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AN EXPLORATORY STUDY OF APEX FENCE
FLAPS ON A 74-DEGREE DELTA WING

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ABSTRACT

An exploratory wind-tunnel investigation was performed to observe the flow-field effects produced by vertically deployed 'apex fences' on a planar 74-degree delta wing. The delta-shaped fences, each comprising approximately 3.375 percent of the wing area, were affixed along the first 25 percent of the wing leading edge in symmetric as well as asymmetric (i.e., fence on one side only) arrangements. The vortex flow field was visualized at angles of attack from 0 to 20 degrees using helium-bubble and oil-flow techniques; upper surface pressures were also measured along spanwise rows. The results were used to construct a preliminary description of the vortex patterns and induced pressures associated with vertical apex fence deployment. The objective was to obtain an initial evaluation of the potential of apex fences as vortex devices for subsonic lift modulation as well as lateral-directional control of delta wing aircraft.

It was concluded that the relatively small apex fences, when symmetrically deployed, enhanced the average suction level on the wing upper surface, which may amount to a 10-percent increase in the normal force over the angle-of-attack range (0° to 20°) of this test. Indications are that even higher suction levels may occur between the fences, producing a nose-up pitching moment for longitudinal trimming (i.e., when trailing-edge flaps are used for lift increment). The lateral-directional characteristics due to the deployment of a single fence would depend on the side force acting on the fence itself and the fence vortex-induced effects on the downstream surfaces. To determine these effects, force balance tests would be necessary, and were not performed in this preliminary experiment.

NOMENCLATURE

b	Wing span
c	Wing chord
Cn	Normal force coefficient
Cp	Static pressure coefficient
mV	Millivolts
x	Longitudinal coordinate
y	Lateral (spanwise) coordinate
α	Angle of attack
ΔCn	Normal force coefficient increment ($\Delta Cn = Cn - Cn_p$)

SUBSCRIPTS

p	Planar case
r	Wing root
u	Wing upper surface

INTRODUCTION

In recent years, much research has been directed towards the development of supersonic cruise fighters endowed with a high level of subsonic maneuverability. It is well known that the subsonic aerodynamics of the highly swept delta wing, which is frequently selected for supersonic fighters due to its low wave drag characteristics, are largely determined by the formation and behavior of leading edge vortices. Accordingly, the study of vortex characteristics has attracted renewed interest, particularly in the context of controlling and modifying them to the aerodynamicist's advantage. A variety of vortex management concepts have been proposed and investigated in recent years (Ref. 1) which are aimed at developing practical devices for specific aerodynamic functions such as lift augmentation, drag reduction, and flight path control. Two of these devices (the upper vortex flap and the apex flap) will be referred to in this report.

The 'apex fence' of this investigation was proposed by Dr. D. M. Rao as a vortex control concept for delta wings (or related planforms such as cranked and arrow wings having a highly swept apex region) whose non-linear aerodynamic characteristics, such as the vortex-induced lift and pitching moment, could be modulated independently of angle of attack. The apex fence, therefore, is intended for functions similar to the apex flap (Ref. 2), although its geometry and vortex-generation characteristics have more in common with the upper vortex flap (Ref. 3). Conceptually, the apex fence is an upper-surface hinged panel which is controlled by varying its upward deflection angle with respect to the wing plane. However, for the purpose of this exploratory study, a fixed deflection of 90 degrees was used. Both symmetrical and non-symmetrical arrangements (i.e. with fences on both sides or one side only) were tested with the latter representing a lateral and/or directional control mode. The use of a 74-degree delta wing was mainly to allow direct comparison with the apex flap, which had previously been tested with the same model. The scope of this report, however, is limited to a presentation and discussion of the main flow and pressure characteristics observed with the apex fence.

EXPERIMENTAL TECHNIQUE

PRESSURE SURVEYS

Pressure tests were conducted utilizing a transducer with a 48-channel scanner which measured static pressures on the upper surface of the model at a flow velocity of 60 miles per hour and a Reynolds Number of 510,000 per foot. Transducer output voltages (+-0.005mV accuracy) were recorded by hand. All recorded data were then reduced to pressure coefficient form by software written for use on a VAX-11/750 system. Graphical output was available through the use of a Tektronix 4014 graphics display terminal. All pressure results were then integrated to give an indication of the local normal force over a specific wing region.

FLOW VISUALIZATION

Two methods of flow visualization were employed. The first of these was the oil flow method. Thirty-weight motor oil whitened with Titanic Oxide was sprayed on the model such that small droplets covered the upper surface. The flow velocity was then raised to 60 miles per hour which corresponded, as in the pressure survey, to a Reynolds Number of 510,000 per foot. After a flow pattern emerged, a photo was taken of the upper surface.

The second method involved using a Sage Action, Inc. Model 3 bubble generator which used a combination of helium, soap, and air to form streams of neutrally buoyant bubbles. The bubble source was held sufficiently far upstream of the model in order to allow the bubbles to follow the natural path of the streamlines flowing over it. This test was conducted at a velocity of 15 miles per hour and a Reynolds Number of 127,500 per foot. An arc lamp placed downstream of the test section illuminated the bubbles while avoiding glare on the surface. The flow patterns were then made visible and could be photographed.

MODEL

A 74-degree flat plate delta planform with a 20 inch root chord was constructed using a 0.375 inch thick balsa core with fiberglass/polyester resin facings (Fig. 1). This technique yielded a strong structure with a smooth exterior finish. In the interest of simplicity, the leading edges were beveled 45 degrees on the lower surface to provide a sharp leading edge and a definite separation point. Data presented by Rao and Hoffler (Refs. 3 and 4) suggest that, although the leading edge experiences a local negative camber effect that promotes premature separation, this geometry is perfectly acceptable since such experiments involve direct comparisons with the planar-baseline configuration.

The model incorporated three spanwise rows of upper-surface static pressure taps (Table 1) located at $x/c_r=0.50$, $x/c_r=0.65$, and $x/c_r=0.80$, respectively. All taps were located in the right semi-span of the wing and extended to approximately 95% of the local semi-span.

A pair of apex fences was cut from 0.125 inch thick plywood in the shape of right triangles. The fence size was determined with two specifications in mind. First, each would extend along the leading edge to $x/c_r=0.25$. Second, when folded onto the main wing, the leading edge of the fences would meet at the apex centerline. These constraints provided a total fence area very similar to that of the apex flap (Refs. 2 and 5), that is, approximately 6.75 percent of the total wing area. After beveling the leading edge of the fences (again to provide a definite separation point), they were affixed perpendicular to the wing leading edges.

FACILITY

Pressure surveys and flow visualization were conducted in the Merrill Subsonic Wind Tunnel at North Carolina State University. The tunnel is of the closed-return type with a variable pitch fan and is capable of speeds up to 100 miles per hour. The vented test section is 45 inches wide, 32 inches high, and 46 inches streamwise. Plexiglass windows on either side as well as on top of the test section permit viewing and flow visualization photos to be taken. The tunnel has a turbulence factor of 1.2.

RESULTS AND DISCUSSION

BASIC WING

In order to evaluate the apex fence effects, it was necessary to first establish the basic wing characteristics. Although the aerodynamics of a planar 74-degree delta wing are well known, the large asymmetric bevel on the leading edges of the wing model simulated a negative camber and was expected to influence the vortex growth characteristics and, consequently, the upper surface pressure with increasing angle of attack. The pressure distributions presented in Fig. 2 indicate that the leading edge separation already exists on the basic wing at $\alpha=0$, as expected. This is confirmed by the oil flow pattern for this case (Fig. 3); due to the small scale of the vortex, however, the helium bubble technique (Fig. 4) was unsuccessful in revealing its presence. At higher angles of attack, the primary vortex develops normally as indicated by the rising suction peak and its inboard movement. The well known secondary separation is also clearly shown by the oil flow patterns.

SYMMETRIC APEX FENCES

A detailed comparison with the basic wing of upper-surface spanwise pressure distributions at the three stations and with increasing angle of attack is presented in Fig. 5. Typically, the fences result in a suction peak located at 2y/b=0.50 to 0.70, and generally higher in magnitude than the basic wing suction peak. This boost in the maximum suction level increases markedly with angle of attack. On the other hand, the suction level both near the centerline and the leading edges is reduced, as particularly evident at the forward station (x/c_r=0.50). The local upper-surface normal force obtained by spanwise integration of the pressure data, presented in Fig. 6, shows a net improvement in the normal force in the presence of the fences at all angles of attack except zero. The average increase in normal force is approximately 10 percent over a region comprising the aft 75 percent of the total wing area. There is also a strong trend of increasing Cn towards the forward station, implying an even higher Cn over the remaining 25 percent forward portion of the wing area.

The oil flow patterns with symmetric fences, Fig. 7, show, in each case, a vortex pair having a stronger "footprint" than evident at the same alpha on the basic wing, as judged by the greater spanwise deflection of the oil streaks. This correlates with the higher induced suction peaks as already noted in the pressure data. The intense vortex footprints were also present on the wing surface between the fences (a region which, unfortunately, is obscured in the photographs). It is therefore reasonable to expect that this apex area of the wing will be subject to intense suction, and so generate a high local normal force coefficient in the fence region.

Helium bubble visualizations of the symmetric fence arrangement are presented in Fig. 8. These side views clearly show the fence-generated vortex core trailing at a nearly constant height above the wing, except at the highest angle of attack (20 degrees). Vortex trajectories measured from planview helium bubble photographs (not presented) are shown in Fig. 9 for α=0 to 10 degrees. A pronounced outboard bending of the vortex core occurs between α=4 and 6 degrees which probably indicates its merging with the leading edge vortex sheet.

