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RESEARCH MEMORANDUM

A VARIABLE-GEOMETRY AXISYMMETRIC SUPERSONIC

INLET WITH TELESCOPING CENTERBODY

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RESEARCH MEMORANDUM

A VARIABLE-GEOMETRY AXISYMMETRIC SUPERSONIC

INLET WITH TELESCOPING CENTERBODY

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SUMMARY

For achieving good supersonic inlet performance over a wide range of Mach number, an axisymmetric variable-geometry technique has been proposed and demonstrated. A centerbody consisting of a number of individual, translating, concentric elements was used to produce a discontinuous surface, the envelope of which approximated any desired contour. Several stepped-spike configurations were studied at Mach number 3.85 and appraised on the basis of schlieren observations and pressure surveys of the resulting compression fields. Experimentally, it was observed that local elements of boundary-layer separation occurred ahead of each surface discontinuity and produced an effective bridging for the main flow.

An inlet with such a telescoping spike was designed and experimentally evaluated. Maximum total-pressure recoveries of 0.60 and 0.89 were realized at Mach numbers of 3.05 and 1.90, respectively. At both Mach numbers, supercritical mass-flow ratios near unity were obtained with subcritical stability ranges of 21 and 38 percent of maximum possible capture mass flow. The losses incurred as a result of surface discontinuities amounted to total-pressure-recovery decrements of 0.04 and 0.03 at free-stream Mach numbers of 3.05 and 1.90, respectively, when compared with that obtained with equivalent smooth-contour centerbodies. Increases in angle of attack generally produced moderate decreases in both recovery and mass flow.

INTRODUCTION

For application to jet aircraft operating over a wide range of supersonic Mach number, the air induction system must incorporate some degree of flexibility in order to maintain a high level of efficiency. Consideration must be given such design variables as the degree of compressive flow turning (surface angle), flow detachment factors (cowl-lip angles), internal-area contraction (ducting), and initial-shock-angle

variation (cowl-position parameter). The attainment of high performance throughout the speed range requires, in general, that the inlet design be somewhat compromised and include variable-geometry features. Compared with the two-dimensional inlets which can use axial ramp translation or variation of the compression-surface angles, or both, the axisymmetric inlets present a more complex problem for variable Mach number operation.

Current axisymmetric technique is simply one of spike translation (ref. 1). For Mach numbers up to approximately 2.0 or for a very limited speed range, this method appears adequate. However, for operation to considerably higher Mach numbers, this technique which utilizes a fixed spike contour results in steep-angle cowls and large cowl projected areas, largely because of the necessity of avoiding internal contraction. For high variable Mach number operation, then, there is a definite need for improved axisymmetric variable-geometry technique for supersonic inlets.

The investigation reported herein was conducted at the NACA Lewis laboratory to explore the possibilities of effecting a spike contour variation in addition to axial translation. The proposed method schematically illustrated in figure 1 is to use a number of individual elements that can translate relative to one another as in a telescoping arrangement and produce a discontinuous surface. The envelope of this surface coincides with the desired contour as in figure 1(b). Aerodynamic considerations suggest that the boundary layer would separate ahead of each surface discontinuity, or step, and produce an effective bridging for the main flow. The use of a conical separation element for a proposed inlet application is successfully demonstrated in reference 2. From a structural viewpoint, of course, the complexity of such a telescoping spike depends upon the number of elements, and some arrangement must be made for scheduling their relative positions with flight Mach number.

The present study is specifically directed toward evaluating the pressure losses incurred as a result of centerbody surface discontinuities and determining the performance of a simulated axisymmetric variable-geometry inlet. At Mach number 3.85, surveys were made of the flow over spikes with surface bumps and compared with that over a smooth spike. At Mach numbers of 3.05 and 1.90, the performance of a simulated telescoping inlet was evaluated in terms of pressure recovery and mass-flow ratio. Angle-of-attack effects were also determined.

SYMBOLS

The following symbols are used in this report:

M   Mach number

m   mass flow, slugs/sec

P   total pressure, lb/sq ft

R   duct radius at diffuser exit, ft

r   local tube radius, ft

α angle of attack, deg

Subscripts:

l local pitot

0   free stream

3   diffuser exit

APPARATUS AND PROCEDURE

The experimental program was conducted essentially in two parts; the first was a preliminary survey study of the flow over several spikes with various surface discontinuities at Mach number 3.85, and the second was a performance evaluation of a simulated variable-geometry axisymmetric inlet with telescoping centerbody at Mach numbers 3.05 and 1.90.

Spike Survey Study

Probe surveys of the flow over various spikes were made at a Mach number of 3.85 in the Lewis 2- by 2-foot wind tunnel. The air was maintained at a stagnation temperature of $200^\circ \pm 5^\circ$ F and at a dew-point temperature of $-20^\circ \pm 5^\circ$ F. In the test chamber, the Reynolds number per foot was approximately 1.03×10^6 and the simulated pressure altitude was 108,000 feet.

The survey-spike configurations are illustrated in the photographs of figure 2. Coordinate dimensions are given in table I. The smooth-contour spike (the same as that used in ref. 3) was designed for focused compression by the method of characteristics. Except for the initial conical shock loss (0.99 total-pressure recovery), the flow along the

spike was to be compressed isentropically down to a Mach number of 2.45. As shown in figure 2, discontinuous spike contours were fabricated with step elements having leading-edge angles of 90° and 30°. The envelope contours of these spikes were identical to that of the smooth-contour spike.

As in the procedure of reference 3, a pitot probe traversed the flow field in a radial line from the axis of symmetry and passed through the main shock intersection as determined from schlieren observations. The probe tip was alined parallel to the spike surface and was actuated by a motor and screw arrangement. An electric contact indicator was used to determine a zero reference position. As measured by a static tap on the spike surface at the survey station, the static pressure was assumed constant through the flow field out to the shock. This static pressure and the probe pitot pressures were used to calculate the local stream Mach numbers.

Variable-Geometry-Inlet Study

The inlet experiments were conducted in two different facilities in order to obtain the desired Mach numbers. Tests were run at a Mach number of 1.90 and a simulated pressure altitude of 45,000 feet in the Lewis 18- by 18-inch wind tunnel. The air was maintained at a stagnation temperature of $150^\circ \pm 5^\circ$ F and at a dew-point temperature of $-30^\circ \pm 5^\circ$ F. Based on the 2.90-inch inlet capture diameter, the Reynolds number was 0.78×10^6. The Mach 3.05 tests were run in another Lewis 18- by 18-inch wind tunnel. The test conditions were as follows: stagnation temperature, $150^\circ \pm 5^\circ$ F; dew-point temperature, $-20^\circ \pm 5^\circ$ F; Reynolds number, 0.44×10^6; and simulated pressure altitude, 82,000 feet.

As shown in the schematic drawing of figure 3(a), the diffuser model was strut-mounted from the tunnel wall. A movable exit plug was used to regulate the inlet back pressure. In the support assembly, provisions were incorporated to permit angle-of-attack variation. A twin-mirror schlieren system was used to observe the inlet air-flow patterns.

The experimental version of the axisymmetric variable-geometry inlet with telescoping spike is illustrated in the schematic drawing of figure 3(b) and the photograph of figure 3(c). For this investigation, solid spikes with the discontinuities cut into them were used to simulate the telescoping geometry. Coordinate dimensions of the cowl and the two spikes are given in table II. The inlet was designed to capture the maximum possible free streamtube of air and to maintain attached shocks on the cowl at Mach numbers of 1.90 and 3.05. The centerbody envelope contours were designed for focused compression at

the cowl lip by the method of characteristics. Existing characteristics
solutions (for spikes of refs. 4 and 5) were used with the consequence
of having the different initial cone angles of 40° for the Mach 1.90
spike and 30° for the Mach 3.05 spike. Actually, in order to reduce
the number of elements, it would have been desirable to have had the
same initial angle for tests of such a variable-geometry inlet applica-
tion. The theoretical final Mach number at the diffuser entrance was
approximately 1.26 and 1.76 at free-stream Mach numbers of 1.90 and 3.05,
respectively. Eight translating concentric elements were rather arbi-
trarily selected to make up the centerbody. For each element, the up-
stream face contour was determined by the steepest-angle required at
either end of the Mach number range. Thus, the face contours of the
initial elements were determined by the Mach 1.90 envelope contour with
its greater initial angle and the rearward elements by the Mach 3.05
envelope contour with its greater surface flow-turning angles. The
resulting configuration (figs. 3(b) and (c)) then consisted of a spike
at Mach 3.05 with moderately small surface discontinuities near the tip,
but otherwise a smooth contour back into the diffuser. At Mach 1.90,
the spike telescoped into a smooth external compression surface up to
the entrance, but with rather abrupt surface discontinuities on the
turn or shoulder.

Two other spikes were fabricated in order to establish a basis for
comparison. These were the smooth-contour geometries which the tele-
scoping spike was designed to approximate. The contours of these spikes
were then identical to the envelope contours of the telescoping
arrangement.

The internal-duct area variations based on the envelope contours
are presented in figure 3(d). Downstream of the common point, the area
distribution conformed approximately to an equivalent 5° conical area
expansion. Initially the Mach 1.90 spike had a constant-area section
that corresponded to the turning of the flow back to the axial direction.
In contrast to this, the Mach 3.05 contour had initially fairly rapid
area divergence to the common point and a very slight internal
contraction.

At the diffuser exit were located a 21-tube total-pressure rake and
4 wall static-pressure orifices. Total-pressure recovery was obtained
by an area-weighted integration. Mass flow was based on the measured
static pressure at the rake station and the sonic discharge area at the
plug with the assumption of isentropic one-dimensional flow between the
two stations. A calibration of this measuring technique was obtained
from data with an inlet capturing a known free streamtube of air.

RESULTS AND DISCUSSION

Spike Survey Study

The air-flow patterns obtained with the stepped spikes are shown in figure 4. With the 90° stepped spike, the first several steps were neatly bridged by individual elements of boundary-layer separation. The rearward steps, however, were submerged in the boundary layer with separation appearing to extend over the steps with some unsteadiness in the local flow. In general, the over-all pattern showed the flow following, at least approximately, along the envelope contour of the spike.

With 30° angles on the face of each step, the configuration represented a spike which could be telescoped back into a single-shock, 30° half-angle cone, such as would be suitable as a centerbody at a free-stream Mach number of 2.0. The resultant pattern (fig. 4(b)) appeared considerably different from that of the 90° stepped spike. Schlieren observations indicated that the flow was quite steady with bridging occurring across each step as a result of local boundary-layer separations. In some of the rearward steps, the amount of separation might even be somewhat inadequate because the flow seemed to overexpand at the shoulders and thus produce stronger shocks (and correspondingly higher losses) than if the separation had completely filled the surface discontinuity. From these observations, it was concluded that, because of the generally satisfactory over-all compression envelope and shock coalescence, such a telescoping arrangement might find application as a supersonic inlet centerbody.

