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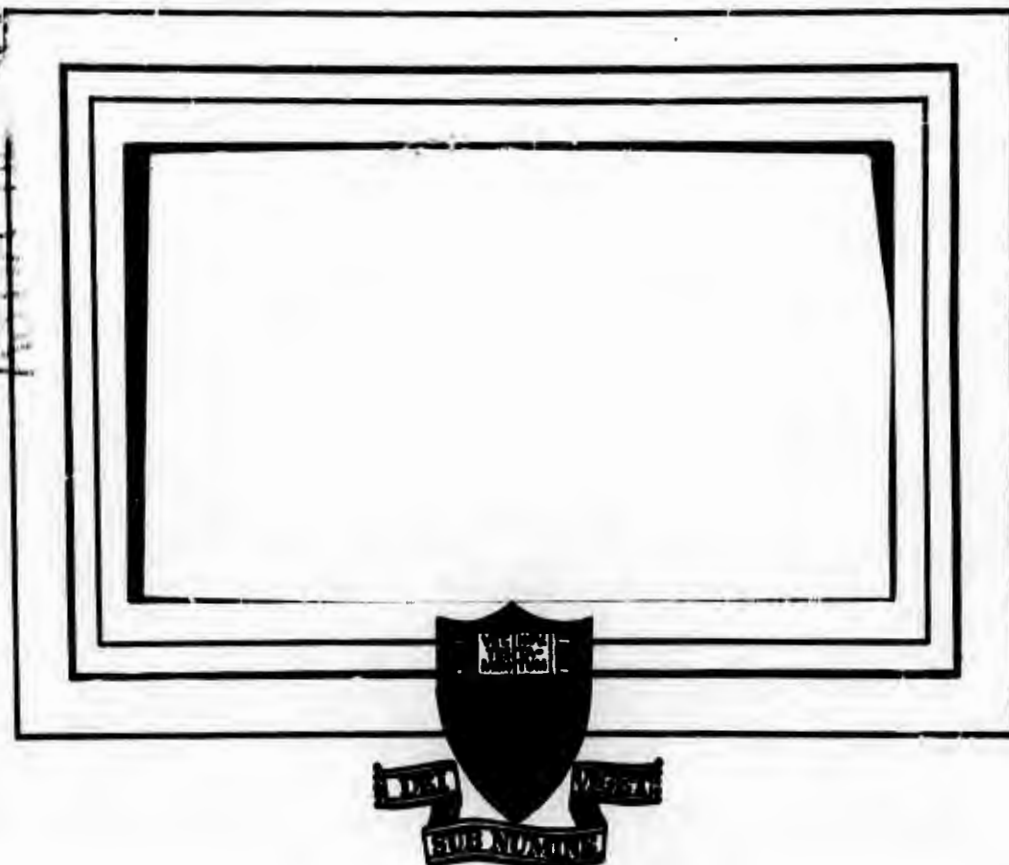
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PRINCETON UNIVERSITY

DEPARTMENT OF AERONAUTICAL ENGINEERING

**SMOKE FLOW STUDIES CONDUCTED AT
PRINCETON UNIVERSITY**

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Report No. 290

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Summary

A general discussion of the principles of subsonic flow visualization by means of smoke is given. Detailed descriptions of the construction and operation of the two two-dimensional and one three-dimensional smoke tunnels, in which this work was carried out, are presented as well as an outline of the photographic techniques employed.

The experimental results obtained are divided into three groups, corresponding to the studies made in each of the three tunnels. The 2" x 14" tunnel, the smallest of the three, has been used primarily for vortex stability studies. A series of studies of flat plates and circular cylinders, generating starting vortices and a Karman Street are shown. The effect of splitters extending up and down stream upon the vortex stability is explored as is the influence of shrouds or cowls behind the vortex generator. These tests were extended to examine the effects of various forms of boundary layer and circulation control. Finally, pictures of a suction stabilized vortex are presented.

The work in the 2" x 36" two-dimensional tunnel has been of a more applied nature, although some results obtained from high speed movies of the flow past various patterns of cylindrical obstacles are shown. Use is made of color photography to show the equivalence of a "free-stream" and a "splitter-stabilized stagnation point on a "lobster pot" profile, such as that studied by Cambridge University. Profiles equipped with various forms of boundary layer and circulation control systems are examined, and high speed motion picture studies of blowing jet structure and boundary layer transition are presented. The results obtained by utilizing the high speed photographic technique to study a profile oscillating in pitch are also given.

The pictures taken in the 12" x 16" three-dimensional tunnel are perhaps the most revealing of all. Three models are shown -- a rectangular wing, a swept wing, and a delta wing. Various combinations of flap and aileron deflection are examined. The effect of the strong spanwise sub-boundary layer flow, which occurs at low angles of attack, is explored. Various special photographic techniques are employed to examine the tip vortex, the three-dimensional flow field of the wake, and the boundary layer transition pattern. The three-dimensional effects of boundary layer control are also demonstrated.

The techniques developed in the three-dimensional smoke tunnel are extended to an examination of the wake below a hovering helicopter rotor.

A 16 mm motion picture film supplement of this work has been prepared and will be loaned by the Forrestal Research Center Library of Princeton University on request.

Introduction

Certain flow visualization techniques have become accepted commonplace methods of modern experimental aerodynamics. The greatest development of these visualization techniques has occurred in the very high speed regime, where Schlieren, interferometer and shadowgraph devices have become indispensable research tools yielding results and data obtainable in no other way. Paradoxically, for the subsonic regime, in which most other research techniques are far more easily applied than for the supersonic case, it has proven almost impossible to develop a successful air flow visualization method for anything other than certain limited types of flow.

Certain techniques of applying substances, such as lamp-black suspended in oil to an aerodynamic surface and examining the resulting patterns after the surface has been exposed to the wind stream, have proven useful in some cases, but the resulting patterns are frequently confusing and difficult to interpret. Sublimation techniques, which utilize the difference in mixing rates between turbulent and laminar flow to influence the evaporation rate of a surface coating, have been used with some success to examine transition regions, while tufts or small balanced vanes have been used to explore the extent of separated regions and recently, tuft grids placed downstream of the model have permitted investigation of wake patterns within wind tunnels.

These methods, with the exception of the tuft grid arrangement, share the common limitation of being restricted to surface flows and hence indicating little or nothing about the external flow field and its influence upon such surface conditions. In addition, the results of such techniques can not always be trusted; get the lamp black and oil mixture spread too thickly on a curved surface, and a Solomon would have difficulty separating flow effects from those of gravity and induced surface roughness; spread the material to be evaporated unevenly over the surface, and tailor-made transition patterns can be achieved; locate the tufts or vanes in a region of fairly deep boundary layer cross flow and the resulting tuft deflection is an unknown compromise between the boundary layer and free stream flow direction and even in the case of the tuft grid, the presence of the grid and its supporting structure is disturbing to the flow, and the use of this technique is somewhat tricky when wake flows in the neighborhood of the fuselage or the tail are to be studied.

But in spite of these limitations, these techniques are constantly resorted to both in wind tunnels and in free flight, because there is an ever increasing desire to visualize the flow, particularly since the advent of the serious consideration of flow control as a means of influencing the aerodynamic characteristics of a body by the use of flow singularities represented by suction or blowing slots.

It must be clearly realized that all such flow visualization techniques are a means to an end and not an end in themselves. The true appreciation of any aerodynamic phenomenon rests upon the ability of the

aerodynamicist to predict its characteristics with mathematical certainty, in other words, the ability to fit a satisfactory mathematical approximation to the physical reality. The mathematical treatment of any physical phenomenon must generally be an approximation, since the physical case is usually far too complicated to analyze exactly, but only when the physical model is fully understood can the mathematical treatment be intelligently applied.

In the foregoing, a discussion of smoke as a means of visualizing the flow has purposely been avoided, for although smoke is probably the oldest and most obvious subsonic flow visualization method, it is also one of the most difficult to accomplish correctly and one of the most confusing and frequently misleading when improperly employed.

It is, perhaps, unfortunate that investigators are unwilling to publish unsuccessful researches, for it is certain that the number of incorrect evaluations of smoke flow results is far greater than the number of correct interpretations. These incorrect evaluations can very simply be attributed to one cause, inadequate equipment. It is not easy to make airflow visible with smoke in a useful manner under any conditions, but the degree of difficulty increases extremely rapidly with increasing airflow velocity, hence most smoke investigations have been made in an extremely low Reynolds Number range where the flow patterns made visible have little, and in some cases, no relation to the patterns occurring around the same body at higher velocities. As a result, smoke tunnels have come to be considered as toys and instructional tools rather than research instruments.

It is the purpose of this paper to describe some of the work conducted in the smoke flow visualization tunnels located at the Forrestal Research Center of Princeton University, and by describing these tunnels, which were developed under the sponsorship of the Air Branch of the Office of Naval Research, and the techniques employed in obtaining and interpreting the data presented, to demonstrate how the smoke tunnel has advanced from its toy-like stage and has become a valuable research tool.

NOTATION AND ABBREVIATIONS

x	abscissa of physical plane
x_c	abscissa of point on the airfoil chord
y	ordinate of physical plane
H	wind tunnel height
z	vertical distance from origin to singularity
u	velocity component parallel to the X-axis
v	velocity component parallel to the Y-axis
u_∞	free stream velocity
Γ	circulation (positive clockwise)
z	complex variable
X_v	potential function for a vortex bounded by 2 parallel walls
X_d	potential function for a doublet bounded by 2 parallel walls
X_s	potential function for a source bounded by 2 parallel walls
X_∞	potential function for the parallel stream
μ	strength of doublet (source on left)
r	radius of effective cylinder created by doublet of strength μ
Q	volume flow (source positive)
α	angle of attack
L	two dimensional lift
ρ	density
l	length to mounting point from leading edge
C_l	two dimensional lift coefficient
C_d	two dimensional drag coefficient
$C_{m/4}$	three dimensional pitching moment coefficient about quarter chord
x	distance from leading edge to point of angle measurement

NOTATION AND ABBREVIATIONS (contd.)

- Θ angle between free streamline and X-axis
 C_q volume flow coefficient
 L chord length

2. Outline of the Development of the Smoke Flow Visualization

Techniques Employed in the Princeton University Tunnels.

2.1 Smoke Generation Techniques

Since the great majority of the investigators who have made significant contributions to the field of smoke flow visualization have done so indirectly and in many cases unintentionally, it is extremely difficult to present any truly comprehensive picture of the development of these techniques. A search of the literature will show that, although many smoke experiments have been performed, they have usually been conducted as an aid to some other research and generally are awarded only one or two lines in the final report.

It would seem that early investigators used practically anything to generate their smoke. Chemical smokes were tried fairly early, and to the present, although they are generally both corrosive and irritating, enjoy occasional use. Of these, the best smoke producer seems to be titanium-tetrachloride, which gives off a very dense white smoke, although its smoke generation suffers fluctuations depending upon the temperature and humidity of the surrounding atmosphere. The smoke produced contains hydrochloric acid and is extremely irritant to the eyes and throat and corrosive to a large number of materials.

Because of these unfortunate characteristics, many substitutes have been tried. One of the more colorful ones was the attempt to smolder rotted manure in a restricted atmosphere. This did in fact give a fairly dense smoke which overcame the disagreeable characteristics of the chemical smoker, but attacked the senses, particularly that of smell, in an objectionable manner. Other substances such as rotted wood, straw and tobacco (one MCA tunnel utilized cigars soaked in oil¹) were substituted for the manure with varying degrees of success. The major difficulty of all such smokes seems to be that they are distillation smokes composed of fine drops of tarry distillates which tend to create deposits within the generator and delivery tubes as well as on the model, that are detrimental to operation. F.H.M. Brown² of the University of Notre Dame, who has been one of the outstanding pioneers in the field of smoke flow visualization in America, reports that his tunnel equipped with a smoke generator utilizing straw, required about one hour of cleaning for each hour of operation as a result of these deposits.

The first really comprehensive study of a smoke generator designed especially for smoke flow investigations was reported by Preston and Spouting³ in 1933. In the course of an aerodynamic study, Preston had developed a method of bleeding smoke onto the surface of a model and obtaining a picture of the boundary layer flow at relatively high Reynolds Numbers.⁴ The smoke used in the original work had been generated from wood and had proven sufficiently unsatisfactory that a rather intensive study of smoke generators was undertaken. It was found that it was

essentially impossible to make large improvements in the wood smoke since any attempt to remove the tarry deposits reduced the density of the smoke. In fact, it was found that if all the tarry distillate was removed by passing the smoke through a water scrubber, nothing remained but a tarry liquid on the surface of the water.

As a result, attention was turned towards the development of a "solid" or "oil" smoke producer. Although a definite preference for a "solid" smoke, in order to avoid condensation troubles, was evidenced, it was found that "solid" smokes, such as magnesium oxide were very flocculent, i.e. the particles tended to form clumps, and so to eventually clog the tubes. Hence the final development was a generator that bailed kerosine (or most any other oil) and produced a dense white smoke of a quality comparable to that produced by titanium-tetrachloride.

This generator boils the oil and forces the resulting hot oil vapor through a small orifice where it is broken into small particles. It was found that the optimum scatter for ordinary incandescent light occurred when the oil particles were about a micron in diameter and hence an orifice size of $1/3$ mm that gave this result was settled upon. The resulting smoke is dense and white. When blown over the hand, it feels cool and dry, displaying very little tendency to condense. If reasonable precaution is taken in the design of the smoke delivery system, condensation problems can for all practical purposes be eliminated. Fig. 1 demonstrates this type of smoke generator which is standard on the Princeton tunnels.

Although the smoke produced by this generator overcomes most of the disagreeable characteristics of the chemical smokes, some care must be exercised in its use. It is neither corrosive nor toxic in the sense of the chemical smokes, but like most hydro-carbon vapors, can cause respiratory disorders by recondensing in the lungs. Fortunately heavy and repeated exposure is necessary to produce this deleterious result. In reasonable concentrations its odor is not the least objectionable and even in large doses can be tolerated. In the past three years of use at the University it has fortunately been impossible to produce an explosive fuel air ratio in the tunnels even though the flows have been exposed to sparking electric motors and open flames. This, however, does not mean that such a danger does not exist and must be guarded against.

2.2 Smoke Tunnel Design

Smoke generation is only one of the three major problems involved in smoke flow investigations. The others, wind tunnel turbulence level and proper lighting for photographic purposes, are in some ways even more elusive. Dr. A. M. Lippisch in his paper, Results from the Deutsche Forschungsanstalt für Segelflug Smoke Tunnel⁵ delivered before the Royal Aeronautical Society shortly before World War II, pointed out several of the most important aspects of these problems.

The first and most important feature of any smoke tunnel design is the maintenance of low free stream turbulence without which the smoke streams quickly diffuse. The sources of turbulence in a wind tunnel are many and varied. Wherever there is an abrupt change of velocity, density or temperature, a surface of discontinuity is created within the fluid and this is the origin of turbulence.

The scale of turbulence present in a wind tunnel depends a great deal upon the configuration of the tunnel. A large scale turbulence, i.e. large vortices with long period fluctuations, can be created by separation of the boundary layer from the wall, such as may occur in the adverse pressure gradients of diffusers or return passages of a closed return type tunnel, or could arise from disturbances in the flow outside of an open return type tunnel. Small scale turbulence generally arises from obstacles existing in the flow, such as turning-vanes, honey combs, or the fan and fan nucelle.

One of the most effective methods of reducing the turbulence of the flow passing through the test section is the use of a large contraction ratio. According to Dryden⁶ the intensity of turbulence U' varies as

$$\sqrt{\left(\frac{2C}{3}\right) + \left(\frac{1}{3C^2}\right)}$$

where C is the contraction ratio. Hence if U_t is the tunnel velocity, an increase in contraction ratio would result in a reduction of the ratio U'/U_t , the turbulence level of the tunnel.

High contraction ratios have the further advantage that they result in low settling chamber velocities allowing the extensive use of screens to further reduce the turbulence level at a much reduced expenditure of power.

The usefulness of such screens cannot be over emphasized. Schubaur⁷ has presented the expression

$$f = \frac{1}{(1+k)^n}$$

for the factor of reduction of turbulence (f), where k is the coefficient of pressure drop caused by the screen and n is the number of screens employed. These screens have the effect of reducing the approaching turbulence and, unless their Reynold's Number is very low, of introducing a much smaller scale turbulence. Hence the usefulness of such screens lies in the fact that this smaller scale turbulence changes very rapidly.

Since it is the aim of the smoke tunnel to produce conditions under which smoke filaments are maintained visible, i.e. without diffusion, for the greatest possible length at the highest possible velocities, certain design generalizations may be arrived at on the basis of the foregoing discussion.

1. Since it is easier to avoid turbulence than to reduce it once present, keep the initial turbulence low. This suggests the elimination of the closed return as does the fact that with a closed return tunnel the quantity of diffused smoke passing through the test section increases throughout the run, making photography difficult. It is further advisable to isolate all sources of mechanical vibration and noise since these may also be sources of turbulence. The use of wood as a construction material rather than metal is urged due to its superior damping characteristics.

It should be pointed out that Lippisch found that one of the greatest sources of disturbances to the smoke flow was the leakage of air into the tunnel in the form of small jets. Thus extreme caution must be exercised to maintain air tight conditions or a configuration selected that maintains the test section pressure higher than that of the surrounding atmosphere so that any leakage is directed outwards, as this exerts only a negligible effect upon the turbulence level of the flow.

2. Use as large a contraction ratio as possible. It is foolish to be tempted to construct a larger test section than the space available warrants at the sacrifice of the contraction ratio. Contraction ratios of the order of 20:1 are not unreasonable and even larger ratios are recommended if the space is available.

Extensive use of screens is also recommended. If these are placed in the settling chamber where the velocity is low, several layers of very fine mesh cloth can be used without undue power loss. Following the work of Dryden⁸, it is recommended that the fineness of the mesh be increased in each successive layer downstream. These screens should be placed about 200 times the mesh size of the upstream screen apart. A similar distance for the damping of the flow should be allowed behind the last screen and the start of the contraction cone.

If an open return configuration is used, a honey comb must be employed in the entrance bell. Experiments indicate that the effectiveness of such devices vary primarily as the aspect ratio based on opening size and depth. It is recommended that an aspect ratio of at least six be used, larger, if possible. It must also be pointed out that the effectiveness of such devices in breaking up the large scale vorticity is greatly enhanced by the addition of a fine mesh screen at the downstream end of the honey comb.

3. A large and frequently overlooked source of turbulence within the tunnel arises from the method of smoke injection employed. The most common and, in general, most satisfactory method of injecting the smoke into the free stream in the form of parallel streamlines is to employ a smoke injector stack and rake. The smoke injector stack is a large two-dimensional wing, generally extending from the roof to floor of the tunnel into whose hollow interior smoke is pumped from the generator. This smoke is allowed to settle within the stack as in the settling chamber of a wind tunnel and is then allowed to bleed through the injector rake which consists of a number of tubes (the number of tubes corresponding to the number of streamlines desired) extending from the trailing edge of the stack.

Lippisch found, and tests at Princeton have simply confirmed the fact, that the end of the smoke injector tubes should be located at the point of maximum pressure gradient within the contraction cone. At this point the disturbances due to the wake of the stack and rake are squeezed to a minimum and the smoke issuing from the tubes of the rake is squeezed down to the thread-like lines desired. It should also be pointed out that the smoke flow is sensitive to the angles of pitch and yaw of the individual injector tubes, and thus, if operation at high speeds is sought, arrangements for the adjustment of these angles for each individual injector tube should be provided.

It has been the experience at Princeton that the turbulence of the smoke lines is relatively insensitive to the smoke delivery pressure and the length of the tubes. At any given speed setting of the tunnel, moderately large variations in delivery pressure effect only the width and opaqueness of the lines, seemingly requiring a significant difference in the free stream and smoke jet emission velocities to cause flow breakdown. A tube length approximately equal to the injector-stack chord has been found satisfactory since it allows the stack wake to damp before reaching the ends of the tubes. It has been found advantageous to taper the outside ends of the injector tubes so that the wake set up at the blunt edges is minimized.