ASYMMETRIC APEX FENCES

The upper-surface pressures across the wing span, with the fence installed only on the left side, are presented in Fig. 10. Since only the right semispan of the wing was pressure-tapped, two separate tests were conducted at each angle of attack, with the fence being shifted from one side to the other between tests in order to construct the "full-span" pressure distributions depicted in Fig. 10. As expected, these distributions are unsymmetrical with the fence side suction peaks occurring more inboard than on the opposite side. More significantly, the suction peaks on the side of the clean leading edge are considerably magnified in comparison with the basic wing. A suggested cause is the sidewash induced towards the fence which will reduce the effective sweep and, therefore, increase the strength of the vortex of the 'clean' side leading edge as depicted in Fig. 11. Another cause is the fact that the vortex on the clean leading edge side trails closer to the wing upper surface as compared to the basic wing case.

The vortex flow field generated by the asymmetric fence deployment is revealed by helium bubble photographs presented in Figs. 12a and 12b. Two photographs were obtained at each angle of attack with the bubble wand being moved from the clean leading edge to the opposite fence-side leading edge. Comparing Fig. 12a with Fig. 4, it is seen that the vortex trajectory is closer to the surface on the clean leading edge than on the basic wing. Comparing Figs. 12b and 8 shows a higher trajectory taken by the fence vortex in the asymmetric case and, consequently, lower suction levels (Figs. 5 and 10) than in the symmetrically deployed fence case. Another noteworthy feature is seen at α=20 degrees, where vortex breakdown occurs on the 'clean' leading edge but not on the fence side. Note that the planar wing itself had stable vortices at α=20 degrees (Fig. 4). This observation is consistent with an augmented leading edge vortex in the presence of a single fence on the opposing leading edge as noted previously in Fig. 11. A reduction in sweep destabilizes the vortex thus causing breakdown at a lower angle of attack. The oil flow patterns (Fig. 13) also show the unequal vortices generated by this asymmetrical fence configuration.

CONCLUDING REMARKS

Flow visualizations and upper surface pressure measurements on a 74-degree delta wing fitted with relatively small 'apex fences' (each 3.375 percent of the wing area) have shown significant effects on the flow field due to fence generated vortices. Symmetrically deployed vertical apex fences enhance the average suction level on the wing upper surface which may amount to a 10 percent increase in the normal force in the range (α=0 to 20 degrees) of the test. Indications are that even higher suctions may occur in the apex region between the fences, producing a nose-up pitching moment for longitudinal trimming (i.e. when trailing edge flaps are used for lift increment). The lateral-directional characteristics due to the deployment of a single fence would depend on the side force acting on the fence itself and the fence-vortex induced effects on the downstream surfaces. To determine those effects, balance tests would be necessary.

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1. Rao, D. M.; "Vortical Flow Management for Improved Configuration Aerodynamics - Recent Experiences," 1983, AGARD Symposium on Aerodynamics of Vortical Type Flows in Three Dimensions, Paper No. 30.

2. Buter, T. A.; "Experimental and Computational Investigation of an Apex Flap Concept on a 74-Degree Delta Wing," Graduate Thesis MAE 83-1, North Carolina State University, February 1983.

3. Rao, D. M.; "Upper Vortex Flap - A Versatile Surface for Highly Swept Wings," Vigyan Research Associates, Hampton, Virgina 1983.

4. Hoffler, K. D.; "The Aerodynamic Characteristics of Upper Vortex Flaps on a 74-Degree Delta Wing," AIAA Student Conference Paper, April 1983.

5. Rao, D. M. and Buter, T. A.; "Experimental and Computational Studies of a Delta Wing Apex-Flap," AIAA Paper 83-1815, July 1983.

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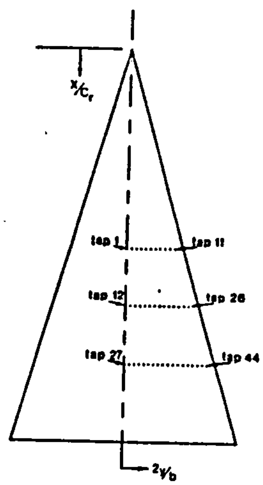
Miss J. L. Vess for providing secretarial support.

TABLE 1 - PRESSURE TAP LOCATIONS

TAP NUMBER	$x/c_r = 0.50$	$x/c_r = 0.65$	$x/c_r = 0.80$
	LOCAL SEMISPAN (2y/b)		
1, 12, 27	.0000	.0000	.0000
2, 13, 28	.0988	.0733	.0662
3, 14, 29	.1871	.1357	.1169
4, 15, 30	.2718	.2091	.1765
5, 16, 31	.3635	.2715	.2360
6, 17, 32	.4518	.3448	.2868
7, 18, 33	.5400	.4072	.3375
8, 19, 34	.6247*	.4805	.3971
9, 20, 35	.7165	.5430	.4478
10, 21, 36	.8056	.6163	.5074
11, 22, 37	.8928	.6787	.5581
23, 38		.7520	.6177
24, 39		.8128	.6772
25, 40		.8799	.7279
26, 41		.9470	.7787
42			.8217
43			.8762
44			.9372



*Note: Tap #8 was defective throughout this investigation and is not presented in the figures.