In order to determine the total-pressure losses associated with such surfaces, a pitot-probe survey was made for each of three contours. The survey line was a radial line from the axis of symmetry passing through the main shock intersection.

The results of these pressure surveys are presented in figure 5. A considerably thicker boundary layer was encountered near the surface of the stepped spikes when compared with the results for the smooth-contour spike (ref. 3). Outside this boundary layer, the survey-plane Mach numbers checked roughly with the theoretical design value. An area-weighted integration of the pitot-pressure distribution was used to obtain an inlet recovery potential for each configuration. This value would thus include the normal shock loss. Compared with the result for the smooth-contour spike (0.47), the 30° stepped spike value (0.40) indicated a 15-percent decrease in potential recovery as a result of the irregular surface; but the 90° stepped spike value (0.37) indicated a 21 percent decrease. It may also be noted that, largely because of the displacement effect of the larger boundary layers, the main shock intersection was located farther out from the surface of the stepped spike than was that for the smooth spike.

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These preliminary results with arbuptly stepped spike configurations
were considered quite satisfactory with respect to applying this tech-
nique to an actual inlet problem, for which fewer and less-severe step
geometries might be suitable. Accordingly, a simulated variable-geometry
inlet was designed and studied at Mach numbers of 3.05 and 1.90.

Variable-Geometry-Inlet Study

Diffuser performance characteristics are presented in figure 6. At
zero angle of attack this variable-geometry inlet with a telescoping
centerbody yielded at Mach number 1.90 a maximum total-pressure recovery
of 0.89, a critical recovery of 0.88, and a maximum mass-flow ratio of
0.98. Stable subcritical operation was obtained down to a mass-flow
ratio of 0.60. Compared with the ideal smooth-contour design, which
gave a maximum recovery of 0.92, the model with internal surface dis-
continuities resulted in a total-pressure-recovery decrement of 0.03.
At a free-stream Mach number of 3.05, a critical pressure recovery of
0.57 was obtained at a mass-flow ratio of 0.99. The maximum recovery of
0.60 was realized at a minimum stable mass-flow ratio of 0.79. When
compared with the performance of the smooth-contour design (maximum
recovery = 0.61), a total-pressure-recovery decrement of 0.04 was
chargeable to the external surface discontinuities. At Mach number 3.05,
the irregular compression surface resulted in a much greater stable
subcritical operating range than was realized with its smooth
counterpart.

Angle-of-attack performance of the variable-geometry inlet is pre-
sented in figure 6 and summarized in the cross plot of figure 7. In
general, increased angle of attack caused reductions in critical
recovery, supercritical mass-flow ratio, and stable subcritical operating
range. At a Mach number of 3.05 and an angle of attack of 6°, extensive
separation off the top or lee side of the spike was encountered at mass
flows less than the minimum stable value. This was a steady pattern;
however, the associated discontinuity in the performance curve at the
minimum stable value was quite pronounced.

Zero-angle-of-attack flow patterns for the variable-geometry inlet
are shown by the schlieren photographs of figure 8. At Mach number 3.05,
boundary-layer separation was observed to bridge the external surface
discontinuities on the spike. A slight shock detachment at the cowl lip
occurred during supercritical operation. At the minimum stable mass-flow
condition, the diffuser shock was located out on the spike forward of the
cowl lip. At Mach number 1.90 (fig. 8(b)) the observed flow patterns
were the same as that observed with the smooth on-design inlet configu-
rations of reference 4. As the diffuser shock moved out on the spike,
the entire flow was quite stable with the boundary layer downstream of

the bow shock appearing to be attached to the surface and to follow the
contour back into the inlet. This lack of separation was a favorable
consequence of the low surface Mach number of 1.20 at the diffuser
entrance. With an increase in back pressure and coincident with the
onset of inlet buzz, the boundary layer was observed to lift and sepa-
rate from the spike because of increased shock strength due to a higher
compression-surface Mach number. This separation presumably choked the
inlet and triggered the buzz cycle.

Air-flow patterns obtained with the variable-geometry inlet at
various angles of attack are also included in figure 8. At Mach number
3.05, body cross-flow effects caused some thickening of the boundary
layer on the top or lee side of the spike with increasing angle of
attack. At an angle of attack of 6° and mass flows less than the minimum
stable value with attached flow, large-scale separation (fig. 8(e))
extended forward to the spike tip. The boundaries of this steady
separation pattern tended to take the form of a cone alined in the free-
stream direction. Coincident with this change in subcritical flow
pattern was a large discontinuity in mass flow into the inlet. Photo-
graphs of the shock patterns at a Mach number of 1.90 for angles of
attack of 4° and 8° are shown in figures 8(d) and (f), respectively.
These patterns are again practically the same as those observed for the
on-design fixed-geometry inlets of reference 4.

Total-pressure profiles across the diffuser exit during critical
inlet operation are shown in figure 9. These profiles were, no doubt,
favorably influenced by the approximately 2 diameters of constant-area
mixing length between the diffuser exit and the rake station. At a
free-stream Mach number of 1.90, the wake off the centerbody caused a
dip in the zero-angle-of-attack profile. At Mach number 3.05, the
profiles were quite flat and uniform at zero angle of attack. These
differences in total-pressure distributions were also influenced by the
difference in diffuser-exit Mach number (at $M_0 = 3.05$, $M_3 = 0.15$; at
$M_0 = 1.90$, $M_3 = 0.28$). With increasing angle of attack there was a
tendency at both Mach numbers toward separation in the lower quadrant.

CONCLUDING REMARKS

For application to jet aircraft operating over a wide range of
supersonic Mach number, an axisymmetric nose inlet with telescoping
centerbody has been proposed. Herein, preliminary experimental studies
have demonstrated the feasibility of using boundary-layer separation to
accommodate the flow over steps or surface discontinuties resulting from
telescoping spike configurations. Such an inlet was designed and found
to yield maximum total-pressure recoveries of 0.89 at a Mach number of

1.90 and 0.60 at a Mach number of 3.05. At both Mach numbers, super-critical mass-flow ratios near unity were obtained with subcritical stability ranges of 38 and 21 percent of maximum possible mass flow. Compared with data for the smooth-contour geometry, the flow losses, which were incurred as a result of surface discontinuities, amounted to total-pressure-recovery decrements of 0.03 and 0.04 at free-stream Mach numbers of 1.90 and 3.05, respectively.

Possibilities of lessening the degree of complexity without penalizing performance lie in the direction of reducing the number of translating elements. For the configuration studied, this could have been accomplished by the choice of the same initial cone angle for each Mach number. Accordingly, minimizing the number of elements and optimizing the location and design of these elements would require further research.

Lewis Flight Propulsion Laboratory
    National Advisory Committee for Aeronautics
        Cleveland, Ohio, July 5, 1955

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1. Gorton, Gerald C.: Investigation at Supersonic Speeds of a Translating Spike Inlet Employing a Steep-Lip Cowl. NACA RM E54G29, 1954.

2. Moeckel, W. E., and Evans, P. J., Jr.: Preliminary Investigation of Use of Conical Flow Separation for Efficient Supersonic Diffusion. NACA RM E51J08, 1951.

3. Connors, James F., and Woollett, Richard R.: Characteristics of Flow about Axially Symmetric Isentropic Spikes for Nose Inlets at Mach Number 3.85. NACA RM E54F08, 1954.

4. Connors, James F., and Meyer, Rudolph C.: Performance Characteristics of Axisymmetric Two-Cone and Isentropic Nose Inlets at Mach Number 1.90. NACA RM E55F29, 1955.

5. Hunczak, Henry R.: Pressure Recovery and Mass-Flow Performance of Four Annular Nose Inlets Operating in Mach Number Region of 3.1 and Reynolds Number Range of Approximately 0.45×10^6 to 2.20×10^6. NACA RM E54A07, 1954.

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TABLE I. - DIMENSIONS OF SURVEY SPIKE CONFIGURATIONS

[30° Survey spike formed by adding rings indicated by solid areas.]
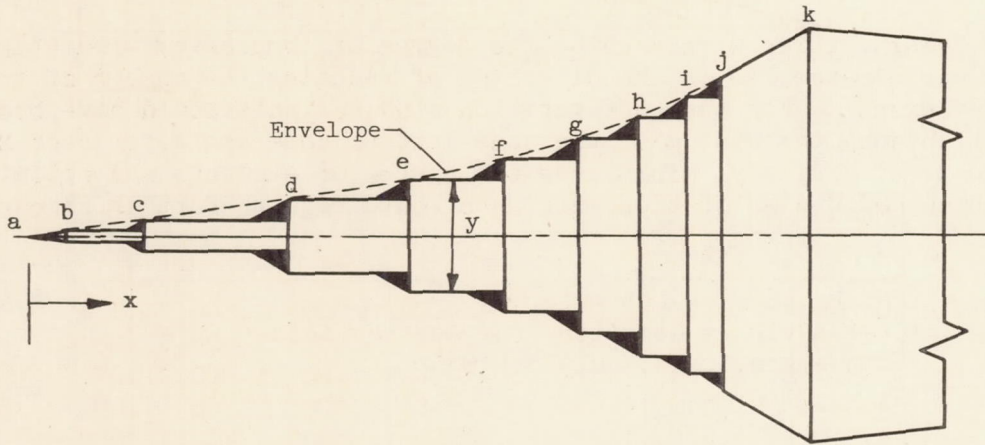
Point on envelope contour	Coordinate dimensions	
	x	y (Diam.)
a	0.000	[a]0.000
b	.408	.125
c	1.350	.375
d	3.056	.875
e	4.520	1.375
f	5.642	1.875
g	6.540	2.375
h	7.272	2.875
i	7.880	3.375
j	8.274	[a]3.796
k	9.304	4.970

[a]Followed by straight taper section.

