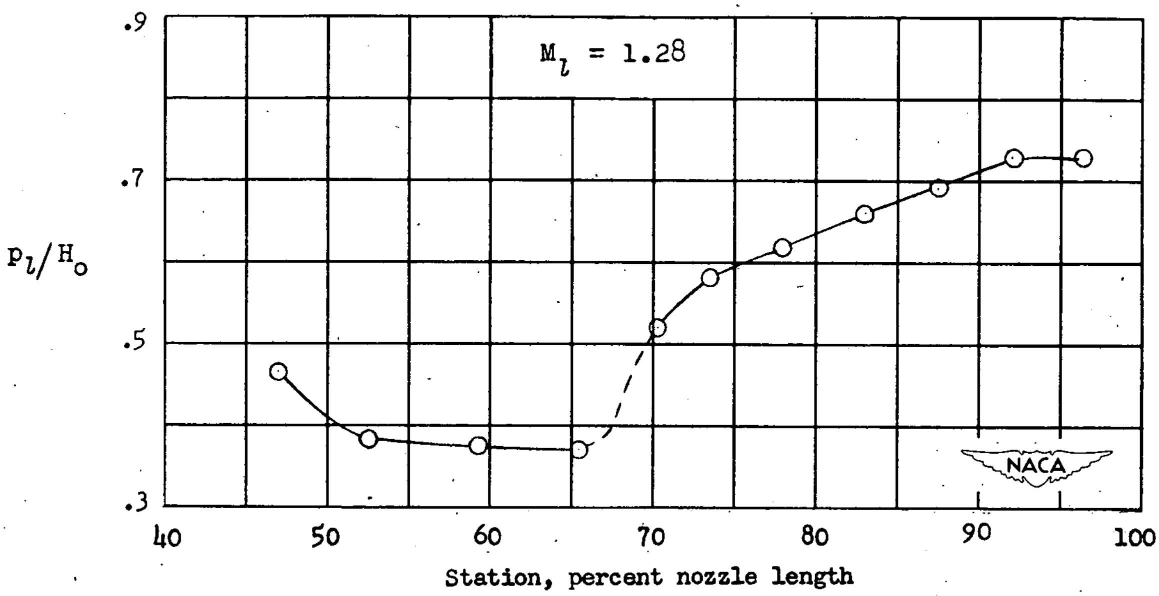

Figure 13.- Pressure distribution over expansion surface of arrangement IV.

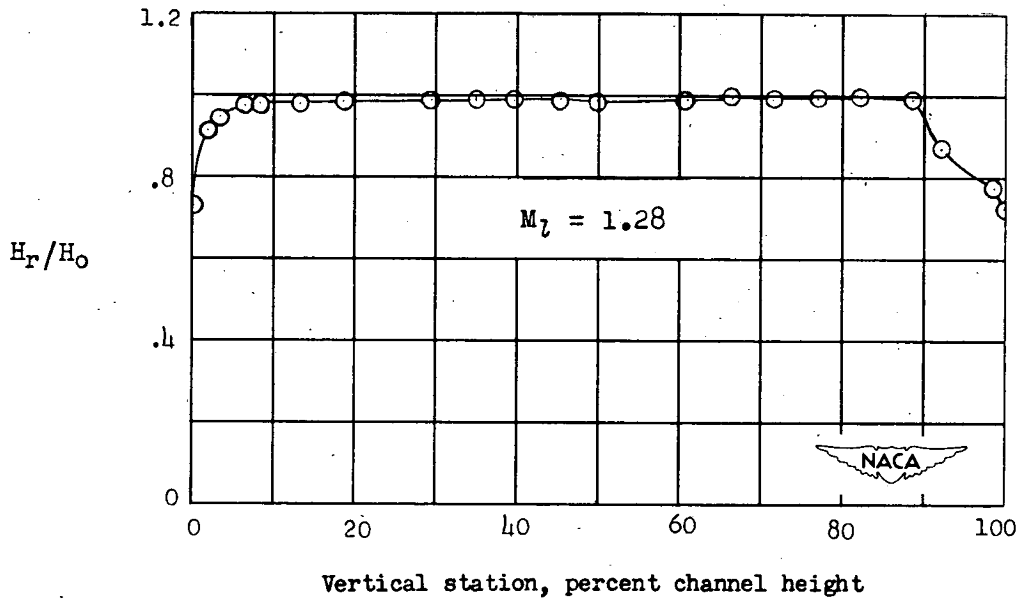

Figure 14.- Wake surveys, arrangement IV.