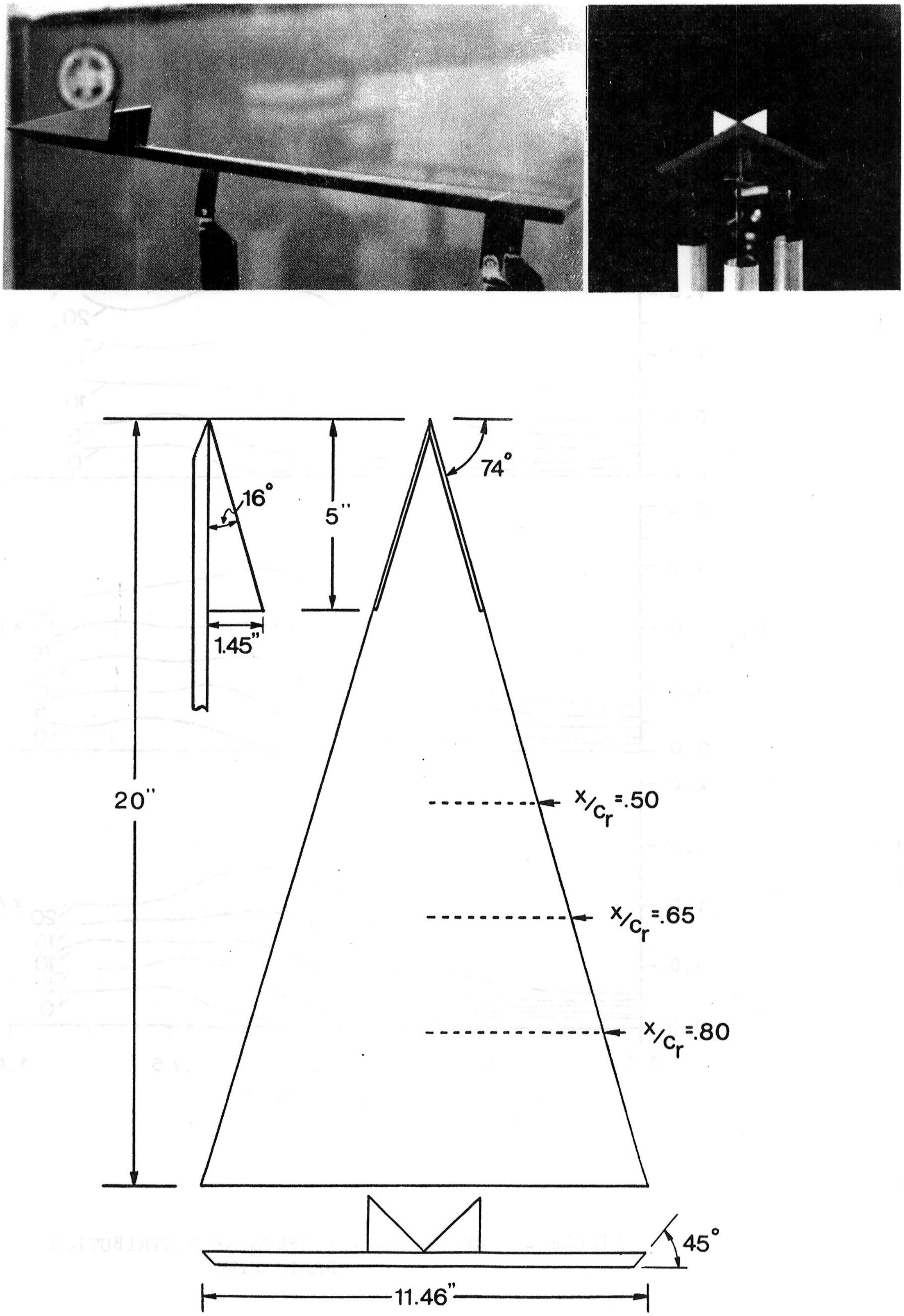


FIGURE 1 - 74 DEGREE DELTA MODEL

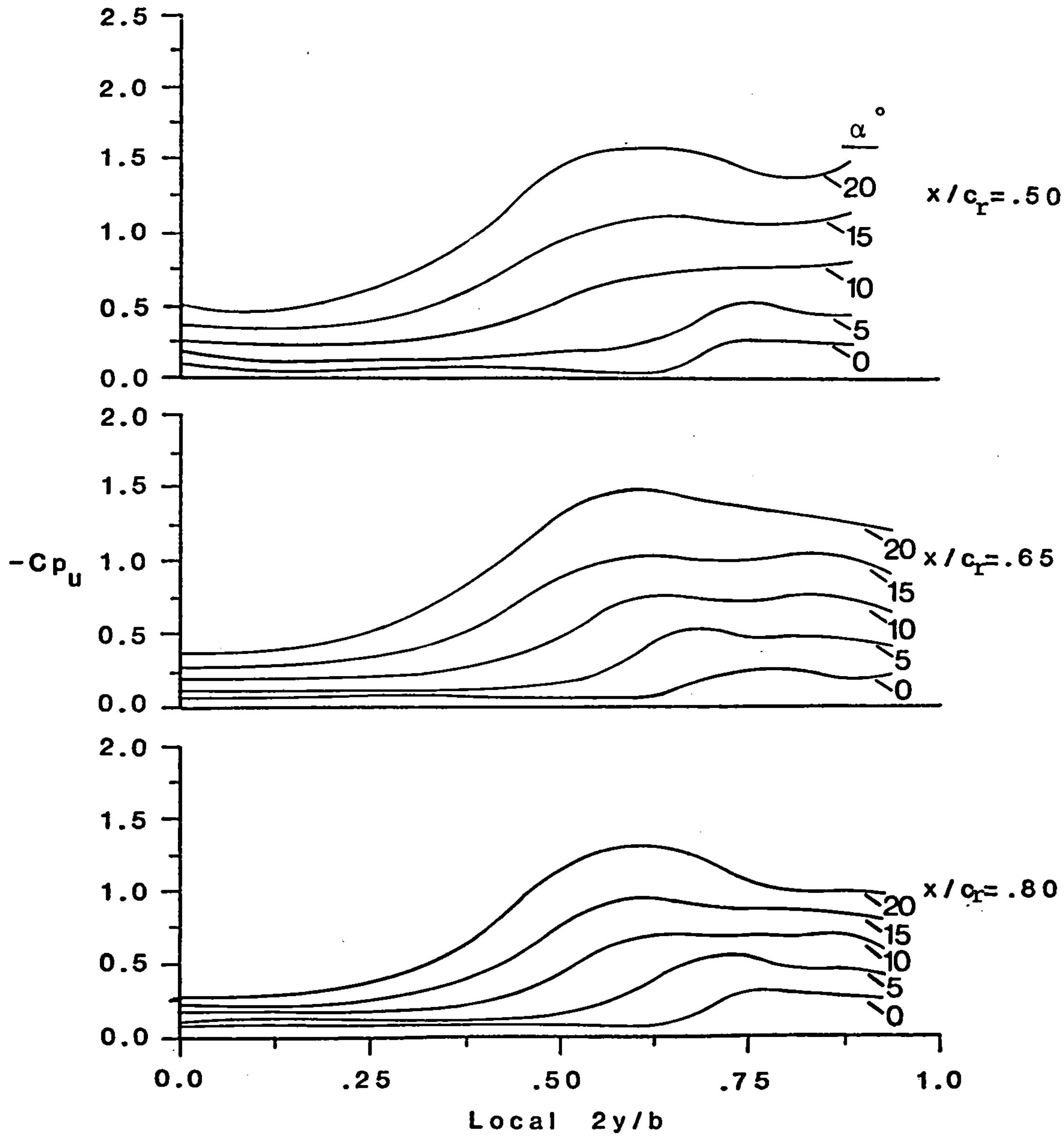


FIGURE 2 - UPPER SURFACE PRESSURE DISTRIBUTION
BASIC WING

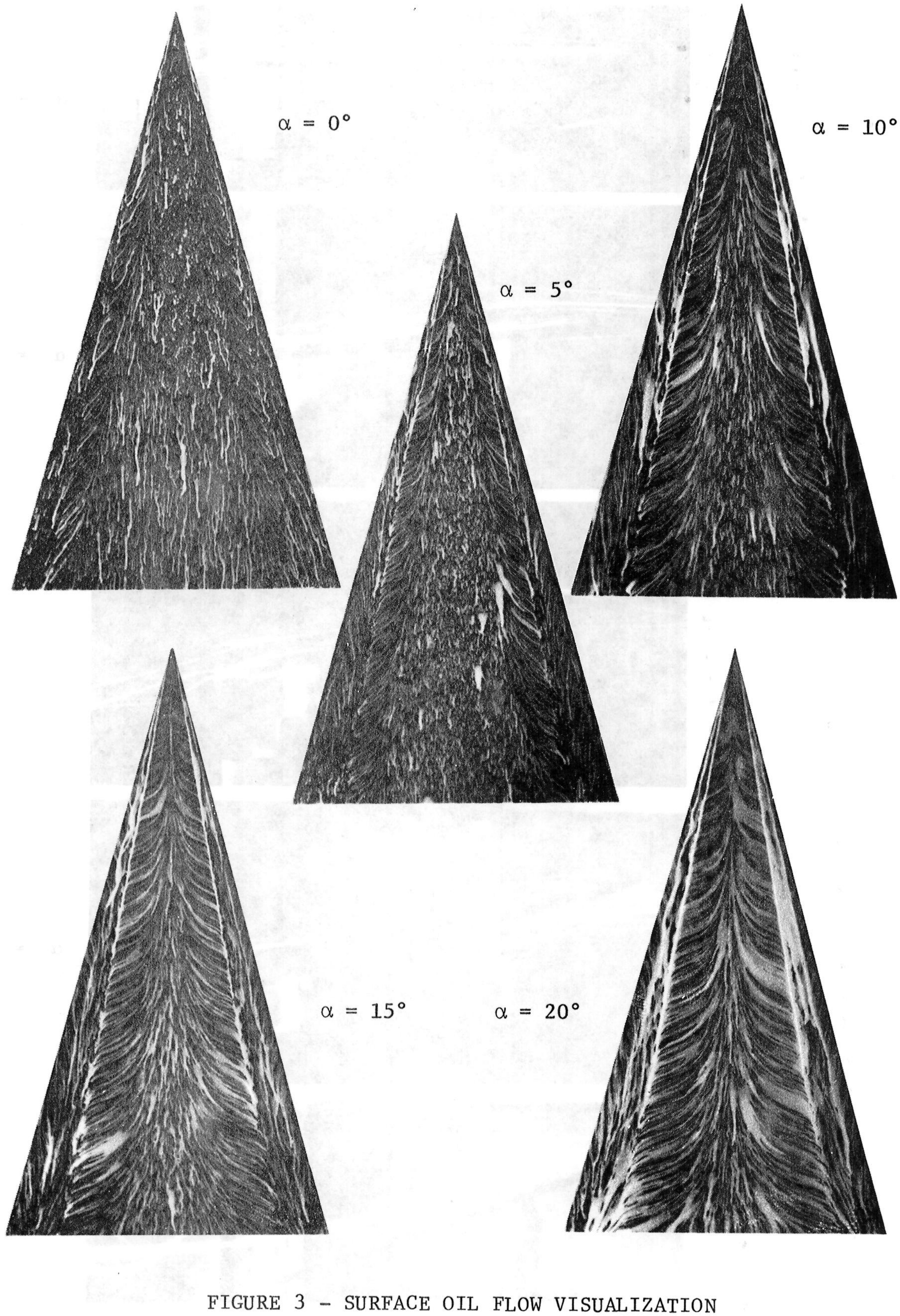
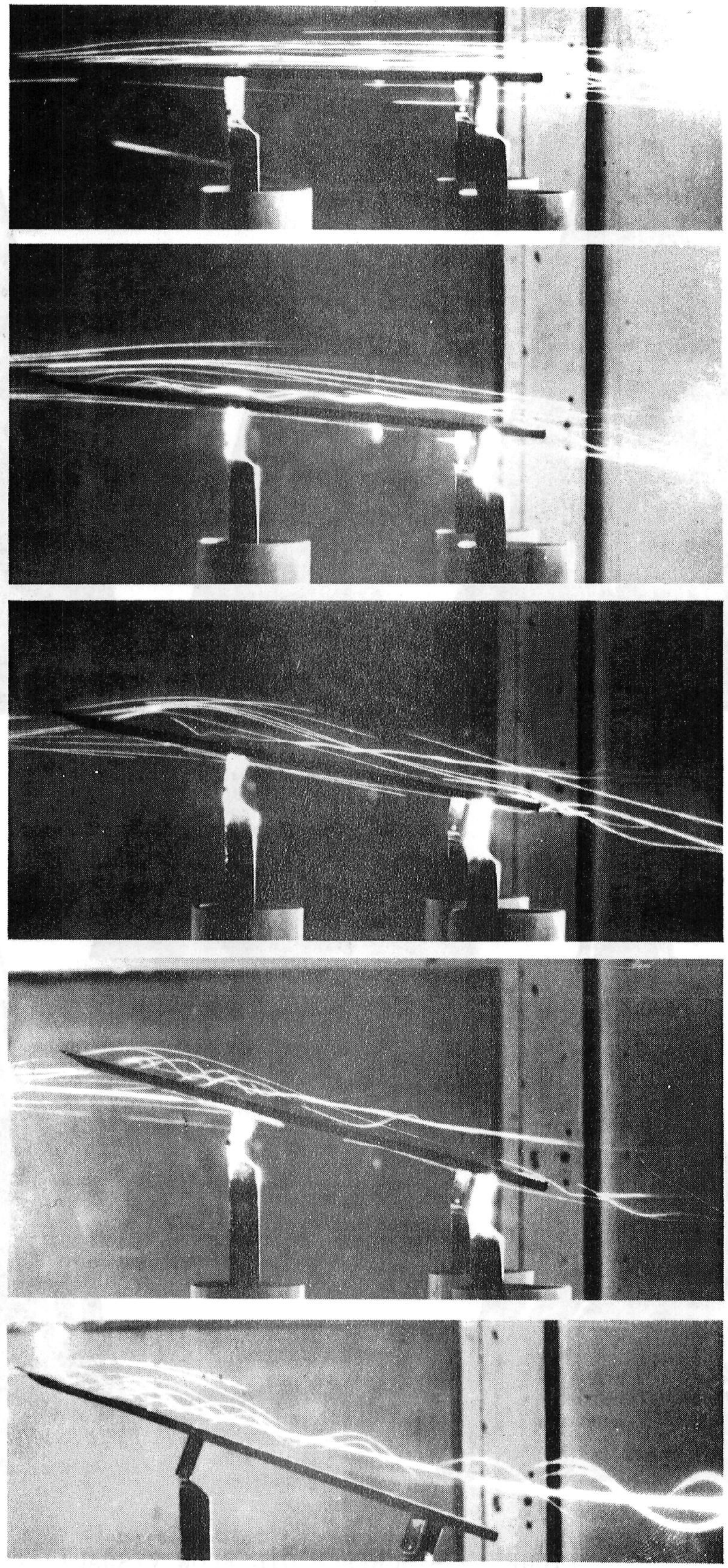