It must, of course, be realized that the flow within the injector tubes must be non-turbulent. This has never been much of a problem for the Princeton tunnels, but it does establish a limit on the inside injector tube diameter, for the flow within the smoke tube should be maintained below the critical Reynold's Number for the tube (approximately 2,000). This criterion can be easily expressed in terms of smoke flow quantity and tube diameter in the following manner. Continuity gives:

$$Q = AV$$

where Q = smoke quantity emitted per second per tube, A = the cross-sectional area of the tube and V = smoke velocity within

the tube. The above expression may be rewritten as:

$$Q = \frac{\pi d^2}{4} V$$

from which:

$$V = \frac{4Q}{\pi d^2}$$

which then substituted into the Reynold's Number expression yields the criterion

$$\frac{4Q}{\mu \pi d} < 2,000$$

2.3 Test Section Lighting Considerations

It seems strange that, since a smoke tunnel is only as good as what can be seen in it, the very important question of test section arrangement for the most advantageous lighting is generally overlooked, or considered only after the rest of the design has been frozen and it is too late to change. To give some idea of the magnitude of the lighting problem involved, one of the Princeton tunnels utilizes 1 1/2 horse power to operate the fan, but uses over 35 horse power to operate the lights.

The requirements for good test section lighting are easy to state, but rather difficult to obtain. Simply stated, these requirements are that the smoke streams must be lighted laterally with an intense and uniform light, arranged to give the highest possible contrast against a black background.

A highly successful arrangement employed by Lippisch and incorporated by him in one of the Princeton two-dimensional tunnels utilizes a test section having a glass front and back wall (the models being mounted on a bearing located within the back wall). The lights are located behind the back wall at the top and bottom of the test section and are oriented to shine through the test section towards the front wall. This arrangement reduces the amount of reflected light and allows the use of a "black box" background which consists of a structure about 3 feet deep located behind the test section and lined with black velveteen to give the greatest possible contrast.

Different types of lights are used, depending upon the test being conducted and the type of photography being employed. For visual tests and regular speed black and white motion picture photography or stills, General Electric RSP2 photo spots are adequate and allow tunnel runs of reasonable duration without danger of scorching the model or cracking the glass test section walls. If high speed motion picture photography (and successful pictures up to 6,000 frames/sec have been taken in the Princeton tunnels) or color techniques are to be employed, the lights are changed to General Electric 750 R pre-focused photo spots that give a much more intense light. These lights may be used for periods of several seconds only, because the intense heat generated tends to damage

the models and presents the danger of excessively straining the glass walls. For very high speed stills strobe lights of 100 watt second energy are employed. Only with these is it necessary to employ an external parabolic reflector designed to make the light converge on the central part of the field.

It should be noted that in the two-dimensional tunnels it is necessary to paint the models with a low reflective flat black paint since any reflected light tends to form a halo about the model. A water base paint is used for this purpose, partly because it seems about on a par with the best low reflective paints available and partly because, unlike oil-base paints, it does not blister under the action of the intense heat from the lights.

The lighting requirements for three-dimensional studies are very different from those of the two-dimensional tunnels. The three-dimensional test section is constructed with its top and one side wall of glass, the other two surfaces being of wood and painted with a glossy black enamel. The reason for this is simply that, unlike the two-dimensional tunnels that are always viewed and photographed from the same angle, the three-dimensional phenomena might best be viewed from any of a number of angles in either the vertical or lateral plane or even in some cases from directly down stream. Hence the lights cannot occupy any fixed position, but must be arranged on racks equipped with fittings for individual adjustment.

To give some idea of the variety of lighting arrangements possible, a number of the most common set-ups will be described.

When the model is viewed from the top, a battery of lights is set up to shine through the side of the test section. These are aimed to shine slightly upwards, leaving the tunnel floor in the dark as the black background. If the wake is of particular interest, lights may be arranged within the tunnel behind the test section, shining up the wake. Under these conditions a glossy black test section and model tend to reflect the light away with a minimum of glare and scatter. For this reason the black enamel is advantageous in the three-dimensional tunnel, whereas mat black gives the best result in the two-dimensional tunnels.

If the model is to be viewed from the side, a very similar technique is employed, except the main battery of lights are directed through the top of the test section, aimed slightly forward to have the back wall in darkness. One highly effective technique focuses the light through a slot so that only a plane of the smoke is illuminated. Such techniques make it possible to examine downwash patterns at any desired spanwise location.

This slit or plane of light technique is remarkably effective when the flow is viewed from downstream as it is possible to section the wake at any desired location. The major problem is the obtaining of sufficiently parallel rays of light of sufficient intensity. At Princeton,

it has been found that the General Electric 750 R pre-focused photo spots combined with a minor reflector system gives sufficiently good results, but Lippisch in his early experiments found he had to resort to a heliostat.

Lighting will probably always be a problem in smoke tunnel design. There never has been a case where a tunnel had too much light, but the line must be drawn somewhere so a compromise must be reached between complexity, cost, ease of operation, and the desired results. To some extent a lack of light can be compensated by over exposing photographic negatives and prints and by the use of special developers.

3. The Princeton University Smoke Tunnels

3.1 2" x 14" Smoke Tunnel

Having discussed the general criteria of smoke tunnel design, many of which were arrived at as a result of experience gained in the Princeton tunnels, a detailed description of these tunnels seems warranted.

The Aeronautical Engineering Laboratory located at the Forrestal Research Center, has been employed for a number of years on a flow control program sponsored by the Office of Naval Research. In the course of this work, wind tunnel data frequently yielded results that were confusing and difficult to interpret. The gross effects of a system could be ascertained from balance readings, but the flow mechanisms giving rise to these effects could only be guessed. Pressure distribution studies aided the guessing, but still left considerable doubt about many of the more radical flows. Thus, the need of some form of flow visualization became apparent.

It was found that Dr. A. M. Lippisch was located with the Collins Radio Corporation and was interested in the construction of a smoke tunnel. As a result of a number of discussions, an order was placed with him for a tunnel similar to the one described in his paper.⁵

As it was apparent that at least from six months to a year had to elapse between the placing of the order and the actual delivery of this tunnel, it seemed desirable to construct a small pilot tunnel, in which many of the flow problems could receive preliminary investigation and with which the personnel to be employed on the large tunnel could obtain experience with the problems of smoke flows.

This tunnel (described in detail Reference 9) can only in the very broadest sense be considered as a pilot model of the larger smoke tunnel. From rough sketches of Dr. Lippisch's Darmstadt tunnel, the general configuration was determined. (the configuration of the Collins Radio Tunnel was later changed, but this tunnel was maintained as originally planned). The configuration used, shown in Fig. 2, consists of

an entrance bell with a fan, followed by a diffuser, and a settling chamber in which is located eight layers of 16 mesh screen and the smoke injector stack, then the contraction cone with the smoke injector rake, the test section, the downstream diffuser, and finally a downstream fan. After leaving the downstream fan, the air is fed into a plenum chamber and exhausted in a high speed jet to the outside (a system designed to prevent disturbances from the outside air from disrupting the smoke flow)

The overall length of the tunnel is 13' 3"; the test section measures 24" in length, 14" in height and 2" in width. The tunnel, operating on two universal motors of approximately 1/3 HP, each driving two bladed propellers, will give a maximum test section velocity of 50 ft/sec. with the rear plenum chamber removed, although for the purpose of photography, all testing is done at speeds from 2 to 10 ft/sec. At higher speeds the smoke lines, due to increasing mechanical vibration, are rapidly diffused.

This tunnel is notable for the fact that, although it contains a large number of incorrect design features, it proved the value of such flow visualization techniques and answered many of the questions that the force and pressure distribution investigations had been unable to. It is informative to consider these faulty design features as they highlight many pertinent facts of smoke tunnel design.

Two major errors were the size, and the materials of construction chosen. With the size limitation of the test section models of a six inch chord were the largest that could reasonably be tested, thus even if the maximum speed of the tunnel could have been maintained, the resulting Reynold's Number, although over the critical range, would still have been very small. In practice, the Reynold's Number was generally well below the critical and the flow could be described only in its broadest outlines. Fortunately, for many problems this is sufficient. It is probable that, had the tunnel been constructed of wood instead of metal, much of the noise and mechanical vibration could have been damped and speeds allowing operation above the critical Reynold's Number range achieved.

The installation of the upstream fan represented another design misconception. It was felt that the pressure within the test section should be controlled since leakage was known to be a problem. This was correct as far as it went, but insufficient flow straightening and quieting space was provided, the battery of coarse mesh screens being quite inadequate for the task; thus at the higher speeds, the upstream fan proved quite destabilizing.

It should be mentioned that the design of the contraction cone does not seem to be overly critical, as long as the resulting velocity distribution at the entrance of the test section exhibits slightly higher

velocities at the walls than at the center. (Tests have shown it difficult to maintain stable smoke lines when the initial velocity distribution is even or peaks at the center.) Although the testing has by no means been exhaustive, a 45° sine curve contraction seems best, although good performance can be achieved with 60° contractions as well.

The final major error incorporated in the design of this little tunnel was in the test section and lighting arrangement. The test section has a solid back wall, painted flat black. This arrangement was chosen as it was felt desirable to be able to remove the entire back panel for use in the mounting of models. This has proven highly desirable, but, since the lights are forced by this configuration to be located in light boxes directing the light vertically through slits, it is virtually impossible to avoid lighting the back wall, thus reducing the contrast. This limits the photography in this tunnel to regular speed black and white movies and low speed stills.

In spite of all of the limitations on the performance of this tunnel, it has found wide usage as a tool for examining the mechanisms of basic flow phenomena, which over a large range are independent of Reynolds's Number. In addition, it is constantly in demand for thesis work and student instruction, thus giving some indication of the demand for flow visualization equipment.

3.2 2" x 36" Smoke Tunnel

Approximately 6 months after the completion of the 2" x 14" smoke tunnel, the larger tunnel designed and constructed by the Collins Radio Corporation under the direction of Dr. A. M. Lippisch, was delivered. This tunnel (described in detail in Reference 10) was much larger than the little one, measuring nearly 32' in length and having a test section 60" long, 36" high, and 2" wide.

The configuration of this tunnel shown in Fig. 3 is quite different than that of the so-called pilot tunnel in that the air enters through an upstream fan, is lead through a diffuser to a series of baffles consisting of fiberglass bats, which spreads the stream more or less evenly over the interior of a large silencing chamber. This silencing chamber is lined with acoustical tile, which has a strong damping effect upon the turbulence of the flow and incorporates as well several layers of fine mesh screen. From the silencing chamber the flow is lead through a bell mouth into a settling chamber in which it passes through several more layers of screen. From the settling chamber it passes through the contraction cone, past the smoke injector, through the test section, and to the outdoors by means of the downstream diffuser.

Most of the previous design errors have been eliminated from this tunnel. The material of construction is wood, the fan cooling blowers for the lights and model mount motors, the only direct sources of vibration, are isolated by flexible connections while the use of the acous-

tical tile in the silencing chamber does much to eliminate the effect of noise. It is doubtful if much more can be done to damp the turbulence within the tunnel except possibly the use of a contraction ratio considerably larger than the 19.5:1 ratio currently employed. The use of the "black box" type of photographic background with built-in light racks is highly satisfactory and ease of model mounting and handling is maintained by hinging the entire front face of the test section.

It is felt, however, that the upstream location of the fan is a mistake. It is true that, by pressurizing the flow, any leaks that occur are directed out of the tunnel and hence are not disturbing to the smoke lines, but the initial disturbance created by the fan becomes increasingly difficult to damp, until it is virtually impossible at tunnel speeds in excess of 65'/sec.

Another source of difficulty is the extreme narrowness of the test section. The two inch dimension was selected because of the difficulty of maintaining truly two-dimensional conditions with wider throats. The disadvantage arises from the strong effect of the boundary layer along the tunnel walls. This boundary layer grows in the normal manner, so that, depending upon tunnel velocity, at a point about 2/3 of the length of the test section from the upstream end, the entire cross section is filled. This has several results.

Because it creates a situation analogous to the "horizontal buoyancy" effect, there is a stabilizing pressure gradient in the free stream about the model resulting in an essential increase in the effective Reynold's Number. The effect is not so salubrious when suction or blowing systems are being tested for two reasons. First, the rate of suction or blowing-induced flow varies greatly between the free stream and the boundary layer, thereby invalidating most flow quantity measurements, and secondly, flow separations from the walls due to the large pressure gradients produced by some flow control systems tend to obscure the flow picture.

Although the above sounds as if the usefulness of the tunnel was pretty well limited, it has been found that experience based on comparisons of smoke tunnel and force tunnel results permits amazingly accurate evaluations of the smoke tunnel pictures. It has not proven desirable to incorporate a balance system in this tunnel, and, since pressure distribution studies are laborious and lengthy, the analysis of the results has been greatly aided by the development by M. P. Knowlton of the method of streamline analysis presented in Section 4.

The two biggest factors in this tunnel's superiority over the little pilot tunnel are its size and its speed range. Although for ease of operation, little streamline adjustment being necessary in the lower speed range, test velocities usually range between 30 ft/sec to 40 ft/sec, streamlines can be maintained, albeit with a great deal of individual adjustment of the pitch and yaw of the injector tubes, to a speed of 65 ft/sec. This, combined with the use of 16" to 24" chord models, permits test Reynold's Numbers up to 830,000, not large by any means, but large enough to overcome the most common criticisms of such smoke tunnels.

3.3 12" x 16" Smoke Tunnel

After visualizing flows in two dimensions, it is natural that consideration of three-dimensional visualization techniques would follow. This concept was certainly not new. Early reports from Gottingen dealt with visualization of the tip vortices; Lippisch showed pictures of three-dimensional effects obtained in his two-dimensional tunnel; Brown, in a truly three-dimensional tunnel, had investigated such problems as propeller flows; while Preston and Sweeting had developed techniques of examining boundary layers in three dimensions at high Reynold's Numbers by bleeding smoke from the leading edge of the surface being investigated. The possibilities of flow visualization techniques as an aid in approaching their complicated flow problems had long intrigued many of the people working in the helicopter field with the results that Meiger Drees¹¹ working with models and Frotherhood and Stewart¹² working with full scale machines had used smoke to examine certain conditions of flight.

So far as is currently known, Dr. Lippisch at the Collins Radio Co. was the first to utilize the technique of Preston and Sweeting in a tunnel especially designed for flow visualization. It is unfortunate that, although his resulting movies have been widely shown, he has not yet published anything of this technique.

The 12" x 16" tunnel is actually the pilot model of a much larger tunnel that will be built as soon as the visualization techniques are fully developed. As can be seen in Fig. 4, it consists of a combination entrance bell and settling chamber containing the honey comb and four layers of 120 mesh screen, a two-dimensional contraction cone contracting the flow in the horizontal plane in which is located the smoke injector stack and rake, a transition section and then a two-dimensional contraction cone contracting the flow in the vertical plane from which it enters the test section. After passing through the test section the air flows through a diffuser to the fan and is then exhausted to the atmosphere. In order to damp fluctuations from the fan it was found necessary to equip the diffuser with a pulsing chamber. This consists of simply a break air, the diffuser wall surrounded by a large air-tight box. By sliding the diffuser back and forth within the box, it is possible to "tune" the tunnel in much the same manner as a trombone, and smooth flow can readily be obtained.

The only unusual characteristic of this tunnel, besides the pulsing chamber, is the double contraction cone. This design was resorted to in order to allow the use of a smoke injection rake that could be moved from place to place. Since the injector tubes are sensitive to pitch and yaw, the use of two two-dimensional contractions eliminated the necessity of individual tube adjustments and permits the rake to be yawed as a whole. As a result of this arrangement, the rake can be moved laterally to give the smoke filament at any test section station desired in just a few seconds instead of the much longer period required for individual tube ad-

justment. The rake has been checked for satisfactory operation, but has as yet not undergone extensive tests, so that it is impossible at the present time to determine if a more favorable location exists.

The front and the top of the test section are of glass, the bottom and back of plywood. Models are generally mounted as reflection plane models from the back wall of the tunnel. Since each model is generally photographed from many positions and in many configurations, a portable scaffolding is moved over the test section, which acts as both a camera and light mount.

A number of different types of smoke delivery are employed, depending upon the nature of the test. Smoke can be supplied to the test section in single or multiple heavy streams, such as used by Brown, by injecting from tubes in the honey comb, in much finer streams by using the injector rake, or bled through holes directly on the model surface.

When the latter system is employed, considerable care must be exercised in the design and fabrication of the model. The model should be as nearly a hollow shell as possible to provide the maximum possible space for a smoke settling chamber. Except for special cases, such as bleeding smoke into the boundary layer at a desired location through a porous or perforated material, the smoke delivery holes should be located in a region of favorable pressure gradient to give streamlines as free as possible of disturbances. If the model is such that large variations of pressure exist between several of the various regions in which it is desired to inject smoke, the model should be compartmented and arrangements for individual adjustments of the delivery pressure made. It will also probably be necessary to vary the delivery pressure with each angle of attack change due to the changing pressure patterns.

4. Method of Determining Two-Dimensional Lift Coefficients from Smoke Flow Observations

The following method was developed by M. P. Knowlton¹³ working with results taken from the two-dimensional tunnels and has proven of considerable use in the evaluation of two-dimensional flow pictures. The method allows the lift of a wing section in the two-dimensional tunnel to be approximately determined by the measurement of the streamline angle at a prescribed distance ahead of the model.

Since the necessity of preventing leakage about the sides of the model requires that the model be mounted tightly between the tunnel walls, and the requirement of unobstructed view of the flow field eliminates the possibility of end plates, no practical force balances arrangement for use within the two-dimensional tunnels has yet been developed. The problem of obtaining numerical results is further complicated by the fact that, because of the convenience of not having to make extensive smoke line adjustments, tests are frequently run at speeds of about 30 ft/sec to 40 ft/sec. At such low speeds the conventional method of wind tunnel wall pressure integration to obtain lift coefficients is unsatisfactory. Actually at such low speeds any force or pressure measurement is

difficult due to the small quantities involved. For this reason the study to find some relationship between streamline position and lift coefficient was initiated.

At first a relationship between the stagnation streamline position and the lift coefficient was sought, but this approach was abandoned when it became evident that, unless the model chord was very small compared with the wind tunnel height, the computations became impractically complicated. Another complication arose from the physical problem of having to adjust the rake so that the stagnating streamline was visible in each photograph, since its position could not be sufficiently accurately determined in any other manner.

A more promising approach sought the relationship between the vertical streamline displacement at some point forward of the wing section being studied and the lift being produced by this section. Although the streamline displacement is less than would be predicted by theory, due to the fact that the streamlines are injected by the rake at a finite distance upstream instead of at infinity, this method seemed feasible since a correction can be made by making measurements at two widely separated points upstream and using the difference. This suggested the use of the streamline slope as the determining parameter.

Theoretical and experimental studies of the method were made and it was found that for normal configurations (the cases employing flow singularities are still under study) the lift coefficient is directly proportional to the tangent of the streamline angle about a half chord ahead of the wing section. The factor of proportionality is a function of the distance ahead of the wing and the ratio of the chord to tunnel height. Experimentally it was found easier to obtain the tangents to the desired degree of accuracy than to measure the streamline displacement.

In order to determine the relationship between the angular streamline displacement a given distance ahead of the wing section, it is instructive to examine the potential flow about a vortex, a doublet, and a source placed in a uniform flow in a two-dimensional wind tunnel of height "h". Fig. 5 shows the conventions selected.

It is assumed that the origin is located at the tunnel centerline and that the vortex, doublet, and source are located at $x=0$ and $y=d$. In addition, the tunnel walls impose the condition that image vortices, doublets, and sources be considered in an infinite series.

