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THE FLUORESCENT-OIL FILM METHOD AND OTHER TECHNIQUES

FOR BOUNDARY-LAYER FLOW VISUALIZATION

By Donald L. Loving and S. Katzoff

Langley Research Center
Langley Field, Va.

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SUMMARY

A flow-visualization technique, known as the fluorescent-oil film method, has been developed which appears to be generally simpler and to require less experience and development of technique than previously published methods. The method is especially adapted to use in the large high-powered wind tunnels which require considerable time to reach the desired test conditions. The method consists of smearing a film of fluorescent oil over a surface and observing where the thickness is affected by the shearing action of the boundary layer. These films are detected and identified, and their relative thicknesses are determined by use of ultraviolet light. Examples are given of the use of this technique.

Other methods that show promise in the study of boundary-layer conditions are described. These methods include the use of a temperature-sensitive fluorescent paint and the use of a radiometer that is sensitive to the heat radiation from a surface. Some attention is also given to methods that can be used with a spray apparatus in front of the test model.

INTRODUCTION

In experimental aerodynamic research there is constant need for information on the state and nature of the flow over the surfaces being studied. For example, it is generally desirable, at the least, to identify the regions of laminar and of turbulent flow, the regions of reversed or separated flow, and the regions of significant lateral flow. Where such regions can be clearly identified, other important basic information may sometimes then be immediately deduced, such as the locations and approximate strengths of shocks, the locations of pressure peaks and laminar separation bubbles, and the locations of appreciable lateral pressure gradients.

For obtaining such a qualitative survey of the surface flow, a number of visual methods are being used such as the ink-flow method in which various colored solutions or suspensions are used, the evaporation method in which china clay and a suitable liquid are used (for example, ref. 1), the sublimation method (for example, ref. 2), and the luminescent lacquer method (for example, ref. 3). Such a quick survey of the surface flow can be most useful; yet, many investigators do not use these methods, presumably because of the effort required to develop the spraying technique, to select the liquid or solid of precisely the correct volatility or other physical property, and to work out other details of application and use. Selection for the correct volatility, in particular, may be a very real problem in the case of a large high-powered wind tunnel that takes a long time to bring up to the operating Mach number and stagnation pressure. For such tunnels the fact that only a single test condition can be observed per tunnel operating cycle, which may sometimes consume as much as an hour, is a further deterrent. The unfortunate result, of course, is that the investigator must eventually interpret his data, suggest revised configurations, extrapolate to higher Reynolds numbers, and so forth, without knowing the bare essentials of the nature of the surface flows.

The fluorescent-oil film method, which is described herein, appears to be basically less discouraging in that fewer subtleties of technique are involved, the necessary materials are generally readily available and need not be selected with precision, and several different conditions (such as angles of attack or Mach numbers) can frequently be studied without having to shut down the tunnel between conditions for reapplication of the oil.

This investigation was not very exhaustive or systematic, mainly because most of the experience was incidental to wind-tunnel studies of specific configurations. Although more systematic investigations would doubtless be very useful, it was just the aforementioned lack of sensitivity to precise details of technique that has permitted repeated successful application of the method without such an exhaustive background.

Some brief experiences obtained with other types of visual-flow methods are reviewed. In one method a temperature-sensitive fluorescent paint that is described in reference 4 is used. In another method a radiometer is used for remote observation of the model surface temperature. Other methods involve the use of a spray apparatus in front of the model and are, in effect, adaptations of the fluorescent-oil film method, the china-clay method, and the chemical-indicator method. The main characteristics that were sought in these methods were (1) independence of the time required to bring the tunnel up to the desired test conditions, and (2) capability of showing the flow at several different model or tunnel test conditions during a single test.

FLUORESCENT-OIL FILM METHOD

Method and Application

Basic concepts.- The fluorescent-oil film method consists simply of smearing a petroleum-base lubricating oil over a model and observing the oil film in the dark under ultraviolet light. These oils are among the most brilliantly fluorescent of the readily available organic liquids and are easily detected under ultraviolet light in films that are much too thin to show under visible light. During a test, the action of the air flow sweeps the oil along the surface and, to some extent, evaporates it away, so that the oil film soon develops a pattern indicative of the surface shear intensity and direction.

The use of fluorescence for observing an oil film has two general advantages: (1) The film appears to glow with its own radiance and, hence, visual observation is not confused by extraneous reflections and highlights; and (2) no matter how thin the fluorescent film becomes it can, in theory at least, be made visible by a sufficiently intense beam of ultraviolet light. The oil film is thus basically different from, for example, a thin film of a colored liquid observed under natural light, for which increasing the intensity of the lighting cannot make the film more perceptible. Because of these characteristics and also because of the particular physical properties of the oils, it is often possible to make definitive observations at two or more conditions during a single test if sufficient time is allowed for each preceding pattern to be obliterated and each succeeding one to be established. As long as the film of oil is reasonably fluid, it will change from one pattern to another. For the same reasons just given, the requirement that the oil remain on the model and show the desired pattern after a long period of bringing the airstream up to the desired speed does not make the choice of oil especially critical.

During an especially long test the film will become very thin, with only the least volatile and most viscous constituents remaining. The pattern in such a case is essentially fixed and undergoes no appreciable change while the tunnel is stopping. Such extended tests may be useful for establishing flow patterns on parts of the model that cannot be observed from outside the tunnel during a test but which can be inspected from inside the tunnel after the test. This procedure might also be adapted for determining flow conditions on an airplane in flight.