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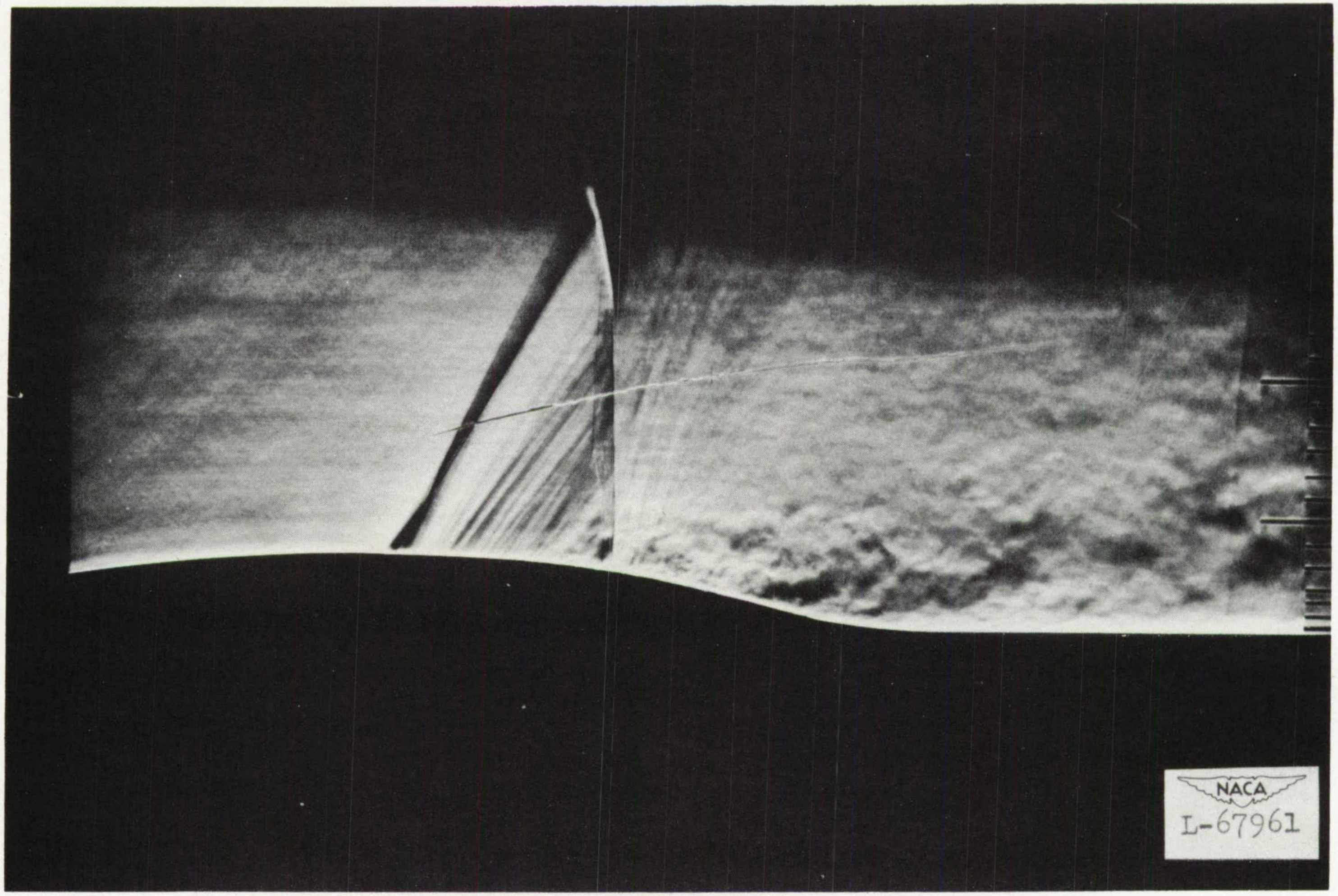

Figure 15.- Flow through arrangement V. $M_l = 1.28$.