The expressions for the potential functions, including the images formed by the tunnel walls, are found to be:

For a vortex:

$$\chi_v = \frac{i\Gamma}{2\pi} \ln \left[\frac{\tan \frac{\pi d}{2h} \left(1 + \tanh \frac{\pi z}{2h} \right) + i \tanh \frac{\pi z}{2h} \left(1 - \tan \frac{\pi d}{2h} \right)}{1 + \tanh^2 \frac{\pi z}{2h} + \tan^2 \frac{\pi d}{2h}} \right] \quad (1)$$

For a doublet:
$$\chi_d = \frac{\mu}{2h} \left[\frac{\cosh \frac{\pi z}{h} \sinh \frac{\pi \bar{z}}{h} + i \cosh \frac{\pi \bar{z}}{h} \sin \frac{\pi d}{h}}{\sinh^2 \frac{\pi z}{h} + \sin^2 \frac{\pi d}{h}} \right] \quad (2)$$

For a source:
$$\chi_s = \frac{Q}{2\pi} \left\{ \ln \left[1 + \frac{1}{2} \left(\sinh \frac{\pi z}{h} + i \sinh \frac{\pi \bar{z}}{h} \right) \right] + \sum_{n=1}^{\infty} \ln(n^4) \right\} \quad (3)$$

For the parallel stream:
$$\chi_f = \omega_0 z \quad (4)$$

This velocity distribution is obtained by differentiating the potential functions with respect to z .

For the vortex, this operation yields:

$$\frac{d\chi_v}{dz} = u_v - i v_v = -\frac{\Gamma}{2h} \left[\frac{\cos \frac{\pi d}{h}}{i \sinh \frac{\pi z}{h} + \sin \frac{\pi d}{h}} \right] \quad (5)$$

When $z = x$, this becomes:

$$u_v - i v_v = \frac{\Gamma}{2h} \left[\frac{i \sinh \frac{\pi x}{h} \cos \frac{\pi d}{h} - \frac{1}{2} \sin \frac{2\pi d}{h}}{\sinh^2 \frac{\pi x}{h} + \sin^2 \frac{\pi d}{h}} \right] \quad (6)$$

Now if equation 6 reduces to

$$\left| \sin \frac{\pi d}{h} \right| \ll \left| \sinh \frac{\pi x}{h} \right| \quad (7)$$

$$u_v - i v_v \approx \frac{\Gamma}{2h} \left[\frac{1}{\sinh \frac{\pi x}{h}} - \frac{\sin \left(\frac{2\pi d}{h} \right)}{2 \sinh^2 \frac{\pi x}{h}} \right]$$

If a profile with its lift distributed along the chord and its leading edge situated at the origin is now considered, its lift may be expressed as:

$$dL = C_l \frac{\rho}{2} \omega_0^2 c f\left(\frac{x}{c}\right) d\left(\frac{x}{c}\right) = \Gamma \cdot \rho \cdot \omega_0 \cdot f\left(\frac{x}{c}\right) \cdot d\left(\frac{x}{c}\right) \quad (8)$$

where

$$\int_0^1 f\left(\frac{x}{c}\right) d\left(\frac{x}{c}\right) = 1$$

so that $\Gamma \cdot f\left(\frac{x}{c}\right) \cdot d\left(\frac{x}{c}\right)$ equals the vorticity over an infinitesimal length of chord dx .

Thus when $\left| \sin \frac{\pi d}{h} \right| \ll \left| \sinh \frac{\pi(x+k)}{h} \right|$, at the point

$-x = x_1 + K$, where k equals the distance ahead of the leading edge, the

expression for the velocity distribution becomes

$$u_v - i v_v \approx -C_l \omega_0 \frac{c}{4h} \cdot \frac{1}{\sinh \frac{\pi(x_1+K)}{h}} \left[i + \frac{\sin \frac{2\pi d}{h}}{2 \sinh \frac{\pi(x_1+K)}{h}} \right] f\left(\frac{x_1}{c}\right) d\left(\frac{x_1}{c}\right) \quad (9)$$

so that
$$\frac{v_r}{\omega_0} = +C_2 \cdot \frac{c}{4h} \int_0^1 \frac{f(\frac{x_1}{c}) d(\frac{x_1}{c})}{\sinh[\pi \cdot \frac{c}{h} (\frac{x_1}{c} + \frac{k}{c})]} \quad (10)$$

Now if $|\sinh \frac{\pi(x_1+k)}{h}| \ll 1$

$$\frac{u_r}{\omega_0} \approx -C_2 \cdot \frac{1}{4\pi} \int_0^1 \frac{d}{c} \cdot \frac{f(\frac{x_1}{c}) d(\frac{x_1}{c})}{(\frac{x_1}{c} + \frac{k}{c})^2} \quad (11)$$

Equation 11 may be rewritten by substituting the expression

$$\frac{d}{c} = \left(\frac{M}{c} - \frac{x_1}{c} \right) \tan \alpha$$

where M represents the location of the mounting point

$$\frac{u_r}{\omega_0} \approx -C_2 \frac{\tan \alpha}{4\pi} \int_0^1 \left(\frac{M}{c} - \frac{x_1}{c} \right) \frac{f(\frac{x_1}{c}) d(\frac{x_1}{c})}{(\frac{x_1}{c} + \frac{k}{c})^2} \quad (12)$$

If the strength of the doublet, $\mu = 2\pi a^2 \omega_0$, similar expressions for the doublet distributions are

$$\frac{u_d}{\omega_0} \approx -\left(\frac{a\pi}{h}\right)^2 \frac{1}{\sinh^2 \frac{\pi(x_1+k)}{h}} \approx -\left(\frac{a}{x_1+k}\right)^2 \quad (13)$$

$$\frac{v_d}{\omega_0} \approx -\left(\frac{a\pi}{h}\right)^2 \frac{2 \sin \frac{\pi d}{h}}{\sinh^3 \frac{\pi(x_1+k)}{h}} \approx -\left(\frac{a}{x_1+k}\right)^2 \cdot \frac{2d}{x_1+k} \quad (14)$$

If use is made of the definition of the flow coefficient $C_q = \frac{Q}{\omega_0 c}$ the expressions obtained from the source distribution are

$$\frac{u_s}{\omega_0} \approx -C_q \frac{c}{2\pi(x_1+k)} \quad (15)$$

$$\frac{v_s}{\omega_0} \approx -C_q \frac{cd}{2\pi(x_1+k)^2} \quad (16)$$

The parallel flow, of course, yields the result,

$$u_f + i v_f = \omega_0$$

$$\therefore \frac{u_f}{\omega_0} = 1 \quad (17)$$

$$\frac{v_f}{\omega_0} = 0 \quad (18)$$

The ratio of the total horizontal velocity at some point k units ahead of the leading edge to the velocity at infinity is given by the summation of equations 12, 13, 15 and 17.

$$\frac{u_+}{\omega_0} = \frac{u_f}{\omega_0} + \sum \frac{u_r}{\omega_0} + \sum \frac{u_d}{\omega_0} + \sum \frac{u_s}{\omega_0} \quad (19)$$

$$\cong 1 - C_L \frac{\tan \alpha}{4\pi} \int_0^1 \left(\frac{M}{c} - \frac{x_1}{c} \right) \frac{f\left(\frac{x_1}{c}\right) d\left(\frac{x_1}{c}\right)}{\left(\frac{x_1}{c} + \frac{k}{c}\right)^2}$$

$$- \sum \left(\frac{a}{x_1 + k} \right)^2 - \sum C_q \frac{c}{2\pi(x_1 + k)} \quad (19a)$$

The ratio of the total vertical velocity at the same point to the velocity at infinity is given by the summation of equations 10, 14, 16, and 18.

$$\frac{v_z}{\omega_0} = \frac{v_f}{\omega_0} + \sum \frac{v_v}{\omega_0} + \sum \frac{v_d}{\omega_0} + \sum \frac{v_s}{\omega_0} \quad (20)$$

$$\cong 0 + C_L \frac{c}{4h} \int_0^1 \frac{f\left(\frac{x_1}{c}\right) d\left(\frac{x_1}{c}\right)}{\sinh \left[\pi \frac{c}{h} \cdot \left(\frac{x_1}{c} + \frac{k}{c} \right) \right]}$$

$$- \sum \frac{2da^2}{(x_1 + k)^3} - \sum C_q \frac{cd}{2\pi(x_1 + k)^2} \quad (20a)$$

Knowlton has shown that the source and doublet terms are negligible if the point considered is of the order of a half chord length ahead of the leading edge. Further, the vortex term in the horizontal velocity term may be neglected since under normal conditions it will be very small compared with one. It must be noted, of course, that in extreme cases of very large angles of attack, strong forward blowing, very thick or oddly shaped wings, etc, some of these assumptions might require modification.

Thus normally

$$\frac{v_z}{u_\infty} (@-k) \cong C_L \cdot \frac{c}{4h} \int_0^1 \frac{f\left(\frac{x_1}{c}\right) \cdot d\left(\frac{x_1}{c}\right)}{\sinh \left[\pi \cdot \frac{c}{h} \cdot \left(\frac{x_1}{c} + \frac{k}{c} \right) \right]} \quad (21)$$

If the character of the pressure distribution is known, the integral may be evaluated. For normal wings, however, it may be assumed that the whole effect takes place at or near the quarter chord point. Thus:

$$\frac{v_z}{u_\infty} (@-k) \cong C_L \cdot \frac{c}{4h} \cdot \frac{1}{\sinh \left[\pi \cdot \frac{c}{h} \cdot \left(\frac{1}{4} + \frac{k}{c} \right) \right]} \quad (22)$$

$$= \tan \Theta @-k \quad (23)$$

where Θ = the angle " α " streamline makes with the horizontal.

Solving for C_L

$$C_L \cong \frac{4h}{c} \cdot \sinh \left[\pi \cdot \frac{c}{h} \cdot \left(\frac{1}{4} + \frac{k}{c} \right) \right] \cdot \tan \Theta \quad (24)$$

or

$$C_L = A \tan \Theta \quad (24a)$$

where
$$A = \frac{4h}{c} \cdot \sinh \left[\pi \cdot \frac{c}{h} \cdot \left(\frac{1}{4} + \frac{k}{c} \right) \right]$$

A is plotted versus k/c for various values of c/h in Fig. 6.

A comparison of the theoretical results and some experimental pressure distribution tests is shown in Fig. 7. It will be noted that both the theory and the experiment yield lift curve slopes that are very low. This effect has also been noted by Lippisch.⁵ A possible explanation of this tendency to act like a low aspect ratio wing may be found in the heavy shedding of vorticity within the wind tunnel wall boundary layer that can be seen when smoke is injected along the wing-wall intersection line. The effect can be calibrated for, however, and good agreement has been found to exist between results predicted from smoke tunnel studies and force tests conducted within the 4' x 5' tunnel.

5. Results from the 2" x 14" Smoke Tunnel.

5.1 General

It seems most advisable to confine a discussion of the photographic and lighting arrangements employed with the actual test results obtained. For this reason the next three sections will be devoted to a discussion of results obtained from each of the three tunnels.

Although, when it was originally constructed, this little tunnel was used for all types of investigations, its Reynold's Number restriction made the larger two-dimensional tunnel more attractive for configuration evaluation tests, and, since the construction of the larger tunnel, only investigations of basic aerodynamic phenomena have been initiated within this tunnel. For this reason only this type of test will be considered here.

The lighting arrangements are simple. Two large light boxes containing 12 75-watt incandescent reflector bulbs each, direct the light through slits in the top and bottom of the test section, furnishing sufficient illumination for 4" x 5" still pictures using Super XX film at F 4.7, 1/20 sec. 16 mm movies up to 32 frames per sec using Super XX film at F1.5 are also possible. No special developing techniques are employed. The possibilities of increased illumination are limited by the fact that the back test section wall scatters the light, reducing the contrast. The fact that the test section is constructed of plexiglass also limits the amount of heat that can be absorbed.

5.2 Flat Plate Studies

The sequences shown in Fig 8 demonstrate the technique by which the starting vortices behind a flat plate have been visualized. The test section was filled with smoke by blowing it into the tunnel through the injector rake with the fans turned off. When a fairly uniform mist was established throughout the test section, the tunnel was started very slowly.

The resulting starting vortices are clearly visible.

It is interesting to note that two sets of starting vortices can be observed. It is not possible when accelerating the tunnel from rest by hand operation of the controls to accelerate the tunnel at a steady rate. This fact, plus the use of only the downstream fan, probably contributes to this double starting vortex phenomenon, which seems to represent a necessary adjustment of the boundary conditions.

It can be seen that the first set of vortices is created by the initial motion of the air. This pair exerts an extremely strong effect upon the surrounding fluid, pulling air into their cores, and while moving slowly downstream increase in diameter. It will be noted that the downstream motion continues for a distance nearly equal to the width of the plate, at which point the vortices cease their translation and apparently dissolve by growing larger and revolving more and more slowly until nothing but a turbulent almost stationary mass of fluid remains. The tendency for this mass of fluid to drop toward the tunnel floor is due to the weight of the vapor.

Before the first pair of vortices is completely dissolved, the second pair begins to appear. They first become visible about a quarter of a plate length behind the plate, and are both more vigorous in their rotation and move in translation with a considerably higher speed than the initial pair, due undoubtedly to the increased tunnel velocity. Like the first pair, they move to a point about a plate width downstream where they halt, grow, and dissolve into an essentially dead air region. One should note that the lines of motion of the vortices' cores approach one another as the flow proceeds downstream due to their mutual attraction.

After the starting vortices have dissolved, the flow continues to leave the edges of the flat plate in a fairly smooth manner, leaving a large dead-air space downstream. Although the boundary of this dead-air space is turbulent, no further large scale vortices are formed until the speed is increased to such an extent that the downstream end of the dead-air region begins to form the familiar Karman Street. As the speed is still further increased, the frequency of the vortex street increases and the extent of the dead-air region decreases until it vanishes completely and a vigorous Karman Street is shed directly from the edges of the plate.

A number of other interesting phenomena have been observed in these tests. One of the most notable features of the flow is the profoundly destabilizing effect that the Karman Street has on the upstream region of the flow. This results from the motion of the forward stagnation point, which moves up and down with a frequency equal to the rate of change in circulation produced by the shedding of the trailing vortices. It is possible by making use of a Strobe-Lux to stop this motion and obtain a direct measure of the vortex frequency.

Another interesting feature of the Karman Street flow pattern is the hysteresis effect displayed at very low Reynold's Numbers. The Reynold's Number required to initiate the Karman Street behind a flat plate depends upon the turbulence present in the flow and the acceleration of the air flow within the tunnel. Under carefully controlled conditions utilizing very small accelerations, it has been possible to achieve stable flow without the vortex formation at velocities well above the speed at which the street normally forms. Once the wake forms, however, it is necessary to reduce to speed of the tunnel until a condition of very nearly zero velocity is obtained in order to return to the dead-air type of wake.

A number of studies of the effect of splitters on the flow about flat plates have been conducted. These surfaces, parallel to the direction of the free stream and perpendicular to the flat plate can have a very marked effect upon the characteristics of the flow field. Fig. 9 shows a typical example of a series of tests conducted with different splitter-plate width combinations with the splitter directed upstream.

These studies are not yet complete, so it is not feasible at this time to draw any significant conclusions, but as can be seen, under certain conditions of velocity, splitter and plate dimensions, a vortex can be created in the corner. The strength of the vortex seems to reach a maximum when the plate width is several times the splitter boundary layer depth. Increasing the size of the plate, while maintaining the splitter size constant eventually leads to the complete dissipation of the vortex and the creation of a stagnation region within the corner. Decreasing the size of the plate on the other hand leads to a condition where the flow lifts from the splitter and flows over the edge of the flat plate. Whether or not the vortex exists under these conditions is a matter of conjecture, since it is not possible to get smoke into the corner to visualize the conditions there.

The vigor of some of these vortices is surprising, for although they are apparently a direct result of a boundary layer separation along the splitter caused primarily by the adverse pressure gradient produced by the presence of the flat plate downstream, their speed of rotation is several orders of magnitude greater than that associated with a separation region such as might occur on a partially stalled profile.

5.3 Circular Cylinders

A series of tests with circular cylinders was conducted to compare the wake shed with that of the flat plate. It was found that, although there were slight differences in the Reynold's Numbers at which the Karman Street was established and vanished and that the dead-air region behind the cylinder persisted to much higher speeds, the wake several diameters downstream of the cylinder could not be distinguished from the wake an equal distance behind the flat plate. A typical example of these tests

is shown in Fig. 10.

In order to see if it would be possible to stabilize a vortex pair, such as some experimenters claim exist behind circular flame holders, behind a circular cylinder, by the simple mechanical process of varying the pressure gradient about the cylinder, a series of tests was conducted in which the cylinder was arranged in various positions with different types of cowls and baffles. A simple example is shown in Figs. 11 & 12.

In this case, a cylinder and two flat plates were used. With the exception of the extreme wake caused by separation from the flat plates, the resulting flow picture is typical of the results obtained. In no case was it possible to stabilize these vortices by such means. When the baffles were placed close to the cylinder, the vortex formation was completely eliminated. As the baffles were moved downstream, the dead-air region behind the cylinder increased until at its edges vortices began to appear. Moving the baffles further downstream permitted the wake to form in the normal manner. When the turbulent wake from the cylinder passed between the baffles, it was squeezed down and smoothed out in the same manner the contraction cone of a wind tunnel reduces the turbulence of the stream.

A series of tests was conducted to examine the effect of splitters directed both up and downstream on the flow field about the cylinder. Examples may be seen in Figs. 13 & 14.

When the splitter extended downstream from the cylinder, it was possible to quite effectively suppress the Karman Street formation for a considerable distance, although it did appear again at a point downstream, but with a reduced intensity. The tests were not extensive enough to determine the optimum length for such a splitter, but it was established that the wake extending perhaps four diameters downstream from the cylinder was relatively insensitive to splitter length, the wake using a splitter two diameters in length being essentially the same as for a splitter of only one diameter. Only when the splitter was reduced to less than a diameter in length did the Karman Street formation initiate appreciably nearer to the cylinder.

Extending the splitters upstream resulted in a flow very similar to that existing around the flat plate and splitter combination as can be seen in Fig. 14. Again the examination was not extensive, only one cylinder and three splitters being investigated, but it was found that the strength of the vortices formed was a function of the length of the splitter. Long splitters gave rise to early separation, with the result it was frequently possible to observe more than one vortex within the so-called corner flow.

One interesting fact that was ascertained was that the vortex formation occurred immediately the air in the tunnel was placed in motion. At the very low speeds, when it was possible to collect a consid-

erable quantity of smoke within the test section; the fact that these vortices were in fact three-dimensional was clearly evident since it was possible to see the vortex filaments extending along the walls and downstream. Although these filaments disappeared at the higher speeds due to the rapid dissipation of the smoke, since there is essentially no change in the structure of the portion of the vortex that remains visible, it seems safe to assume that what is visible in these tests is actually the bound vortex of a horseshoe vortex system, the trailing filaments continuing along the walls within the boundary layer.

Since no discussion of the flow about cylinders would be complete without an investigation of the Magnus effect, a series of studies was made of a rotating cylinder. The sequence of photographs shown in Fig. 15 demonstrates the essential characteristics of the test. It was not possible to get as clear a definition of the downstream flow as desired, for although the flow on the downstream surface of the rotating cylinder was attached, the pressure gradients produced by the diffusion of the free stream in this region caused separation on the wind tunnel walls, distorting the flow picture. The free stream velocity was maintained at 10 ft/sec for these pictures and the speed of rotation increased up to 3,000 rpm, although for all rotational velocities above 1200 rpm, the wall effects were so severe that the flow became very unsteady.

5.4 The Effects of Boundary Layer Control

In order to obtain some idea of the difficulties encountered in the application of boundary layer control to aerodynamic shapes, a series of studies was made of a cylinder equipped with both suction and blowing systems.

Fig. 16 shows a sequence of photographs of the cylinder equipped with the suction slot. The first tests were conducted with the suction slot at the location of the downstream stagnation point in potential flow. As suction was turned on and gradually increased, the flow underwent a series of radical changes. First, the majority of the suction quantity was drawn from the dead-air region directly behind the cylinder, but a slight increase in suction caused the stable boundaries of this region to break down and to begin to oscillate in a manner analogous to the normal Karman Street, but with a higher frequency. Increasing suction caused the amplitude of the disturbance to increase and its frequency to decrease. When sufficient suction, the exact quantity was not measured but it was very large, was applied, it was possible to cause a stagnation point to fasten to one of the tips of the slot. Whether it was the upper or lower lip depended upon the small disturbances within the flow, but under no conditions was a free stream stagnation point observed.