FIGURE 3 - SURFACE OIL FLOW VISUALIZATION
BASIC WING



$\alpha = 0°$

$\alpha = 5°$

$\alpha = 10°$

$\alpha = 15°$

$\alpha = 20°$

FIGURE 4 - HELIUM BUBBLE FLOW VISUALIZATION
BASIC WING

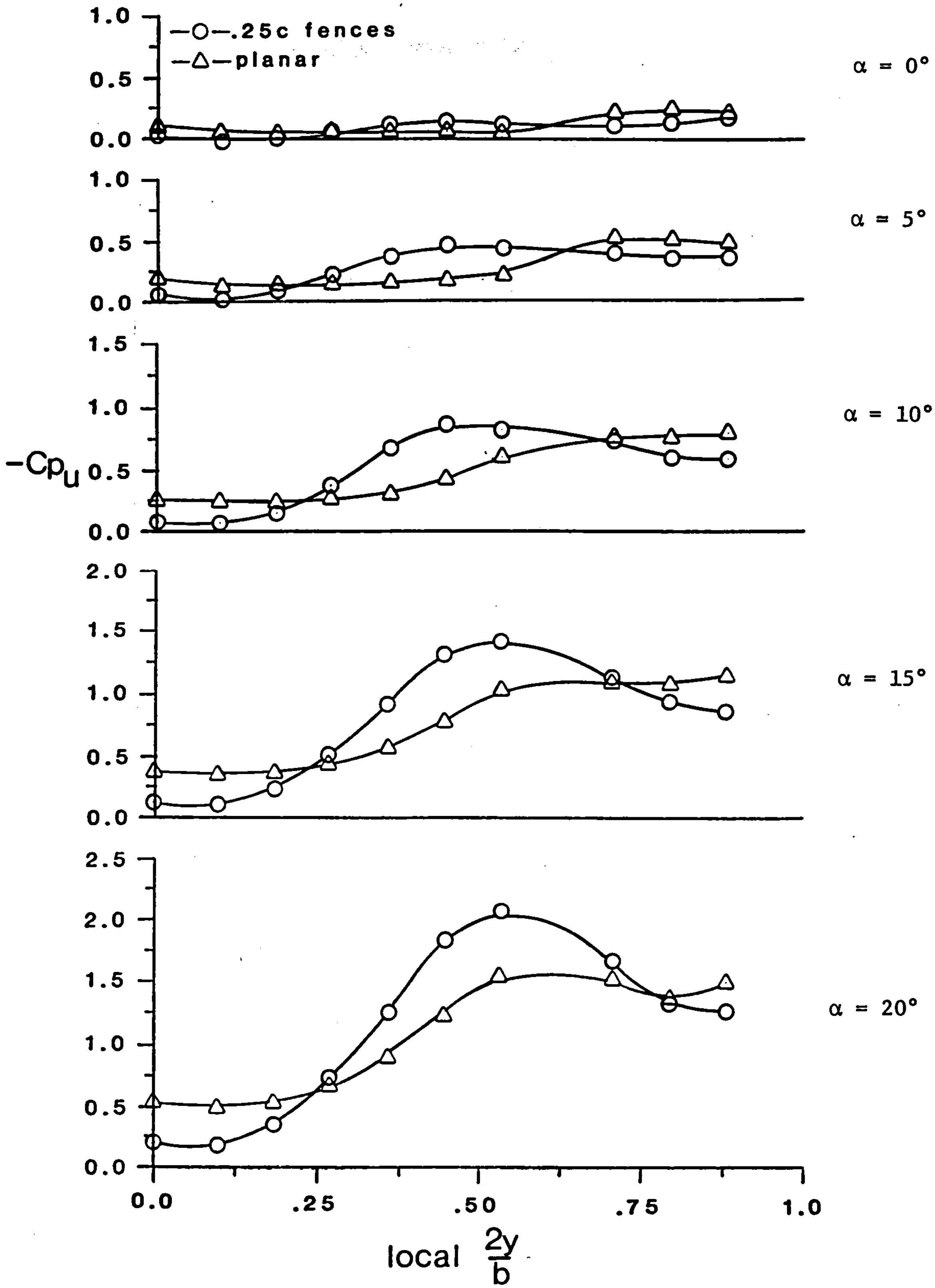


FIGURE 5(A) - UPPER SURFACE PRESSURE DISTRIBUTION