TABLE II. - DIMENSIONS OF VARIABLE-GEOMETRY INLET
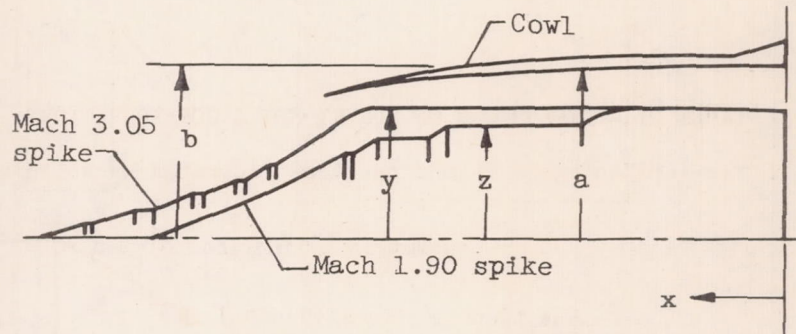
Mach 3.05 spike		Mach 1.90 spike		Cowl		
x	y (Rad.)	x	z (Rad.)	x	a	b
0.000	1.320	0.000	1.320	0.000	[a]1.800	[b]2.074
.360	1.332	.320	1.332	.600	[a]1.800	[a]1.900
.667	[a]1.340	.670	[a]1.340	1.390	1.800	[a]1.900
4.340	1.340	1.570	1.340	1.890	1.795	1.900
4.440	1.330	1.670	1.339	2.390	1.777	1.888
4.540	1.309	1.820	1.324	2.690	1.760	1.888
4.640	1.262	1.970	1.273	2.890	[b]1.760	1.850
4.740	1.198	2.100	1.189	3.390	1.760	1.799
4.890	1.088	3.502	1.189	3.890	1.657	1.732
5.040	.983	3.001	1.115	4.140	1.633	1.688
5.290	.831	3.700	1.041	4.390	1.592	1.629
5.437	.744	4.270	1.041	4.640	1.528	1.550
5.459	.744	4.370	.967	4.888	1.450	1.455
5.590	.667	4.488	.891			
5.723	.595	4.570	.891			
5.816	.595	4.770	.773			
5.940	.532	5.070	.605			
6.114	.446	5.320	.476			
6.260	.446	5.470	.405			
6.440	.371	5.608	[b].352			
6.627	[a].298	6.570	.000			
6.796	[b].298					
7.212	[a].149					
7.359	[b].149					
7.790	.000					

[a]Followed by cylindrical section.

[b]Followed by straight taper section.

Concentric cylindrical elements

Position 1 (simulated cone)

Position 2 (simulated contoured spike)
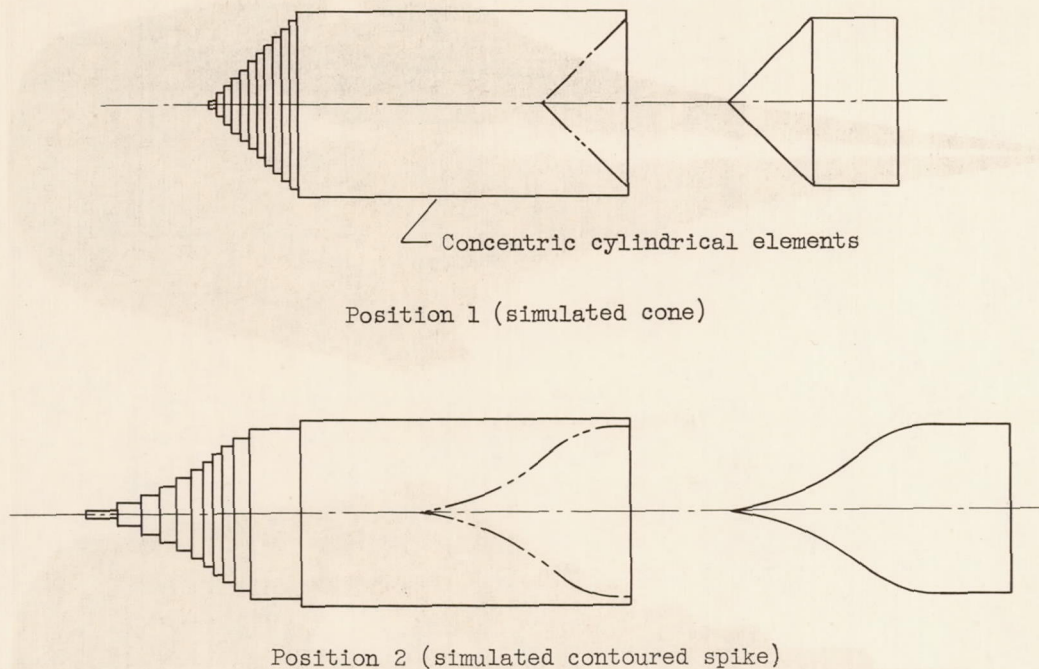
(a) Variable-geometry centerbody (telescoping spike) scheme.

Desired flow contour

Separation bridges ahead of
each step element

Flow

CD-4544
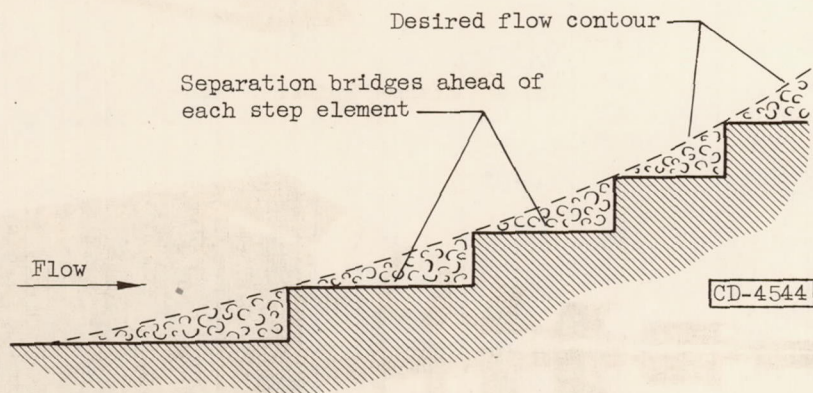
(b) Flow pattern along surface discontinuities.

Figure 1. - Schematic sketches of proposed axisymmetric variable-geometry technique.
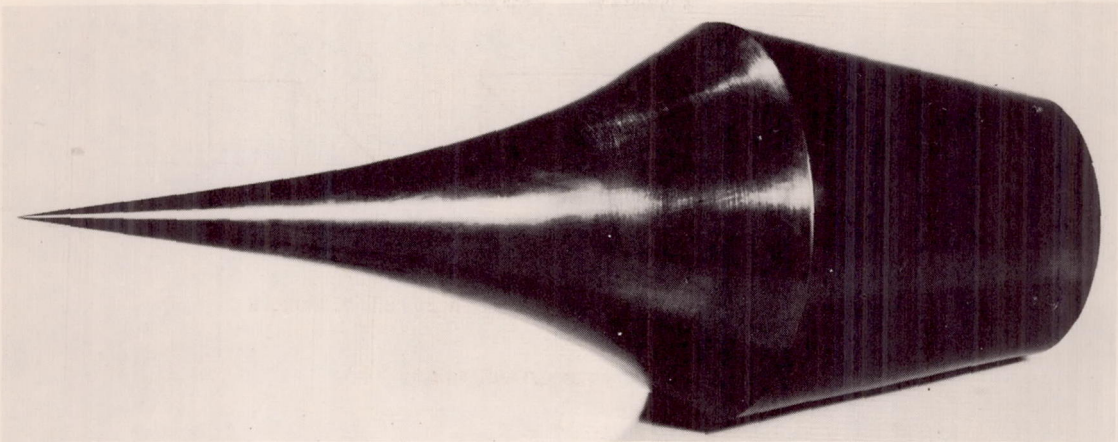
(a) Smooth-contour spike.
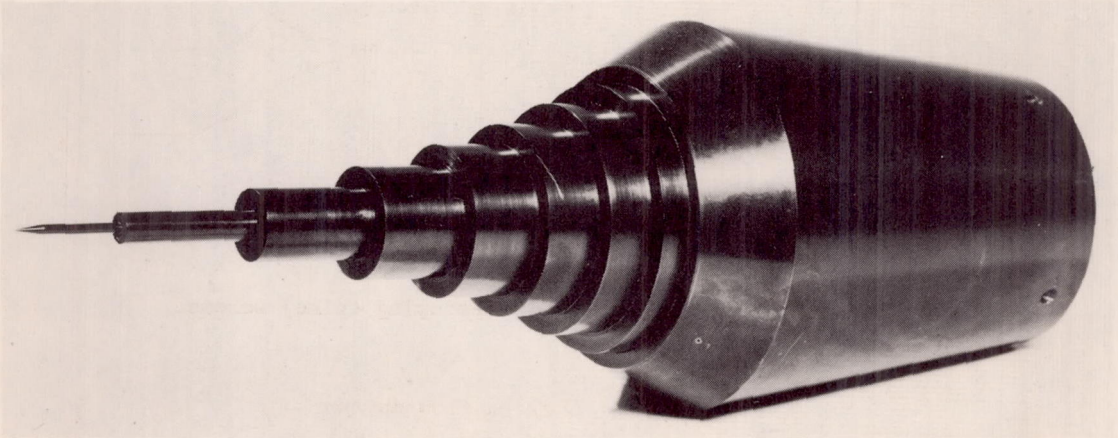
(b) 90° Stepped spike.
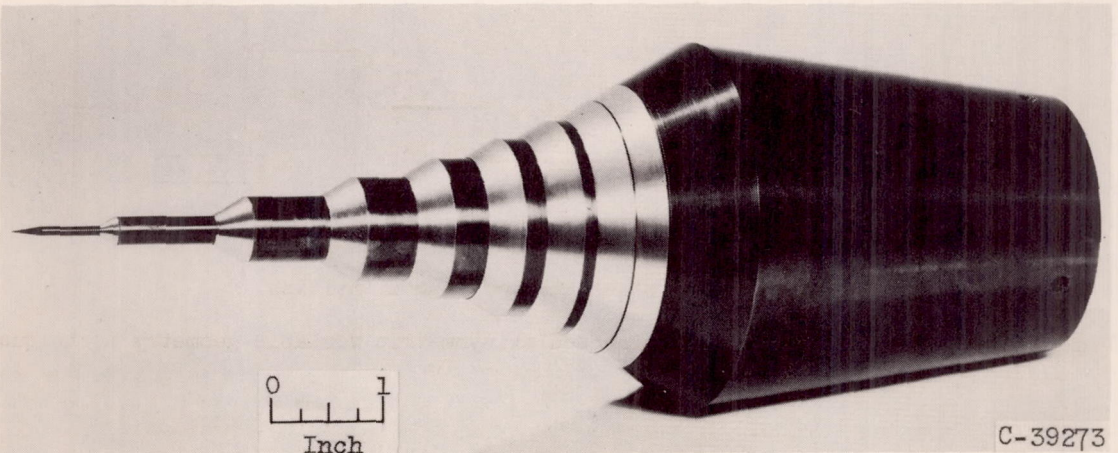
(c) 30° Stepped spike.