A further characteristic of the fluorescent-oil film method is that the oils may be applied directly to the polished metal surfaces of a typical wind-tunnel model without special preparation, precautions, or technique. In addition, the oil film produces no appreciable effect on the aerodynamic forces, so that flow-visualization tests can be made simultaneously with the force tests. The use of fluorescent-oil films for visual-flow studies was discovered at the Langley Research Center several years ago and was mentioned very briefly in reference 5.

Preparation of model and application of oil.- As just noted, a typical metal model requires no special preparation before the oil is applied. Wooden models or models having wooden additions, patches of filler material, or similar nonmetal areas may, however, present a problem. Filler materials either fluoresce or absorb oil and remain brightly fluorescent throughout the test; wood is appreciably fluorescent and, furthermore, unless finished, similarly absorbs oil and remains brightly fluorescent. Accordingly, such models should be given a coating of some light-colored nonfluorescing material and allowed to dry thoroughly before the oil is applied. On the few occasions in which this problem arose, zinc chromate was used successfully, although the coating is very slightly fluorescent and is not as light as could be desired. Some further search for a white nonfluorescing coating might be warranted where this problem arises often.

The reasons why a white or light-colored (or shiny metallic) surface is desirable are: (1) The white or metallic surface serves to reflect the ultraviolet light back through the oil and thus effectively doubles the intensity of the ultraviolet illumination; and (2) such a surface reflects that half of the fluorescent light which is directed toward the model surface and which would be absorbed by a dark surface. The two effects combine to make the net fluorescence intensity when the oil is on a white surface four times as much as when the oil is on a black surface. This reasoning, of course, assumes that the white surface is a perfect reflector and that the oil film is so thin that it absorbs only a negligible fraction of the incident ultraviolet radiation or of the fluorescent light.

As previously mentioned, no special technique is necessary in applying the oil which may be applied, for example, with a clean brush or daub, and the coating need not be particularly uniform. Where emphasis is on determining the direction of boundary-layer crossflows, it may help to apply the oil in small discrete dabs which then stretch out into lines that show the direction of the surface shear. Where transition has been fixed by a row of roughness particles, the particles accomplish a similar result by causing the oil to appear in a series of fine lines extending back from the individual particles.

Oil selection.- The primary factor in selecting an oil for a particular test is its viscosity, which determines the ease with which the oil forms the patterns and the length of time it remains on the model. It is also important that the oil wet the surface easily; wettability can be improved, if necessary, by adding some organic acid. The test characteristics involved in the choice of the oil are the time required to bring the tunnel up to the test conditions, the dynamic pressure and temperature (or recovery temperature) of the airstream, and the model size (to the extent that the size determines the boundary-layer thickness and other characteristics of the boundary layer and, hence, the surface shear). Since the exact choice of oil is not overly critical, relatively little effort is involved in making an appropriate selection. For example, a single test in which two or three different oils are tried on different areas of the model will generally suffice to indicate an adequate choice. The only real difficulty arises when the air temperature (or recovery temperature) is low, as in unheated supersonic blowdown tunnels, since the oils then tend to become very viscous.

For the lower speed ranges and temperatures, kerosene and other light oils must be used. Since the natural fluorescence of these oils is very weak, it must be augmented by adding a soluble fluorescent additive, such as those given in appendix A. Here also, however, low temperatures of the order of 30° F or less introduce a difficulty since the solubility of the additive decreases with decreases in temperature. Not enough work has been done at the low temperatures to justify any particular recommendations; possibly advantage might be taken of the fact that the additive is relatively more soluble in the aromatic hydrocarbons.

Kerosene (with the fluorescent additive) has been used for speeds up to about 80 miles per hour and temperatures from 40° F to 75° F. Very few studies from this speed range up to about a Mach number of 0.5 have been made; the meager experience indicates, however, that No. 2 and No. 3 fuel oils and the lower weight lubricating oils, all with fluorescent additives, (with the lowest weights, of course, used for the lowest speeds) are satisfactory for this range. Tests at transonic speeds in the large transonic tunnels have been successfully made with two gear oils (Navy Symbol 5190 and 6135) with and without kerosene or Penetone Formula 602 as a thinner. Tunnel stagnation temperatures for these tests ranged from 125° F to 180° F. The thinned gear oils also appear to be acceptable for the lower speeds, since patterns could be seen in the oil film well before the tunnel speed came up to the transonic test range. Apparently, the solvent keeps the film relatively fluid at the lower speeds but has sufficiently evaporated by the time the transonic test range is reached that the viscosity of the film is then essentially the viscosity of the gear oil alone. The gear oils, with and without thinner, have also been used at Mach numbers up to 3, with stagnation temperatures of about 125° F. In this case, as with the large transonic tunnels, use of the gear oil was, in part, dictated by the long time required to bring the tunnels up to the desired range of test conditions and by the desire to observe more than one test condition of the model.

This brief discussion of the oils that have been used is obviously vague concerning proportions. Somewhat more detail is given in the section entitled "Examples of Applications." Nevertheless, insensitivity to such details is actually characteristic of the method, and "optimum" formulation would itself be vague and difficult to define or establish.

Other fluorescent liquids.- Many organic liquids exhibit fluorescence, but it is believed that relatively few fluoresce as intensely as do the heavier lubricating oils. Of the liquids that were available, two that were brightly fluorescent and exhibited acceptable wetting characteristics were methyl anthranilate and ethyl anthranilate. The volatility of these two liquids, however, is very high (comparable to that of kerosene); therefore, their range of applicability is limited. Further studies might be profitable, both to compare systematically the chemicals that might appear promising and also to concentrate or isolate the fluorescent components of the lubricating oils or perhaps merely to determine what petroleum sources and refining processes might yield the best products for this purpose.