SYMMETRIC FENCES, x/c_r = 0.50

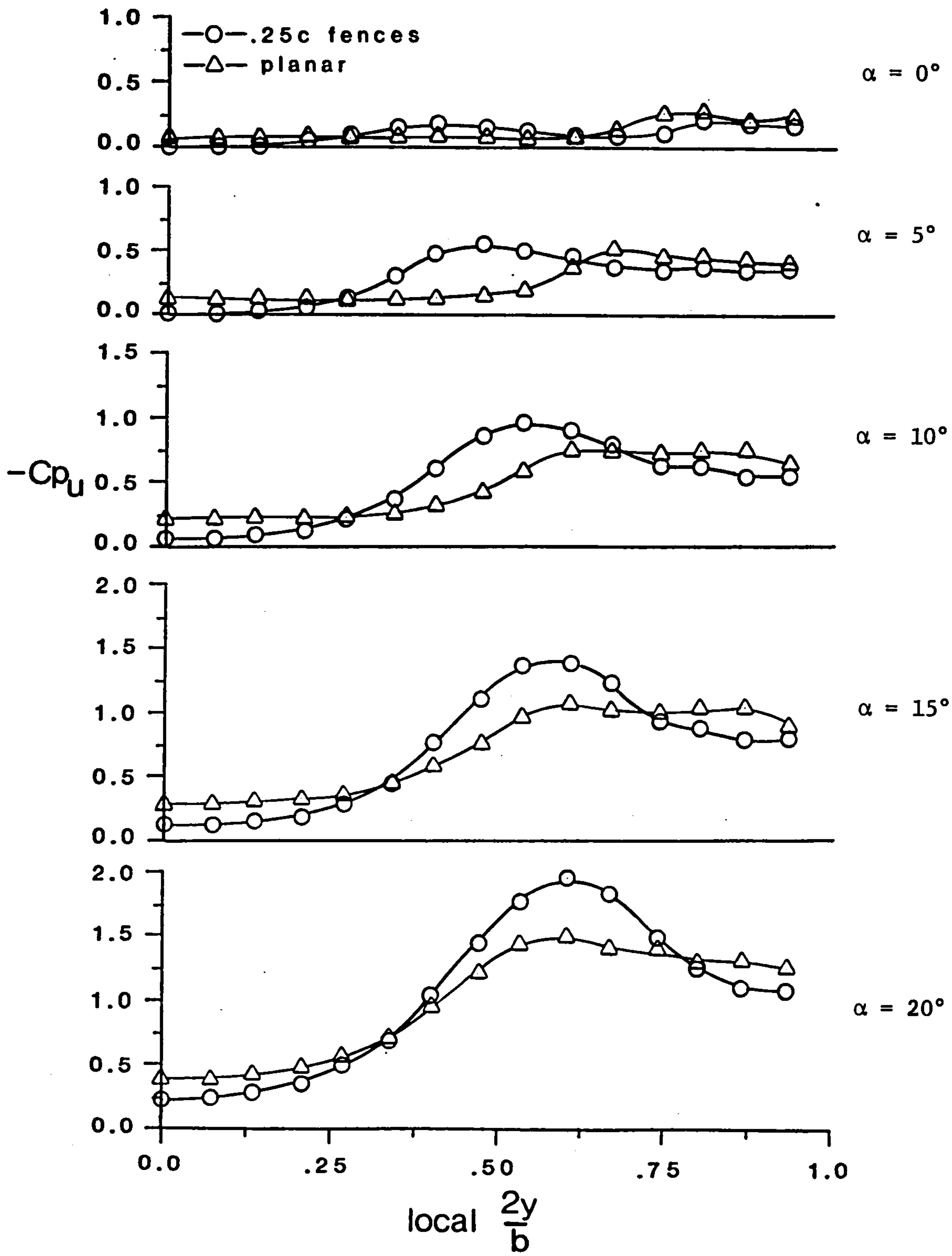


FIGURE 5(B) - UPPER SURFACE PRESSURE DISTRIBUTION SYMMETRIC FENCES, $x/c_r = 0.65$

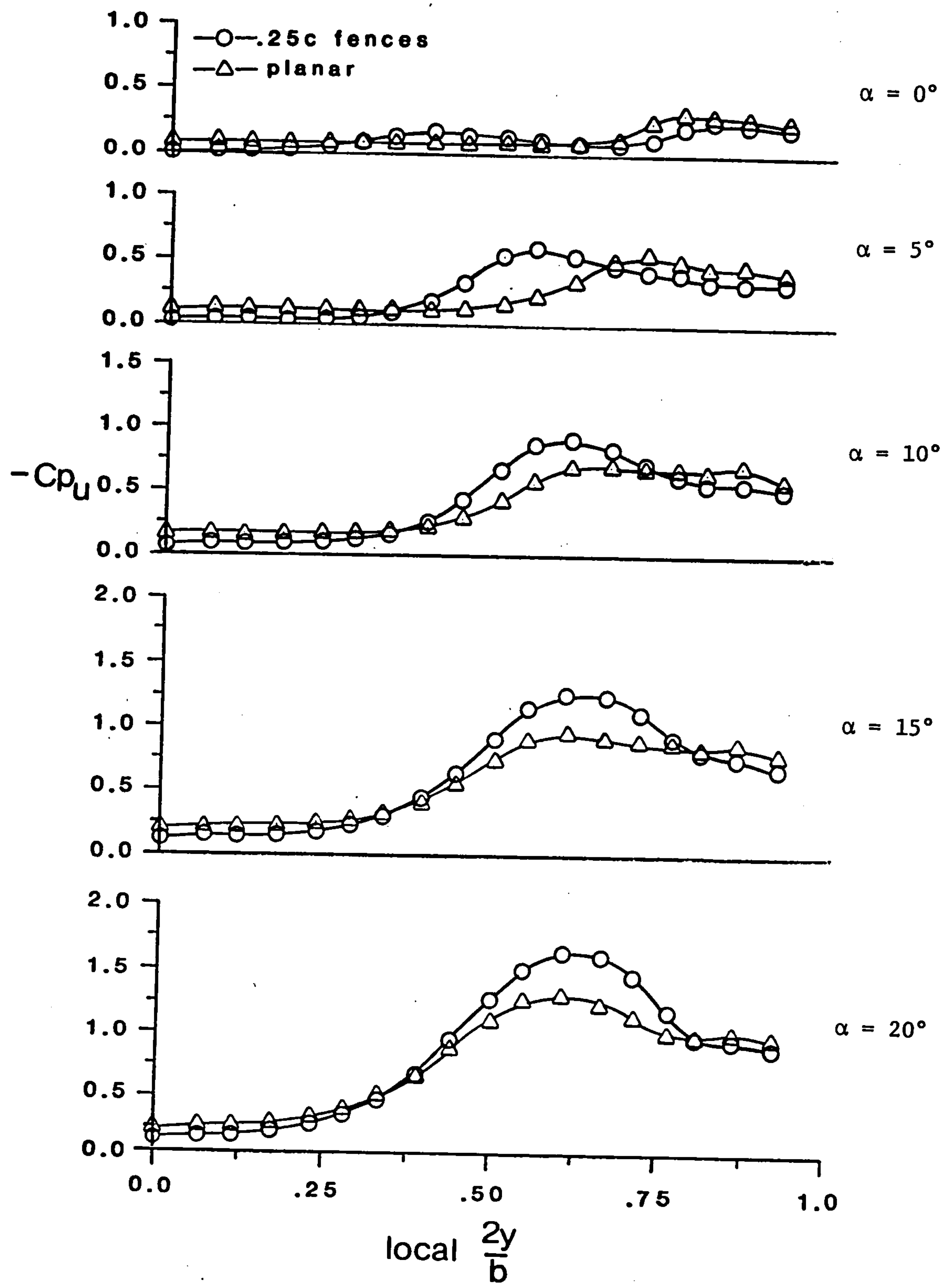
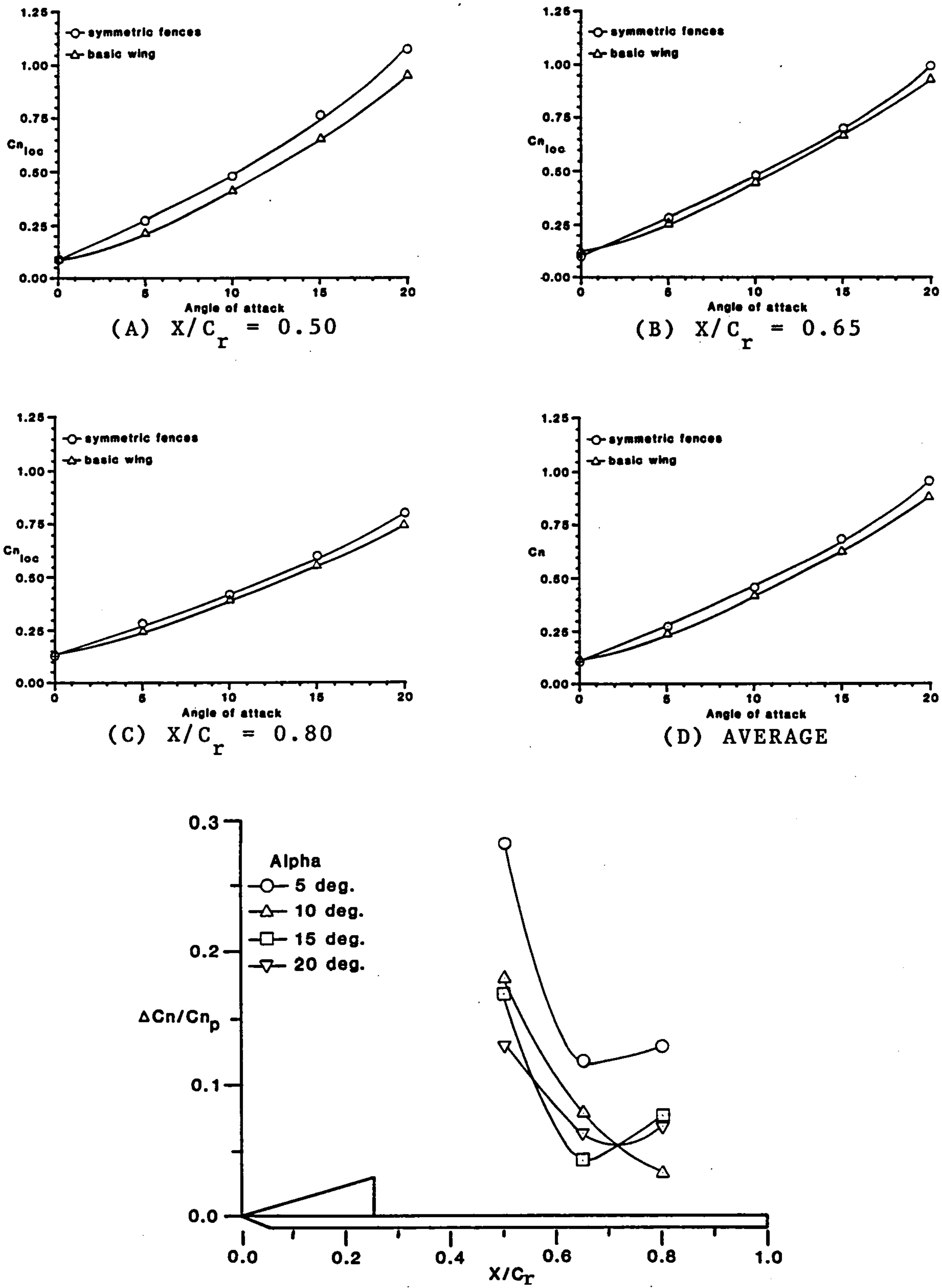


