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FLOW SEPARATION, REATTACHMENT, AND VENTILATION OF FOILS WITH SHARP LEADING EDGE AT LOW REYNOLDS NUMBER

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Naval Ship Research and Development Center
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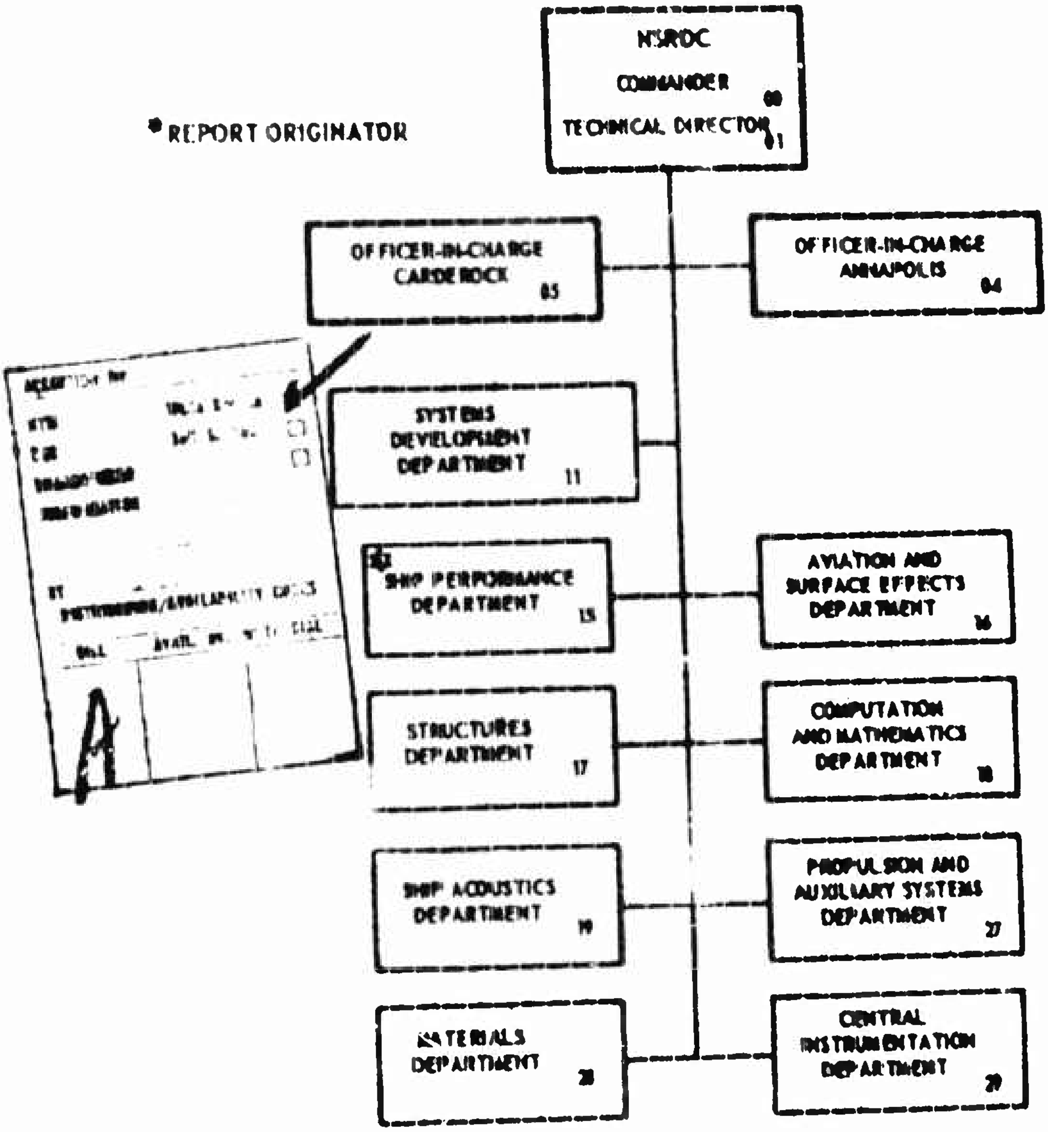

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Two two-dimensional foils (a wedge and a modified Tulin two-term foil) were used to study the ventilation of foils with sharp leading edges at low Reynolds number. Flow visualization by dye injection techniques and by tufts was used to determine the reattachment point of the separated streamline in nonventilated flow.

The results indicate that if air is forced into a separated region, it is possible to achieve a fully developed cavity. This can be accomplished at speeds too low for any cavitation to occur by resorting to relatively high angles of attack. Hence, it is possible to go directly from noncavitating flow to fully developed cavity flow. Results of pressure measurements over the surface of the curved foil are included.

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ABSTRACT

Two two-dimensional foils (a wedge and a modified Tulin two-term foil) were used to study the ventilation of foils with sharp leading edges at low Reynolds number. Flow visualization by dye injection techniques and by tufts was used to determine the reattachment point of the separated streamline in nonventilated flow.

The results indicate that if air is forced into a separated region, it is possible to achieve a fully developed cavity. This can be accomplished at speeds too low for any cavitation to occur by resorting to relatively high angles of attack. Hence, it is possible to go directly from noncavitating flow to fully developed cavity flow. Results of pressure measurements over the surface of the curved foil are included.

ADMINISTRATIVE INFORMATION

Funding for this work was provided under Naval Ship Systems Command (NAVSHIPS) Subproject S-46-06X, Task 1722, Work Unit 526-123. This material was originally published for limited distribution as Hydromechanics Laboratory Test and Evaluation Report 243-H-01 in April 1968. The present report was prepared under Work Unit 4-1500-001.

INTRODUCTION

Ventilation, the filling of a cavity with air, is one method to achieve transition from noncavitating to fully cavitating operation of propellers and hydrofoils. Such a transition is relatively stable since there is essentially instantaneous transition with no period of partial cavitation. Hence, the propeller or foil passes from one "stable" condition to another. In practical cases, the parameters which can be varied are limited to section shape, section angle of attack, section speed, air pressure, and the size and pattern of the air supply hole. When all the proper conditions are met, an air-filled cavity springs from the sharp leading edge and extends beyond the trailing edge. Ventilation inception can be defined, then, as those conditions of static pressure, velocity, orientation, and airflow at which a given section sustains an air-filled cavity from the leading edge past the trailing edge. If the conditions are not sufficient, air simply flows from the air supply opening and streams back.

The ventilation of sharp-edged hydrofoils at speeds of about 85 fps (50 knots) requires angles of attack in the order of 6 deg, with 20–60 psig air pressure. Propellers which have relative section velocities as high as 600 fps operate at angles of attack around 2 deg. Normally 20-psig air is sufficient to cause ventilation if the air is admitted into either a separated region or a region of sheet cavitation. The desirability of ventilating before cavitation starts indicates that ventilation into a separated region is required.