Moving the slot to the upper half of the cylinder resulted in the creation of a positive lift; moving it to the lower half created a down force. As long as the suction slot was located more than $\pm 15^\circ$

away from the downstream stagnation point, the wake instability was not noted at any value of suction.

After investigating the effect of a finite slot, the entire 180° downstream portion of the cylinder was equipped with a porous surface and tested at various quantities of suction. In this case again, the violent flow disturbances were observed as shown by Fig. 17, but when the suction was increased to a very large value, it was possible to stabilize the flow, and it is probable that, had it not been for the destabilizing effect produced by the wall separations, a free stream stagnation point could have been observed.

This same experiment was repeated, but this time with a splitter flap extending downstream. In this case the initial application of suction again produced the disturbances previously noted in the unflapped case, until sufficient suction caused the flow to adhere to the entire downstream portion of the cylinder at which point a stagnation point stabilized on the splitter and the wake flow became smooth and steady.

The next series of experiments examined the effects of a flowing jet on the flow about the cylinder. Fig. 18 demonstrates the results. As the flowing jet is applied, the wake contracts as the outer flow is drawn into the region of high velocity, and the flow adheres more and more closely to the cylinder, although in no case was it possible to cause the flow to fully attach to the downstream side. Revolving the cylinder to move the jet seems to produce little lift other than the momentum effect, for the flow almost immediately separates from the cylinder as the jet moves away. It is interesting to note that even though separation occurs on the cylinder, the jet seems to exert a strong stabilizing effect upon the wake in many cases of injection angles and velocities being able to completely suppress the Karman Street.

One interesting effect observed during these tests was the creation of a fairly strong vortex within the separated region ahead of the jet when the cylinder was turned so that the jet angle was about 75° from the horizontal. Fig. 19 shows a close-up of this effect. Although the boundary conditions are different, this separation vortex appears to be substantially the same as those appearing in the splitter tests. The vortex persists, growing smaller in diameter as the jet is strengthened, until the low pressure region of the jet becomes sufficiently powerful to eliminate the separation region.

5.5 The Suction Stabilized Vortex

In the course of an experimental program investigating the nature of the vortex formation, a series of experiments was conducted with several different configurations of suction stabilized vortices. One of the more interesting of these is shown in Fig. 20.

The shape tested in this case was that of a very thick profile. (roughly 30%), in which two large circular cavities with their axes per-

pendicular to the chord were located. On one end of these cavities, small holes through which small quantities of suction could be applied were located.

When this profile was tested without suction being applied, separation occurred at the rear lip of the forward cavity and moved forward rapidly with increasing angle of attack. When suction was applied, however, a flow very similar to that existing within a Hilsch tube was created. The free stream air flowed into the cavity with the velocity of the local stream and rotated much like a ball bearing while developing a small axial velocity along the circular cavity away from the suction orifice. Upon reaching the end of the cavity, the flow tightened, decreased in diameter and increased in rotational velocity and flowed within the center of the original flow towards the suction orifice on the opposite wall.

With two such cavities within the profile, it was possible to keep the flow unseparated up to and even exceeding angles of attack of 90° . The high flow quantities and suction powers involved make such angles impractical, but these profiles are currently being used on a program to investigate the magnitude of the mass flow required to maintain vortex motion.

6. Results from the 2" x 36" Smoke Tunnel

6.1 General

The work conducted in this tunnel has been of a more applied nature than that in the little tunnel, although its increased Reynold's Number capabilities have been utilized to study such basic flows as those about various arrangements of circular cylinders and similar objects.

The lighting arrangements within this tunnel are quite flexible. The test section is equipped with two light racks at the top and bottom of the test section providing space for a total of 36 lights. When full field high speed movies are to be taken 36 General Electric 750 R pre-focused spots are used. Regular speed movies and most stills are taken while using 20 General Electric RSP2 photo-spots. Close ups of restricted field photographs employ the number and variety of lights necessary to give the required light intensity. A single Mighty Light Deluxe Model speedlight rated at 60 watt-seconds and 1/1000th second flash duration is also available for taking high speed stills of restricted field phenomena.

The photographic equipment employed is as varied as the lighting arrangements. For quick comparisons during the initial phases of a program, a Land-Polaroid camera is used. Most stills are taken with a 4" x 5" Speed Graphic, but some color work has been done with a 35 mm Contax. All of the high speed movies have been taken with a 16 mm Wollensak Fastax camera. Regular speed (16 frames/sec) and slow motion movies (64 frames/sec) are taken with a Bolex H-16 camera.

The processing for all the black and white stills and movies is standard except for the high speed movies in which the film is highly overdeveloped. 35 mm photograph, 4 x 5 stills, and 16 mm regular speed movies using Kodak Super XX film are given standard development in Microdol or DK 60. The high speed movies using Kodak Super XX and Tri X negative film are developed for 16 to 20 minutes in straight Dekloll. Even with this severe overdevelopment the film is quite satisfactory, i.e. not excessively grainy.

6.2 Arrangements of Circular Cylinders

The series of photographs shown in Fig. 21 was taken from a series of investigations made to determine the character of the wake behind various configurations of two-dimensional bodies. The bodies shown here are three two-inch circular cylinders. The first configuration shows them arranged in a line perpendicular to the flow, spaced so that they touch. As can be seen, even though there is slight leakage between the cylinders, the effect is that of a flat plate with a strong Karman Street being shed. When the spacing is changed to one diameter between cylinders, the character of the wake is totally changed due to the presence of the jets of air passing between them. A large dead-air space appears behind the center cylinder as the jets of air are drawn to the outer flow. The violence of the wake of the outer cylinders is also greatly reduced.

The next arrangement placed the cylinders at the apices of an isosceles triangle with its base downstream. When the cylinders were touching, the resulting wake resembled that of a single four-inch diameter cylinder. Moving them apart a distance equal to the radius produced a flow about the upstream cylinder similar to that previously investigated for the cylinder with the downstream baffles. The formation of the Karman Street was delayed until a point about four diameters downstream. Increasing the spacing by another radius produced no major flow pattern change, but did increase the size of the airstream passing between the two downstream cylinders. It is interesting to note that this stream does not extend directly downstream but oscillates with a low frequency between being directed upwards and downwards.

6.3 "Lobster Pot" Profile Studies

The study of this profile was prompted by a report by Preston which indicated that working with such a profile (the title "Lobster Pot" is his) results were obtained which tended to indicate that a stable free stream stagnation point was an unlikely phenomenon. As tests at Princeton reported at the Fourth International Aeronautical Conference indicated that not only did it occur, but that it played an important part in the limitation of the lift obtainable from trailing edge suction, it was felt unwise to allow these seemingly contradictory results to go unexplored.

This profile, shown in Fig. 22, is a 25% thick profile designed to achieve laminar flow back to the 90% chord point. At this point the profile curves to a blunt trailing edge in the center of which is located a suction slot. In the Cambridge tests, the profile was equipped with a splitter type flap that could be withdrawn into the slot. In the Princeton tests this was simulated by extending grooved plexiglass walls beyond the profile trailing edge which could support splitters of any desired chord. In the photographs, these plexiglass walls show as the bright triangular regions aft of the profile trailing edge.

Fig. 23 demonstrates the results of these tests. It was found that, like the cylinder with the downstream suction, unless the splitter was present to stabilize the stagnation point, the application of suction produced violent instabilities, whose frequency decreased and whose amplitude increased with increasing suction. Above a certain suction quantity, the motion of the wake became extremely erratic, the stagnation point attaching to one or the other of the slot lips in a completely random manner, occasionally staying attached for very considerable period of time. A further increase of suction produced the formation of a free stream stagnation point, which, if not as stable as those observed behind more conventional profiles with sharp trailing edges, was vastly more stable than any of the other suction flows without the splitter.

The quantity of suction to achieve this result was extremely high, of the order of $C_q = .3$, and hence well above the range of practical interest. The quantity of suction required to produce a similar result with a trailing edge suction profile can be very much lower, depending upon the configuration of the slot, particularly the overhang of the lower lip.

In order to compare the flow fields occurring at this suction quantity with and without the splitter flap, use was made of a double exposure color technique. One of the flow conditions to be examined was first photographed through a green filter. The camera was then re-wound to the initial frame and the second condition photographed through a red filter. The resulting double exposures offer an excellent technique by which the character of the differences in the two flows can be examined. The instability of a flow pattern is also strikingly demonstrated.

As can be seen from Fig. 24, the regions where red and green streamlines cross appear on the film as yellow. Thus, when the circulation of one of the two cases is different from the other and has displaced the streamlines, yellow regions appear around the model. These regions are characteristically in the form of rings, the number of rings being within the accuracy permitted by the streamline spacing, a measure of the circulation produced. These characteristic rings form a very handy means of studying the flow stability, for since the streamlines generally cross with fairly acute angles, a small vertical motion of a streamline results in a large motion of the yellow patterns, thereby magnifying the effect.

6.4 Boundary Layer and Circulation Control Profiles

Fig. 25 shows the results of an investigation of a profile equipped with seven suction slots on its upper surface. The first sequence shows this profile, a NACA 23015, being taken from a low angle of attack up to the stall. As can be seen, the stall proceeds from the trailing edge in the manner customary for thick profiles. The second sequence shows the effect of applying suction.

The interior of this model is hollow and acts as a plenum chamber, thus the suction distribution is achieved by the slot location. Since this model was built primarily to demonstrate the effect of suction, little effort other than spacing the slots closer in the region of the leading edge was made to tailor the boundary layer growth. However, the angles of attack achieved demonstrate the effectiveness of such a system in delaying stall. It is interesting that with suction applied, the stall, although more violent than without control applied, still progresses from the trailing edge forward.

The multislot suction profile is a good example of a boundary layer control system; that is, a system designed either to maintain the flow attached and hence to achieve higher usable angles of attack, or to maintain the flow laminar and hence to reduce the drag. The profile shown in Fig. 26 is a good example of a circulation control system which differs from the boundary layer control approach in that it aims to produce a change in lift without a change in angle of attack.

The first sequence shows the profile with a droop nose and a deflected flap without blowing being applied. It will be noted that the stall proceeds forward from the trailing edge. Tests made without the nose droop showed that, in this configuration, the stall resulted from a growth of the separation bubble at the leading edge. The second sequence shows the effect of blowing. The circulation of the wing is greatly altered and, due to the very large local angle of attack, the stall in this case, even with the nose drooped, develops as a separation bubble from the leading edge. A direct comparison of the flow fields before and after the application of the flow control is shown in Fig. 27.

6.5 Blowing Jet and Boundary Layer Studies

The use of high speed movies has allowed a series of very illuminating studies of the structure of blowing jets and boundary layers to be made. Fig. 28 is an example of a free blowing jet. This picture was taken from a movie, at the rate of 3,000 frames a second, and very clearly shows the jet expansion rate, the region of turbulent mixing, and the character of the entrained streamlines. This experiment has been repeated for a series of jet nozzle configurations so that it has been possible to obtain the jet characteristics as a function of nozzle size, jet velocity, free stream velocity, and the angle of jet ejection measured with respect to the free stream.

Figure 29 is a photograph of a different type of blowing jet, this one issuing from a slot located near the nose of a 6% profile. In this case, the jet structure is quite different, as the presence of the profile surface retards the flow on one side of the jet while at the same time preventing any inflow from this retarded side. It can be seen that this particular jet, which is located at the 5% chord point, is located too far from the leading edge to prevent the formation of the leading edge bubble. Actually for this particular configuration, increasing the jet to free stream velocity ratio resulted in an increase in the size of this separation region since the change in circulation occasioned by the high velocity jet caused the stagnation point to move aft thereby increasing the local angle of attack. Similar studies for various slot locations and blowing quantities have been made. Although these studies are not complete, they seem to indicate that, within certain as yet unestablished limits, the closer the slot can be located to the leading edge pressure peak the better.

The close-up high speed photographic techniques employed in making these blowing jet studies proved so successful that they were employed in an investigation of the laminar boundary layer transition. This transition could be clearly seen with the naked eye whenever a streamline was brought close to the surface which could be done either by adjusting the smoke injector rake vertically or by injecting smoke near the forward stagnation point directly on the profile surface. Viewed with the naked eye (or the regular speed movie camera) the streamline was seen to remain steady and laminar in the region of favorable pressure gradient, but it rapidly became turbulent and diffused when this gradient became adverse.

When high speed close-up pictures of this phenomenon were taken, the structure of the transition appeared as shown in Figs. 30 and 31. As the streamlines approached the transition point they began to oscillate with a wave-like motion, the frequency of which was determined to be essentially that of the Tollmien-Schlichting waves. The amplitude of these waves increased until the flow turned down into a vortex which moved downstream, breaking up rapidly and giving rise to a large turbulent region. Fig 32 demonstrates the fact that this same vortex structure is present in the transition that takes place in the separation bubble at the sharp leading edge of a wedge.

6.6 Oscillating Wing Studies

The extent to which any oscillating lifting surface, particularly a helicopter rotor blade can be studied two-dimensionally is a matter of conjecture, but using the high speed camera to study pitching profiles within the tunnel has produced some very interesting results. These tests, portions of which are shown in Fig. 33, have involved tests of several different profile shapes oscillated about several different chord positions with and without boundary layer control by blowing.

It has been found that the characteristics of the flow are strongly affected by changes in the frequency of oscillation. If a wing is oscillated

slowly ($1/5$ cycle per sec) below its normal stall angle, the flow will remain attached to the wing during both the upward and downward motions of the blade and the circulation change will closely follow the change in angle of attack. As the frequency is increased, a lag in this change in circulation develops so that the motion of the blade and the forward stagnation point can get considerably out of phase, the stagnation point actually beginning to move aft over at least a portion of a cycle as the angle of attack is decreased. This lag tends to reduce the average lift produced by the blade and may be considered as the equivalent of a reduction in the slope of the lift curve.

This effect is further aggravated by the tendency of the blade to stall. When the blade is increasing angle of attack, the flow tends to attach to the surface. If the frequency is high enough and the amplitude low, it is possible that complete attachment will not be obtained, particularly if the flow was badly separated at the start of the upward motion of the leading edge, but in general the static stall angle can be considerably exceeded as long as the rate of increase of α is sufficiently great. The situation when the angle of attack is being decreased is just reversed. If the profile has become stalled, or is even close to the stall, at the maximum angle of attack achieved, the rate of decrease of α may be of sufficient magnitude to produce a local angle of attack large enough to produce complete stall. If this is the case, the stall will persist to low angles of attack, in the case of the higher frequencies not reattaching until the angle of attack is again increasing.

Investigations of this effect have shown the extreme sensitivity of the blade to this type of separation. If the blade is oscillating at a given rate between some low angle and an angle of attack just below the stall, a slight separation is noted just as the profile leading edge starts downward, but this rapidly disappears and the flow remains completely attached throughout the majority of the cycle. If the maximum angle is now increased so that the profile is just stalled, a change of the order of perhaps a degree, the nature of the cycle is completely changed, since the blade tends to remain stalled throughout the entire portion of the cycle that the angle of attack is decreasing, not reattaching until the angular velocity approaches zero or changes sign. It is interesting that the location of the pivot point on the profile seems to have only a minor effect upon the character of the flow, the flows obtained when the model was pivoted at the 50% chord position showing only a slightly greater tendency to separate than those when the model was pivoted about the leading edge.

The effect of boundary layer control on the character of the flow about the oscillating profile was also examined. It was found that some systems utilizing blowing or suction at points aft of the 20% chord point, although yielding reasonable results under static conditions, were unable to prevent leading edge separations even at angles well below the controlled stall angle. Tests were then conducted on leading edge blowing jets which were found to be most effective, holding the flow attached even at frequencies in excess of 15 cycles per second. Results of these tests are shown in Fig. 34.

The pictures shown in Figures 33 and 34 were taken with the Fastax camera. The full field studies were made at 3,000 frames per second while the close-ups were at 4,000 frames per sec. For the full field studies a technique was used that was discovered quite by accident. When sufficient condensation occurs in the smoke delivery line, a bubble of kerosene forms which produces disturbances in the smoke streams. These disturbances are generally small enough to escape notice until viewed by the high speed camera when they appear as a small wave front. These wave fronts were considered the source of considerable annoyance until it was noted how nicely they demonstrated the velocity distribution throughout the field. They have since become a valued and useful tool in analyzing observed flow fields.

7. Results from the 12" x 16" Smoke Tunnel

7.1 General

The desire to visualize flows in three dimensions was very much heightened at Princeton by the work being conducted here in the field of flow control. It is extremely valuable to understand the mechanisms by which the two-dimensional characteristics of a flow about a profile utilizing such a control are established, but if this material is to be applied, it is essential that the influence of the two-dimensional characteristics upon the three-dimensional flow field be understood. New and severe problems, due to the unusual spanwise load distributions produced by controlling portions of the wing as well as the complex downwash fields produced by such controls, make it absolutely mandatory that the three-dimensional flow field be understood. For this reason, this little tunnel was constructed as a pilot model of a much larger tunnel that it is planned to build.

Even though this tunnel is small and capable of speeds of only 40 ft/sec, some of the most interesting results obtained during this entire program have been obtained from it. The same photographic techniques employed in the other tunnels are used here, the major difference being that the lighting is flexible, the lights being set in any position that gives sufficient light for the photograph desired. Both the model and the test section are painted glossy black in order to reflect the light away from the lens instead of scattering it as flat black would do. The attempt is made when setting up the lights to leave the background unlighted to provide contrast. The use of photospots greatly facilitates this.

Unlike the two-dimensional tunnel, where the major smoke injection method involves the production of streamlines, the customary technique employed with three-dimensional models is to bleed the smoke from the leading edge, although for special purposes it is possible to inject streamlines from a rake or heavy streamers of smoke from a large tube upstream. Bleeding smoke out of the leading edge, of course, does introduce disturbances

into the flow but as Preston and Sweeting, and later Lippisch, have shown, if it is bled out at low rates and in a region of strong favorable pressure gradients, these disturbances will damp.

7.2 The Rectangular Wing

The first model to be placed in this tunnel was the rectangular wing shown in Fig 35. This wing is a semi-span model of an untwisted, untapered wing with an aspect ratio of 4, utilizing the NACA 23015 profile. This model is equipped with a 25% plain flap extending from $b/2 = 0$ to $b/2 = .60$. Outboard of the end of the flap is a 20% aileron extending to the tip. The wing is equipped with blowing ducts so that a jet of air can be directed tangentially over the deflected flap or aileron or both simultaneously.

Although this model was selected as the first to be investigated primarily because it was felt that it would serve as a form of calibration of the tunnel since the flow characteristics about the rectangular wing were well known, the first few tests indicated that several unexpected phenomena existed. The first and most marked of these is shown in Fig 36. As can be seen in these photographs, there is a strong spanwise flow of the boundary layer from the tip towards the root. This flow exists even at the low angles of attack, and, as the angle of attack is increased, the affected region moves forward, the major cross flow always being just ahead of the transition point as illustrated by Fig 37.

These pictures, taken at the rate of 3,000 frames per sec. clearly show the structure of the transition pattern. The streamlines are seen to first develop a wave-like motion and then to break up into little puffs of smoke, corresponding to the vortex motion observed in the two-dimensional tunnel. Some clue to the origin of the spanwise flow can be obtained from these pictures by examining the formation of the tip vortex which is seen to curl above the wing, producing a stagnation line on the upper surface of the tip forming a demarkation between the flow into the vortex and that over the wing. The boundary layer air responding to the pressure gradient is drawn spanwise away from the tip.

Another method of visualizing this phenomenon is shown in Fig. 38. This photograph was obtained by blocking off all but the tip openings that contribute to the tip vortex and the spanwise flow, and photographing the resulting flow patterns through a red filter. These smoke openings were then closed, the others opened, and the resulting patterns photographed through a green filter after having rewound the film to the initial frame. The resulting photograph clearly demonstrates the tip vortex contribution to the spanwise flow.