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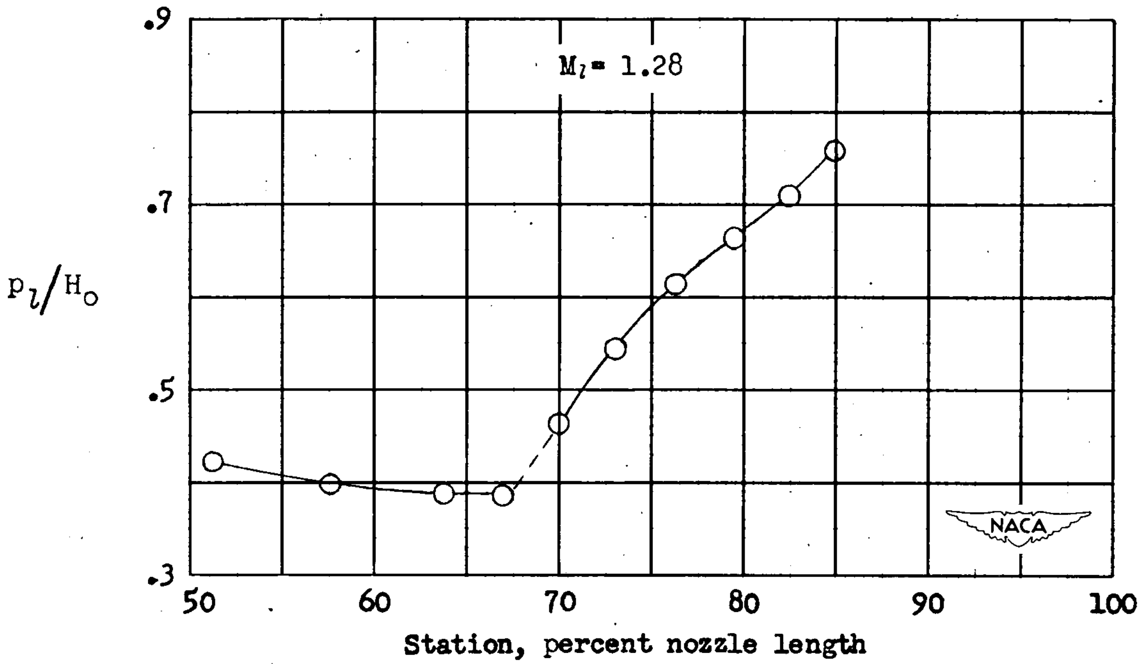

Figure 16.- Pressure distribution over expansion surface of arrangement V.