Separation on foils with sharp leading edges is of the laminar type (also called "thin airfoil" type) in which the length of the separated region is mainly a function of the angle of attack.[1,2] It is important to know the location of the reattachment of the separated streamline (1) because in order to achieve low drag, it is necessary to keep the angle of attack as low as possible and (2) because it is desirable to inject ventilation air into the separated region. It must be remembered, moreover, that because of structural requirements, the air admission slots cannot be at the leading edge and so should be toward the rear of the separated region. Hence, this investigation was performed to determine where the reattachment occurs on realistic foil shapes and thus enable predictions on where to supply air.

An experimental investigation was carried out since there is presently no adequate theory which predicts ventilation inception. Furthermore, theory cannot be used to accurately predict the reattachment of a separated streamline.

PROCEDURE

The experimental work was carried out in two parts. First, flow visualization studies were made with a wedge-shaped foil and a modified Tulin two-term foil to determine the reattachment point of the separated streamline at various angles of attack. Ventilation tests were then conducted with the modified two-term foil. Air was admitted from a slot in the suction surface of the foil and the angles of attack necessary to achieve a ventilated cavity were determined. Cavity pressures were measured by means of flush-mounted pressure transducers.

TEST EQUIPMENT

Foils

The two foils studied were a 10-deg wedge and a modified Tulin two-term section.[3] Cross-section drawings of these foils are shown in Figure 1. The Tulin section is typical of one that would be used for propellers. Both foils had a 10-in chord and a 7.625-in span. The curved foil was calculated from Equations (3), (5), and (7) of Reference 3 with $C_L = 0.408$ and $\alpha = 3.25$ deg. The lower surface of the wedge and the nose tail line of the curved foil are the reference lines.

For part of the tests, the curved foil was modified to provide air passages at 0.6 in from the leading edge (6-percent chord). Several pressure gages were also mounted on the upper surface. The foil with these modifications is shown in Figure 2.

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[1] McCullough, G. B. and D. C. Gault, "Examples of Three Representative Types of Airfoil Section Stall at Low Speed," NACA Technical Note 2502 (Sep 1951).

[2] Barr, R. A., "Ventilation Inception," Hydronautics Technical Report 127-4 (Mar 1963).

[3] Tachmindji, A. J. et al., "The Design and Performance of Supercavitating Propellers," David Taylor Model Basin Report C-807 (Feb 1957).

Pressure Transducers

The pressure transducers used were 1/4-in-diameter, flush-mounted diaphragm type. The sensitive elements are semiconductor strain gages mounted in a four-arm bridge. These gages were developed at the Naval Ship Research and Development Center (NSRDC) for measuring cavitation pressures and incorporate a special nonelastic bonding for mounting them to the diaphragm. In addition, the chamber behind the diaphragm is evacuated to very low pressures. These gages will measure 0–50 psia within ±0.1 psi or about ±2 ft of water.

FACILITIES

The NSRDC 9- x 12-in blowdown water tunnel was used for the flow visualization work. Water is supplied from a 6-ft-diameter tank with a maximum head of 12 ft. For short periods of observations, the flow is assumed constant. Because of large blockage and tunnel wall effects, this facility was used only for observations and no pressure or air flow measurements were made.

The tests in which air was admitted and pressures measured were conducted in the NSRDC towing basin. The speed regulation on the towing carriage (±0.02 fps) allowed accurate speeds to be set and maintained. The foils were mounted between end plates at a depth of 2 ft (Figure 3). Surface effects should be negligible at this depth (2.4 chords). The test rig allowed angle of attack to be adjusted from −4 to +24 deg and was suspended under the towing carriage.

RESULTS AND DISCUSSION

FLOW VISUALIZATION

Several dye injection techniques were tried during the water-tunnel flow visualization studies. Other techniques such as hydrogen bubbles were not used since it was felt that the buoyancy of the bubbles would distort the downward parth of the streamline. Figure 4 shows the emission of dye from a single tube at the leading edge of the curved foil. Note that a separated region formed at 10 and 14 deg. However, dispersion of the dye made this technique cumbersome and inaccurate. Finally, after several dye injection techniques had been tried, tufts were attached to the upper surface of the foil and wedge with tape. The tufts were placed perpendicular to the flow (Figures 5 and 6; the foil leading edge is on the left and the flow is from left to right). The separated region is roughly defined as that in which the tufts point forward and indicate reversed flow. Tufts that point toward the trailing edge indicate attached flow. Since the tufts at the side of the foil were in the same general direction as the center tufts, the indication is that three-dimensional effects were relatively small.

Figure 7 shows the location of the reattachment of the separated streamline as a function of angle of attack. The data are for Reynolds numbers 1.0 to 3.0×10^5. The slope of the tunnel curve increased slightly with Reynolds number but was not included since wall effects were larger. The tunnel data show that reattachment occurred right at the leading edge at an angle of attack of 7 deg and moved progressively aft as the angle increased. However, there was considerable scatter in the data. A line $x/c = 0.065 (\alpha - 7)$ approximates the data; here x/c is the nondimensional chord length and α is angle in degrees. Results of tests with tufts performed in the basin are included in Figure 7 for purposes of comparison. The differences are attributed to wall effects in the small 9 x 12-in tunnel.

VENTILATED TESTS ON CAMBERED FOIL

In the towing basin investigation, air was injected into the flow through a slot at 6 percent of the chord. The angle of attack was varied from 0 to 20 deg and the air pressure from 0 (nonventilated) to 30 psig. The leading edge of the foil was submerged 2 ft (2.4 chords). One would expect from Figure 7 that ventilation, as defined in this report, would not be achieved at an angle of attack less than 15 deg when air was admitted at $x/c = 0.06$. In fact, ventilation was achieved at a 14-deg angle of attack but could not be achieved at a 12-deg angle. With relatively thick cavities, ventilation was achieved at angles greater than 14 deg.

A fairly thick stable cavity would be expected at 20 deg. However, air bubbles indicate the presence of fluid near the rear of the foil and above its surface (Figures 8 and 9).* In other words, the lower outline of the cavity was partially above the surface of the foil. Figure 10 illustrates this type of cavity; it is still considered ventilation since the air continues to feed forward from the air slot to the leading edge. In contrast, Figure 11 shows air being admitted aft of the reattachment point and streaming back, so that ventilation is not achieved; for purposes of comparison, a photograph of ventilated flow is also shown in Figure 11. Because the buoyant force of the air exceeded the drag due to flow, there was a rise of the lower cavity boundary near the aft end of the cavity. Hence, the resultant velocity of the air in the cavity had large vertical components. Higher speeds would have kept the cavity lower boundary attached.

The above description of flow is of general interest; however, the significant fact to be remembered is that ventilation, as defined herein, could not be achieved at angles of attack lower than 14 deg. It was stated in the introduction that the purpose of this work was to develop methods of achieving ventilation before cavitation starts. From this point of view,

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*These photographs are blowups of high-speed movies[4] and hence are not of the best quality. The specks at the top of the pictures are reflections.