Figure 2. - Experimental survey spikes for study of flow over surface discontinuities at free-stream Mach number of 3.85.
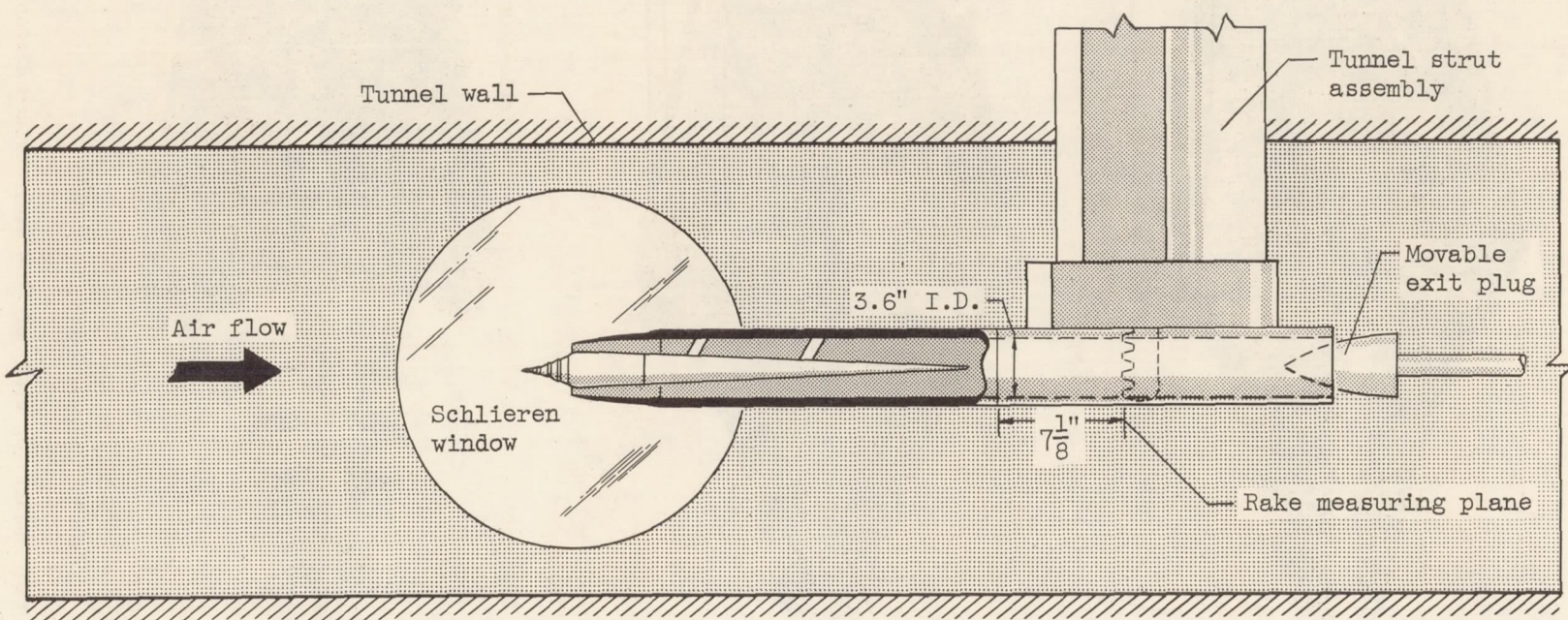
(a) Tunnel installation.

Figure 3. - Experimental apparatus for study of variable-geometry inlet.
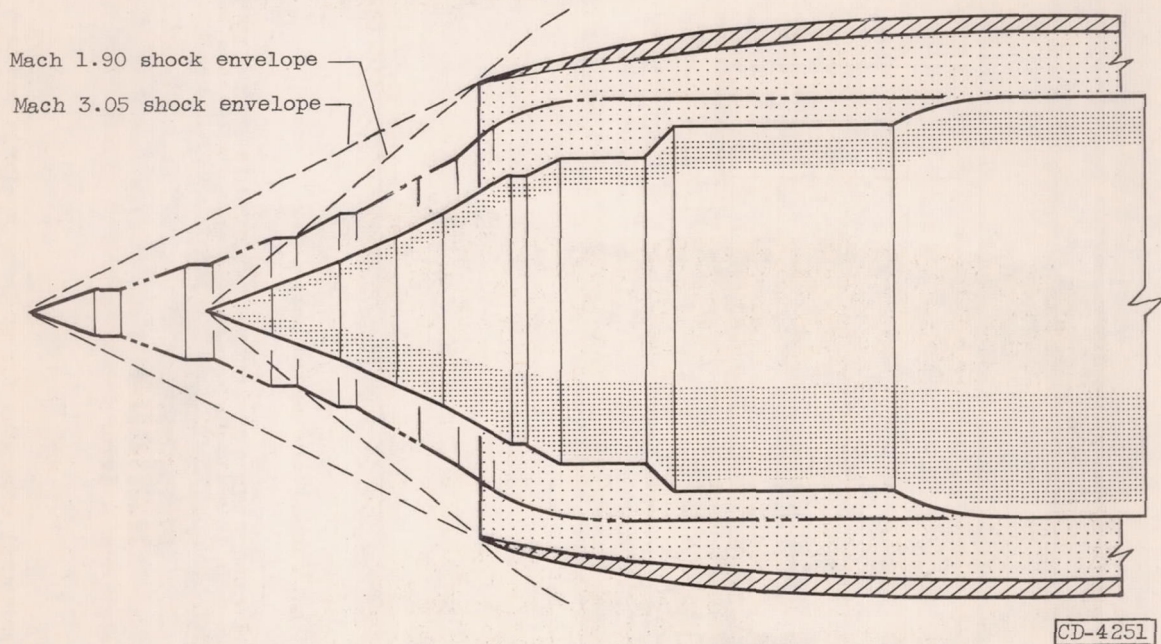
(b) Variable-geometry inlet (telescoping spike).

Figure 3. - Continued. Experimental apparatus for study of variable-geometry inlet.
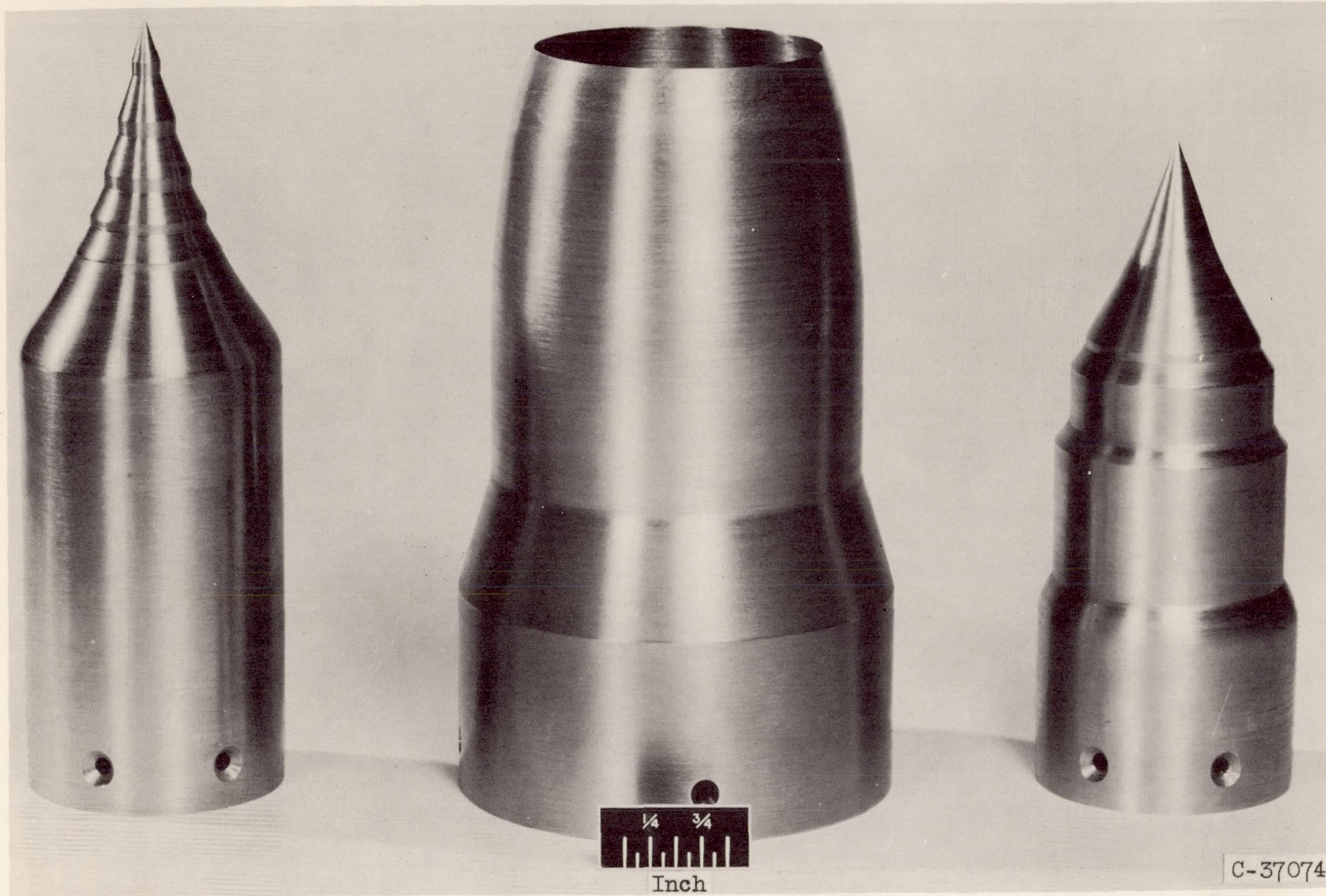
(c) Cowl and spikes.