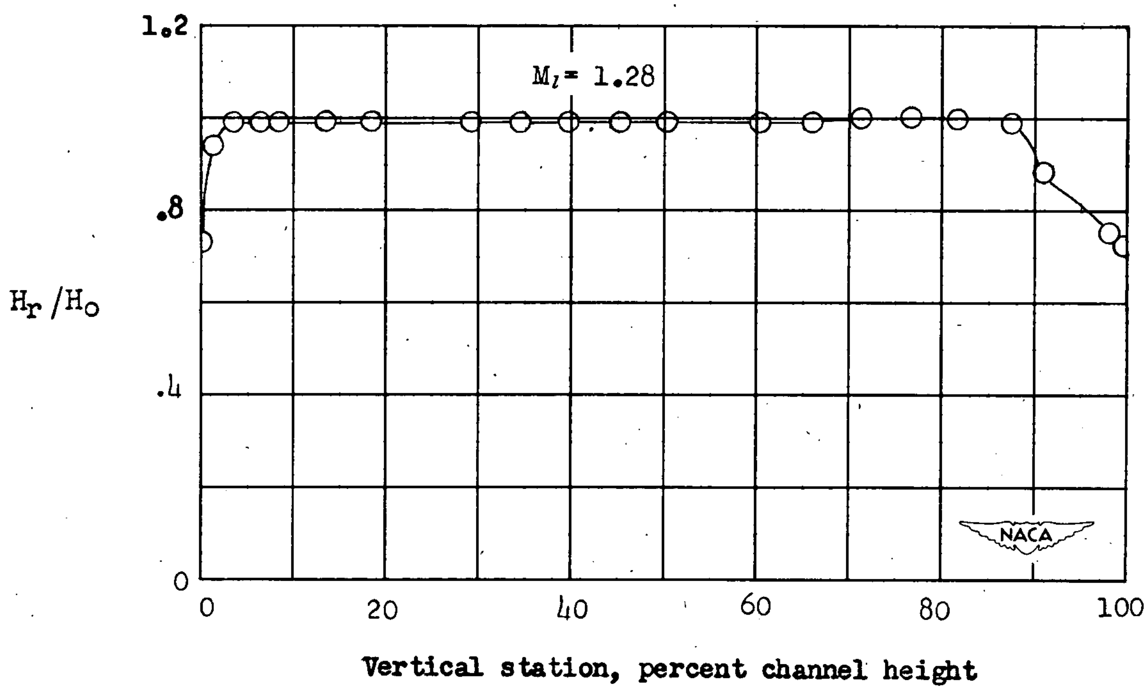

Figure 17.- Wake survey, arrangement V.

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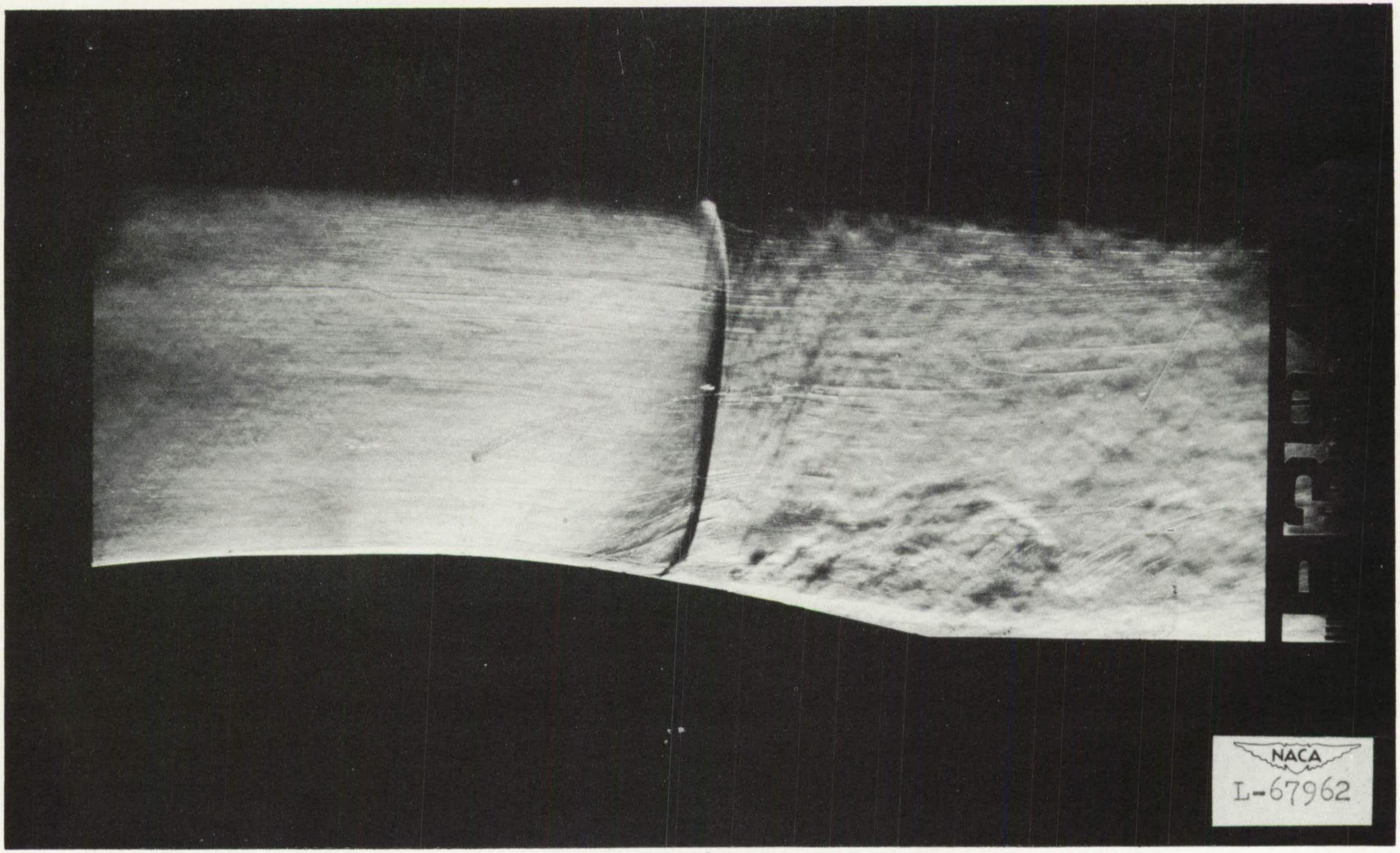