The most startling and instructive type of photographs taken within this tunnel are shown in Figs. 39 and 40. These pictures were obtained by shining light perpendicular to the wake through a narrow slit and photographing the resulting section of the wake from downstream. In

this tunnel it is necessary to photograph directly through the fan, thereby limiting the photographic speed, but in the larger tunnel currently under design, arrangements will be made to view this flow from a point just downstream of the test section, thus permitting the use of high speed photography. A further improvement is expected when an optical system producing parallel beams of light replaces the crude arrangement of shining photospots through a slit currently being employed.

Examination of these pictures demonstrates several interesting phenomena. Since the structure of the tip vortex can be clearly seen, it is possible to determine its location and size at any point downstream of the wing. It will be seen that it extends backward from the tip trailing edge in an essentially straight line with very little horizontal or vertical deflection when no control is applied. The tendency for the wake to roll up into the tip vortex can also be seen, although it will be noticed that, even though the vortex grows in diameter as it moves downstream, it is still far from complete roll up several chord lengths behind the wing.

The effects of blowing over the flap and aileron are also clearly shown in Fig. 39. One of the most notable effects is the motion of the tip vortex, blowing over the aileron moving it down and outboard, blowing over the flap moving it up and inboard, while the combined controls seem to exert little or no influence upon its position. The vortex shed at the aileron flap intersection displays somewhat similar characteristics, being moved down and out by blowing over the flap and up and inward by blowing over the aileron. The blowing of the flap apparently exerts the major influence on this vortex, for with the control applied over both the flap and aileron, this vortex moves down and out.

Examination of these pictures allows not only the complete determination of the tip vortex, but it also gives a plot of the entire wake. As can be seen, blowing over the aileron produced a fairly uniform flow, but blowing over the flap was badly disturbed by a blockage in the blowing jet. It is interesting to note how little of the downward momentum of the jet is transmitted across this blocked region.

The sequence of pictures shown in Fig. 40 is an investigation of the wake of the wing when it is taken from a negative stall slowly through a range of angles of attack, passing through the zero lift condition up to the positive stall. The tip vortex is seen first to steady as the increasing angle of attack causes the wing to recover from the negative stall then to grow smaller and finally to disappear at the point of zero lift only to reappear again, rotating in the opposite direction when the lift becomes positive.

7.3 The Swept Wing

In an effort to become familiar with the types of flow to be expected when dealing with swept wings, two untapered swept wing semi-span models, each with a 45° sweep, a 6" chord and a 13" semi-span, were

constructed. Each model was equipped with blowing flaps and ailerons. The only difference in these two wings lay in the fact that one employed a thick section, a NACA 23015, the other a relatively thin section a NACA 0006. This difference was sufficient to give the considerable difference in flow patterns demonstrated by Figs. 41 & 42.

As can be seen from these figures, the thick wing was equipped with holes along the leading edge through which the smoke could be bled, while, owing to the reduced space available within the thin wing, it was found more advantageous to bleed smoke from slots located slightly aft of the leading edge. It will be seen that both techniques give clear pictures of the flow.

From Fig. 41, it will be seen that at low angles of attack, several spanwise flow regimes exist in the boundary layer of the thick wing. The major spanwise flow is directed from the root to the tip, but at the tip there exists a flow similar to that observed on the rectangular wing where the flow moves inboard from the tip vortex. These two flows meet and interact in the region occupied by the aileron. As the angle of attack is increased, the tip flow becomes more indistinct and the flow, due to sweepback, moves forward, as does the transition point. It will be seen that the stall of the wing starts as a conical vortex at the wing tip and works along the leading edge with increasing angle.

The thin wing displays somewhat the same type of flow at the low angles of attack as can be seen from Fig. 42. The major difference between the flow patterns of the two wings occurs at the higher angles of attack. As the angle is increased, the leading edge bubbles, typical of thin profiles, forms a vortex that extends from root to tip along the leading edge. The fact that the smoke on this wing is bled from slots located aft of the leading edge serves to demonstrate the phenomenon very graphically since the smoke is transported forward into the vortex tube. As the angle is increased, this leading edge vortex develops into the conical vortex at the tip and moves inboard along the leading edge until the entire wing is covered.

Fig. 43 is a sequence of photographs taken through the wind tunnel fan looking upstream at the swept-back wing employing the thick sections. The first views show the test section fully lighted and demonstrates both the spanwise flow of the basic wing and the marked straightening effect exerted on the streamlines by the application of blowing over a deflected surface. The second views are taken employing the slit techniques. These show the strong effect on the downwash distribution of the blowing jet.

This sequence of photographs also indicates the rather amusing relation between the size of the models employed and the size of the test section. In defense of these tests it must be pointed out that they were made more as an exploration of the technique than as an attempt to obtain correct aerodynamic data.

7.4 The Delta Wing

As in the case of the swept wing investigations, two models of 45° delta wings were constructed, one employing a NACA 23015 profile, the other a NACA 0006. Figs. 44 and 45 show the differences in the flow patterns over the two wings. As in the previous case, the thick delta employs holes through which smoke is bled from the leading edge while the thin wing employs slots. An examination of the sequences shown in the two figures demonstrates the fact that the streamlines of the thick wing curl over the leading edge, seemingly endeavoring to flow perpendicular to the leading edge, while those of the thin wing are strongly affected by the creation of the leading edge vortex and upon reattachment to the wing surface flow more nearly parallel to the free stream.

The stall patterns of the two wings are significantly different also. The thick wing begins to stall at a fairly low angle of attack, a separation starting at the tip and working inboard along the leading edge to the root. This separation displays little or no tendency to curl up into a leading edge vortex. The thin wing on the other hand, maintains its flow to relatively high angles of attack, the leading edge vortex gradually growing in a conical shape until it covers the entire wing.

Although these models were geometrically similar in all respects other than their airfoil sections, they were built to test two different applications of a flow control system. The thick wing, as illustrated by Fig. 46, was equipped with a blowing jet under the elevon. Although this reduced the lift coefficient of the wing, it greatly improved the elevon efficiency and seems to present a plausible method of reducing the trim drag of tailless deltas. The thin wing, on the other hand, was built to simulate the trimmer of a Canard configuration and, as demonstrated by Fig. 47, was equipped with a blowing flap. It can be seen that such devices are fairly effective, but it must be pointed out that the maximum gains were achieved when control was applied to the leading edge as well.

8. Helicopter Studies

A number of very profitable flow visualization investigations of the flow through helicopter rotors and propellers have been made in the past, although none seem to have developed to the point where anything other than qualitative measurements could be made. For this reason, the attempt was made to apply the techniques developed in the three-dimensional tunnel to the problem of the helicopter rotor downwash pattern. For simplicity the investigations were restricted to the hovering case.

Fig. 48 shows the apparatus employed in these tests. A two-bladed 6 ft. diameter rotor was placed on a 12-foot-high thrust stand. Because these tests were merely exploratory, an existing set of wooden rotor blades was used. Holes were drilled along the leading edge and at the tip into which cotton was stuffed. When a test was to be run, this cotton was saturated with titanium tetra-chloride, which produced suffi-

cient smoke for 20-second runs. Later a small reservoir was built into the blade from which the tips were fed, boosting the testing duration by about 30 seconds.

The lighting source for these tests was a 5,000 watt theatrical spot light. Opened wide, it provided light for the full field studies of which a typical example is shown in Fig. 49, closed down to a narrow slit and directed vertically parallel to the shaft of the thrust stand, it gave a plane of light that permitted the wake sectioning technique demonstrated by Fig. 50.

Since this program is still in its infancy, it is dangerous to attempt to interpret and draw any conclusions from the results other than to say that it seems to be an immensely powerful technique for studying both transient and steady state phenomena.

The first set of pictures shows the development of the rotor starting vortex. This is a tip vortex formed by the initial motion of the blade which moves downward and outward, rolling the subsequent vortices up into a smoke-ring-like structure. The second set of photographs demonstrates the steady state condition that exists after the rotor has come up to speed. The order r.p.m. in this case was of the order of 400 and the blade pitch was set at $\Theta = 10^\circ$.

It will be seen that the tip vortex moves radially more rapidly than vertically immediately under the rotor, but by the time it has reached a point about 85%R inboard of the tip and 10%R below, practically all radial motion has stopped and seemingly the final wake diameter has been established. An unexplained disturbance occurs at a point 90% R below the blade. As the thrust stand is several rotor diameters from any obstacles, the reason for this disturbance is not yet understood, but it is believed that flow field investigations currently under way will explain the effect.

The great advantage of this procedure over those used before is that it allows an accurate and direct measure of the axial velocity in the wake. Since it is not necessary to visualize only the tip vortex, measurements can be made of the complete downwash field in the presence of any obstacle such as a fuselage shape that may be desired. The results of an early tip vortex study are shown in Fig 51.

9. Future Developments

It is not for a moment believed that the work so far performed represents anything more than a start. Not only does there remain a staggering number of problems that may yield to the techniques so far developed, but there are endless extensions and refinements of the techniques and equipment that must be made.

One first and obvious step will be the construction of a larger three-dimensional tunnel. Current plans call for a 3' x 4' test section and speeds up to 100 ft per sec. Such a piece of equipment will not be easy to construct considering the turbulence level that must be maintained, but seems feasible if an ample contraction ratio is provided. It is probable that a new smoke generating system will have to be developed to handle the increased quantity demanded, but no particular difficulty is anticipated from this source.

Once this facility is available, the number of subjects that can be investigated is tremendous. The increased size and speed will allow testing in a more reasonable Reynold's Number range while the corrections made to the downwash measurements will be greatly reduced. Central mounting with the smoke delivery through the mounting struts or in the form of free stream streamlines will permit the intensive study of the flow about bodies of revolution and similar shapes. It is also possible that rotor and propeller tests can be conducted in this facility, particularly if the test section is removable so that the wall boundary problem is alleviated.

The thrust stand type tests can also be very greatly improved. The construction of new models utilizing oil smoke instead of titanium tetra-chloride will greatly facilitate the testing. The completion of equipment currently under construction, such as smoke wands and rakes, permitting smoke injection at various points of the flow field, will greatly aid in the understanding of the induced fields outside the rotor wake, while the construction of a new building will permit testing under much more nearly disturbance-free conditions. It is planned to conduct forward flight investigations on the 450' restrained flight track being built at the Forrestal Research Center for the investigation of forward flight stability. The use of an auxiliary carriage on the track to carry the necessary lights and camera equipment is contemplated.

Finally, an attempt to develop a full scale flight flow visualization technique will be made. This will, of course, require a fairly extensive research program investigating smoke production, injection, and photographing techniques to deal with problems orders of magnitude greater than those currently faced with the model facilities. It is hoped, however, that within a year initial tests will be made on a L-21 or similar type aircraft.

10. Conclusion

It has been the purpose of this paper to indicate the potentialities of modern smoke flow visualization techniques as an aid in the understanding and appreciation of subsonic aerodynamic phenomena. A discussion of these techniques has been given and a number of results from the Princeton tunnels shown by way of demonstration. Space has not permitted a full discussion of the significance or implications of all of these results, but reports are being prepared, which deal in detail with the more important aspects of these tests. It is hoped that these demonstrations will be of interest and that they will cause others to employ these techniques so that they will realize the full promise of their potentialities.

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13. Knowlton, M.P.: Theoretical Investigation on the Determination of Lift Coefficients in Two-Dimensional Smoke Tunnels. Princeton University Dept. of Aeronautical Engineering Report No. 289.