Figure 3. - Continued. Experimental apparatus for study of variable-geometry inlet.
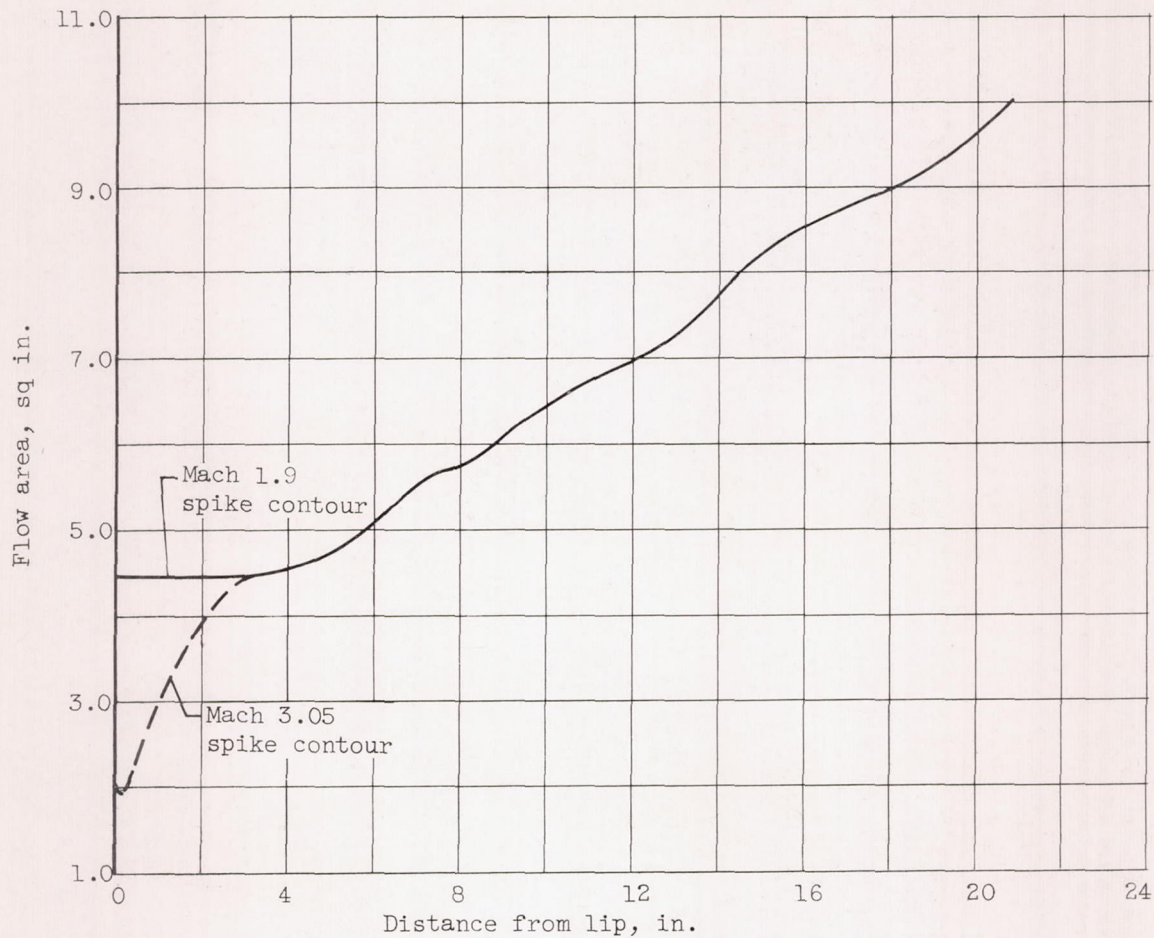
(d) Internal duct area variation based on envelope contours.

Figure 3. - Concluded. Experimental apparatus for study of
variable-geometry inlet.
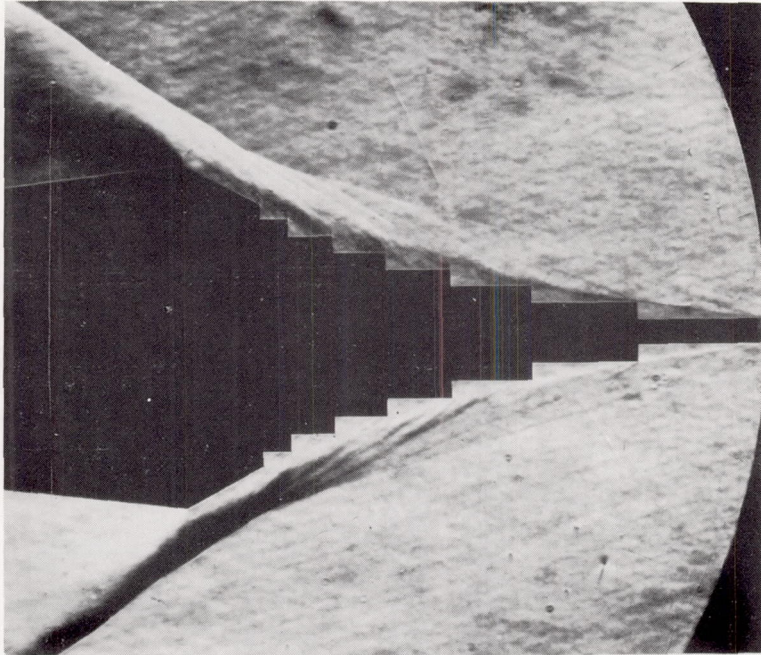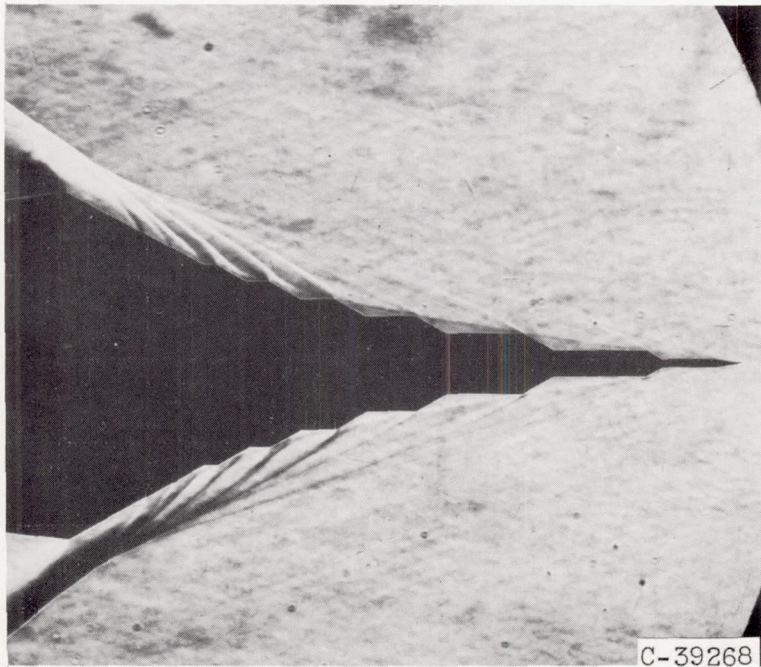
(a) 90° Stepped spike.

(b) 30° Stepped spike.

Figure 4. - Flow patterns obtained with stepped spikes. Free-stream Mach number, 3.85.

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CZ-3 back
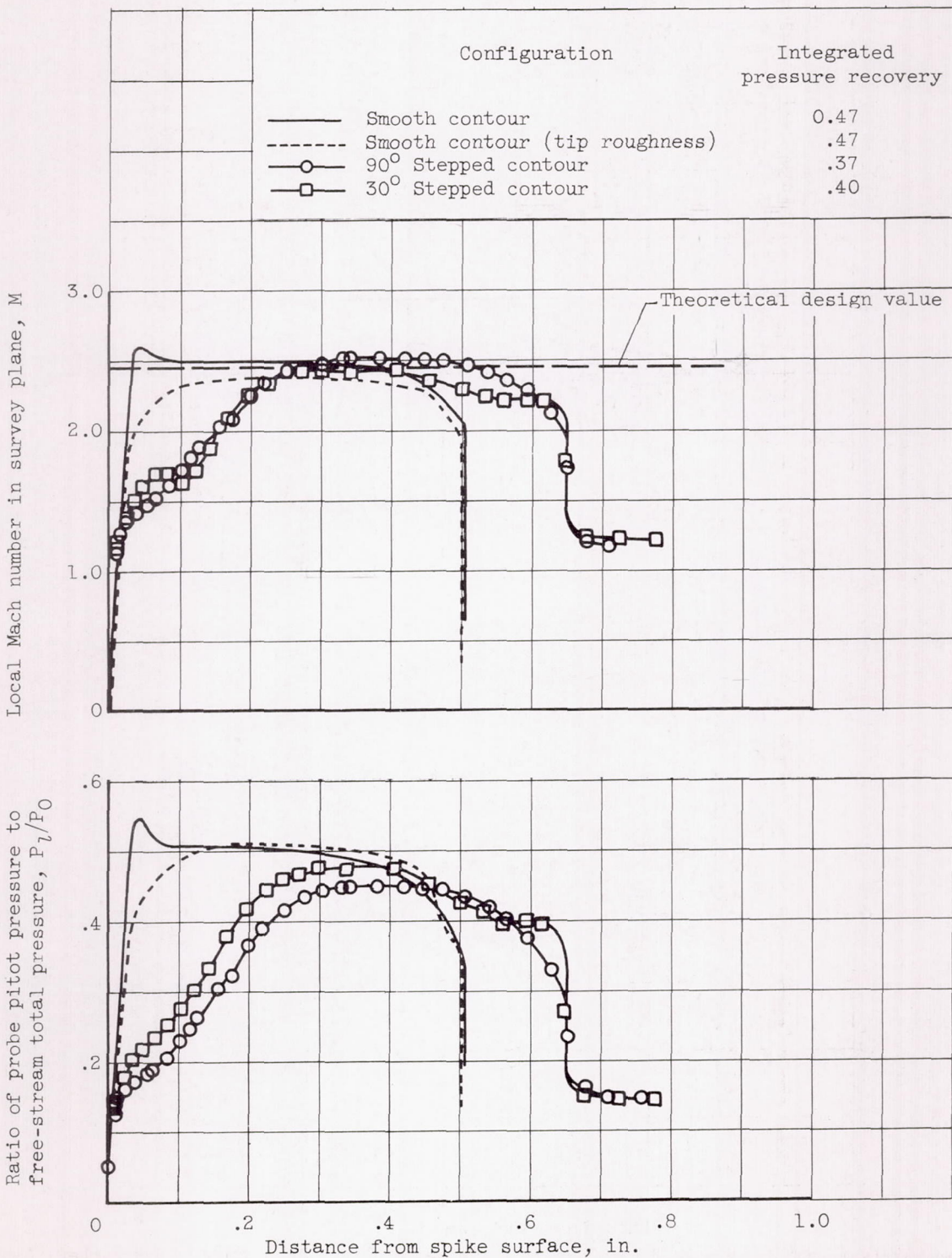
Figure 5. - Mach number and pitot-pressure profiles for stepped and smooth spikes. Free-stream Mach number, M_0, 3.85.
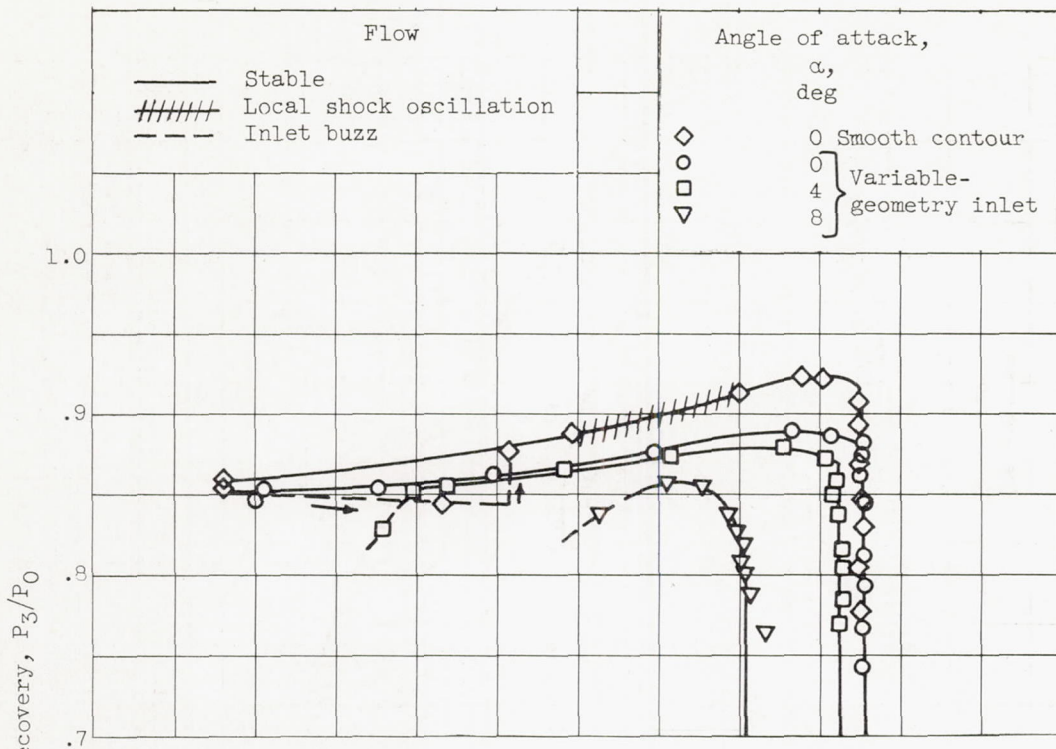
(a) Free-stream Mach number, M_0, 1.90.
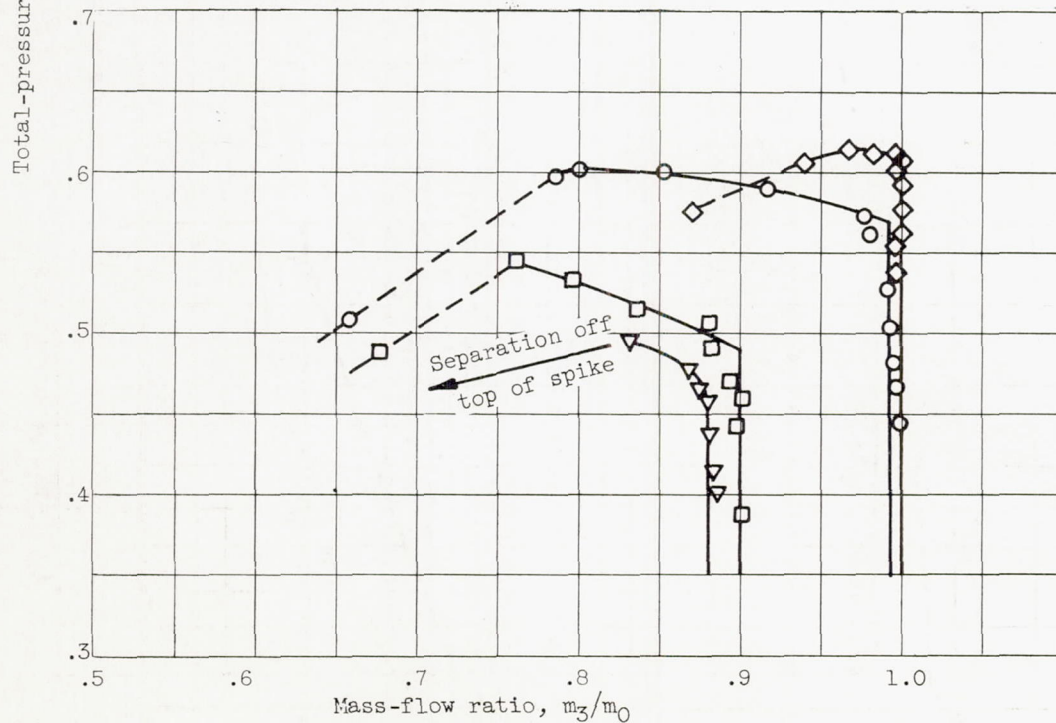
(b) Free-stream Mach number, M_0, 3.05.