Figure 18.- Flow through arrangement VI. $M_l = 1.33$.

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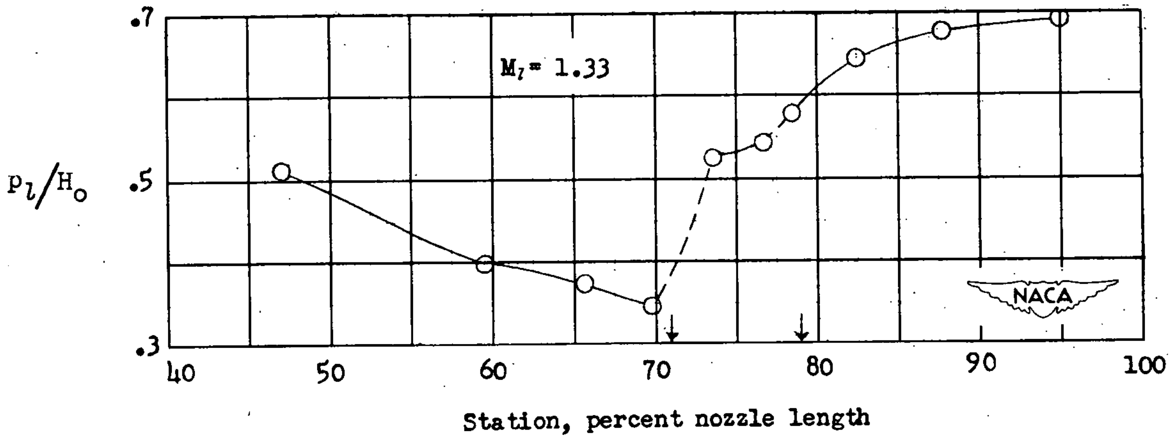

Figure 19.- Pressure distribution over expansion surface of arrangement VI. (Arrows represent active slot location.)