Attempts were made to use the Dow Corning 200 silicone fluids for flow-visualization studies, especially at the low and high temperature extremes encountered in some test facilities where the oils did not work well. These fluids are not fluorescent, but they may be made fluorescent by dissolving in them a suitable fluorescent additive. (See appendix A.) The solubility is relatively low; therefore, the solution does not fluoresce very brightly. Another approach was to suspend in the silicone a very fine insoluble fluorescent powder. (See appendix A.) The suspension is very brightly fluorescent; however, since it is not a homogeneous solution, its characteristics are not quite comparable to those of the oils. In particular, the pigment tends to adhere to the surface in certain areas where the suspension has thinned out gradually, and these areas then tend not to show further changes with changes in test conditions. Thus, clear definition of the pattern for more than one test condition was sometimes difficult to obtain, and even the first pattern sometimes seemed questionable when the starting time for the tunnel was especially long.

Required intensity of ultraviolet light.- Ultraviolet-light requirements are primarily dependent on the distance from the light source to the model and on the model size. The quantity, location, and intensity of these sources must be worked out for each individual test. For visual observation of the flow patterns, an ultraviolet spotlight is satisfactory. For photography, ideally, the ultraviolet radiation should be uniform over the portion to be photographed. This uniformity may be obtained by the use of floodlights or several spotlights. Visible radiation should be kept at a minimum. Several successful arrangements are discussed in a later section entitled "Examples of Applications." Glass and plastic material generally used in wind-tunnel windows do not constitute a problem in letting sufficient ultraviolet radiation through to produce fluorescence in the oil film.

Mercury arc floodlights or spotlights with near-ultraviolet filters provide good ultraviolet sources. The simplest of the three types of ultraviolet sources successfully used at the Langley Research Center is the commercially available 100-watt E-H4 mercury vapor lamp with a long-wave ultraviolet filter and a 125-watt transformer attached. Another type is the 1,000-watt B-H6 mercury arc lamp fitted with a long-wave ultraviolet filter and a condensing lens. Each such lamp unit is cooled by forced air and powered by a 1,200-volt supply. The third type is a 1,000-watt A-H12 mercury vapor lamp, equipped with a 1,000-watt transformer and fitted with a long-wave ultraviolet filter. A large Fresnel lens was used with this source to project the beam 10 to 15 feet.

A rough estimate of the number of ultraviolet lamps required for variously sized tunnels and models may be determined from the following table of E-H4 lamp units used to obtain satisfactory photographs of oil-film patterns. It is assumed that the beams are directed toward the test surface so as to give maximum ultraviolet-light intensity on a total area of from 1 to 2 square feet of the model.

Distance from ultraviolet source to model, ft	Number of E-H4 lamp units
1 to 2	1
3 to 4	2
5 to 7	3
8 to 10	4

More or less ultraviolet light may be desirable for any particular test setup. A few test photographs should be made to determine the most advantageous arrangement.

If possible, the ultraviolet lamps should be mounted so that the radiation streams in toward the model at an angle and minimizes the amount of ultraviolet light reflected back to the camera. Also, care should be taken to prevent lengthy exposure of the eyes and skin to ultraviolet light. Sun glasses or other ultraviolet absorbing lenses will afford protection for the eyes.

Photographing the flow patterns.- Normal photographic practices should be followed in taking pictures of the boundary-layer flow patterns. With presently available high-speed films and proper irradiation, very satisfactory results can be obtained with any camera suitable to the test setup. It is advisable to place a filter over the camera lens to absorb ultraviolet and visible blue light that might reach the camera directly from the ultraviolet lamp or by reflections. Filters such as the Kodak Wratten Filter Numbers 2A or 2B will serve the purpose. It is advantageous to use high-speed photographic film because of relatively low light values associated with fluorescence. With ultraviolet illumination approximately as described, excellent results have been obtained with Kodak Tri-X film in an Aircraft Type K-24 camera set at 3/4 second and f/4.0. Generally, the flow patterns must be observed and photographed while the tunnel is running, since the pattern will change while the tunnel is slowing down if the oil film is still reasonably fluid.

Examples of Applications

The present section describes some examples of the application of the fluorescent-oil film method in facilities of the Langley Research Center and presents some of the photographs that have been obtained. The nature of the flow indicated on most of these photographs is fairly evident. Interpretation of a given photograph may not always be simple; however, a comparison of photographs or observations of patterns for a range of, for example, angles of attack and Mach numbers will often provide the understanding that could not be uniquely deduced from only the single photograph. Experience in aerodynamics on the part of the experimenter is necessary in any case.

Tests in 1/15-scale model of the Langley full-scale tunnel.- Boundary-layer flow over an airfoil model in the open jet of the 1/15-scale model of the Langley full-scale tunnel was observed for an angle-of-attack range from 0° to 40° at tunnel velocities up to 120 feet per second. Kerosene containing about 1 percent of Fluorescent Green C.H. 185% dye (see appendix A) and fuel oil No. 2 containing about the same percentage of the oil-soluble fluorescent additive were both used successfully. One 100-watt E-H4 lamp unit located approximately 2 feet from the model provided adequate ultraviolet radiation to make the fluorescent flow patterns clearly visible.