Figure 6. - Performance characteristics of variable-geometry inlet.
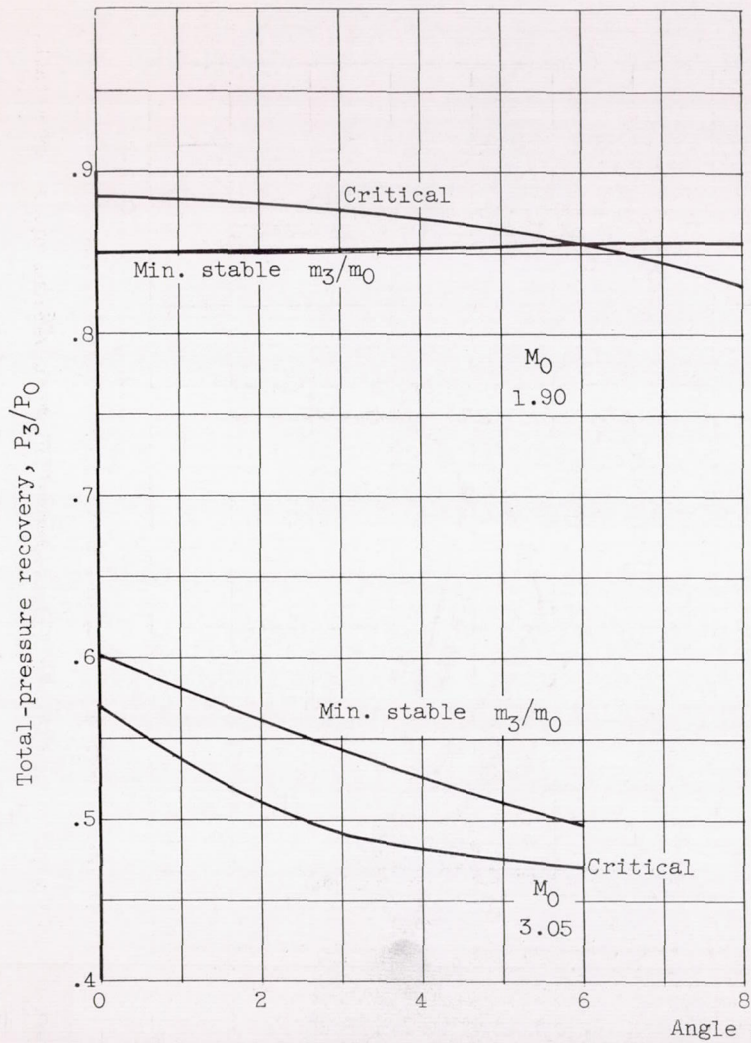
(a) Total-pressure recovery.
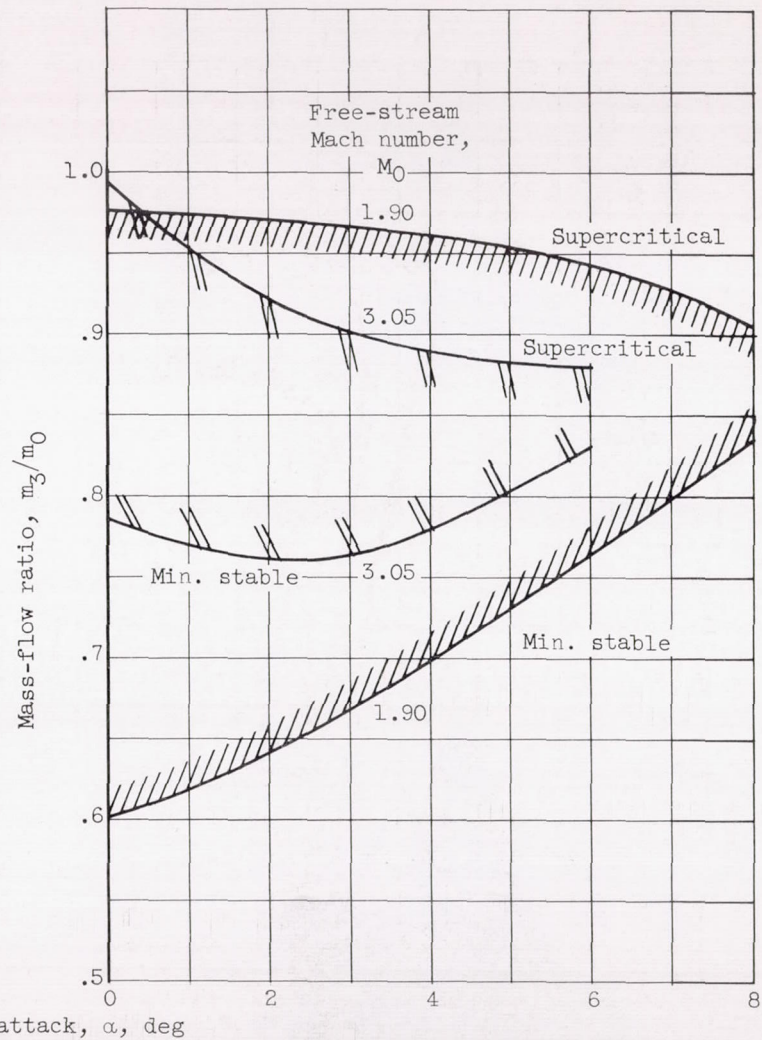
(b) Mass-flow ratio.

Figure 7. - Effect of angle of attack on performance of variable-geometry inlet.