FIGURE 5(C) - UPPER SURFACE PRESSURE DISTRIBUTION SYMMETRIC FENCES, x/c_r = 0.80



(A) $X/C_r = 0.50$

(B) $X/C_r = 0.65$

(C) $X/C_r = 0.80$

(D) AVERAGE

(E) NORMAL FORCE INCREMENT

FIGURE 6 - NORMAL FORCE DISTRIBUTIONS

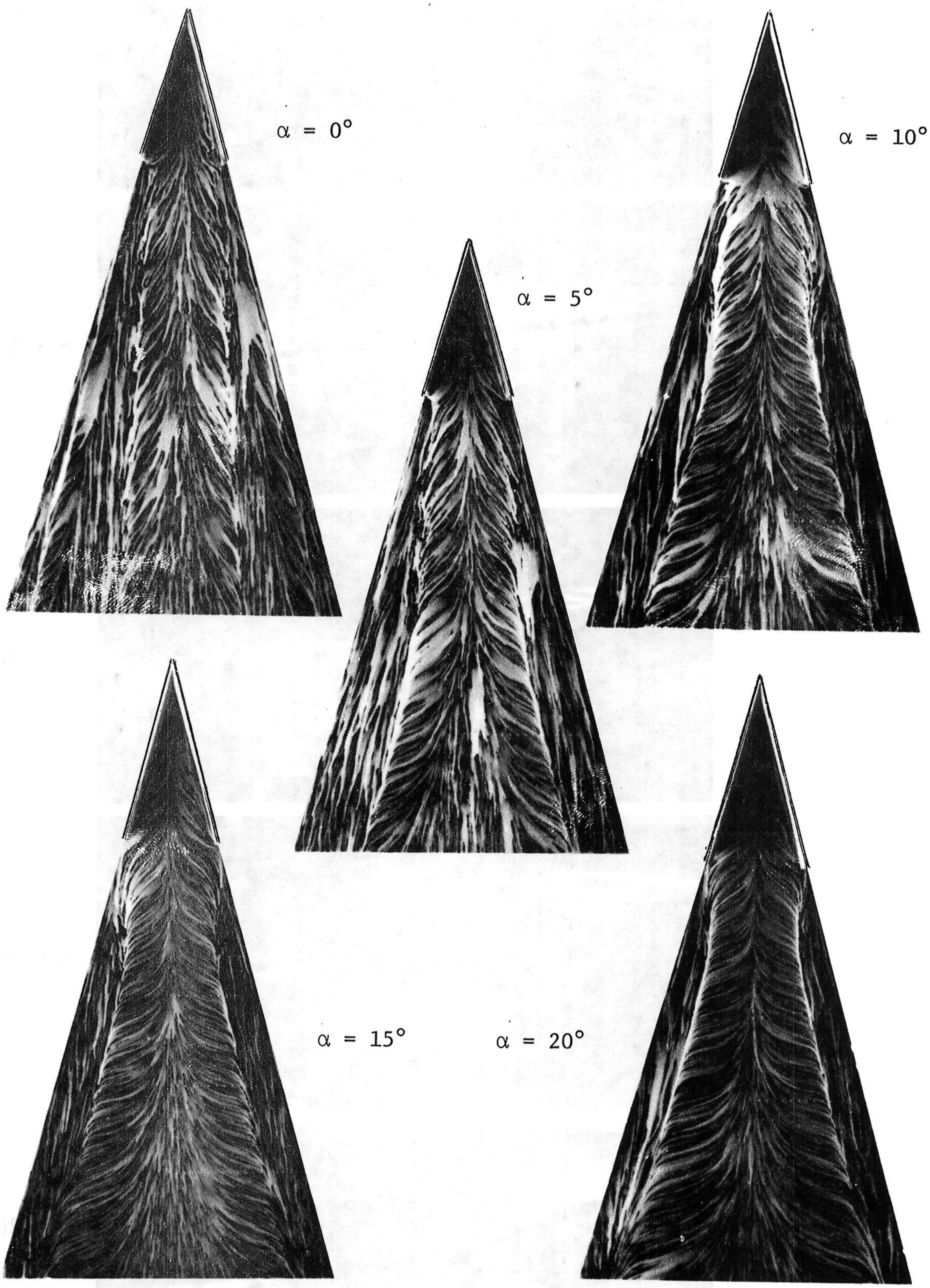
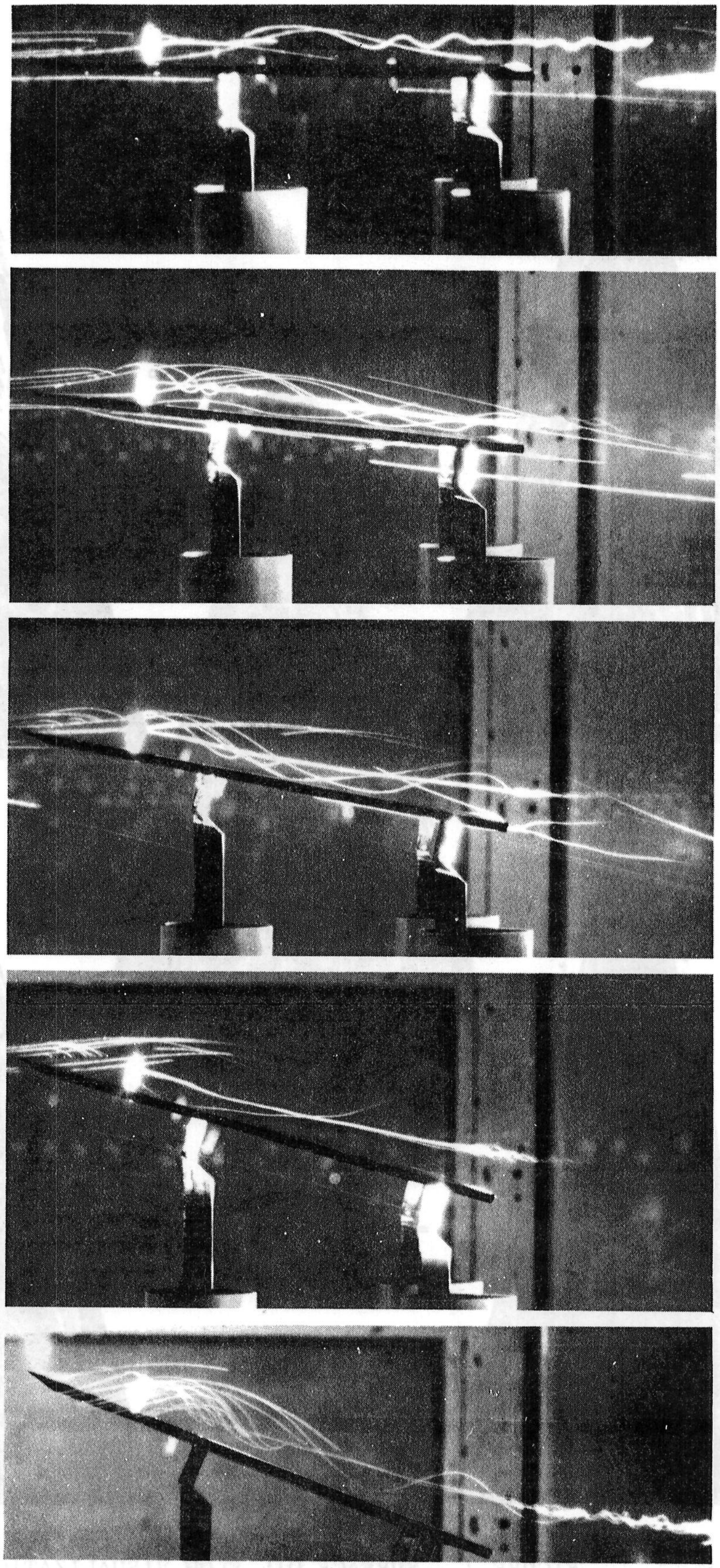