[4] Hecker, R. and G. L. Ober, "Techniques of Ventilation at Low Speeds of Hydrofoils with Sharp Leading Edges," short paper with movie presented at ASME Annual Meeting, New York (Nov 1966).

the investigation was not successful. The required 14-deg angle of attack is not reasonable for hydrofoils nor for propeller sections which normally operate at angles of attack to the flow of around 2 to 6 deg. For this reason, either (1) the separated region will have to be made longer at lower angles of attack by increasing the Reynolds number or (2) ventilation will have to be delayed until some leading edge cavitation occurs. Until more information is available, the latter method will be more reliable in achieving ventilation.

Concurrently with these latter tests, pressure transducers were mounted on the surface of the foil so that cavity pressures could be measured (Figure 12) when ventilation was achieved. The cavity pressures measured along the chord were approximately 35 ft of water which means that ventilation reduced the operating cavitation index from about 25.0 to 1.0. The pressures were relatively independent of gage location and angle of attack within the range of the tests.

Direct comparison with a similar study by Wetzel and Foerster[5] is not feasible because of dissimilarities in geometries, e.g., wedge angle, design C_L, aspect ratio, etc. It is of interest to note, however, that the slopes of the curves for bubble lengths versus angle of attack are essentially similar in the two studies. The results of air injection from tubes along the surface were reported to be unsatisfactory even though some of the air entered the separated region.[5] These results support the present NSRDC data which indicate that air must be introduced *into* the separated region in order to achieve ventilation.

CONCLUSIONS

This study has verified that if air is injected into a separated region where separation is from the leading edge, ventilation from the leading edge will occur.

At slow speeds, the buoyancy of the cavity may cause the trailing end of the cavity to rise off the foil. Nevertheless, information on the location of air passages is valid for higher speeds where buoyant forces are appreciably less than drag forces on the cavity. The pressures and air flow rates measured during these experiments are not necessarily valid at high speeds.

Angles of attack in the order of 12–14 deg are required to achieve ventilation at low Reynolds numbers. Since propellers normally operate in the 2- to 6-deg range, either higher Reynolds numbers which lengthen the separation bubble will be required or inception of ventilation should be attempted only after leading edge cavitation has occurred. Until more data are available, the latter procedure should be used.

The use of tufts at low speeds is a reasonable technique to help predict logical locations of ventilation air openings.

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[5] Wetzel, J. M. and K. K. Foerster, "Measurements of the Leading-Edge Separation Bubble for Sharp-Edged Hydrofoil Profiles," St. Anthony Falls Hydraulic Laboratory Project Report 83 (Jun 1966).