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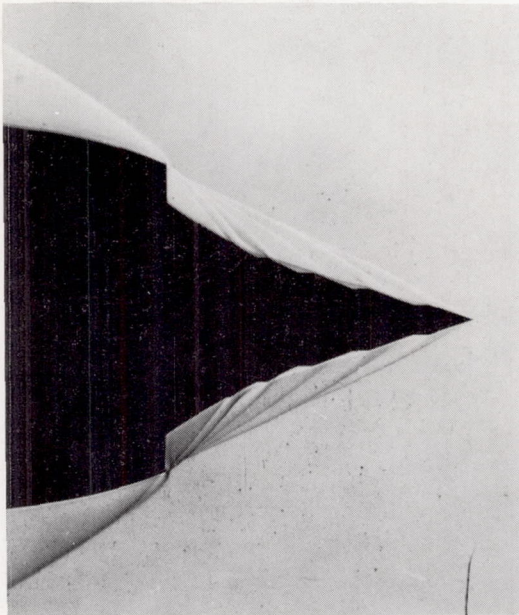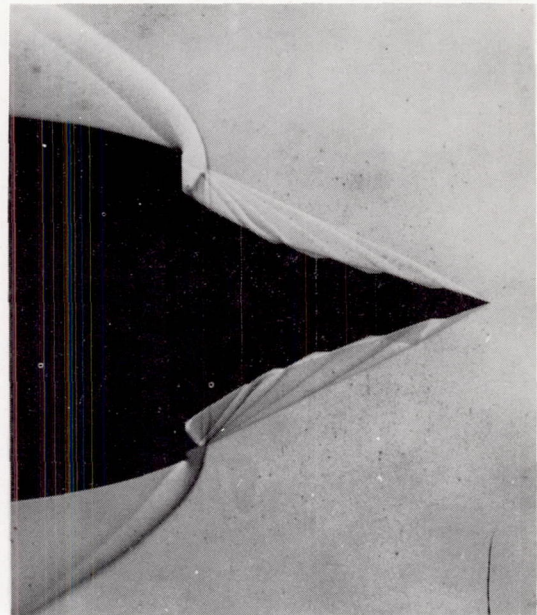
Supercritical   Minimum stable
                        Mass-flow ratio

(a) Free-stream Mach number, 3.05; zero angle of attack.
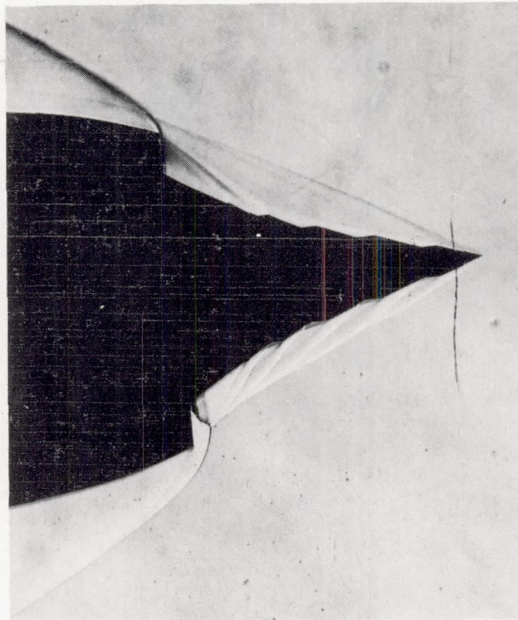

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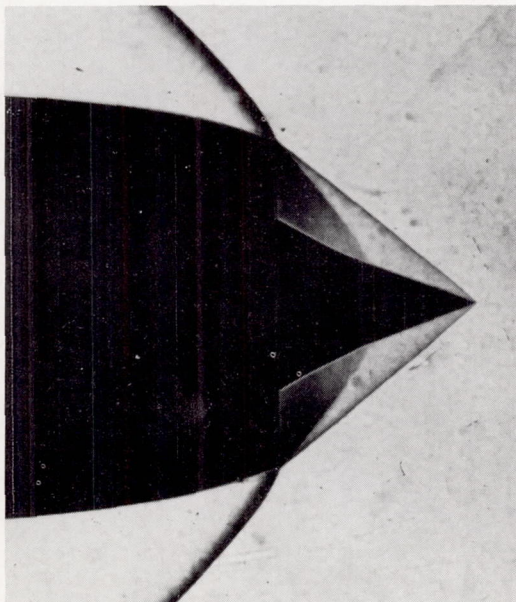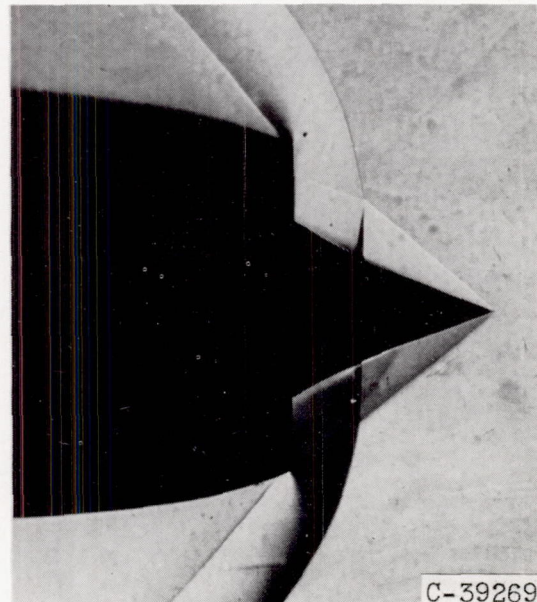
Supercritical   Minimum stable
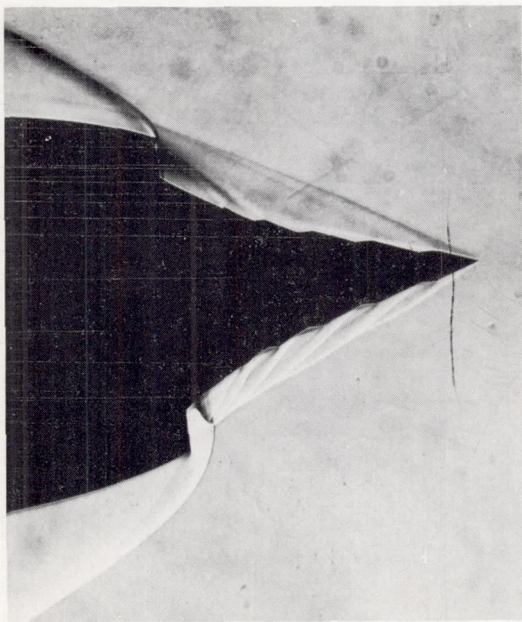   Mass-flow ratio

(b) Free-stream Mach number, 1.90; zero angle of attack.

Figure 8. - Flow patterns for variable-geometry inlet at various angles of attack.
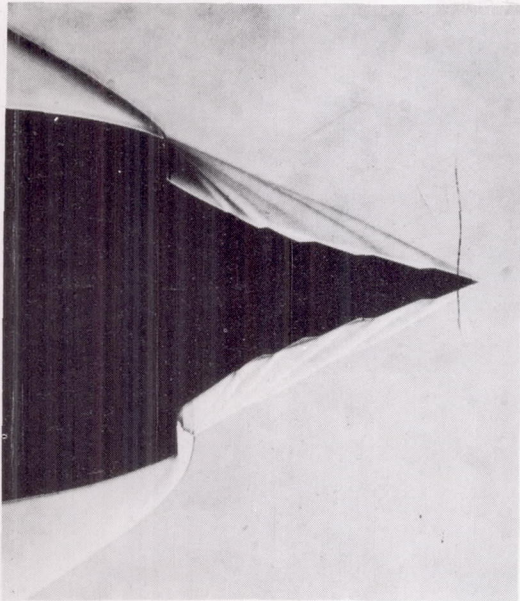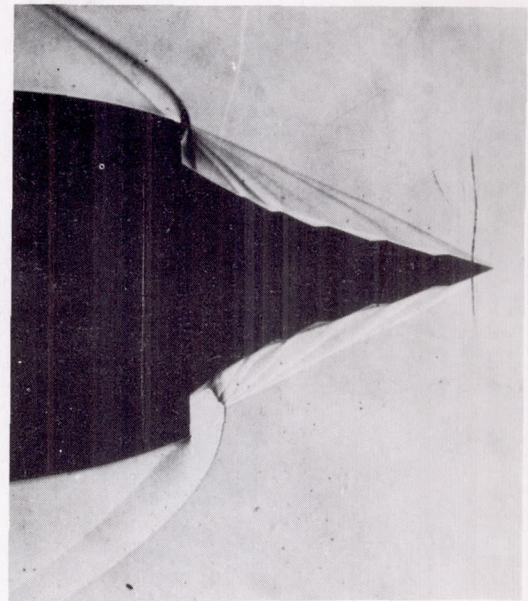
Supercritical   Minimum stable

Mass-flow ratio

(c) Free-stream Mach number, 3.05; angle of attack, 3°.
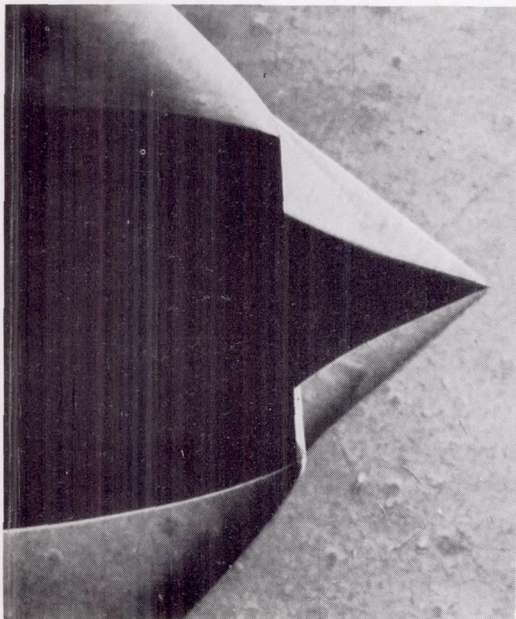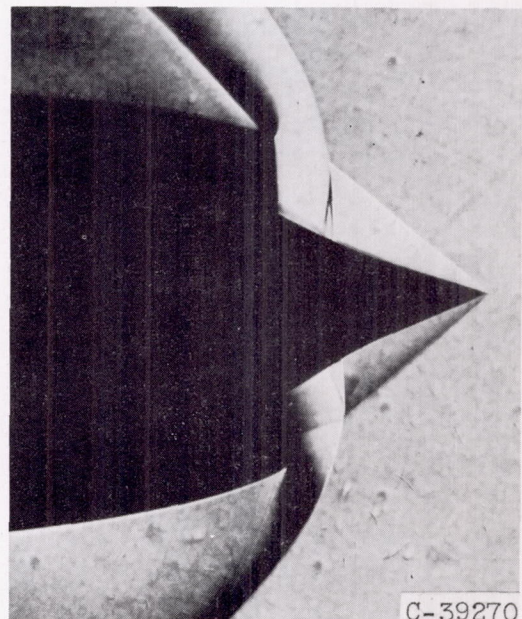
Supercritical   Minimum stable

Mass-flow ratio

(d) Free-stream Mach number, 1.90; angle of attack, 4°.