FIGURE 7 - SURFACE OIL FLOW VISUALIZATION
SYMMETRIC FENCES



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$\alpha = 5°$

$\alpha = 10°$

$\alpha = 15°$

$\alpha = 20°$

FIGURE 8 - HELIUM BUBBLE FLOW VISUALIZATION
SYMMETRIC FENCES

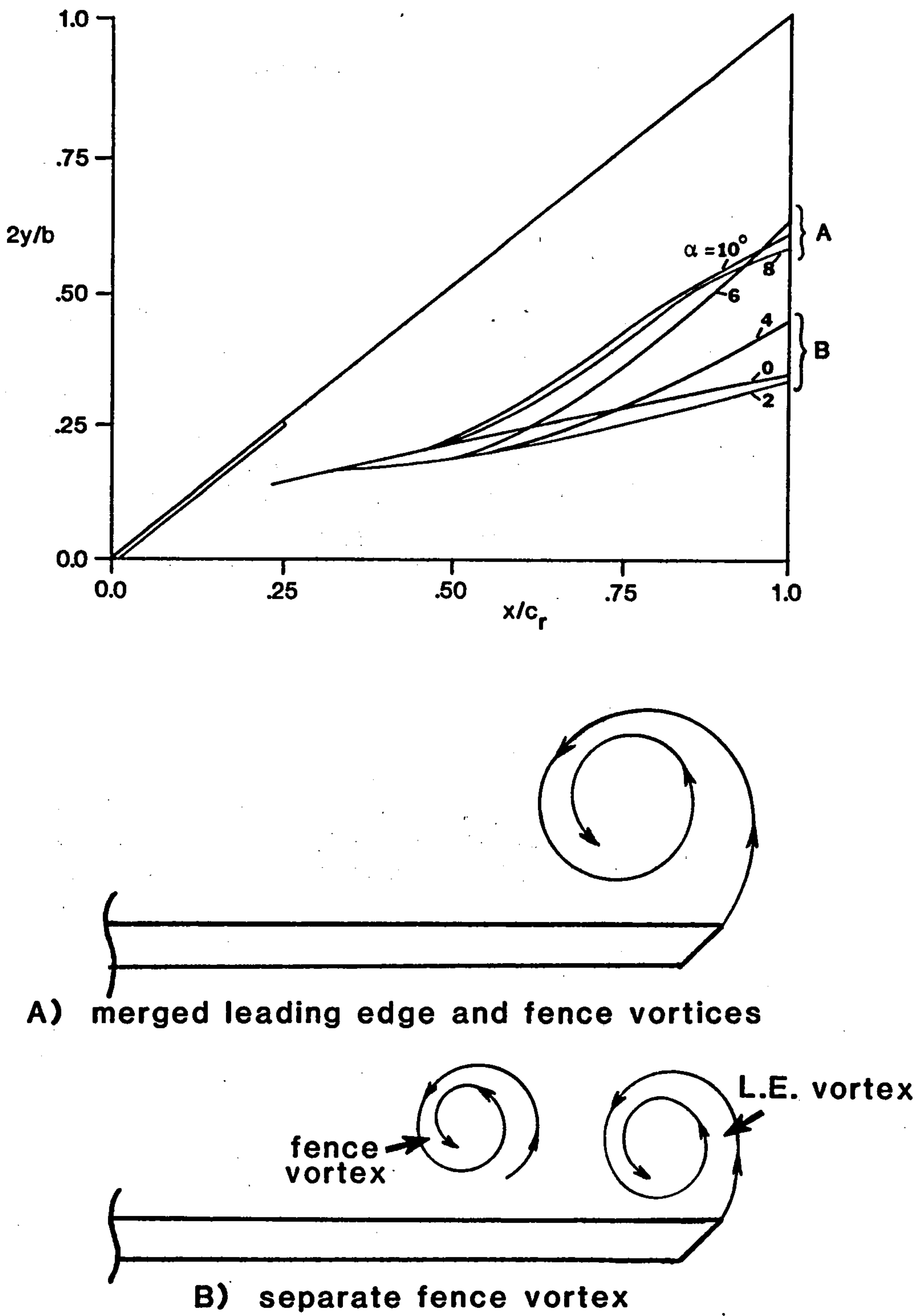


FIGURE 9 - TYPICAL VORTEX TRAJECTORIES

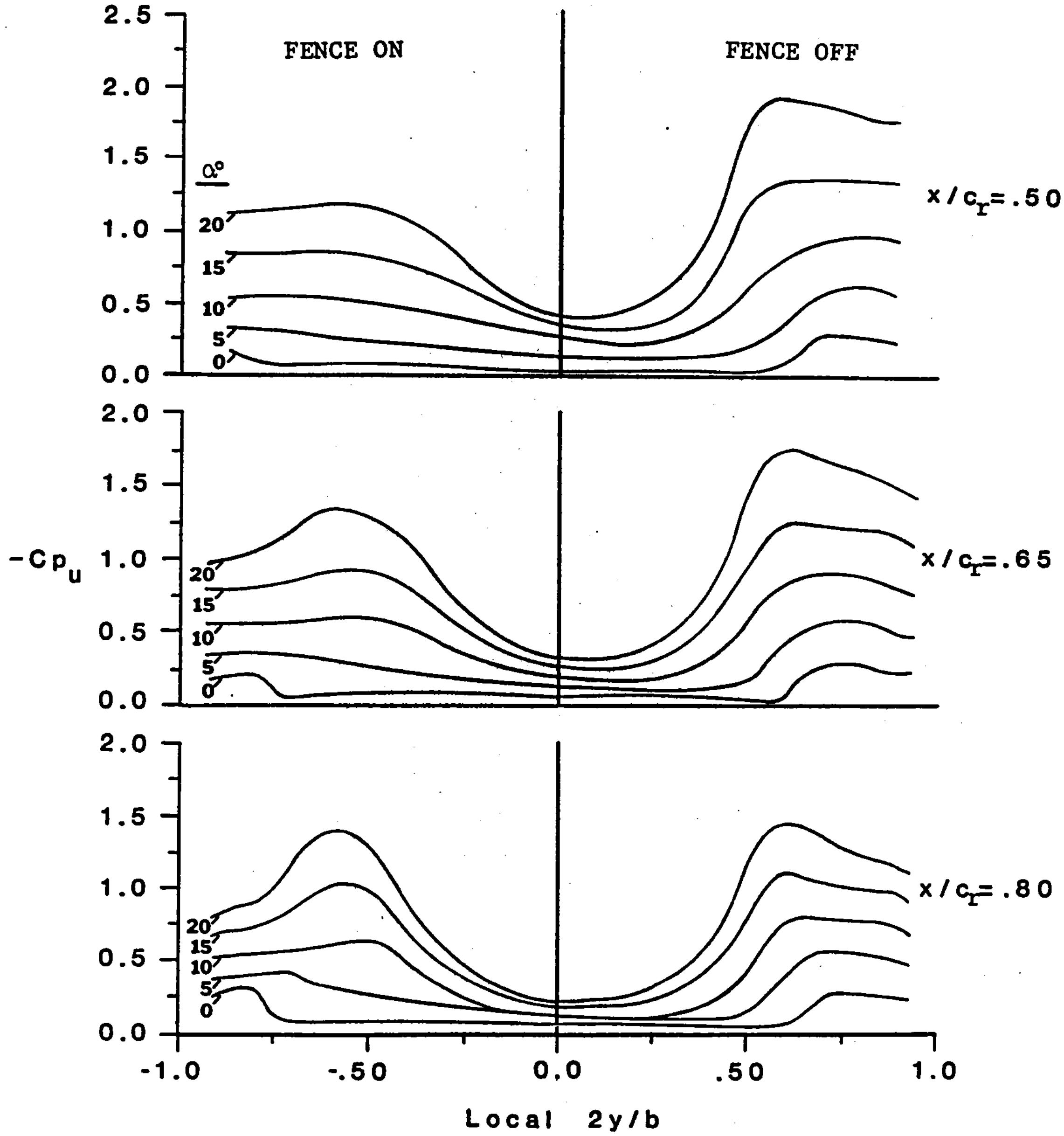


FIGURE 10 - UPPER SURFACE PRESSURE DISTRIBUTION
ASYMMETRIC FENCE

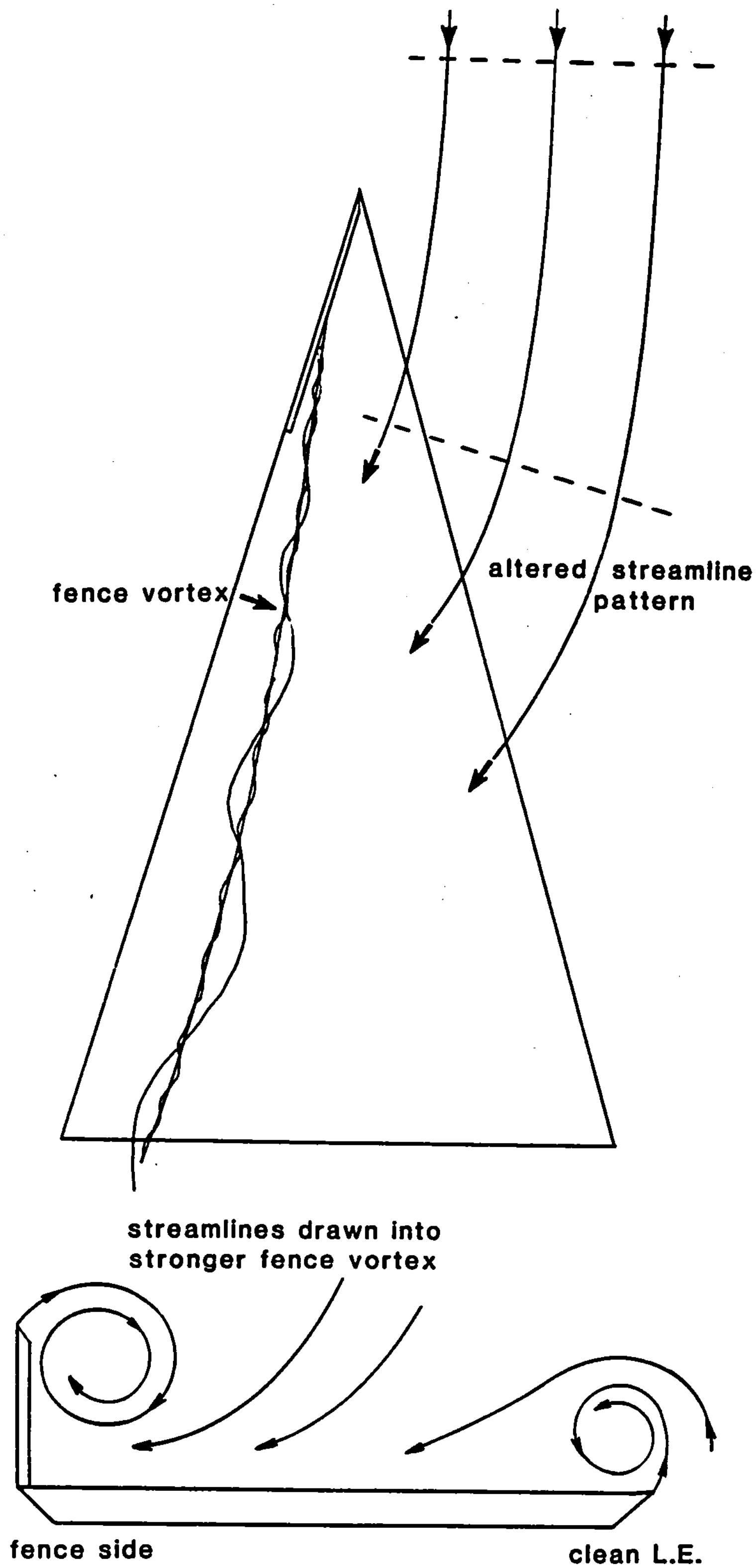
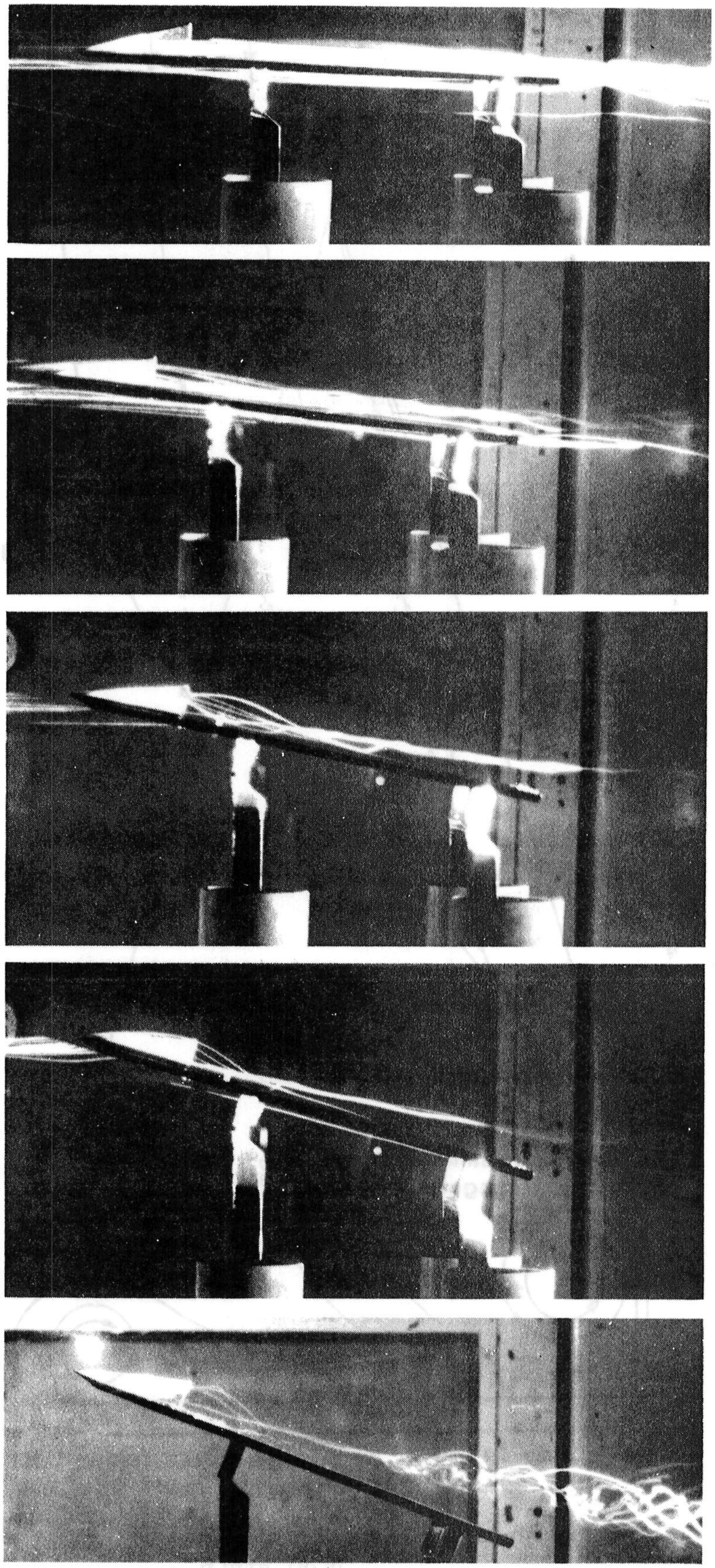