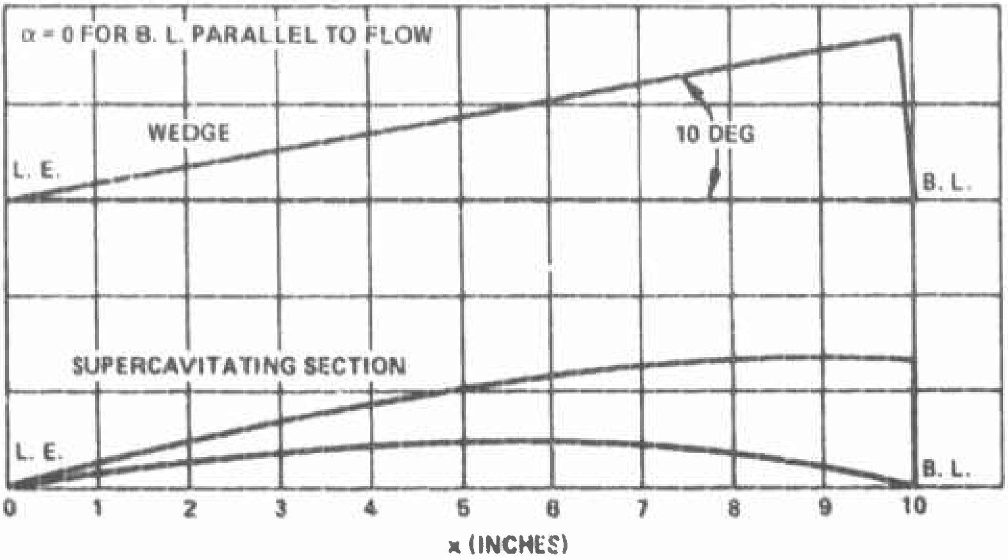


Figure 1 – Outline of Foil and Wedge Sections

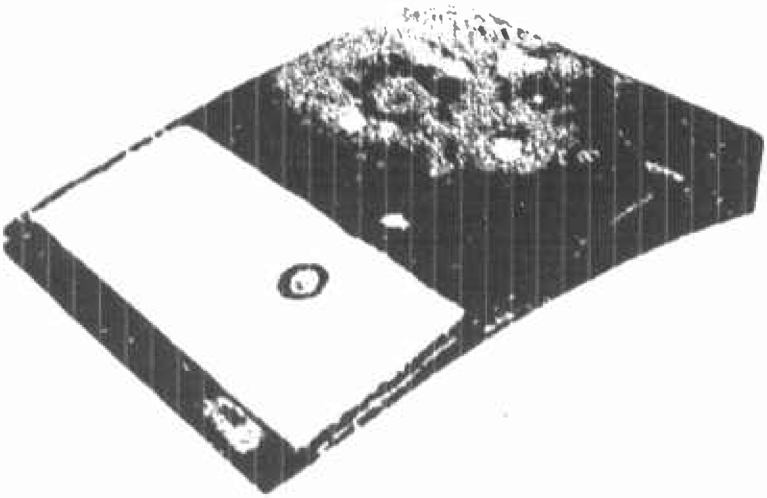


Figure 2 – Curved Foil for Towing Basin Experiments

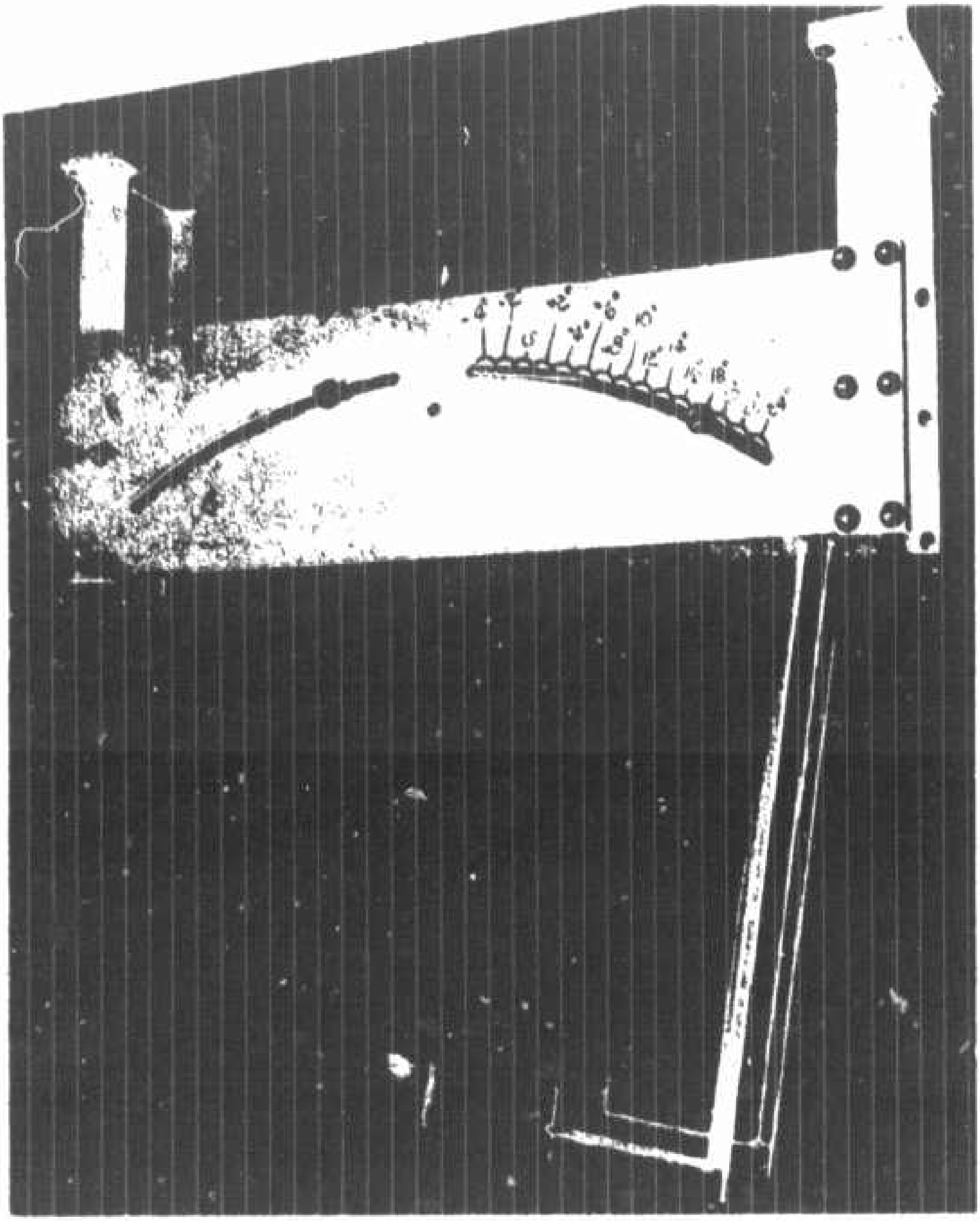