Tests in Langley high-speed 7- by 10-foot tunnel.- Boundary-layer flow patterns on a wing were observed and photographed in the Langley high-speed 7- by 10-foot tunnel for a Mach number range from 0.6 to 0.92, with the angle of attack fixed for each test. The total time from the beginning of the test to the taking of the last photograph was approximately 15 minutes. The stagnation temperature of the free stream was of the order of 120° F. Gear oil (Navy Symbol 6135) thinned with about 25 percent of Penetone Formula 602 was painted on the clean metal wing model prior to the test. Ultraviolet light was provided by two B-H6 mercury arc lamps. An Aircraft Type K-24 camera set at 3/4 second and f/3.5 was used with Kodak Tri-X film. Lamps and camera were located outside a 1-inch-thick Plexiglas tunnel window, approximately 5 feet from the model.

Figure 1(a) shows a typical example of the patterns produced with the fluorescent-oil film method on the upper surface of a cambered and twisted sweptback wing at an angle of attack of 1° and a Mach number of 0.70. Over most of the forward part of the wing, the flow is laminar. A band of turbulence spreads rearward from the root leading edge. Turbulence wedges created by isolated roughness spots near the leading edge are clearly evident. At the tip a disturbance arising from the vortex is shown. The laminar and turbulent areas are clearly differentiated, and the transition line is easily traced. Figure 1(b) shows the indication obtained on the same wing at a Mach number of 0.90 and an angle of attack of 0°. The pattern is similar to that in figure 1(a), but a well-defined laminar separation bubble is now apparent along the 60-percent-chord line. The flow reattaches behind the separation bubble with a turbulent boundary layer, as indicated by the fact that most of the oil has been wiped off. Some indications of the flow in the fuselage boundary layer also can be seen in this figure.

A different type of pattern appears in figure 1(c) which shows the flow on the wing for approximately the same conditions as in figure 1(b) but with a transition strip added along the 30-percent-chord line. The outline of the wing is not clear at the leading edge, where the high surface shear scrubs off the oil. The effect diminishes in the chordwise direction. Behind the transition strip fine streams of oil flowing back from the roughness particles outline the streamlines at the base of the turbulent boundary layer. A shock extending outward from the wing-fuselage juncture results in separation over the inboard region but only a sharp deflection of the boundary layer over the mid-semispan region. A second, weaker shock may also be noted outboard. Figure 1(d), which shows the pattern obtained a few minutes later, is of interest in that it shows a larger separated region than is shown in figure 1(c). Thus, in general, an additional minute or two may be needed to develop fully a flow pattern after the main essentials of the flow pattern have been established.

Tests in Langley 8-foot transonic pressure tunnel.- The photographs shown in figure 2, which were taken in the Langley 8-foot transonic pressure tunnel, are excellent examples of a practical use of the fluorescent-oil film method. The investigation during which the photographs were taken (see ref. 6) was made in order to study a proposal (the addition of bodies to the wing) for delaying the initial drag rise associated with shock-induced boundary-layer separation on a wing at moderate lift conditions. The location and magnitude of this separated area on the original wing was quickly revealed by the fluorescent-oil film pattern shown in figure 2(a) for a Mach number of 0.90. The separated area extended over most of the rear half of the wing. As shown in figure 2(b), the addition of bodies to the upper surface of the wing greatly alleviated this separation. The fluorescent-oil film method was an invaluable aid in determining the effects of these additions and in arriving at an optimum configuration. Marked reductions in transonic drag, a delay in the drag-rise Mach number, and greatly improved stability characteristics were associated with the improved flow.

The models shown in the photographs of figure 2 were painted with zinc chromate before flow visualization was attempted in order to cover wooden additions, patches, and fillings. One application of oil, spread on with a clean soft brush, was sufficient for observing and photographing flow patterns at Mach numbers of 0.85, 0.88, 0.90, 0.92, and 0.95 without the necessity of shutting down the tunnel between test points. The length of time required to bring the tunnel up to the desired speed, to wait for the flow patterns to form fully (2 to 3 minutes) at each test point, and to take photographs was approximately 20 minutes. The fluorescent liquid used was gear oil (Navy Symbol 6135) augmented with a small amount (1 part in 50) of Fluorescent Green C.H. 185% dye. (See appendix A.) This liquid worked satisfactorily, undiluted, in the 120° F to 125° F stagnation-temperature range of the tunnel. Four air-cooled B-H6 mercury arc lamps were mounted outside the 1-inch-thick glass test-section windows (approximately 5 feet from the model). The lamp boxes were arranged so that ultraviolet radiation streamed in toward the model at an angle of approximately 30° to the normal from each side, forward, and rearward of the test configuration. An Aircraft Type K-24 camera was placed just outside the test section and alined normal to the plane of the wing. A Kodak Wratten Number 2B filter was placed over the lens. Kodak Tri-X film was used with camera settings of 3/4 second and f/4.0. This method also has been used successfully in the Langley 16-foot transonic tunnel where testing conditions are roughly comparable to those in the Langley 8-foot transonic tunnel.

Tests in Langley Unitary Plan wind tunnel.- The nature of the boundary-layer flow over the upper surface of a highly sweptback wing with transition fixed has been investigated through use of the fluorescent-oil film method at Mach numbers of 2.36 and 2.87 in the low-speed test section of the Langley Unitary Plan wind tunnel. Examples of the flow patterns observed are shown in the composite photographs of figure 3(a). The photographs were taken on Kodak Tri-X film with an Airplane Type K-24 camera set at 3/4 second and f/4.0. The gear oil with Fluorescent Green C.H. 185% dye was used in order to observe the flow patterns on the wing. The tunnel stagnation temperature was of the order of 100° F.