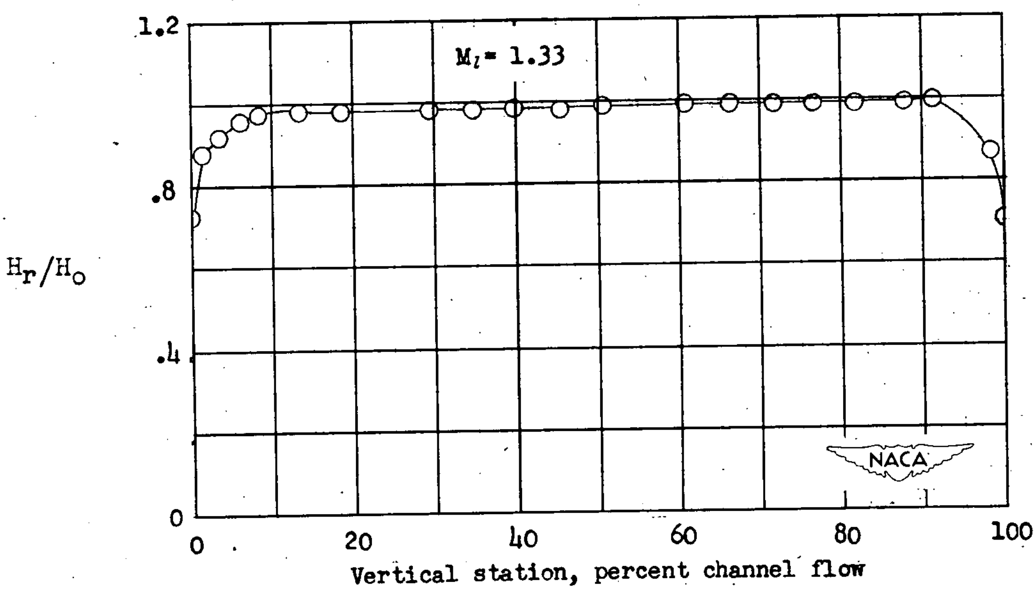

Figure 20.- Wake surveys, arrangement VI.

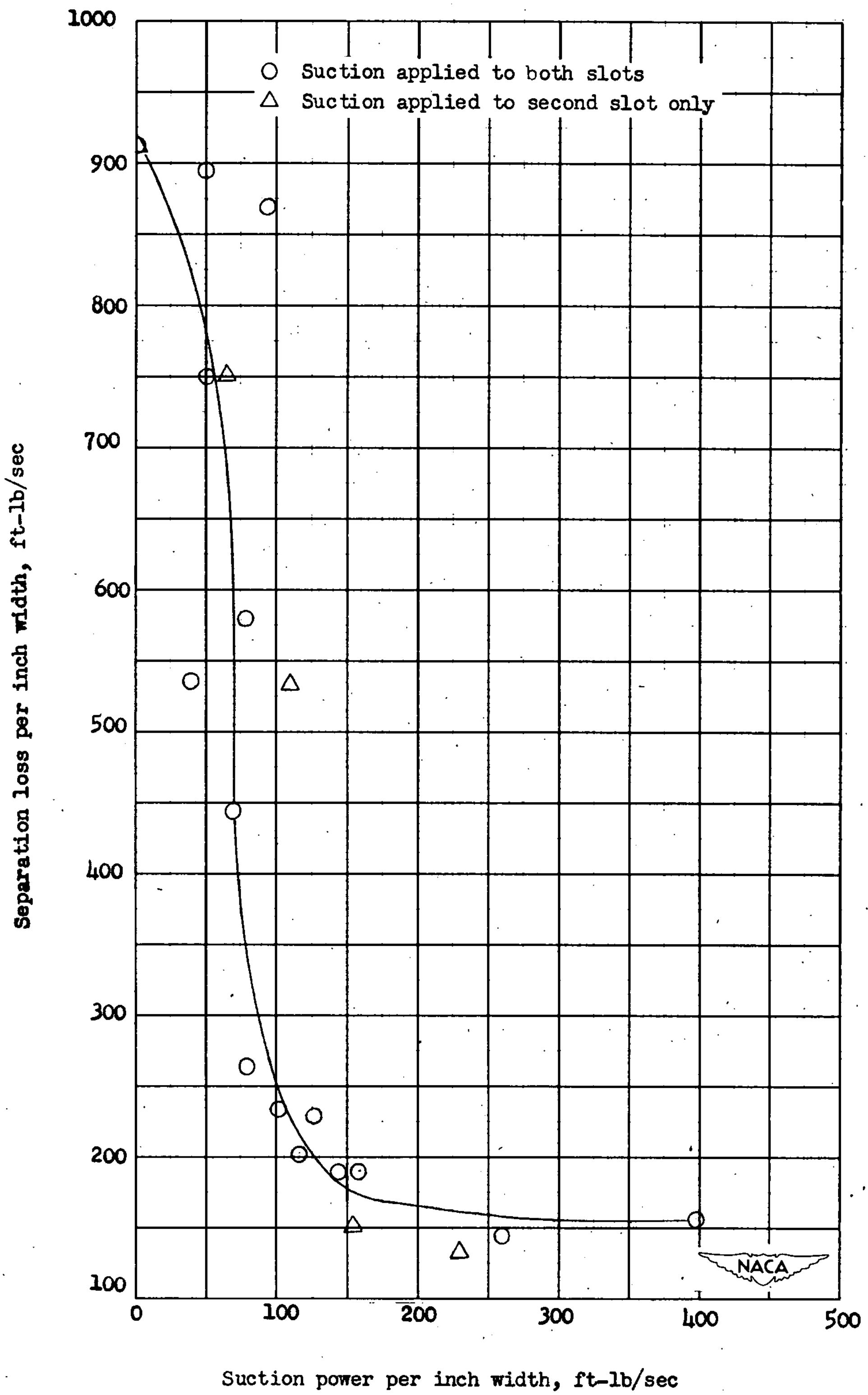

Figure 21.- Variation of separation loss with suction power at M = 1.33, arrangement VI.