Figure 3 - Mounting of Curved Foil for Towing Basin Experiments

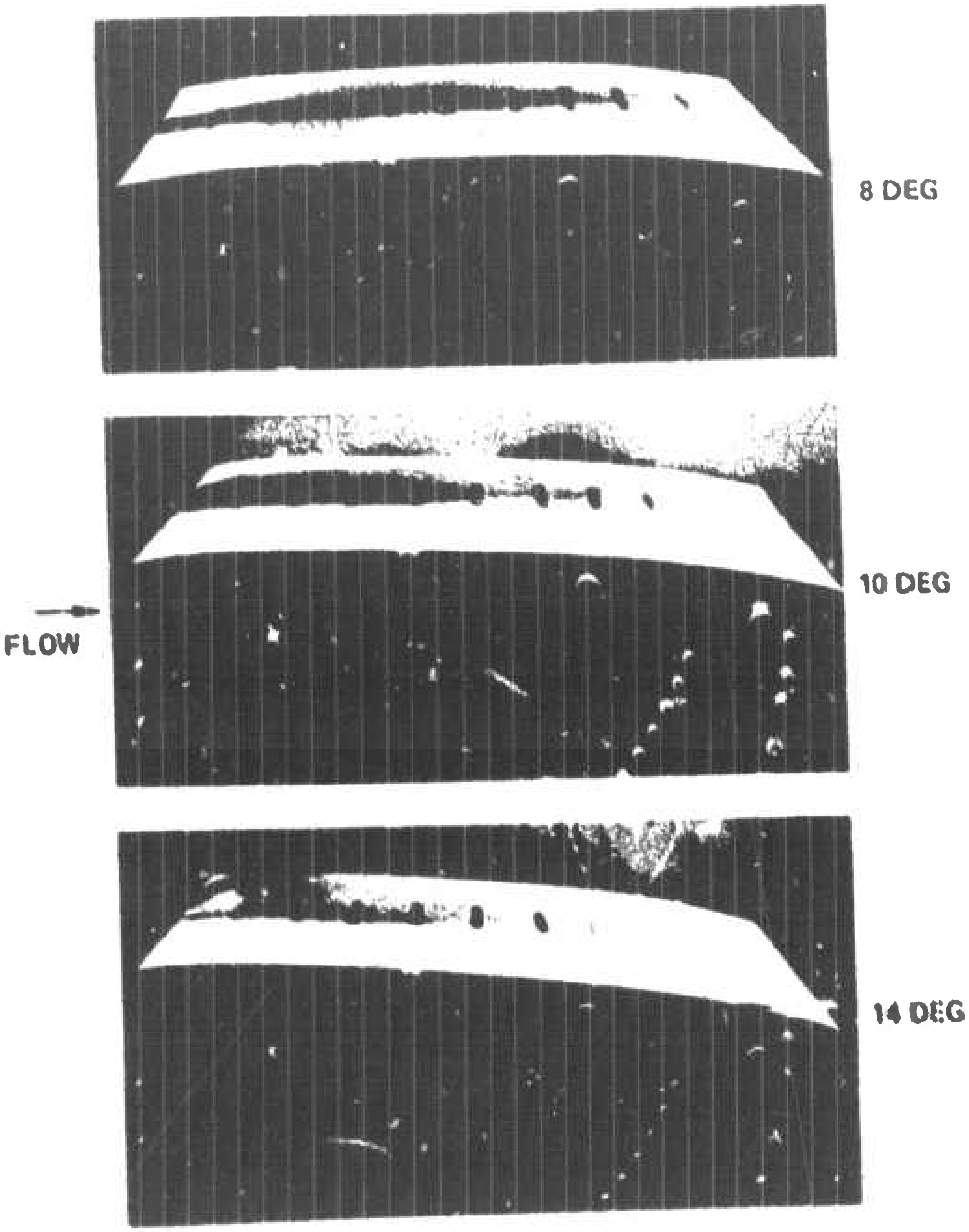


Figure 4 -- Curved Foil with Single Dye Tube at Leading Edge

Figure 5 -- Wedge with Tufts

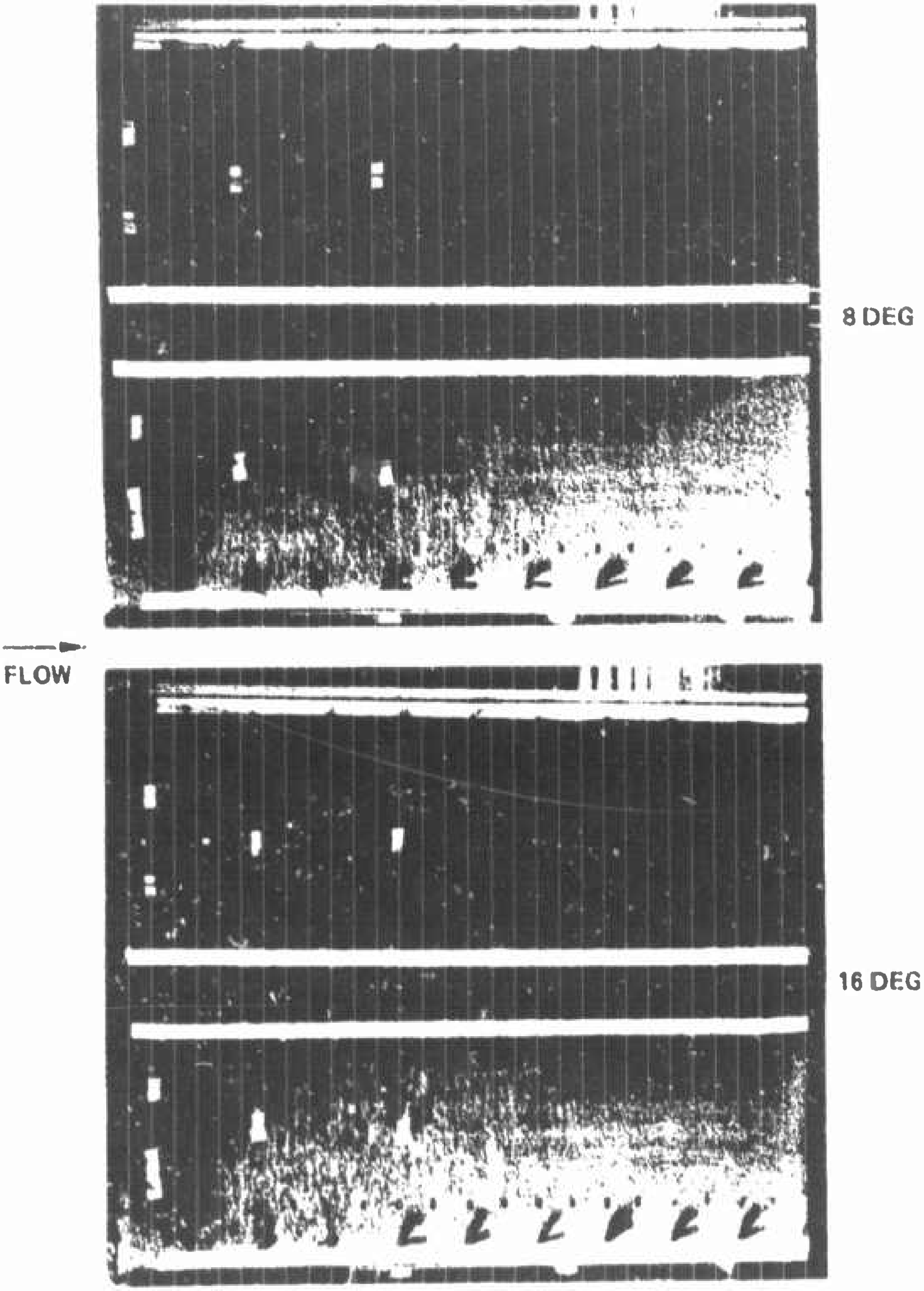


Figure 5 (Continued)