In another phase of the test, gear oil with Fluorescent Green C.H. 185% dye was used in order to observe the flow patterns on the left wing panel. Dow Corning 200 silicone fluid (1,000 centistokes) with a fine fluorescent powder (insoluble pigment) in suspension (see appendix A) was used in order to observe the flow patterns on the right wing panel. Two Airplane Type K-24 cameras were used to take the composite photograph shown as figure 3(b). At the start of the test, the viscosity of the two fluorescent mixtures was comparable to that of an SAE 60W lubricating oil at a room temperature of 75° F. During the test it was noted that the flow patterns formed and stabilized much more rapidly in the gear oil than in the silicone fluid. A characteristic of silicone is that it is much less affected by changes in temperature than is oil. The technique of putting oil on one panel and silicone on the other allowed the observer to visualize quickly the stabilized flow pattern in the oil and then concentrate on the manner in which the pattern was formed by watching the more slowly moving silicone fluid.

Tests in Langley 11-inch hypersonic tunnel. One recent group of tests was made successfully in the Langley 11-inch hypersonic tunnel at a Mach number of 6.9, a stagnation temperature of about 600° F, and a stream total pressure of 30 atmospheres. For these tests a mixture of the gear oil and SAE 40W lubricating oil containing some fluorescent additive was used. A few spots of graphite were placed in the oil near the leading edge of the model to facilitate the observation of the direction of the boundary-layer flow. The tunnel running time for these tests was from 30 to 40 seconds. Motion pictures were taken on 16 mm Kodak Tri-X film at 64 frames per second with a camera setting of f/3.5. Still pictures also were taken on 35 mm Kodak Tri-X film with camera settings of 1/100 second and f/4.0.

Tests in Langley tank no. 2.- The fluorescent-oil film method has been used to observe some of the characteristics of the flow about a surface under water. An experiment was made on a hydrofoil in the Langley tank no. 2 by using a technique similar to that used in the wind tunnels. SAE 30W lubricating oil was applied to the model before it was submerged in the water. The E-H4 lamp unit was attached to the towing carriage above the water and about 2 feet from the model; thus, during the test the lamp and the model together moved with the towing carriage, making possible observation of the development of the pattern during the test. The photograph shown in figure 4 was obtained after the hydrofoil was removed from the water at the end of a test. For this particular test the velocity was 13 feet per second and the water temperature was approximately 48° F. The dark curved line and the disturbed oil region at the 15- to 25-percent-spanwise location indicate the area where the model intersected the surface of the water when submerged. The thin oil film over the forward portion of the hydrofoil, the heavy accumulation of oil around the midchord region, and the almost complete absence of oil over the rear portion correspond, respectively, to laminar flow, laminar separation bubble, and turbulent flow. The large size of the separation bubble is indicative of the low Reynolds number (of the order of 150,000) of the test. Evidence of the tip vortex may be seen in the pattern where the oil has been scrubbed away from the hydrofoil tip.

In another phase of this test, a pattern of oil spots was put on the surface of the model with a small daub. The purpose was to define more distinctly the lateral and forward (that is, reversed-flow) boundary-layer movement. As the hydrofoil was moved through the water, thin lines of oil streaming from these spots revealed the looked-for direction of the boundary-layer flow. This technique of applying small spots of oil has previously been found useful in the tests reported in references 7 and 8.

There is every indication that the flucrescent-oil film method can be a useful tool in the study of the flow over all kinds of submerged surfaces. In selecting the oil for use under water, consideration must be given to the water temperature, which may undergo appreciable seasonal variations with corresponding variations of oil viscosity. It should be remembered, however, that in many hydrodynamics tests the acceleration time is very short or essentially absent (as when the model is lowered to the water after the desired speed has been attained); also, only a single condition may be studied per test. For such cases, the simple ink-flow method (with oil and lampblack, or oil and titanium white) may be adequate.

Tests in other laboratories.- The fluorescent-oil film method for boundary-layer flow visualization has been brought into satisfactory operational use at other research facilities since the initial studies of the method were made at the Langley Research Center. Reference 9 describes the application of this method at the Southern California Cooperative Wind Tunnel. The report also includes an oil-selection chart, presented in terms of tunnel stagnation temperature and tunnel dynamic pressure, to aid in the application of the method.

OTHER FLOW-VISUALIZATION METHODS

The following sections discuss some other flow-visualization methods and describe some brief experiences with them. All of the methods have, at least in principle, these basic characteristics: (1) They permit observation at several test conditions during a single test, and (2) they are adaptable to the large high-powered wind tunnels which require considerable time to reach the desired test conditions. As will be seen, not all are equally promising or equally practical; furthermore, experience with some of the methods has been so slight that their inclusion here constitutes little more than a suggestion. Not all methods are basically capable of showing the same flow characteristics. Some, such as the well-known evaporation method, leave much to inference since they cannot indicate local-flow direction. Some, which depend only on surface-temperature indications, leave even more to inference.

Repeated Application of the Indicating Fluid

Spraying during the test.- Obviously, if a technique existed for spraying, for example, a light fluorescent liquid over the model while the tunnel is running, the pattern would develop quickly and, furthermore, any number of different test conditions could be viewed during a single test. As a simple check of the basic spraying operation, a spray bar was made up and tested, along with a wing model, in a 4- by

8-inch open jet. (See fig. 5.) The spray bar consisted of a somewhat flattened tube with several short tubes, or nipples, brazed to one side. Each nipple had two fine holes drilled in the side where the aerodynamic suction could draw out the fluid. The spray bar was mounted a few inches in front of the wing and could be swung out of the way after the model had been sprayed. The spray bar worked very well. The aerodynamic suction drew out the fluid in a fine spray that covered the wing thoroughly for a total withdrawal of only about 1 or 2 ounces of fluid from the reservoir.