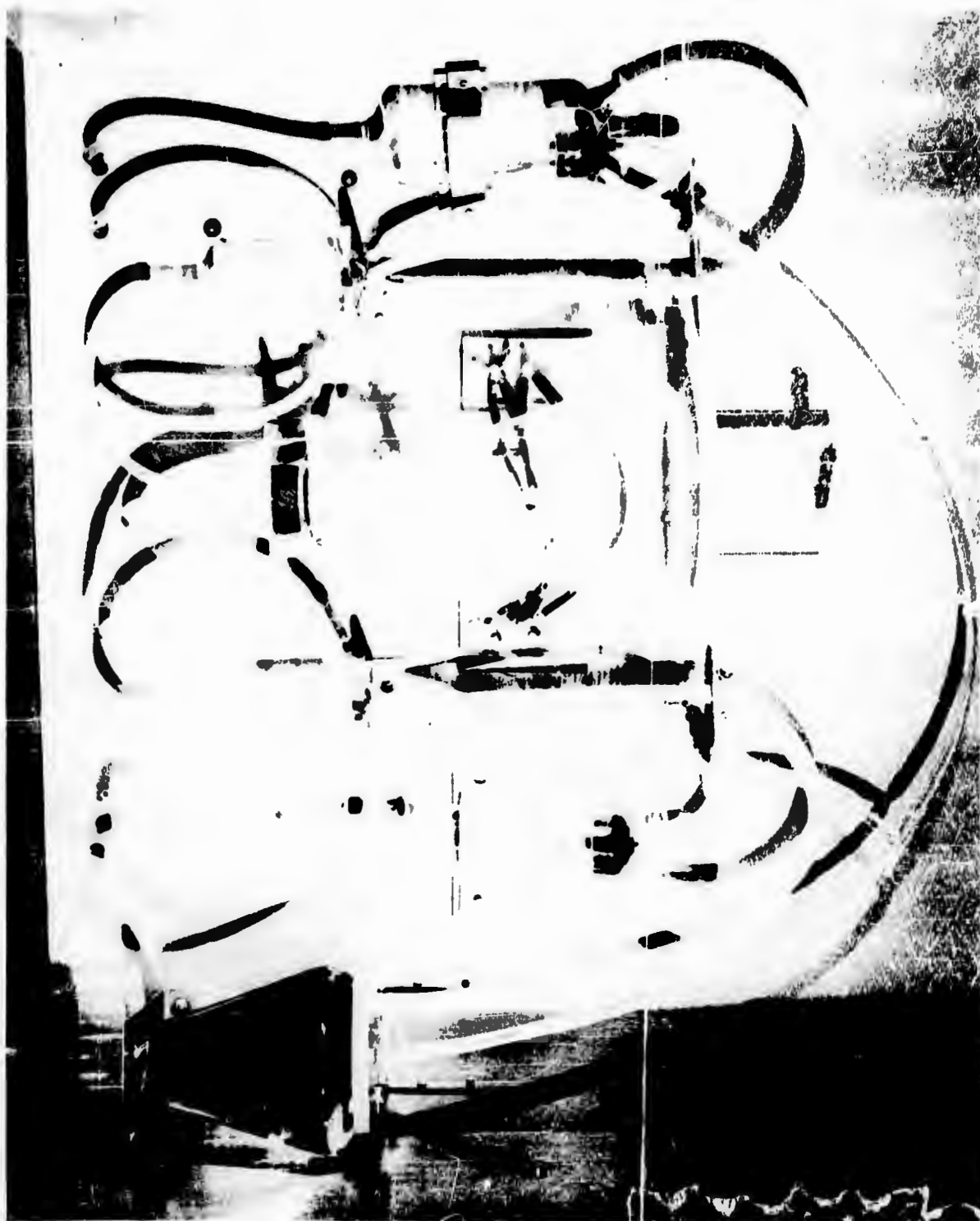


FIG. 1

SMOKE GENERATOR

SMOKE INJECTOR

CONTRACTION CONE

ENTRANCE BELL

UPSTREAM DIFFUSER

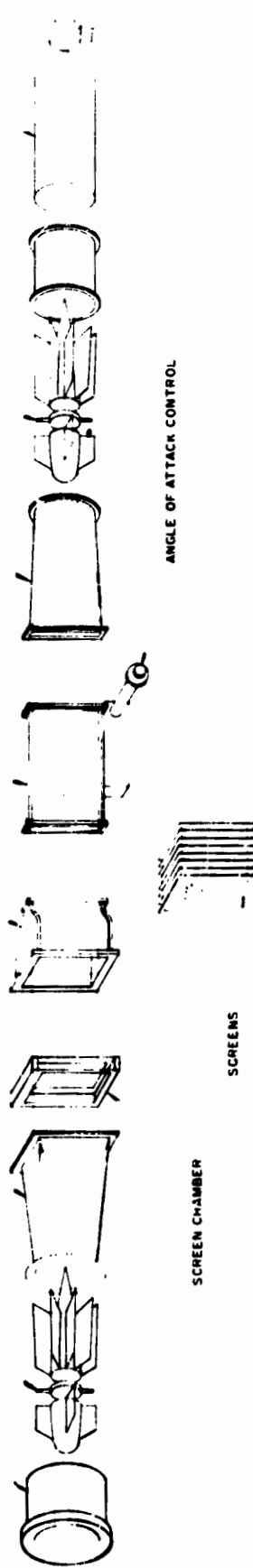
FAN

TEST SECTION

DOWNSTREAM DIFFUSER

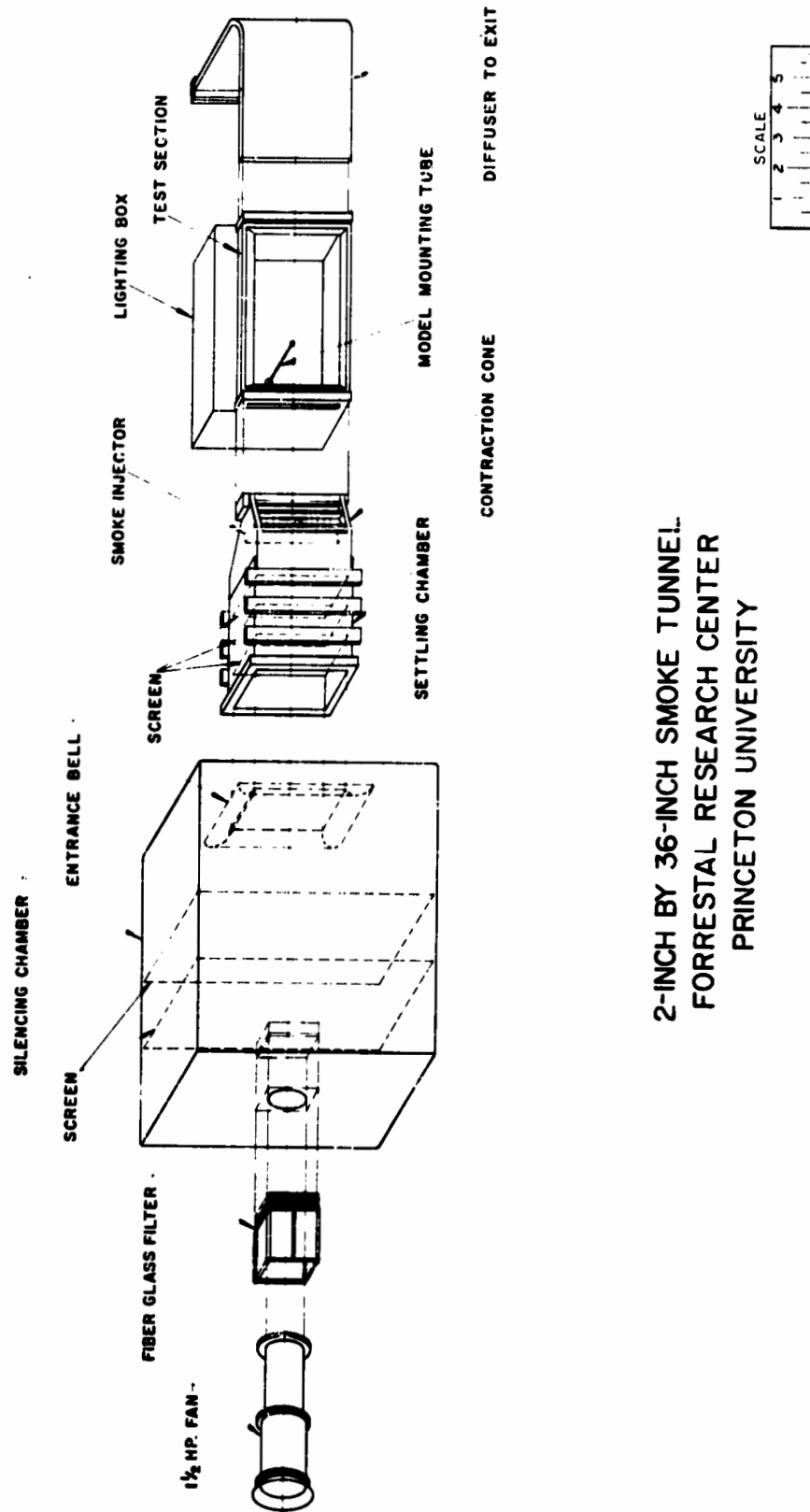
FAN

PLENUM CHAMBER



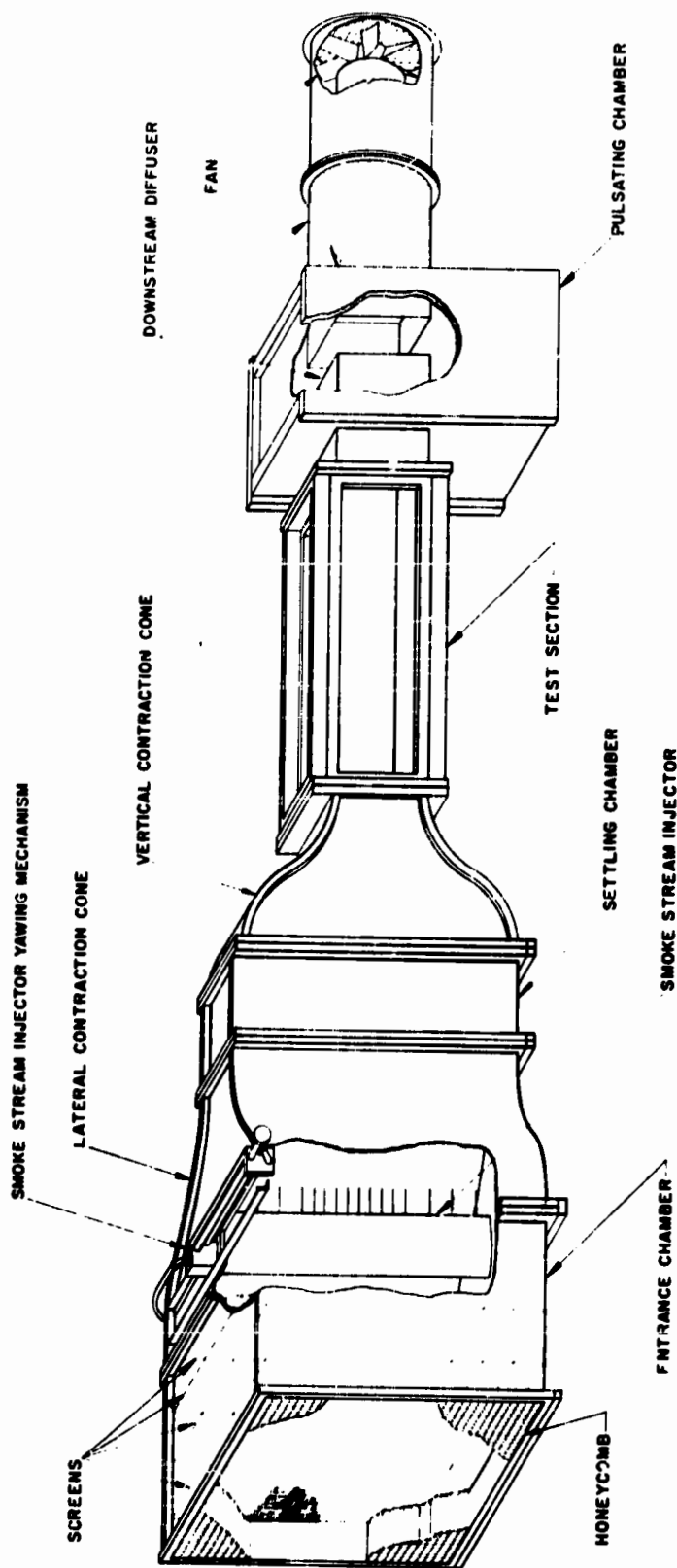
SCALE
1'

FIGURE 2
14-INCH BY 14-INCH SMOKE TUNNEL
FORESTAL RESEARCH CENTER
PRINCETON UNIVERSITY



2-INCH BY 36-INCH SMOKE TUNNEL
FORRESTAL RESEARCH CENTER
PRINCETON UNIVERSITY

FIG. 3



12-INCH BY 16-INCH THREE-DIMENSIONAL SMOKE TUNNEL
 FORRESTAL RESEARCH CENTER
 PRINCETON UNIVERSITY

FIG. 4

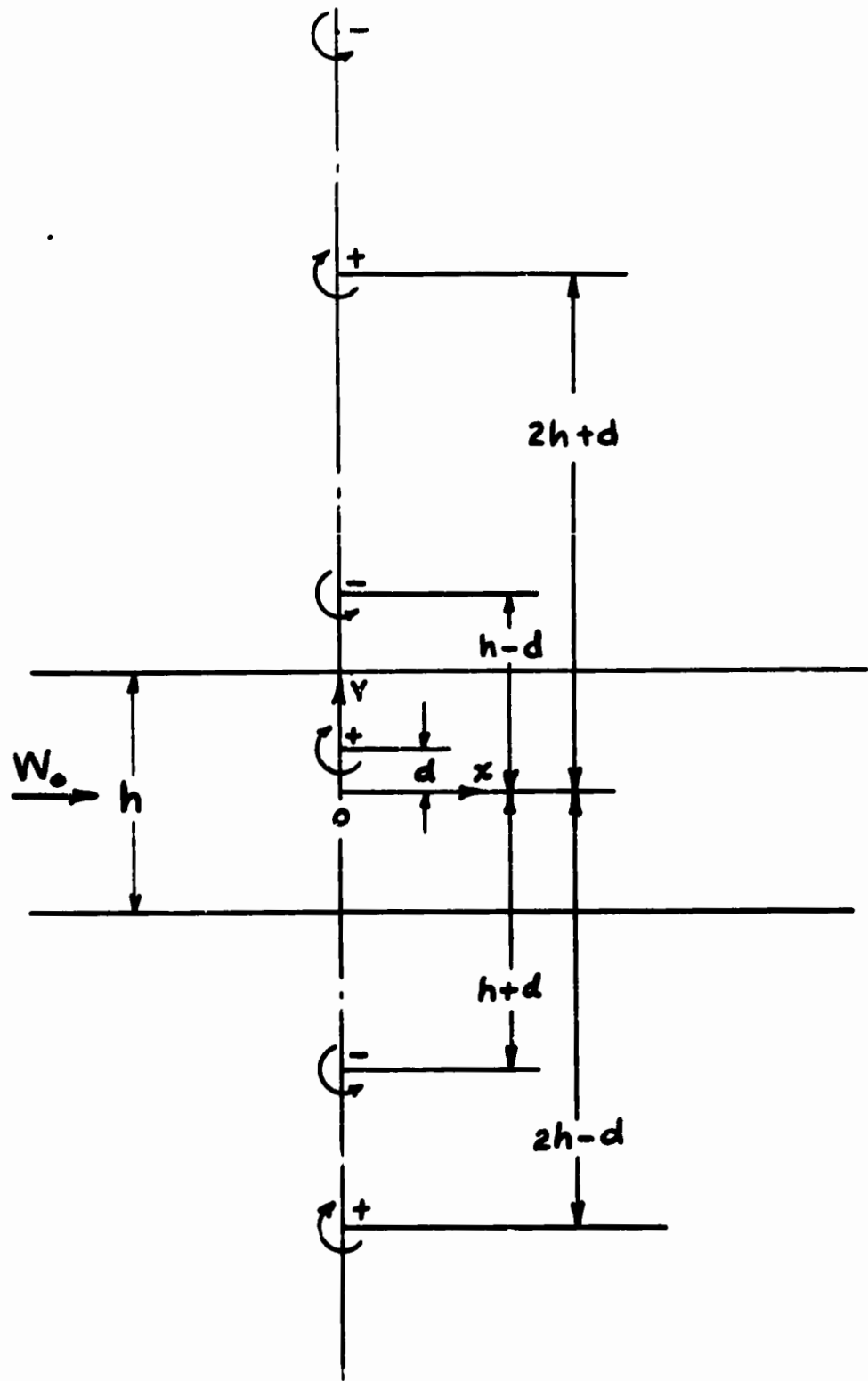


FIG. 5a

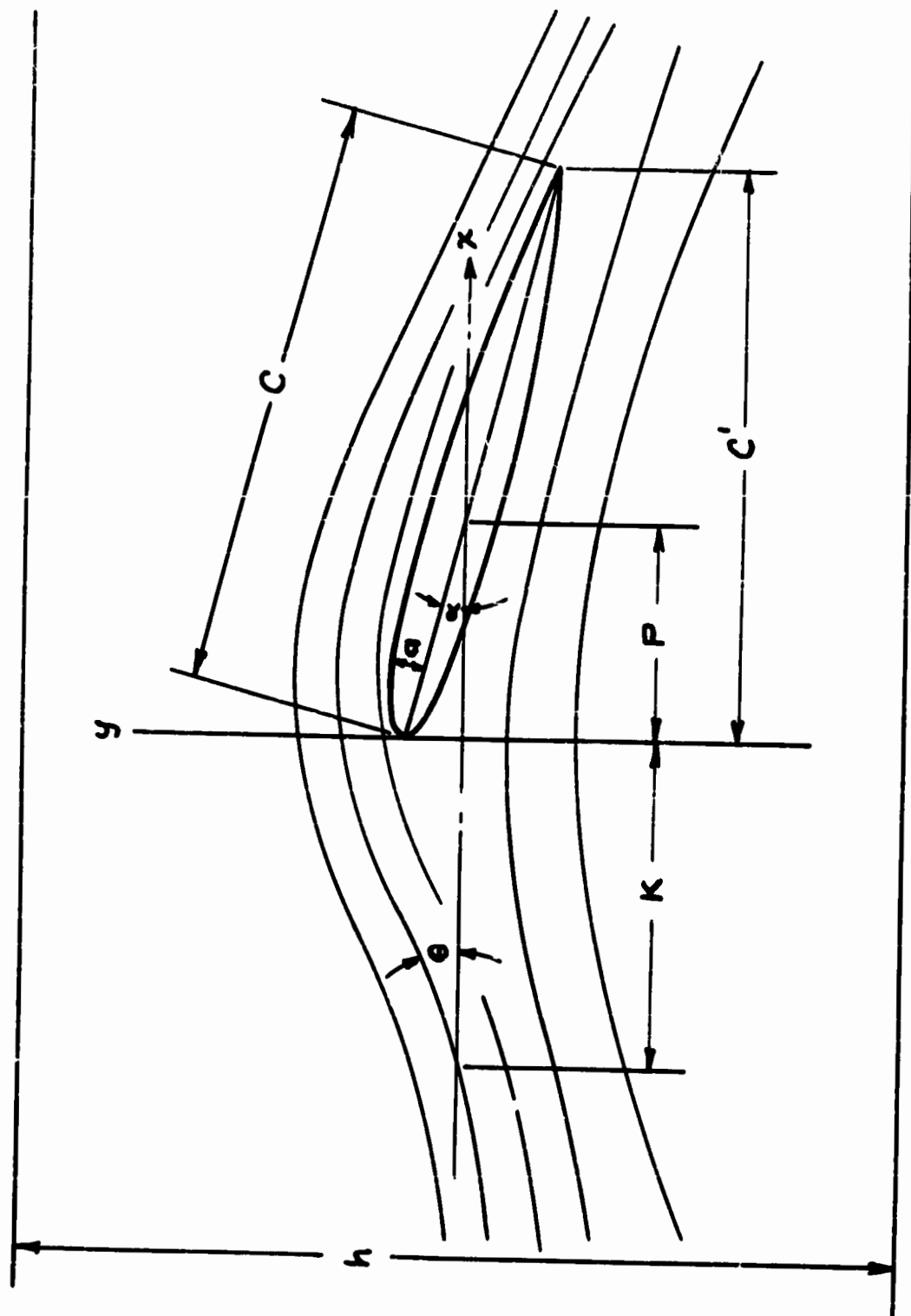


FIG. 5b

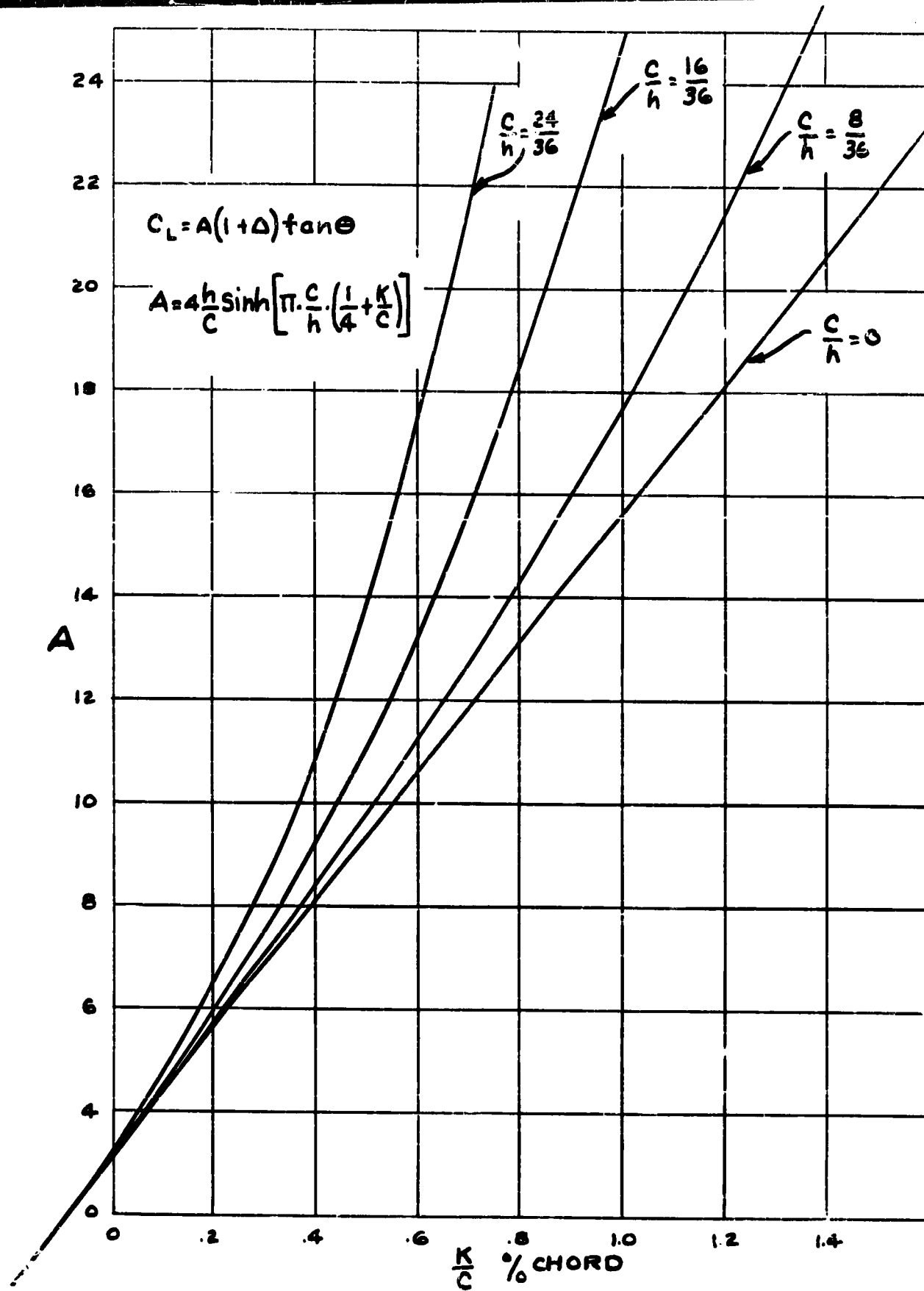
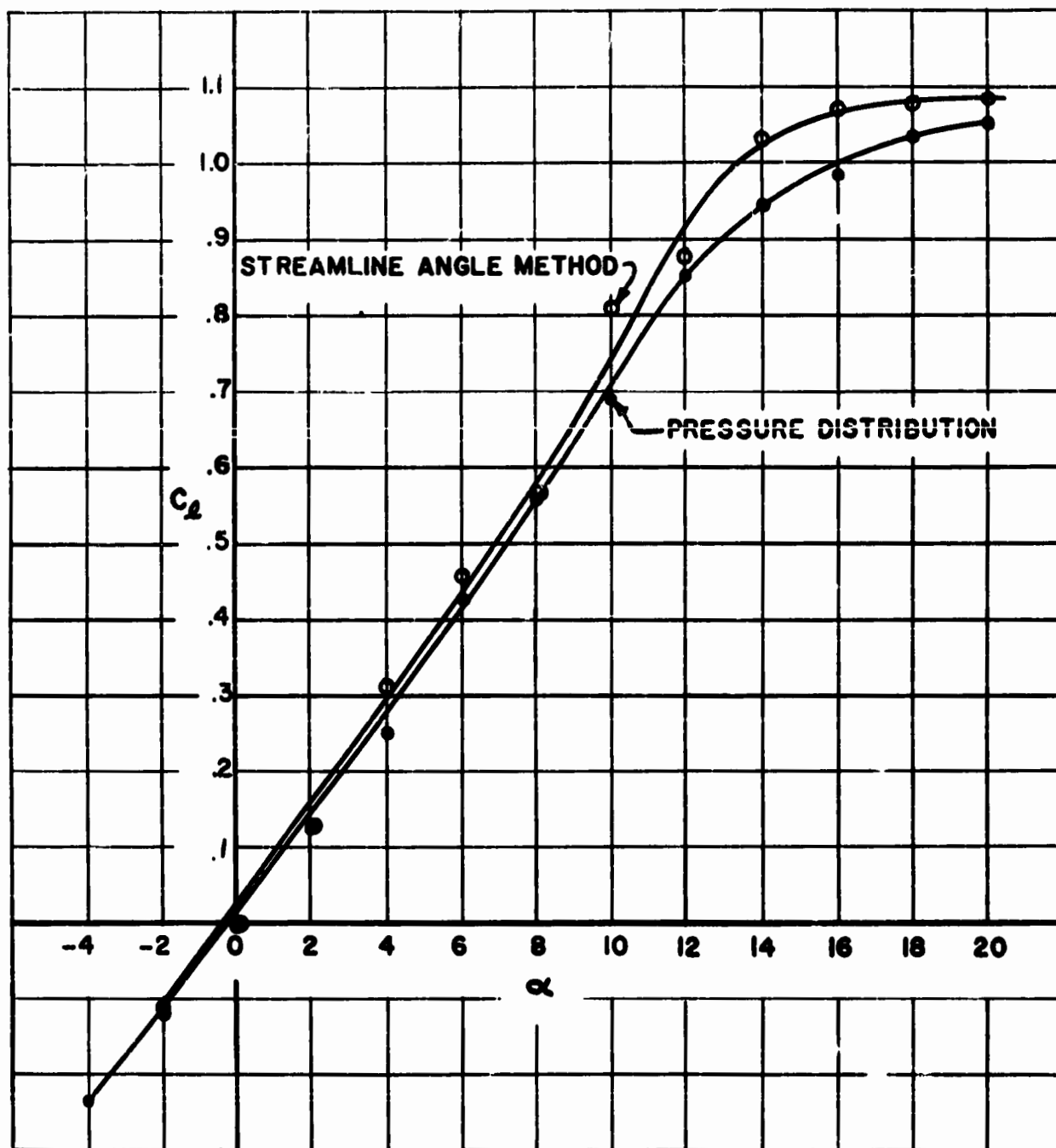
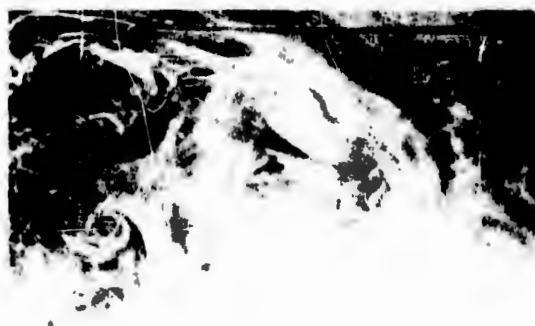


FIG. 6



NACA 23015 16-INCH CHORD
2"x36" PRINCETON UNIV. SMOKE TUNNEL
@ 59.3 FT/SEC.