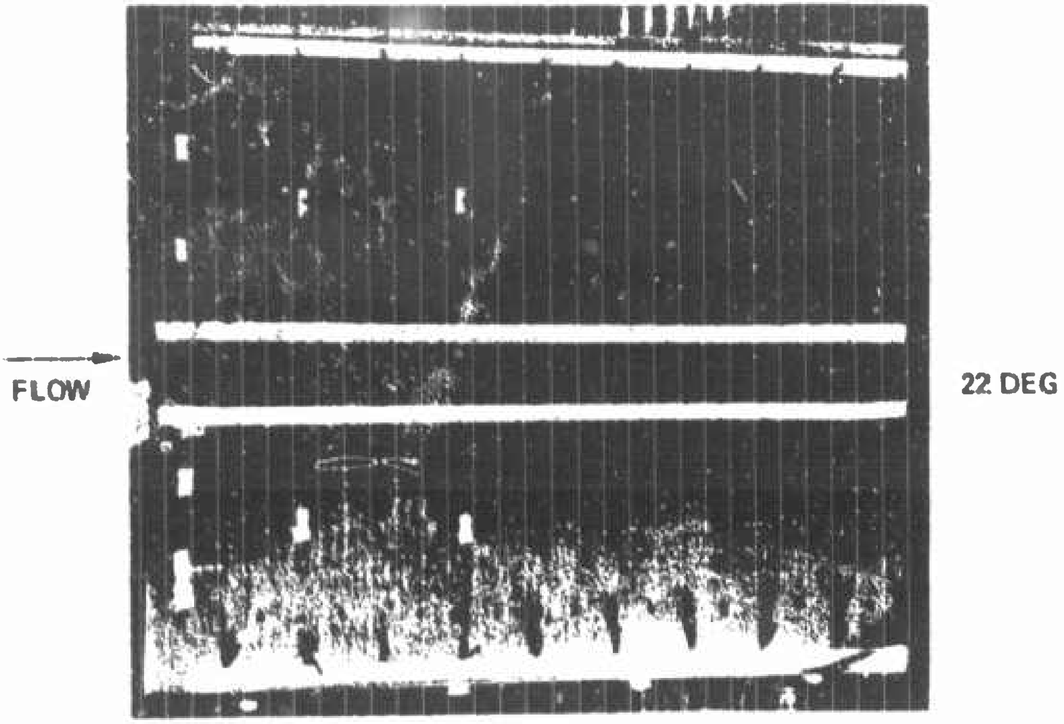


Figure 6 – Curved Foil with Tufts

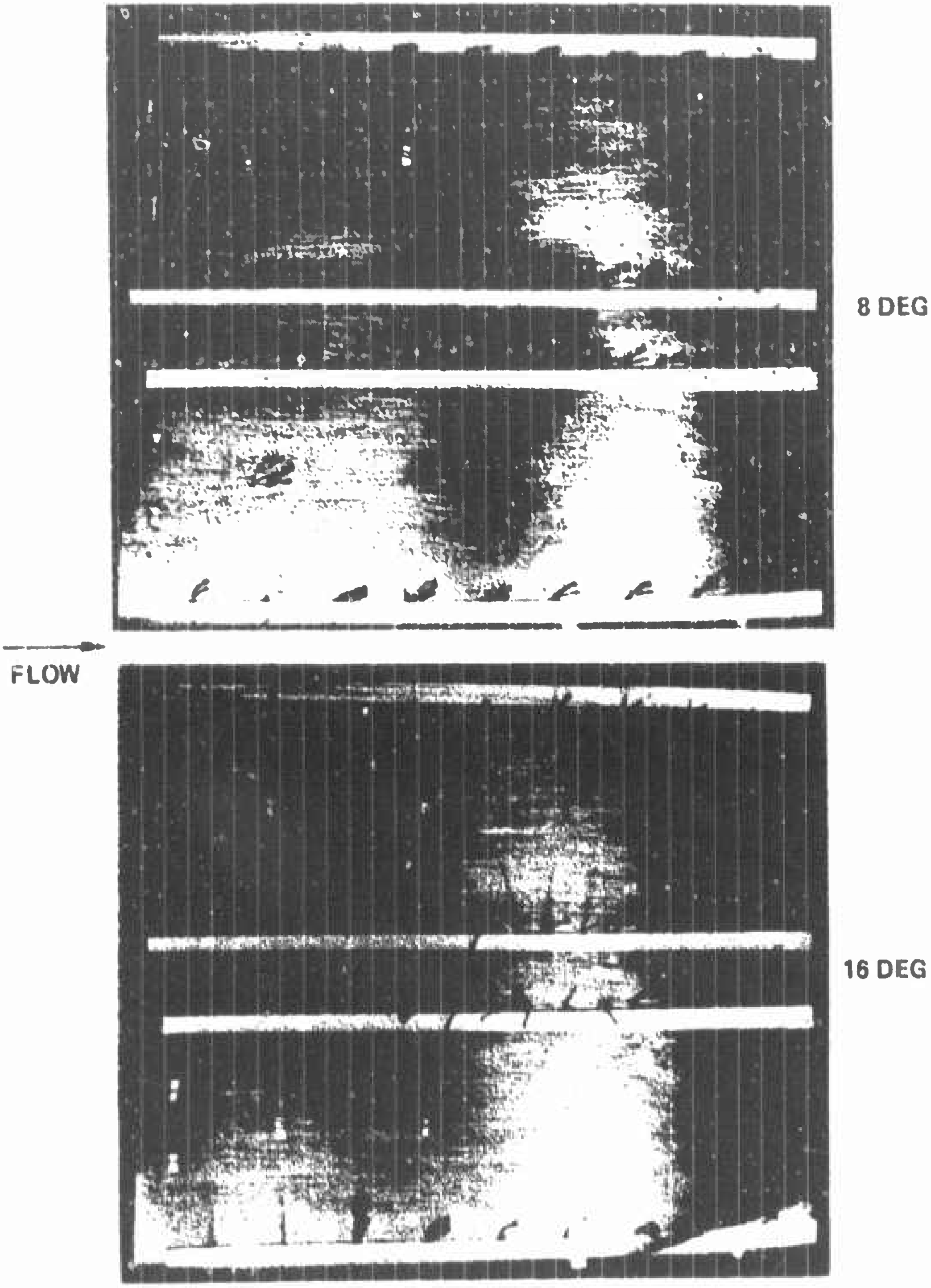
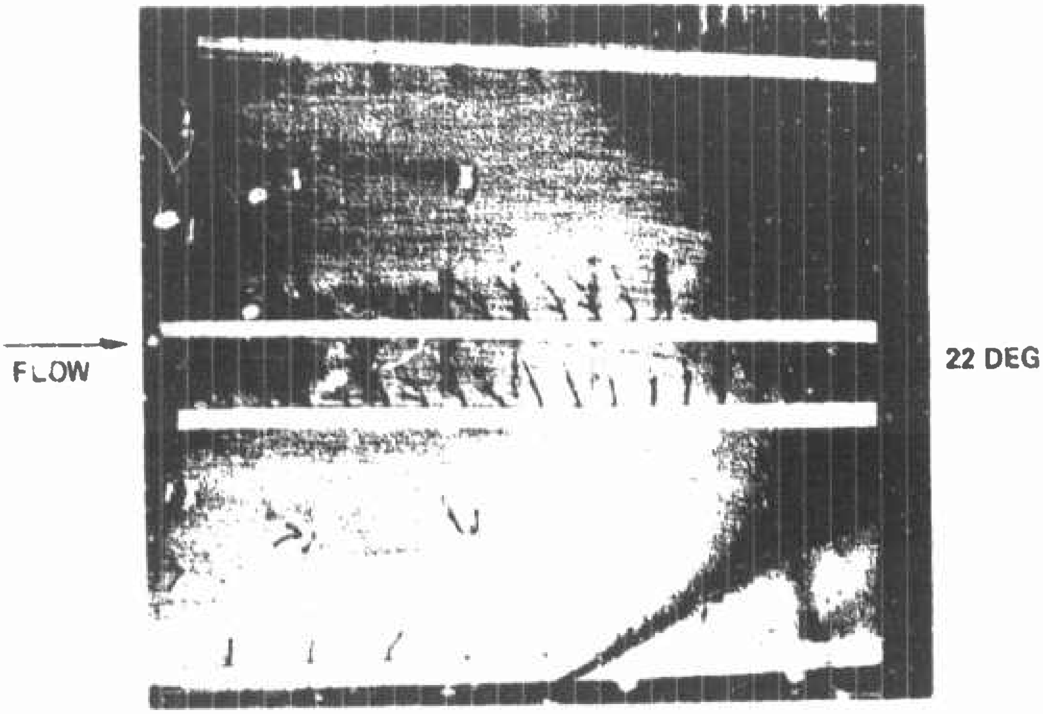


Figure 6 (Continued)