FIGURE 11 - ASYMMETRIC FENCE EFFECT ON
FLOW FIELD



$\alpha = 0°$

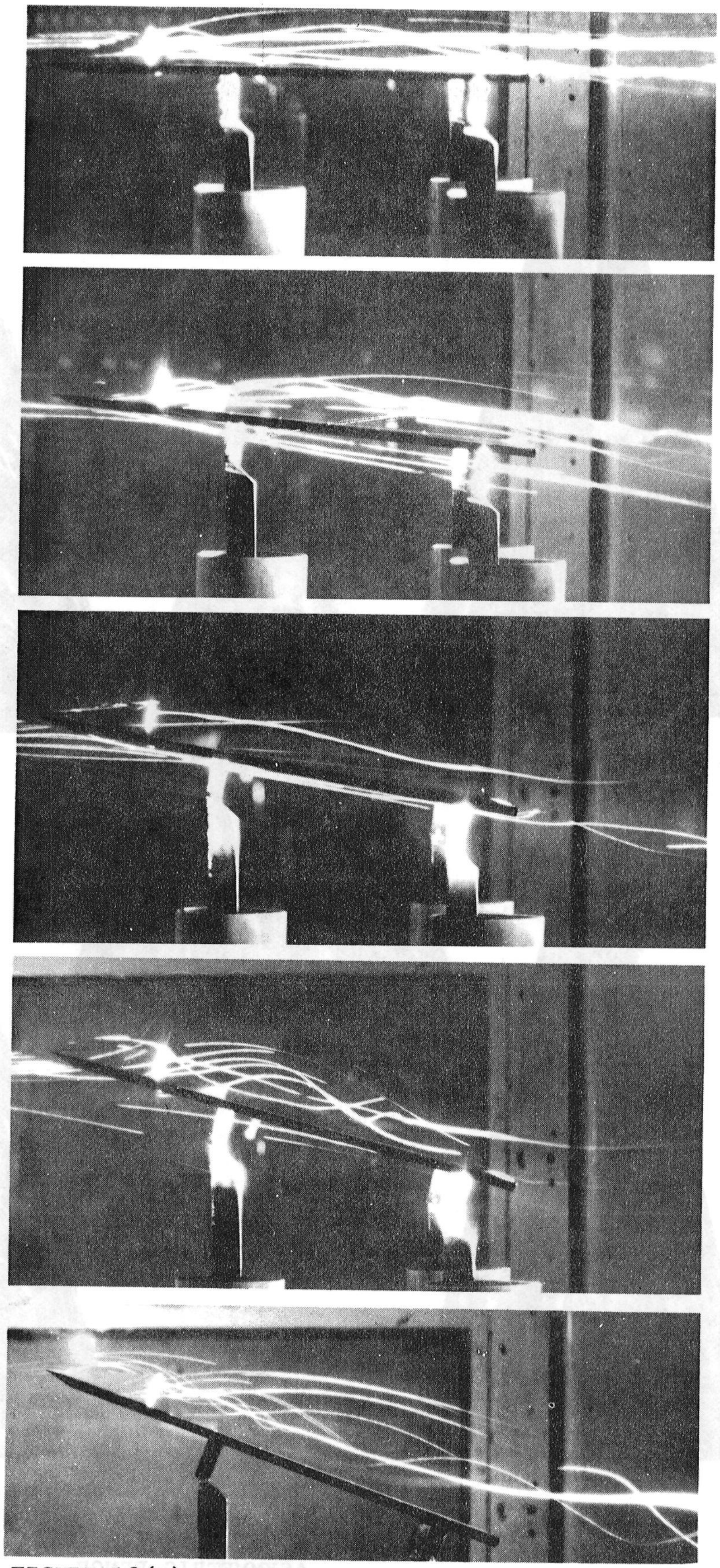
$\alpha = 5°$

$\alpha = 10°$

$\alpha = 15°$

$\alpha = 20°$

FIGURE 12(A) - HELIUM BUBBLE FLOW VISUALIZATION
ASYMMETRIC FENCE, CLEAN L.E. SIDE



$\alpha = 0°$

$\alpha = 5°$

$\alpha = 10°$

$\alpha = 15°$

$\alpha = 20°$

FIGURE 12(B) - HELIUM BUBBLE FLOW VISUALIZATION
ASYMMETRIC FENCE SIDE

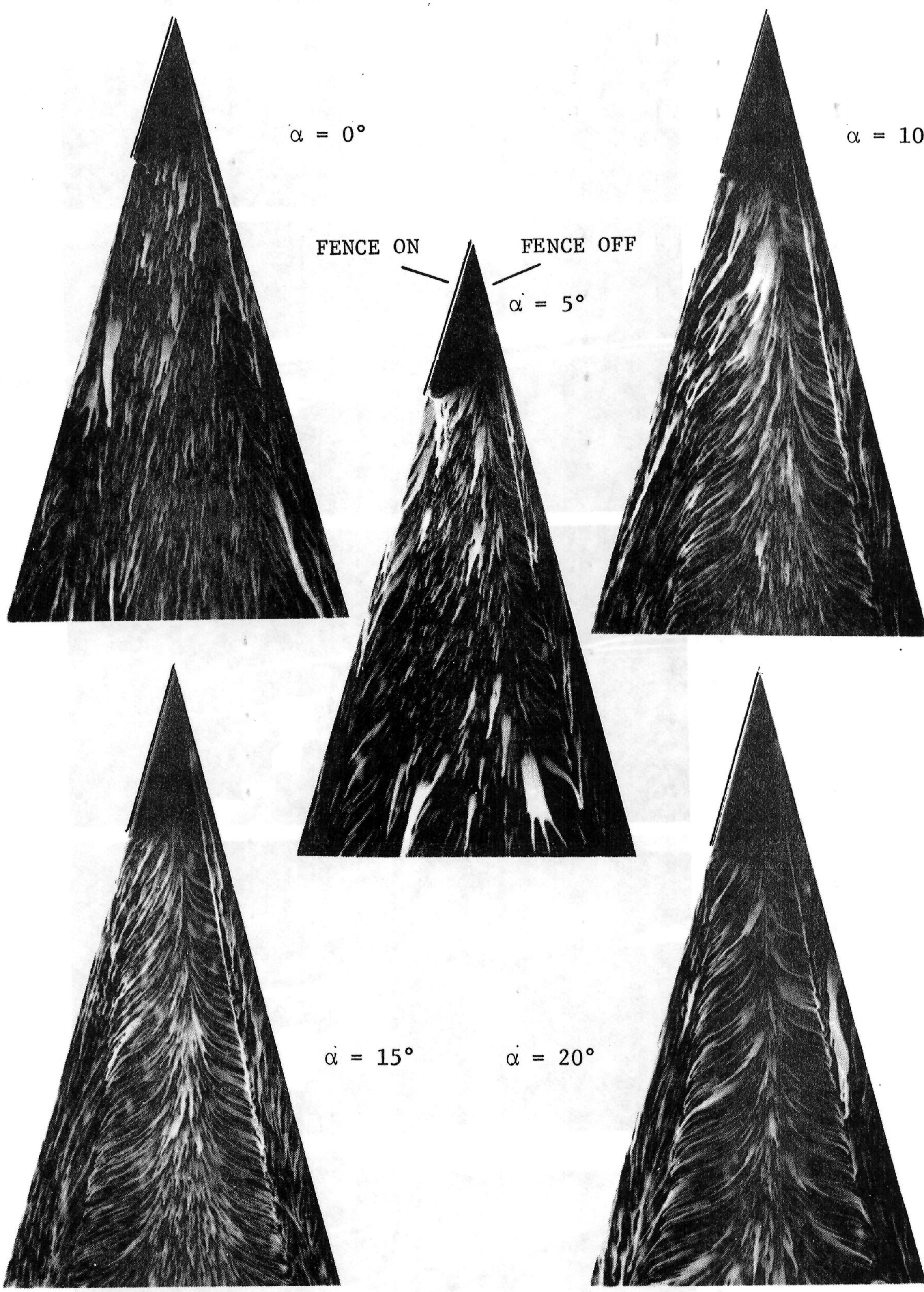


FIGURE 13 - SURFACE OIL FLOW VISUALIZATION
ASYMMETRIC FENCE

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16. Abstract

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