With regard to applying the scheme in a large wind tunnel, a design study made for the Langley 8-foot transonic tunnel indicated that it might be very practical to attach a remotely controlled spray bar to the main sting support behind the model and to actuate the spray bar so that it could move forward to a position just ahead of the model, spray the model, and then withdraw. A device such as this was built, installed, and operated successfully at all test Mach numbers up to the maximum speed of the tunnel (approximate Mach number, 1.2). The spray bar was similar in design to the one used in the 4- by 8-inch open jet just mentioned previously. In figure 6(a) the spray is shown coming from the nipples on the spray bar and coating the wing with a thin film of oil at a Mach number of 1.0. For this particular test, the liquid used was a half-and-half mixture of gear oil (Navy Symbol 6135) and fuel oil No. 2 with Fluorescent Green C.H. 185% dye added. Only a few ounces of liquid were required for each spraying. One spraying with this diluted mixture was sufficient to enable photographs to be taken of the flow patterns at three or four different angles of attack. Figure 6(b) shows the boundary-layer flow pattern obtained on the wing for an angle of attack of 6° and a Mach number of 0.90.

If such a spray-bar mechanism is used in conjunction with a force test, it will be necessary either to verify that the mechanism does not affect the aerodynamic forces acting on the model or to determine the effect of the mechanism on the forces. Another type of retractable spray mechanism is discussed in reference 10. Spraying from a location far upstream, as in the big end of a contraction cone, might simplify the engineering but would require large quantities of the fluid.

<u>Fluorescent liquids adapted to the spraying technique</u>.- The fluorescent oils, of course, are ideally adapted to the spraying technique and give brilliant patterns. Since the oil is not required to remain on the model during the tunnel accelerating period, the very heavy oils are not needed. They may, nevertheless, be used since experience with the spray bar indicated that they spray and cover the model practically as well as do the lighter oils.

Some tests in the 4- by 8-inch open jet were also made with a solution of fluorescein in alcohol containing some glycerine and a wetting agent (aerosol). This solution, although brilliantly fluorescent, did not wet the metal surface of the model very well and ran along the surface in irregular rivulets. The solution might successfully wet other types of surfaces, however, since a similar solution (except for the fluorescein) has been used successfully in a different method of flow visualization (ref. 11).

Incidentally, a modification to this method of reference 11 may be of interest. The method, as described in the reference, consists of spraying the solution of alcohol, glycerine, and aerosol on a black-painted model surface, then running the tunnel for a time judged long enough to dry the film in the turbulent area but not in the laminar area, and finally stopping the tunnel and dusting a white powder on the model. The powder adheres where the film is still wet and provides a clear pattern that remains on the model indefinitely. It is suggested that if a small amount of fluorescein were added to the solution, the drying process might be easily observed under ultraviolet light since the fluorescence ceases when the solvent evaporates.

Nonfluorescent liquids adaptable to the spraying technique.- The china-clay (evaporation) method and the ink-flow method also seem adaptable to the spraying technique. For example, some tests in the 4- by 8-inch open jet were made in which the wing, first coated with china clay, was sprayed with kerosene by means of the spray bar. A clear evaporation pattern quickly developed and then disappeared completely. A similar technique was used in the flight tests reported in reference 12. Kerosene was ejected from nozzles on the lower surface near the leading edge and allowed to flow back over the china-clay-coated upper surface of the wing.

If an ink, such as kerosene and lampblack or kerosene and titanium dioxide, were used the china-clay coating would be unnecessary since the ink is visible without such an aid. No ink-flow tests were made with the spray bar; however, in the work of reference 10 a type of ink solution used in connection with a spray mechanism is discussed.

In the work of reference 13 an ink solution was ejected from the surface pressure orifices that already existed in the model. This technique which is a variation of the spraying technique has been most useful, although, of course, it can be applied only with those relatively uncommon models that are well equipped with pressure orifices.

Use of indicating gases with the spray bar.- One test with a chemical indicator was made in the 4- by 8-inch open jet already mentioned.

The wing model was coated with china clay and then painted with a solution containing the following:

Bromcresol purple	0.1 g
Alcohol	10 ml
Water	10 ml
Glycerol	1 ml
Phosphoric acid	1 drop

A similar solution was used in related studies reported in reference 14. The indicator is yellow in an acid medium and blue in an alkaline medium. Because of the phosphoric acid the model appeared yellow. When gaseous ammonia was passed over the model by means of the spray bar, the model turned blue. When the ammonia was turned off and the spray bar moved aside, the model color returned to yellow as the absorbed ammonia was released and carried off. The surface became yellow first in the turbulent areas, and a well-defined transition pattern appeared, but this pattern lasted for only a few moments before the entire wing surface was yellow. The air speed for this test was about 300 miles per hour. Different proportions, possible with less acid or with no acid, might be better for other speeds or even for this speed.

The air flow in this jet does not recirculate but is captured and passed outside of the laboratory. For the usual closed-return wind tunnel the question would arise as to how much ammonia might be put into the airstream before the model surface ceases to return to the original clear yellow color or before the working area becomes unpleasant.