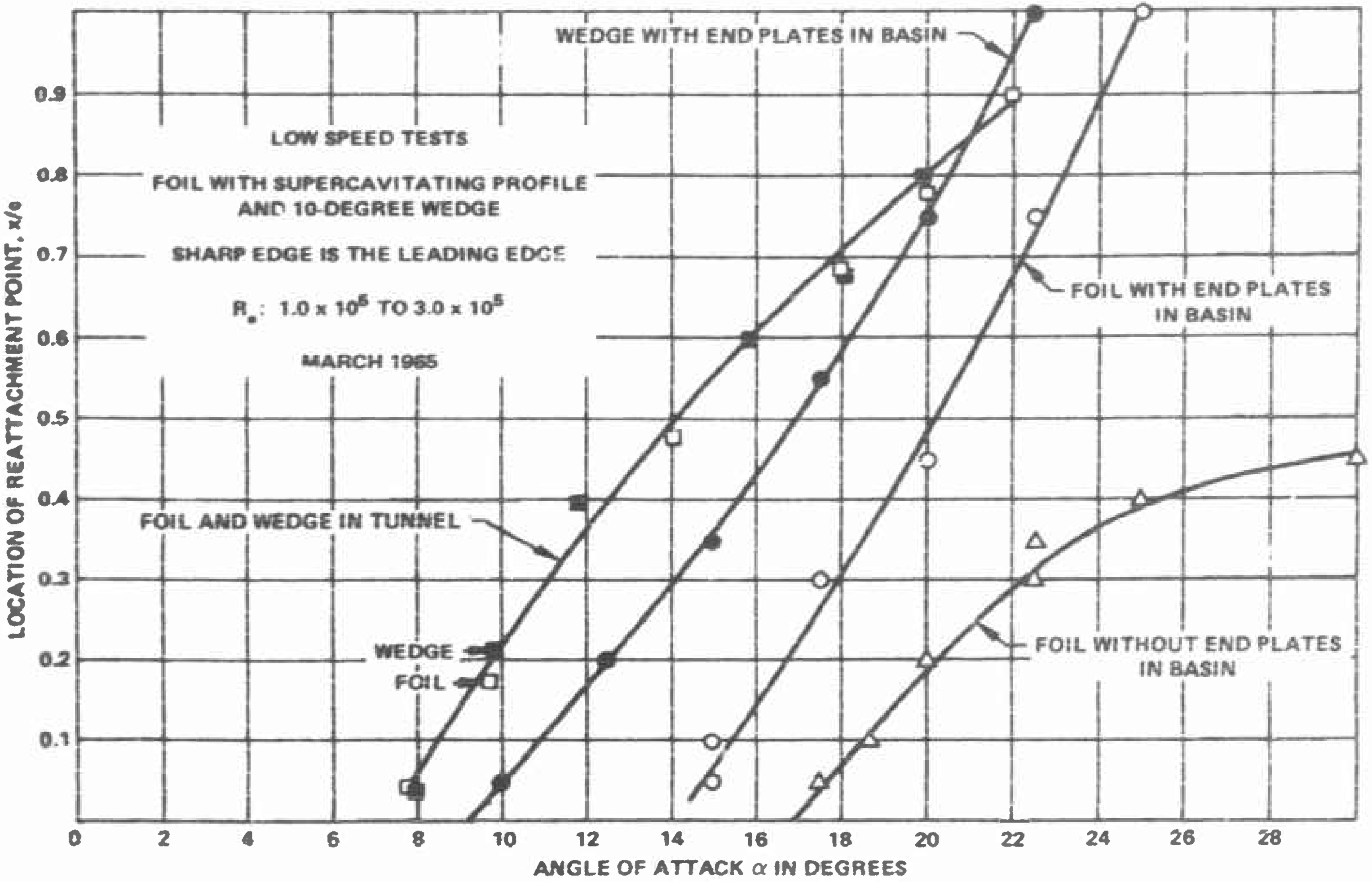


Figure 7 – Location of Reattachment Point

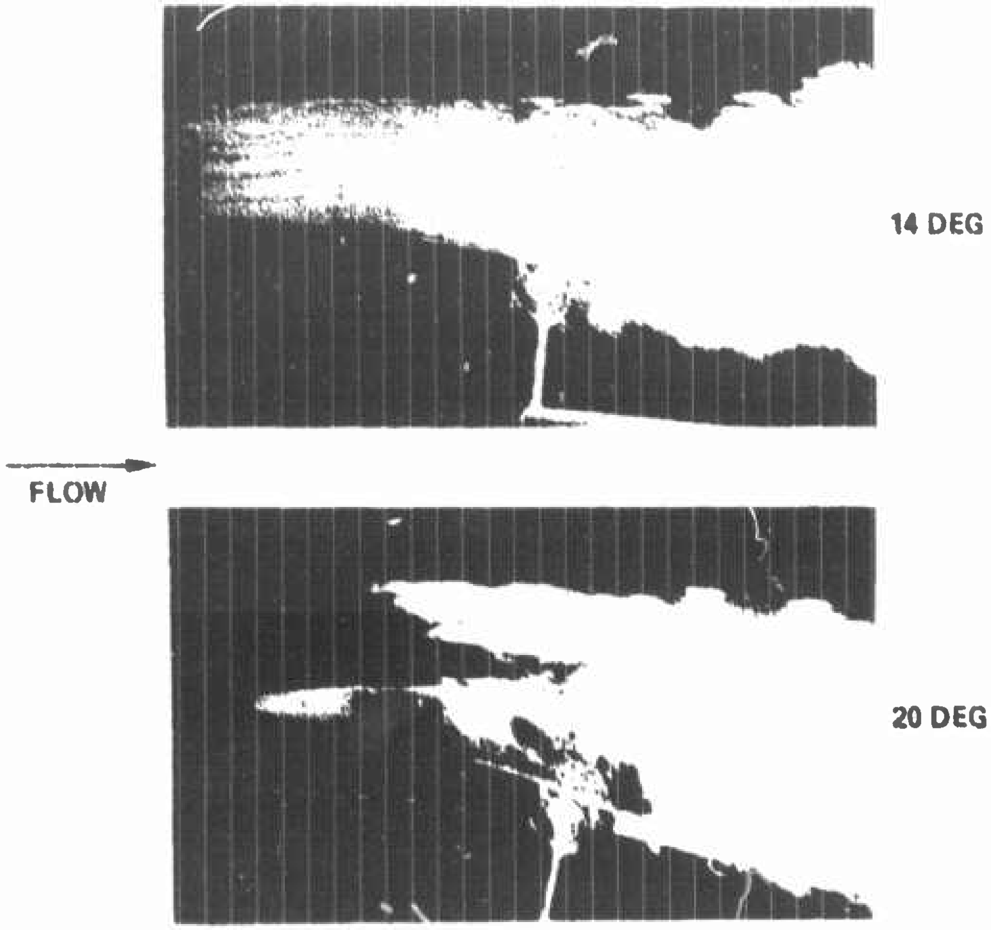


Figure 8 – Side View of Curved Foil in Towing Basin at 14 and 20 Degrees

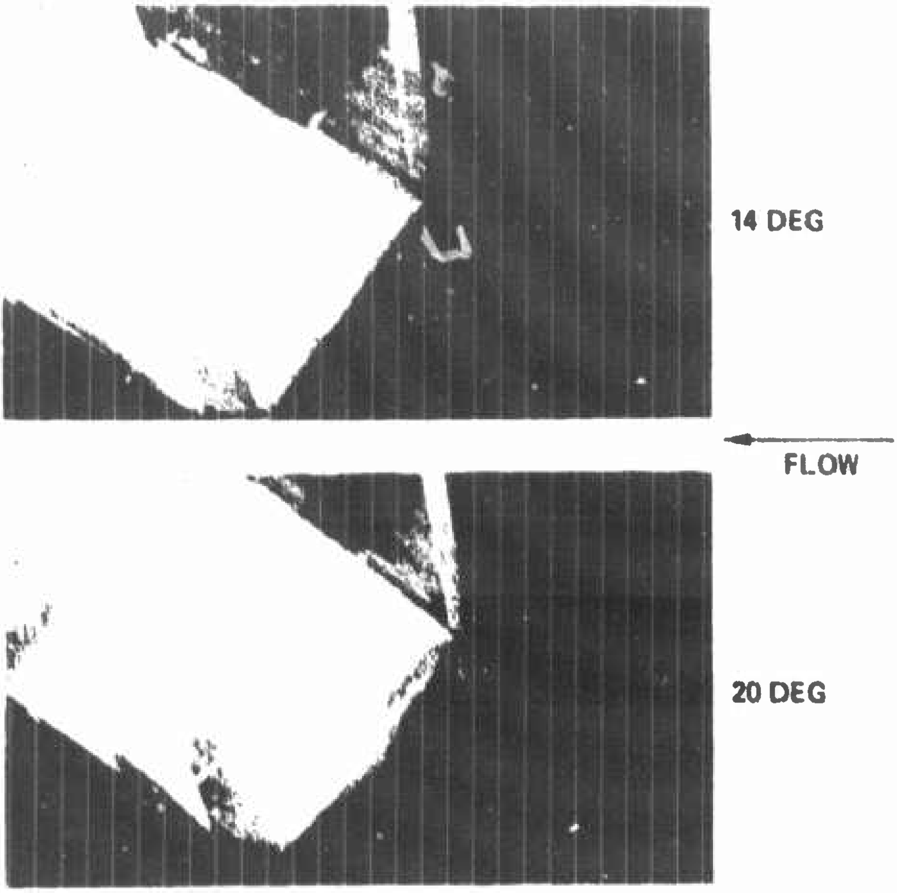


Figure 9 – Top View of Curved Foil in Towing Basin at 14 and 20 Degrees