FIG. 7



A



D



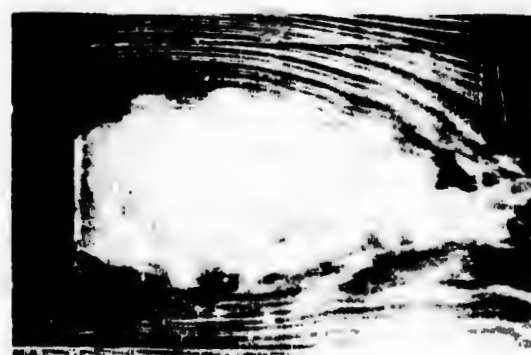
B



E



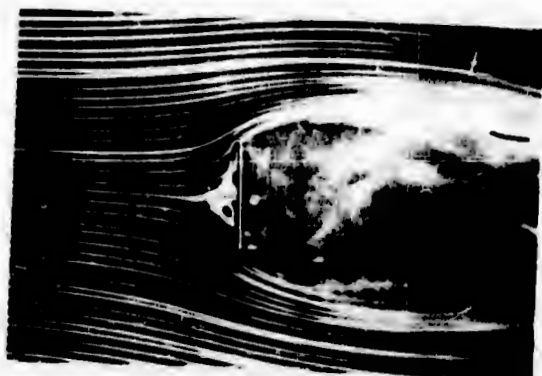
C



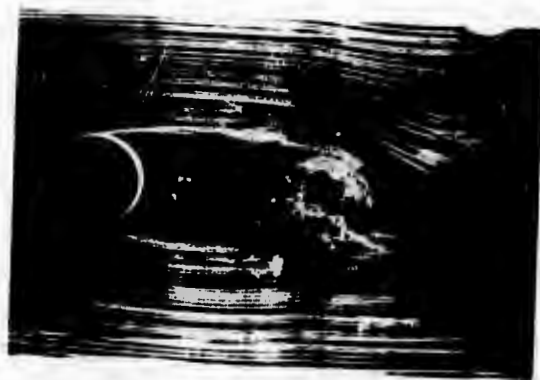
F

STARTING VORTICES BEHIND A FLAT PLATE

FIGURE 8



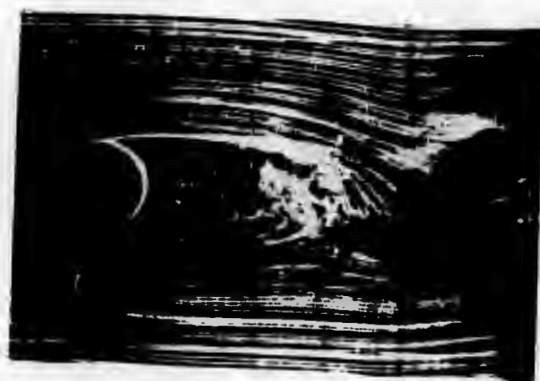
A



A



B



P



C



C

FLAT PLATE WITH UPSTREAM SPLITTERS

FIGURE 9

WAKE BEHIND CYLINDER, VELOCITY
INCREASED FROM A TO C

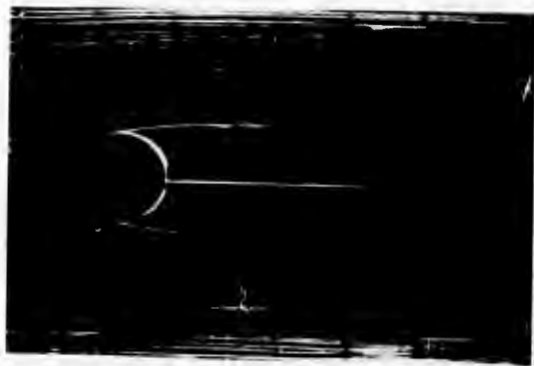
FIGURE 10



FLAT PLATES SPACED CLOSELY TO CIRCULAR CYLINDER
FIGURE 11



FLAT PLATES SPACED DOWNSTREAM OF CIRCULAR CYLINDER
FIGURE 12



A



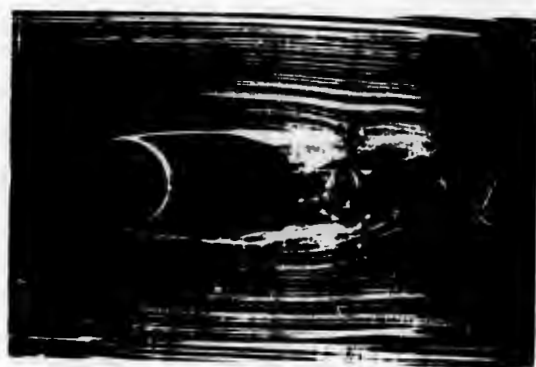
A



B



B



C



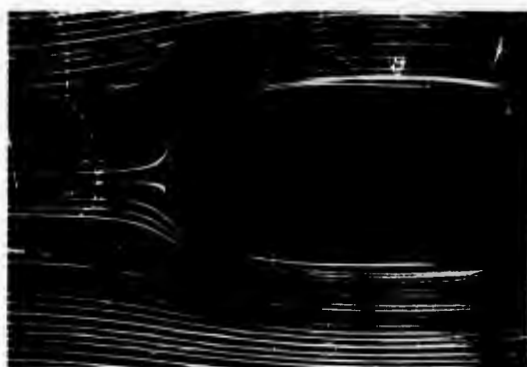
C

SPLITTERS EXTENDING DOWNSTREAM
OF CIRCULAR CYLINDER

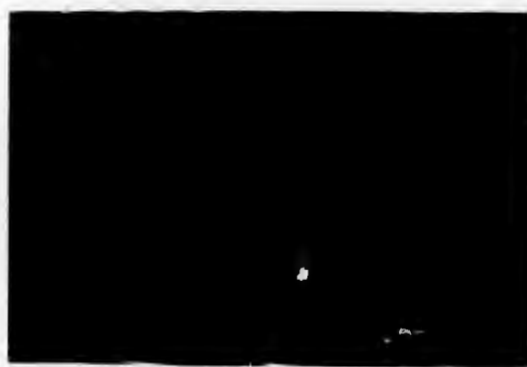
FIGURE 13

SPLITTERS EXTENDING UPSTREAM
OF CIRCULAR CYLINDER

FIGURE 14



A



D



E



E



C



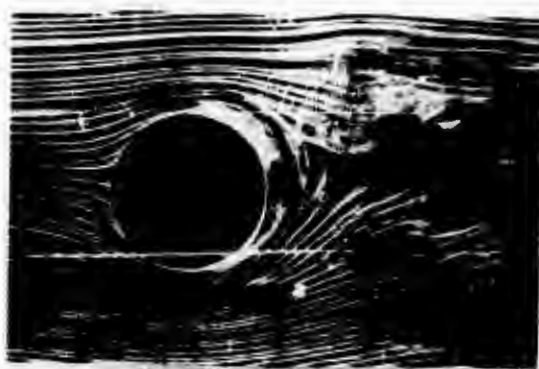
F

CYLINDER WITH INCREASING ROTATIONAL VELOCITY

FIGURE 15



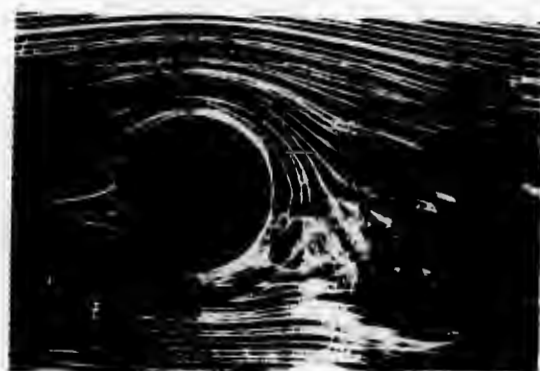
A



B



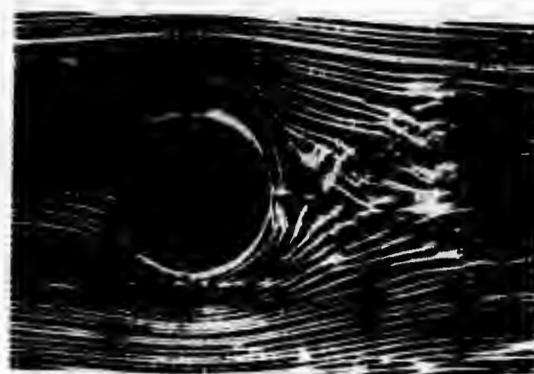
C



A



B



C

CYLINDER WITH SINGLE DOWNSTREAM
 SUCTION SLOT
 FIGURE 16

CYLINDER WITH POROUS SUCTION
 ON DOWNSTREAM
 FIGURE 17



A



A



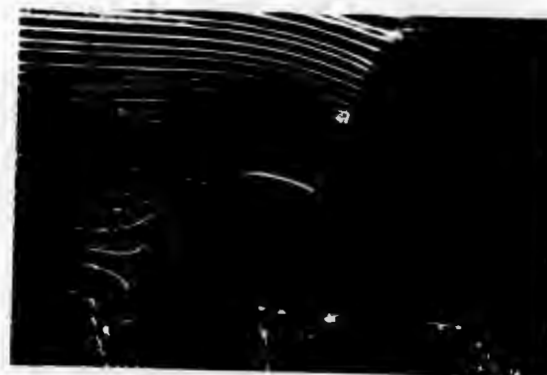
B



B



C



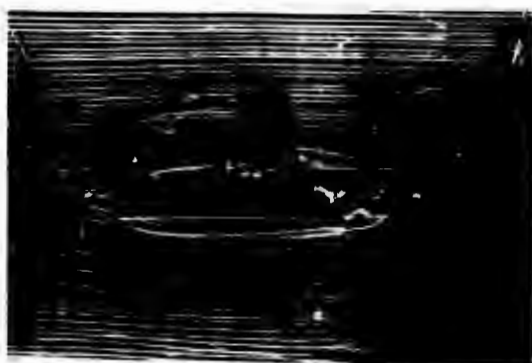
C

CYLINDER WITH BLOWING JET
ISSUING DOWNSTREAM

FIGURE 18

VORTEX CREATED BY INCLINED JET

FIGURE 19



A



D



B



E



C



F

PROFILE WITH SUCTION STABILIZED VORTEX
FIGURE 20



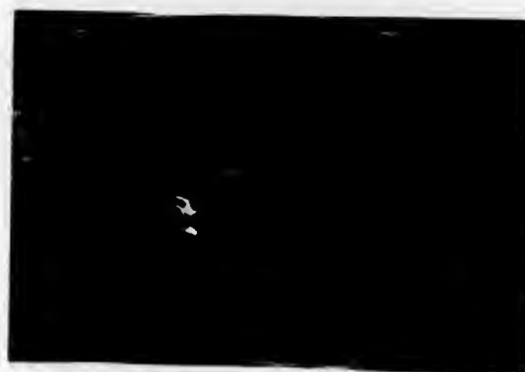
A



C



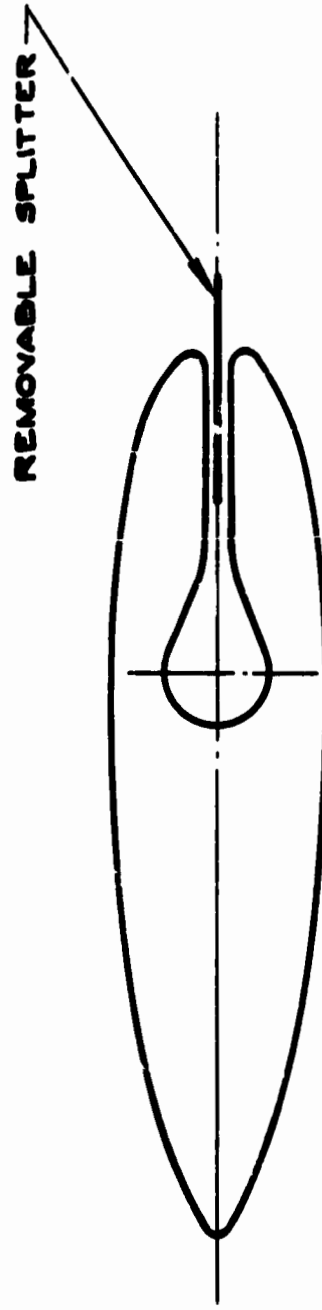
B



D

ARRANGEMENTS OF CIRCULAR CYLINDER

FIGURE 21



LOBSTER POT
10-INCH CHORD 2-INCH SPAN

FIG. 22



A. NO SUCTION APPLIED



D. HIGH SUCTION WITHOUT SPLITTER



B. SUCTION APPLIED WITHOUT SPLITTER



E. LOW SUCTION WITH SPLITTER



C. SUCTION INCREASED WITHOUT SPLITTER
SHOWING ALTERNATE STAGNATION POINT LOCATION



F. HIGH SUCTION WITH SPLITTER

LOBSTER POT PROFILE

FIGURE 23



Comparison of profile without suction to profile with suction applied and splitter installed.

1.

Figure 24 2.



Comparison of profile without suction to profile with suction applied and splitter removed.



Profile equipped with droop nose and tangential blowing over the flap.

Figure 27



Spanwise boundary layer flow from the tip.

Figure 33



A



D



B



E



C



F

INCREASING ANGLE OF ATTACK WITHOUT SUCTION

INCREASING ANGLE OF ATTACK WITH SUCTION

PROFILE WITH DOWN SUCTION SLOTS

FIGURE 25



A



C



P

WITHOUT TANGENTIAL BLOWING



D

WITH TANGENTIAL BLOWING

PROFILE EQUIPPED WITH DROOP NOSE AND
TANGENTIAL BLOWING OVER THE FLAP

FIGURE 26



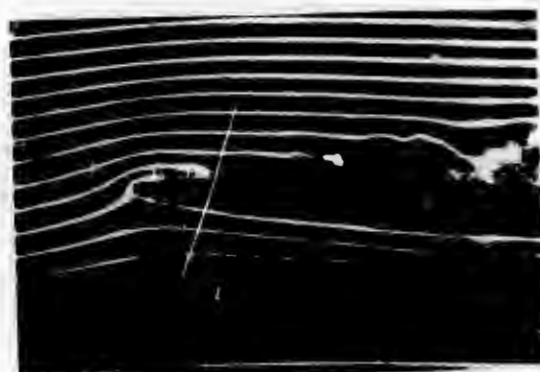
A



A



B



B



C



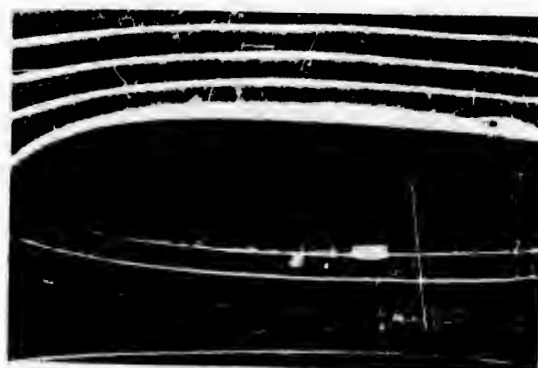
C

FREE STREAM BLOWING JET
FIGURE 28

LEADING EDGE BLOWING JET
FIGURE 29



A



A



B



B



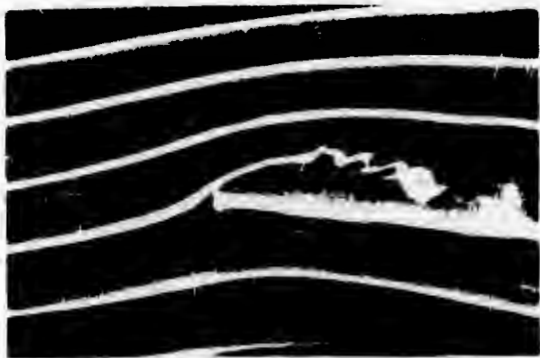
C



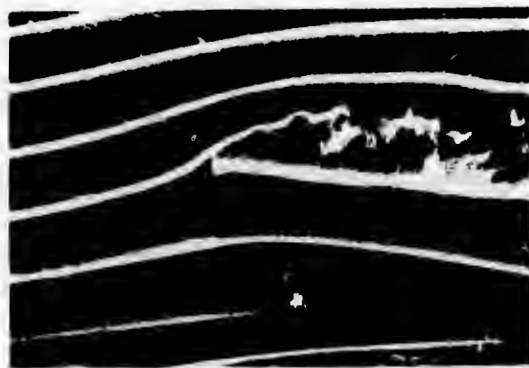
C

TRANSITION STUDIES, SMOKE FLED
FROM LEADING EDGE
FIGURE 30

TRANSITION STUDY, FREE STREAM SMOKE
FIGURE 31



A



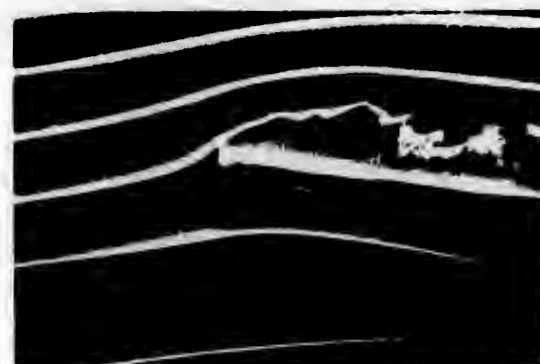
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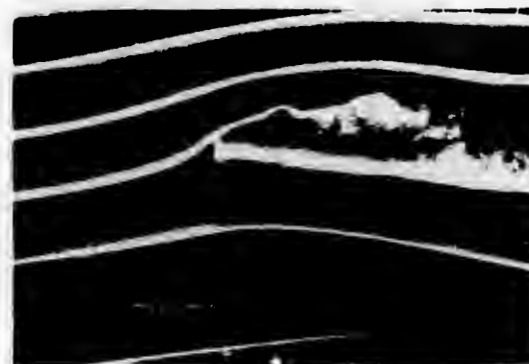
B



E



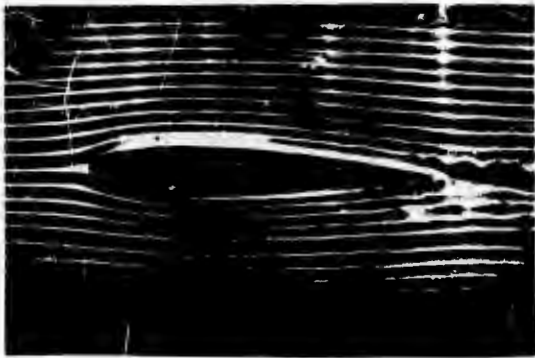
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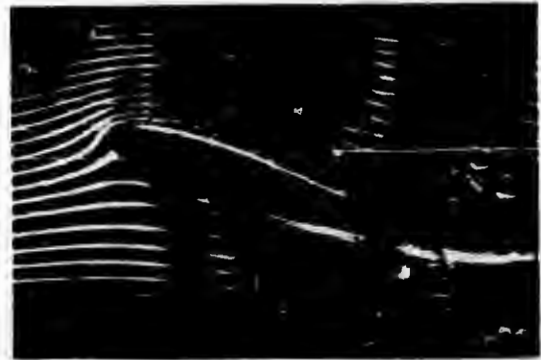
F