Temperature-Sensitive Fluorescent Paint

A temperature-sensitive (thermographic) phosphor is available (see ref. 15) which can be made up into a paint. The fluorescence intensity of this material, when painted on a surface and observed under ultraviolet light, is sensitive to small changes in temperature. According to the manufacturer, the brightness decreases approximately 20 percent per degree centigrade of increase in temperature in the range between 20° C and 50° C under optimum ultraviolet illumination. Accordingly, it should be possible to detect the difference between laminar and turbulent flow over such a phosphor-painted surface because the recovery temperatures (equilibrium surface temperatures) are different for the two types of boundary layers. Reference 4 reports some similar research and shows a photograph in which the turbulent areas are recognizable but are not sharply delineated. Present experiences similarly tend to be disappointing with regard to the sharpness of the transition line, particularly on metal models where heat transfer within the model tends to equalize the temperature and to diffuse temperature boundaries.

A better approach is to use the fact that the rate of heat transfer from a turbulent boundary layer is much higher than that from a laminar boundary layer. If, for example, the model is appreciably cooler than the equilibrium temperature, heat transfer into the surface will cause the surface under the turbulent layer to be considerably warmer than the surface under the laminar layer. In such circumstances, distinct patterns have been observed. Figure 7 shows, for example, some patterns observed at subsonic speeds in the previously mentioned 4- by 8-inch open jet. The sequence photographs of figure 7 are frames of a motion picture taken on 16 mm Kodak Tri-X film at 16 frames per second with a camera setting of f/2.4 and a Kodak Wratten Filter Number 8 (K2-Yellow) over the lens. The jet was accelerating during the test and, correspondingly, continuously increasing its stagnation temperature. The model temperature thus lagged behind the equilibrium temperature, and clear patterns could be obtained. Each transition wedge would appear suddenly and somewhat dramatically when the local roughness Reynolds number at the particular surface imperfection exceeded the critical value.

In the larger continuously operating tunnels, the same effect can be obtained, but not so sharp, by suddenly cutting off the tunnel cooling system. The tunnel stagnation temperature does not rise very rapidly in this case; nevertheless, under favorable circumstances an adequate lag of the model temperature behind the equilibrium temperature may develop. The photograph shown in figure 8 was obtained in this way in the Langley Unitary Plan wind tunnel at a Mach number of 2.3. The missile model had four highly sweptback fins. A transition wedge, indicated by the dark region above and below the side fin, was produced by the disturbance from the leading edge of the fin-body juncture.

A further development has been made toward the application of the phosphor to a surface. A phosphor-painted decal (thermographic decal screen - type TH-1) is now available which, if it can be successfully applied to the types of test surfaces used on wind-tunnel models, will eliminate the troublesome job of spray painting. (See ref. 15.) Spray painting demands considerable care and experience if a smooth uniform coating, free of transition-producing specks, is to be obtained.

Radiometer

A Model R-8B2 Research Radiometer manufactured by Barnes Engineering Company, 30 Commerce Road, Stamford, Connecticut, has been used in preliminary tests to determine the location of boundary-layer transition and flow separation on a test model. The radiometer, which measures the far-infrared radiation from a surface, is claimed to be capable of detecting temperature differences of as little as 0.04° F at room temperature. The model tested was a plastic wing which was painted flat black and mounted in the previously mentioned 4- by 8-inch open jet. The optical head of the radiometer was focused on the test surface from a distance of 12 feet. A bore-sighted telescope with cross hair, mounted on the side of the optical housing, was used to train the equipment on any predetermined spot or to aid in traversing any scan line on the model. The temperature pattern over the model was obtained from both vertical and horizontal (spanwise and chordwise) scans of the surface. A Brown self-balancing recording potentiometer was used to obtain a record of the infrared radiation received by the instrument. Data from two traverses of a given scan line are shown in figure 9. The abrupt change in radiation level indicated at points A, B, and C in the records corresponds to passing from a laminar to a turbulent area or from a turbulent to a laminar area. It was possible, by traversing along systematically spaced scan lines, to map the complete transition pattern of the wing, including several transition wedges. The pattern was in excellent agreement with that obtained by the fluorescent-oil film method on the same wing model.

For a typical test condition (see fig. 9) with the wing at an angle of attack of 2° and a Mach number of 0.90, calculations based on the emissivity of the black-painted plastic wing model and the sensitivity of the radiometer and recorder indicated that the change in radiation level, in going from laminar to turbulent areas (indicated by the difference between L and T in the figure), corresponded to a temperature change of 2.7° F. Calculations of the difference in temperature between the two types of boundary layer for the nonconductive plastic wing also gave 2.7° F, based on the test conditions and theoretical recovery factors of the square root of the Prandtl number and the cube root of the Prandtl number for laminar and turbulent boundary layers, respectively.

The radiometer also appeared to indicate regions of separated flow on the wing panel at a high angle of attack and a Mach number of approximately 0.75. The measured infrared radiation level was lower in the separated-flow region than in the attached-flow region. The separated-flow region had been previously identified by means of the fluorescent-oil film method. The degree and sharpness of the temperature change at the edge of the separated-flow region were not as pronounced as at the transition line between laminar and turbulent regions.

As already noted, these studies with the radiometer were all made with the model mounted in an open-throat tunnel. For observation of a model in a closed-throat wind tunnel, the tunnel would have to be provided with a special window transparent to the far-infrared rays. The radiometer might possibly also be adapted to flight studies, with the instrument mounted in the fuselage and arranged to survey the wing surface through a window transparent to the infrared rays.

CONCLUDING REMARKS

A simple and dependable flow-visualization technique, the fluorescent-oil film method, has been described and its usefulness demonstrated with examples. The technique is suitable for indicating transition, flow direction, shock-wave position, and separation. The method is especially adapted to use in large high-powered wind tunnels which require considerable time to reach the desired test conditions.