[redacted]

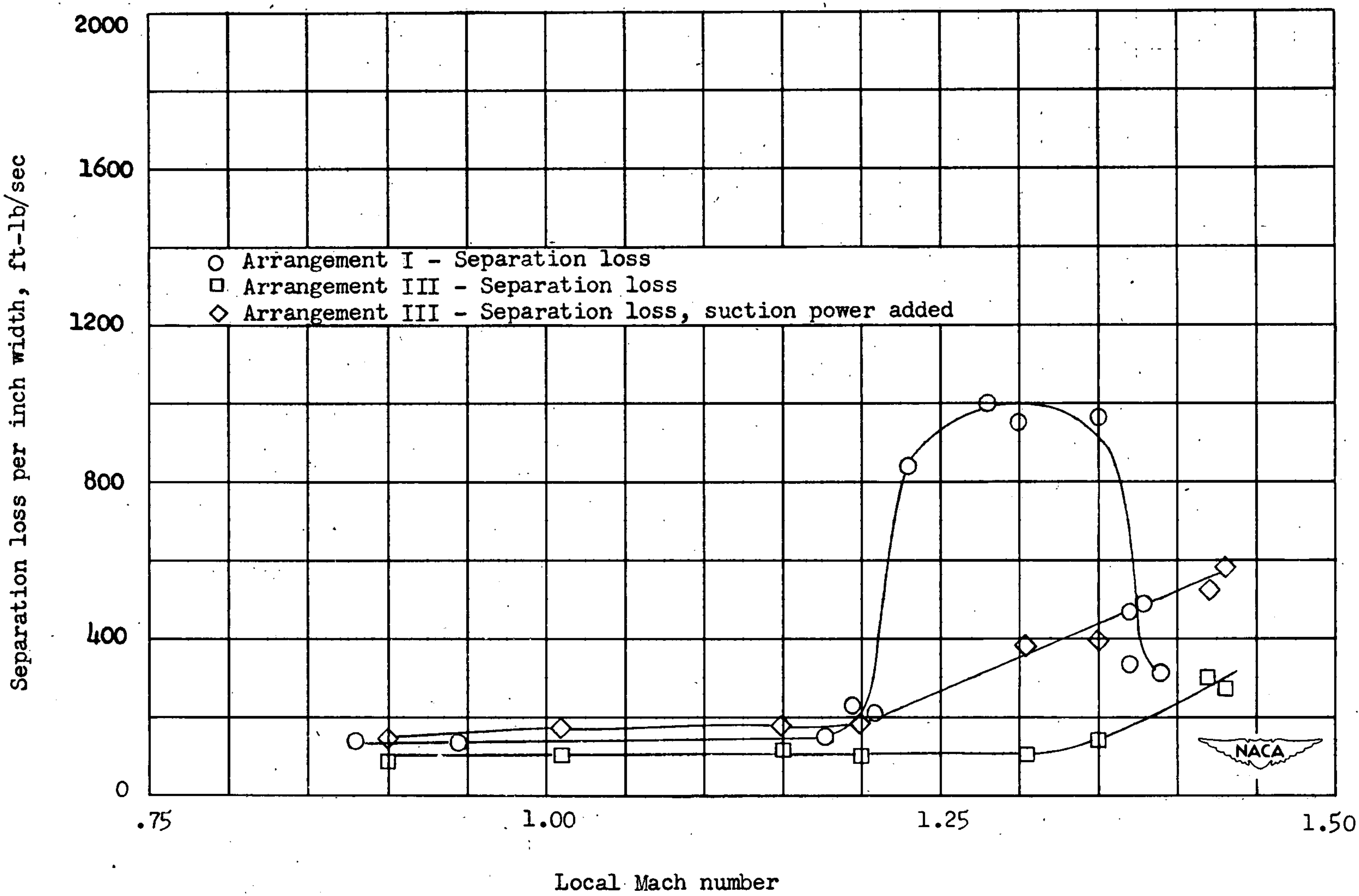

Figure 22.- Effect of suction upon separation power loss.