SEPARATION OF SHARP LEADING EDGE OF WEDGE

FIGURE 32



A



D



F



E. DECREASING ANGLE OF ATTACK



C. INCREASING ANGLE OF ATTACK



F. LEADING EDGE BLOWING

OSCILLATING PROFILE STUDIES

FIGURE 33



A



D



B



E

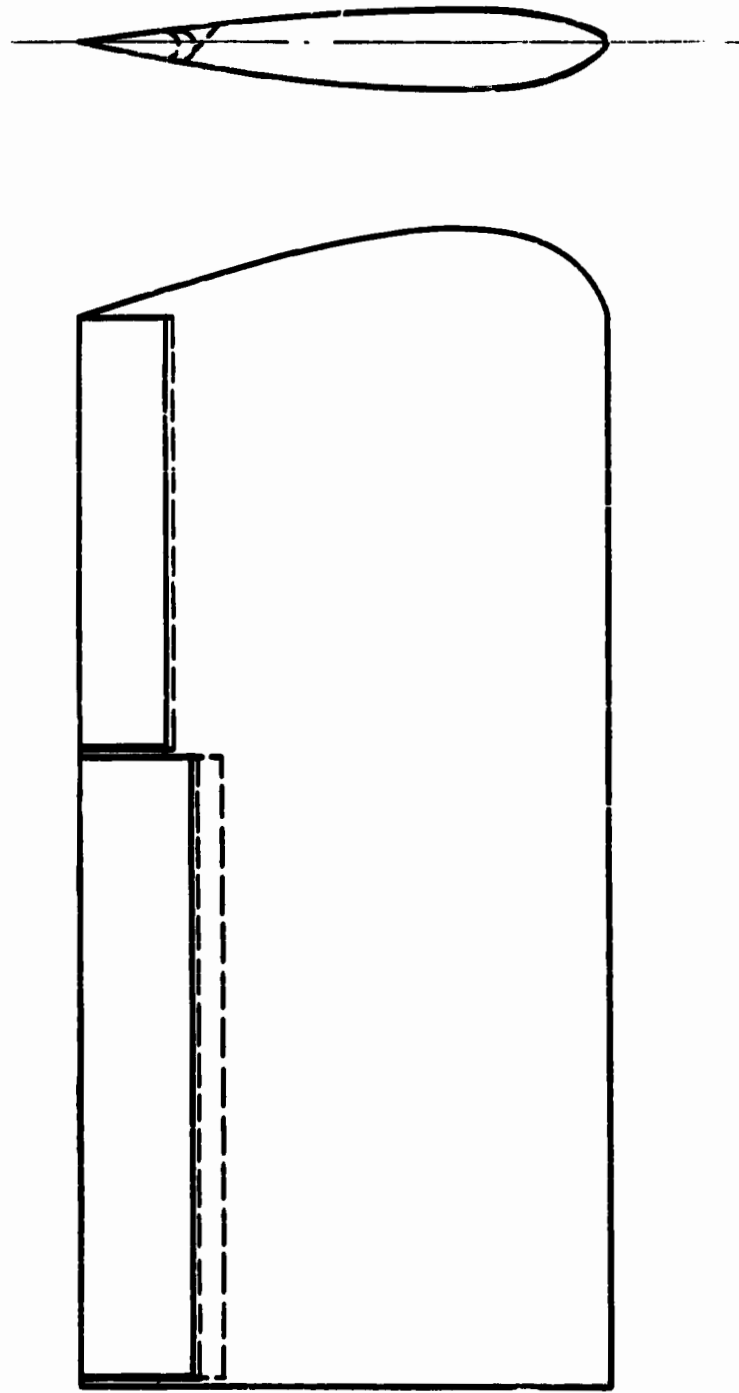


C



F

CLOSEUP OF OSCILLATING WING
WITH LEADING EDGE BLOWING
FIGURE 34

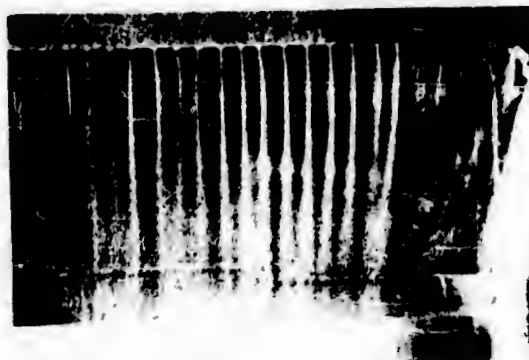


RECTANGULAR WING FOR 3-D SMOKE TUNNEL

FIG. 35



A



D



B



E



C



F

SPANWISE FLOW ON RECTANGULAR WING

FIGURE 36

A. $\alpha = 4^\circ$ B. $\alpha = 8^\circ$ C. $\alpha = 15^\circ$

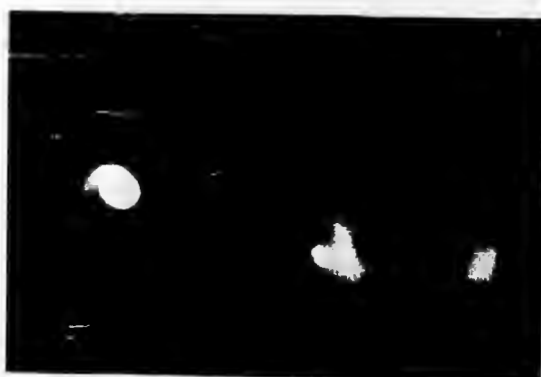
HIGH SPEED PICTURES OF RECTANGULAR
WING TRANSITION PATTERN
FIGURE 37



A. NO CONTROL



C. FLOWING OVER AILERON



B. FLOWING OVER FLAP



C. BLOWING OVER FLAP AND AILERON

RECTANGULAR WING WAKE

FIGURE 39



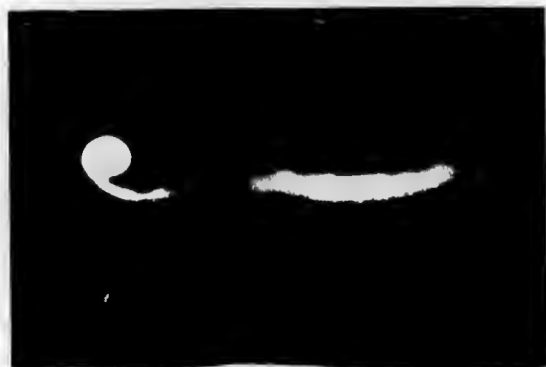
A



D



B



E

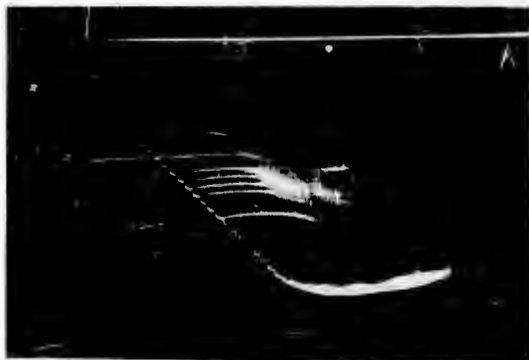


C



F

RECTANGULAR WING INCREASING ANGLE OF ATTACK
FROM NEGATIVE STALL TO POSITIVE STALL
FIGURE 40



A



A



B



B



C



C

FLOW OVER THICK SWEEP WING
FIGURE 41

FLOW OVER THIN SWEEP WING
FIGURE 42



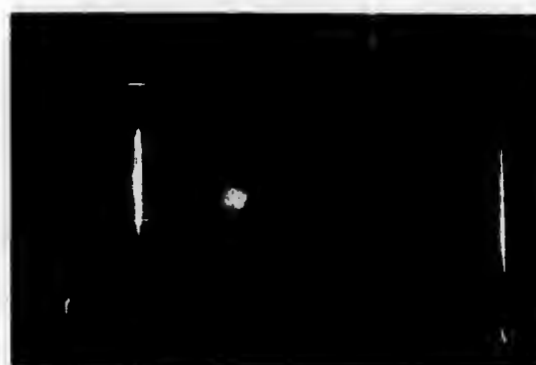
A. NO FLOWING



D. BLOWING OVER FLAP



B. BLOWING OVER FLAP



E. BLOWING OVER AILERON



C. NO BLOWING

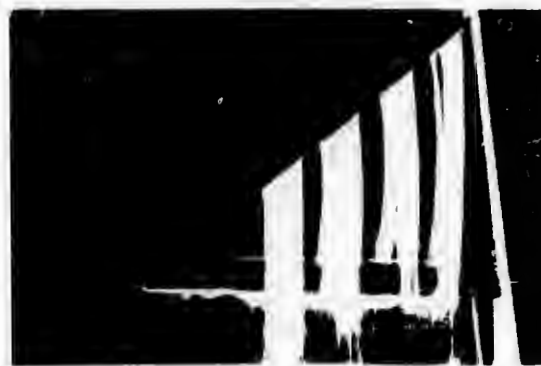


F. BLOWING OVER FLAP AND AILERON

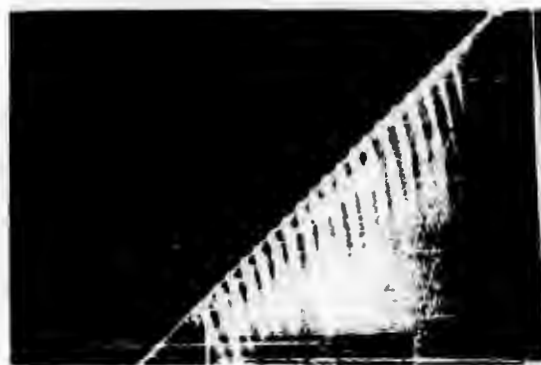
THICK SWEEP WING
FIGURE 43



A



A



E



E



C



C

FIGURE 43
FIGURE 43

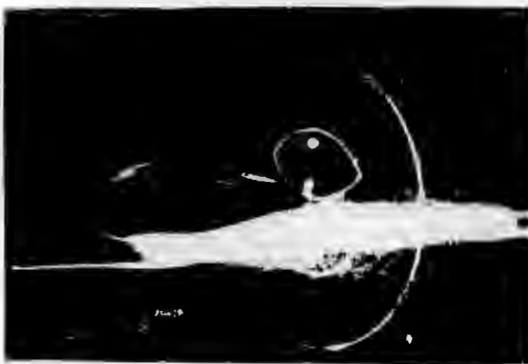
FIGURE 44
FIGURE 44



A. NO FLOWING



A. NO BLOWING



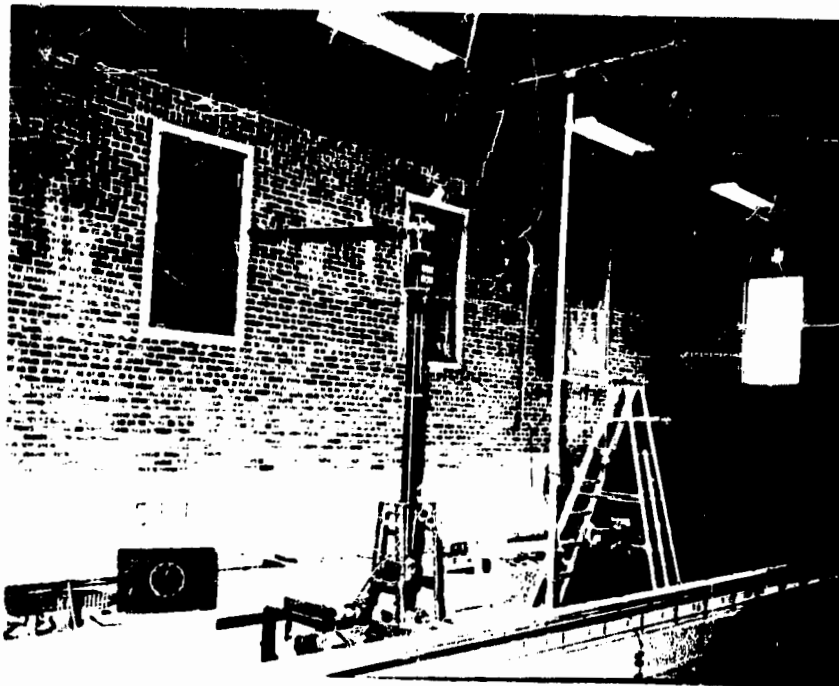
B. BLOWING UNDER ELEVON

FIGURE 46

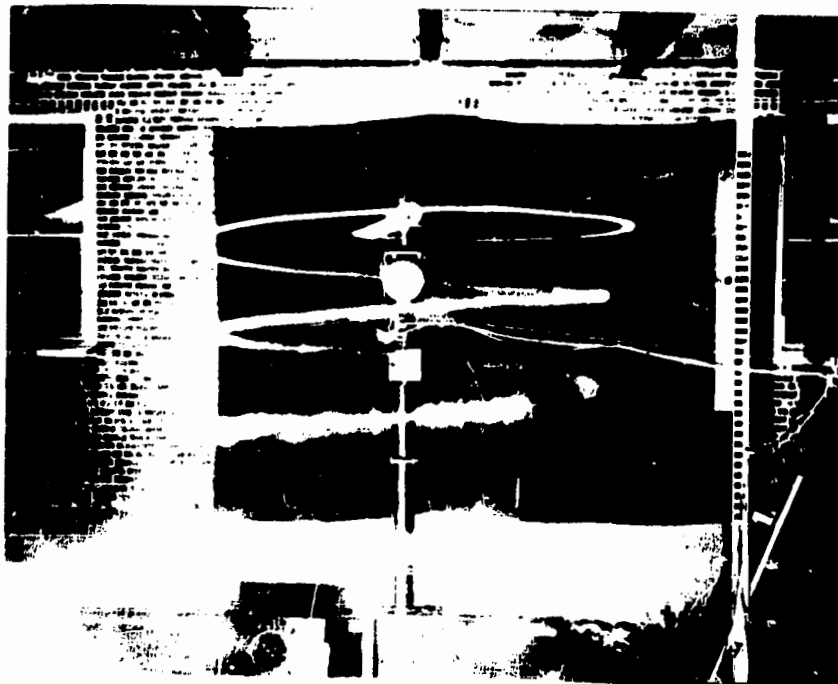


B. BLOWING OVE FLAP OF DELTA TRIMMER

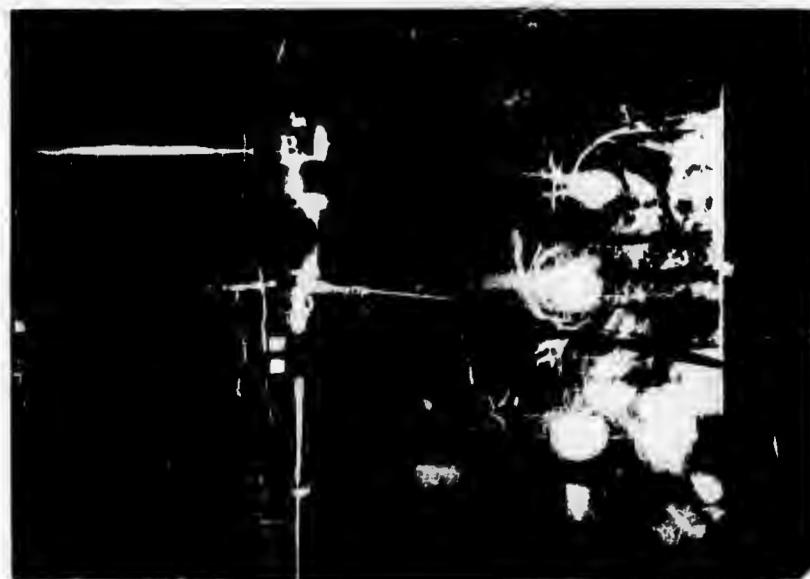
FIGURE 47



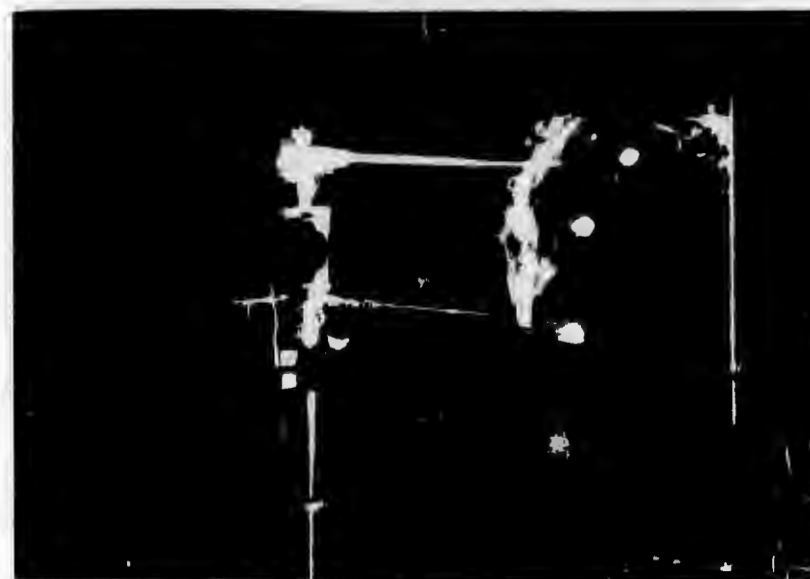
REPAIR TEST AT 7:00 PM
FIGURE 48



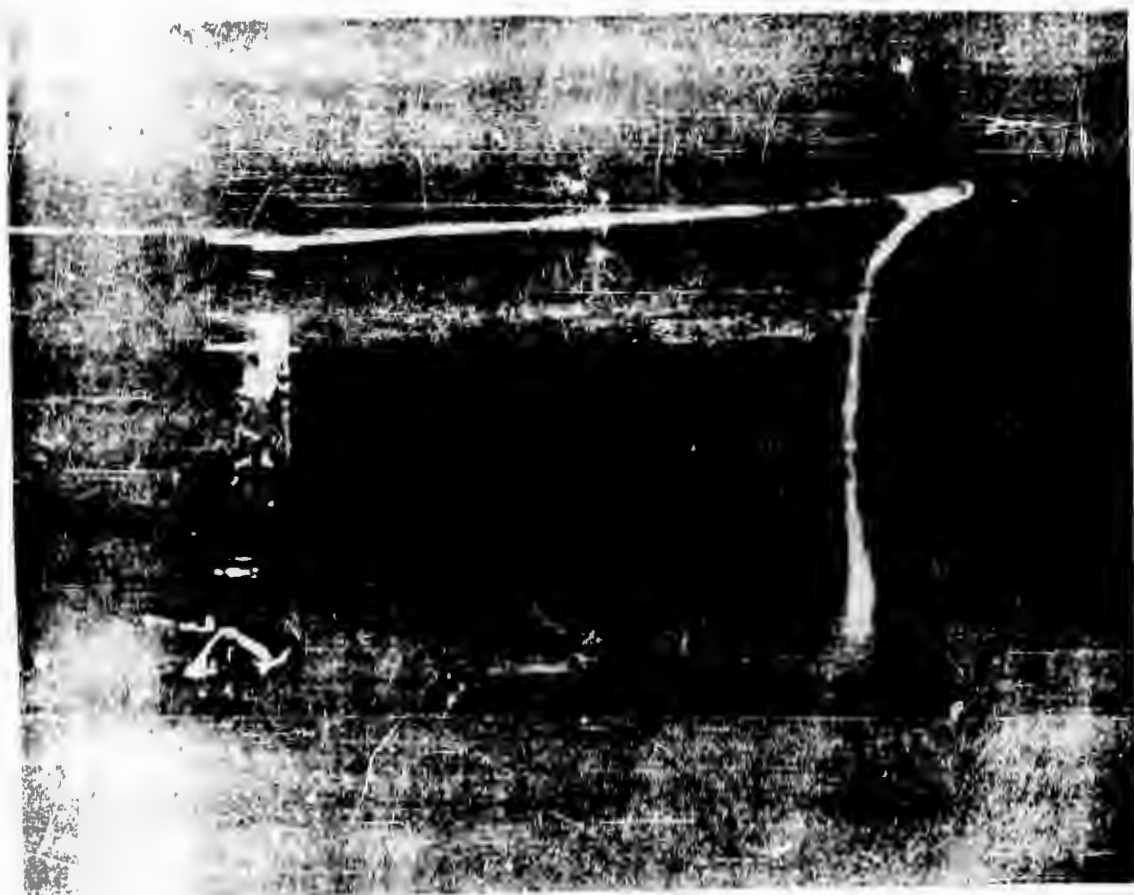
REPAIR TEST AT 7:00 PM
FIGURE 49



A. ROTOR STARTING VORTEX



E. ROTOR AT T. 1.1.1. LIGHT SECTION
THROUGH HILL OF THE LAKE
F. 1.1.1.1.



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