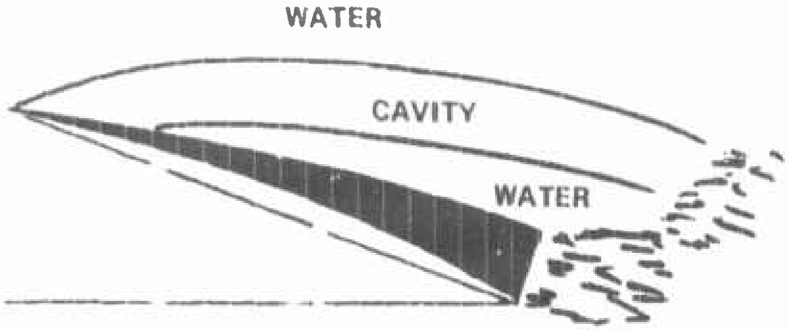


Figure 10 – Cavity as Affected by Buoyancy

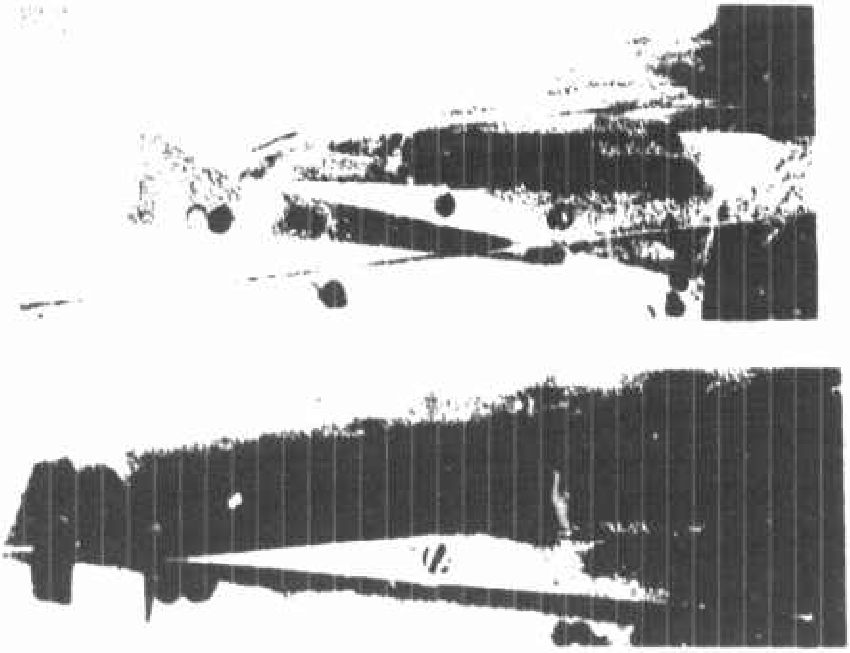


Figure 11 – Ventilated and Nonventilated Flow with Air

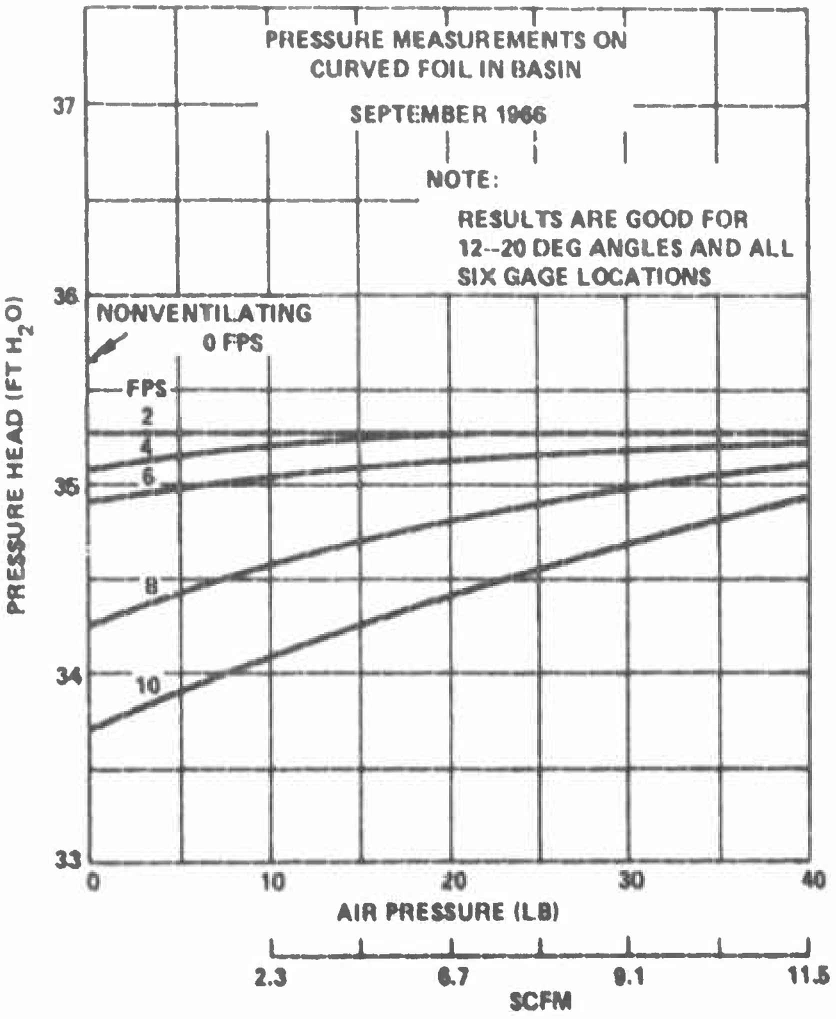


Figure 12 – Results of Pressure Measurements in Towing Basin