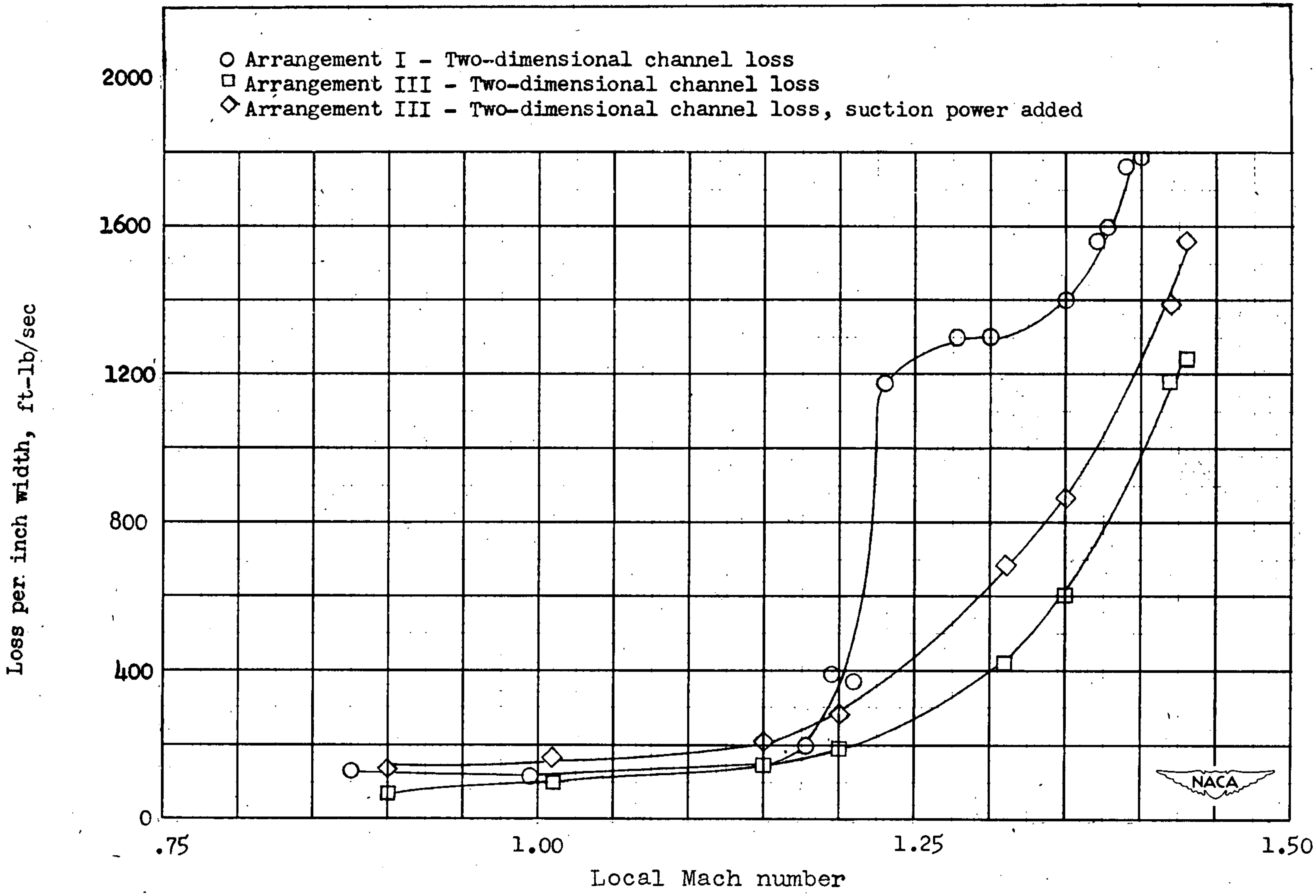

Figure 23.- Effect of suction upon two-dimensional channel loss.