Figure 8. - Continued. Flow patterns for variable-geometry inlet at various angles of attack.
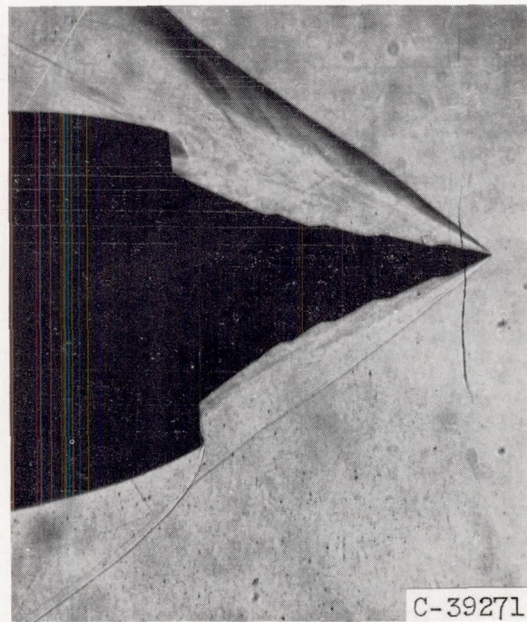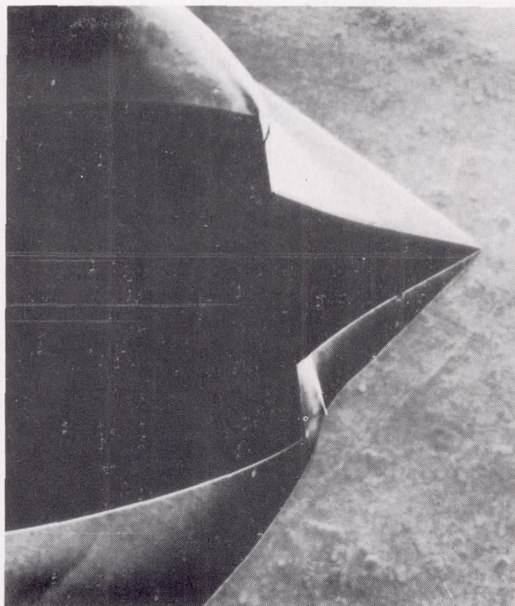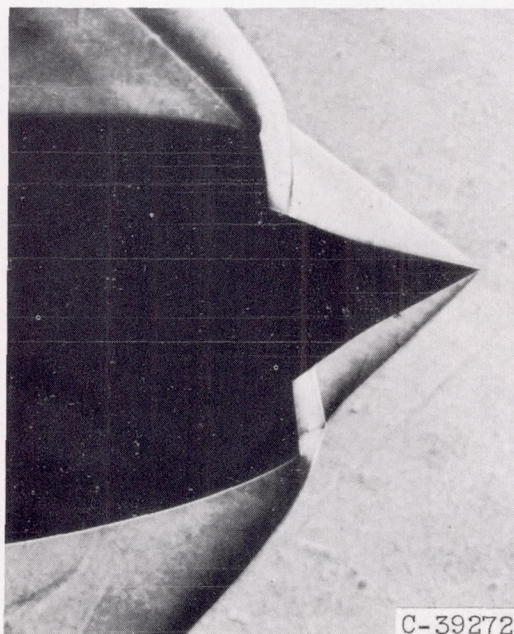
Supercritical

Minimum stable with attached flow   Separation off spike (steady
                                                        pattern)

Mass-flow ratio

(e) Free-stream Mach number, 3.05; angle of attack, 6°.

Figure 8. - Continued. Flow patterns for variable-geometry inlet at various angles
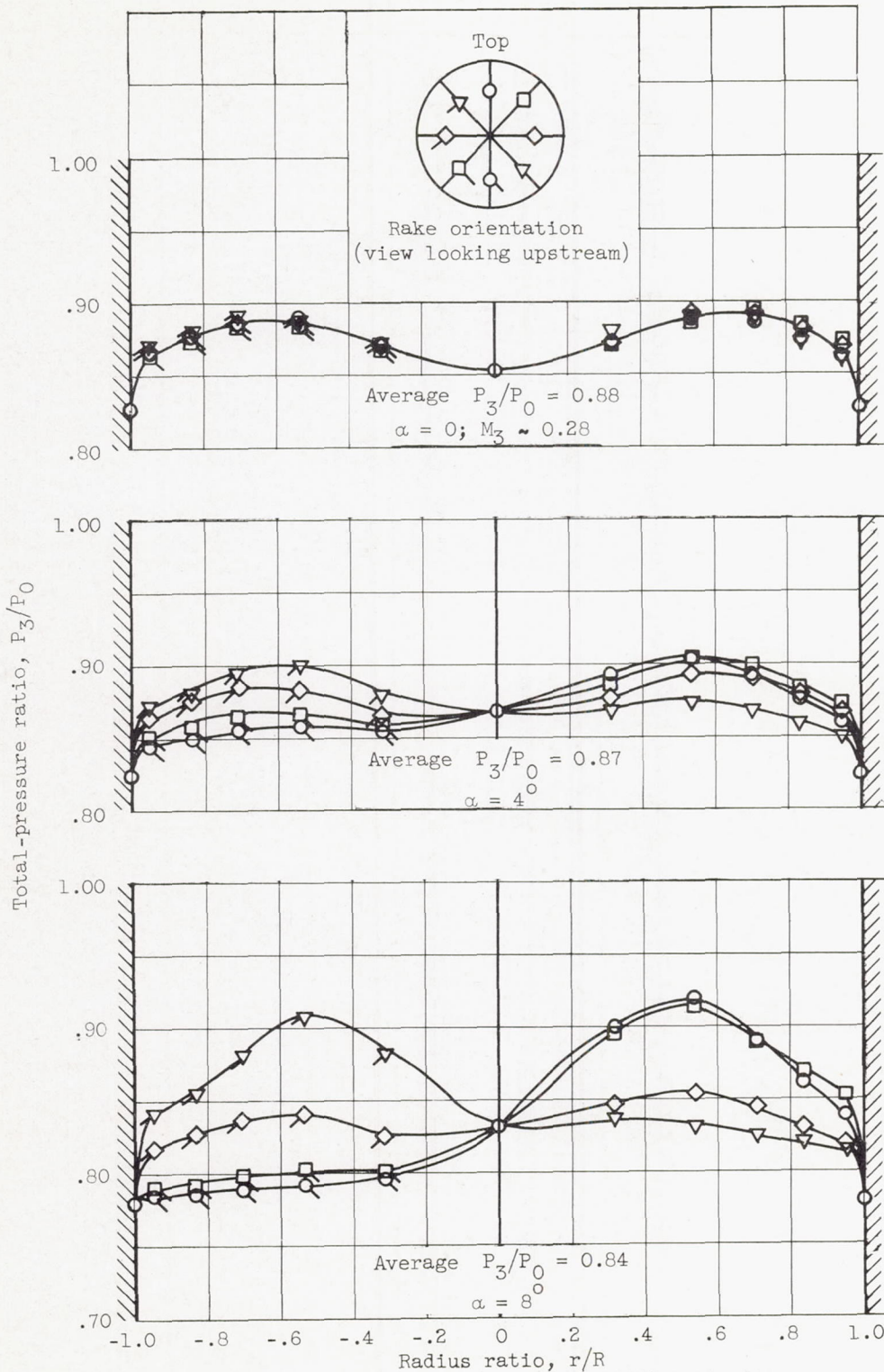   of attack.
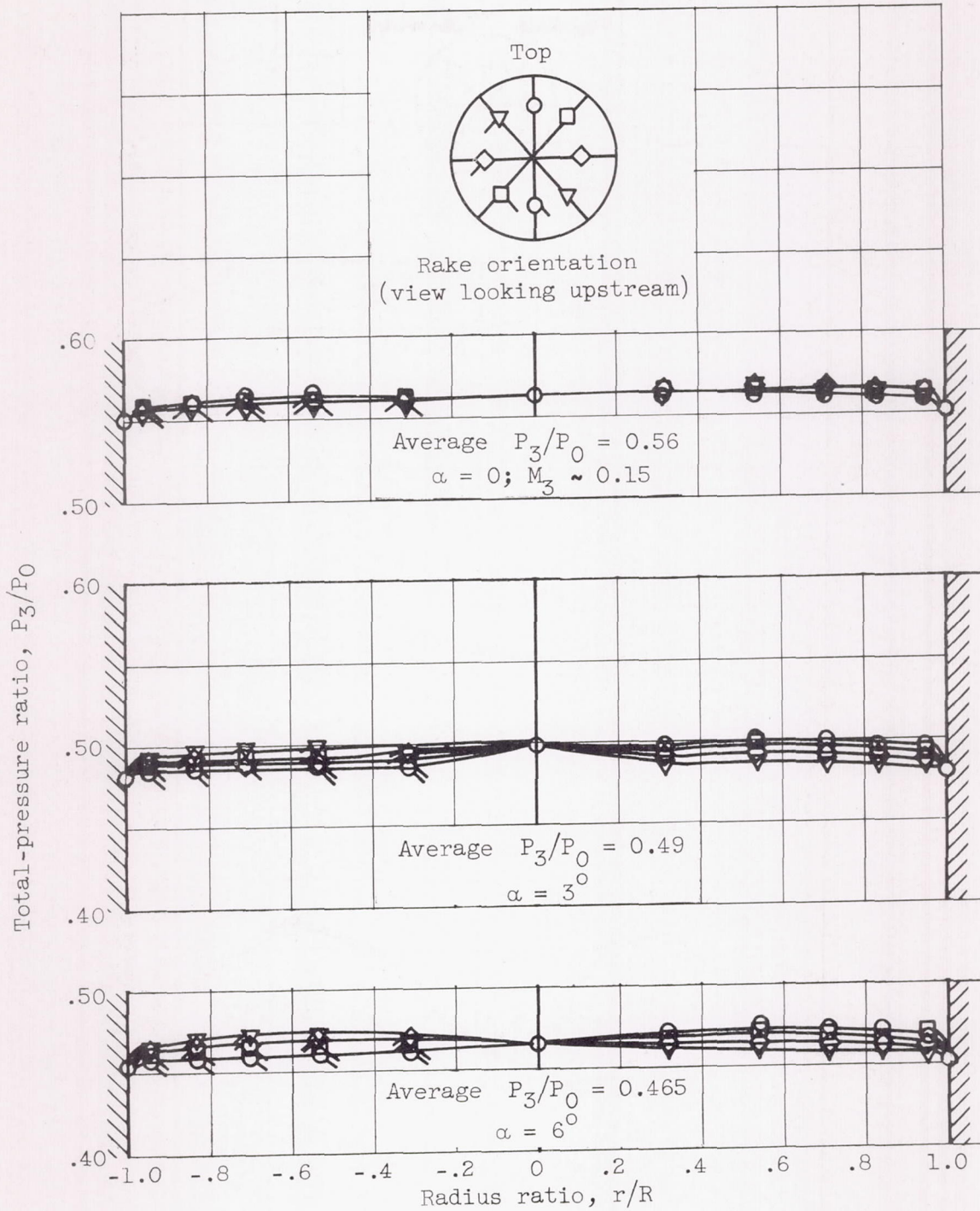
Supercritical

Minimum stable

Mass-flow ratio

(f) Free-stream Mach number, 1.90; angle of attack, 8°.

Figure 8. - Concluded. Flow patterns for variable-geometry inlet at various angles
    of attack.

(a) Free-stream Mach number, 1.90.

Figure 9. - Total-pressure profiles across diffuser exit at
  critical operation.

(b) Free-stream Mach number, 3.05.

Figure 9. - Concluded. Total-pressure profiles across diffuser
    exit at critical operation.