Other methods have been discussed which show promise of being useful in the study of boundary-layer conditions. These methods include a temperature-sensitive fluorescent paint and a far-infrared-sensitive radiometer. Some attention has also been given to methods that can be used with a retractable spray apparatus in front of the test model. Materials used with the apparatus include oils and chemical indicators.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Field, Va. October 23, 1958.

APPENDIX A

A PARTIAL LIST OF FLUORESCENT ADDITIVES AND SOURCES OF SUPPLY

Oil-Soluble Additives

Fluorescent Green C.H. 185% dye
Wilmot and Cassidy, Inc.
108-112 Provost Street
Brooklyn 22, N. Y.

BLAK-RAY Fluorescent Oil additive No. DF-502
Ultra-Violet Products, Inc.
5114 Walnut Grove Avenue
San Gabriel, Calif.
(The properties of this additive are similar to those of the Fluorescent Green C.H. 185% dye.)

Glo-Craft Boundary-Layer Fluorescent Concentrate No. 123-310
Switzer Brothers, Inc.
4732 Saint Clair Avenue
Cleveland 3, Ohio
(This concentrate may be used either full strength or in solution in other oils.)

Silicone-Soluble Additive

BLAK-RAY Silicone additive No. DF-518
Ultra-Violet Products, Inc.
5114 Walnut Grove Avenue
San Gabriel, Calif.

Insoluble-Pigment Additive for Silicone

Glo-Craft Boundary-Layer Fluorescent Concentrate No. 116-1629
Switzer Brothers, Inc.
4732 Saint Clair Avenue
Cleveland 3, Ohio
(This concentrate is in the form of a thick paste.)

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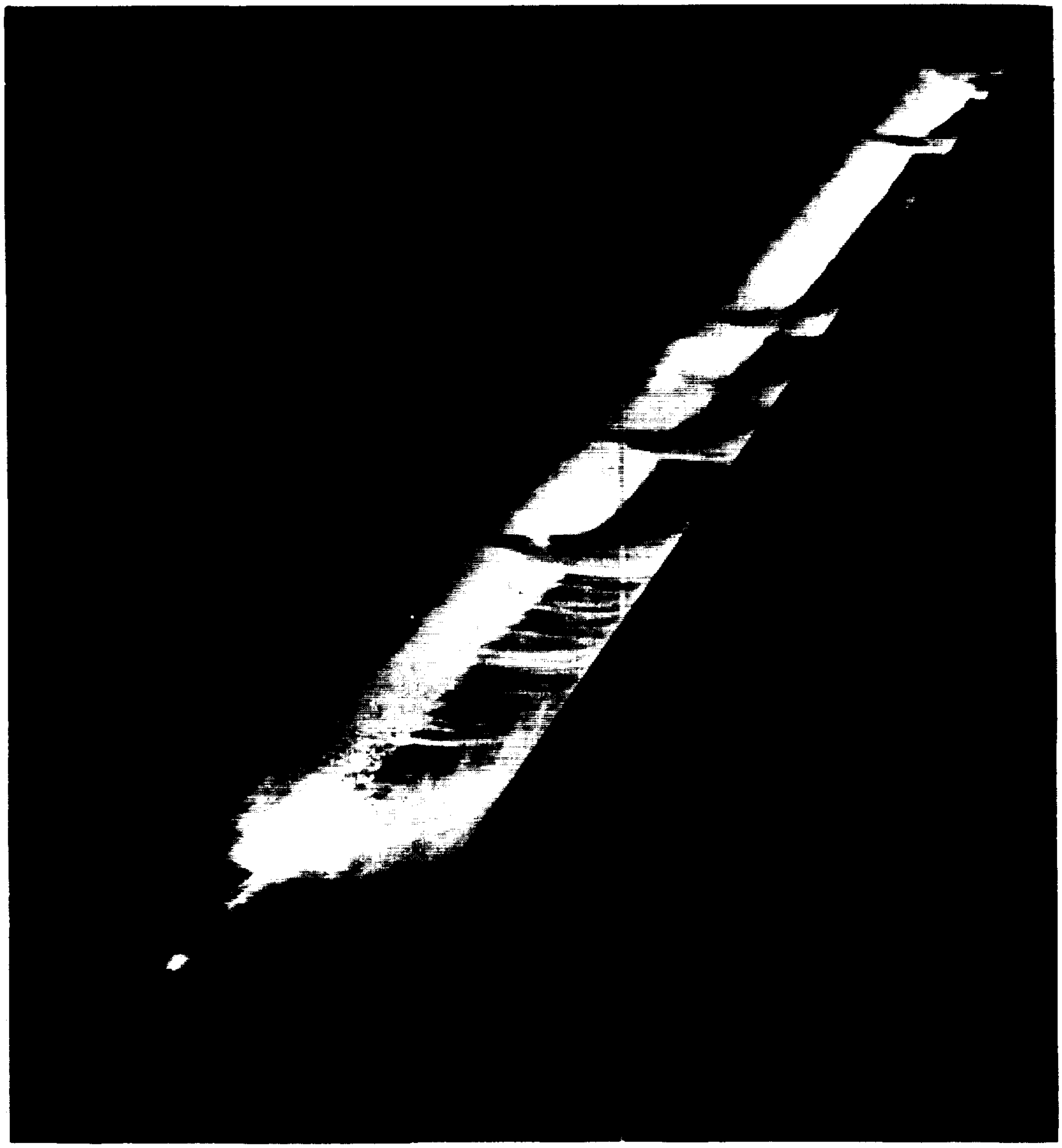


L-58-143a

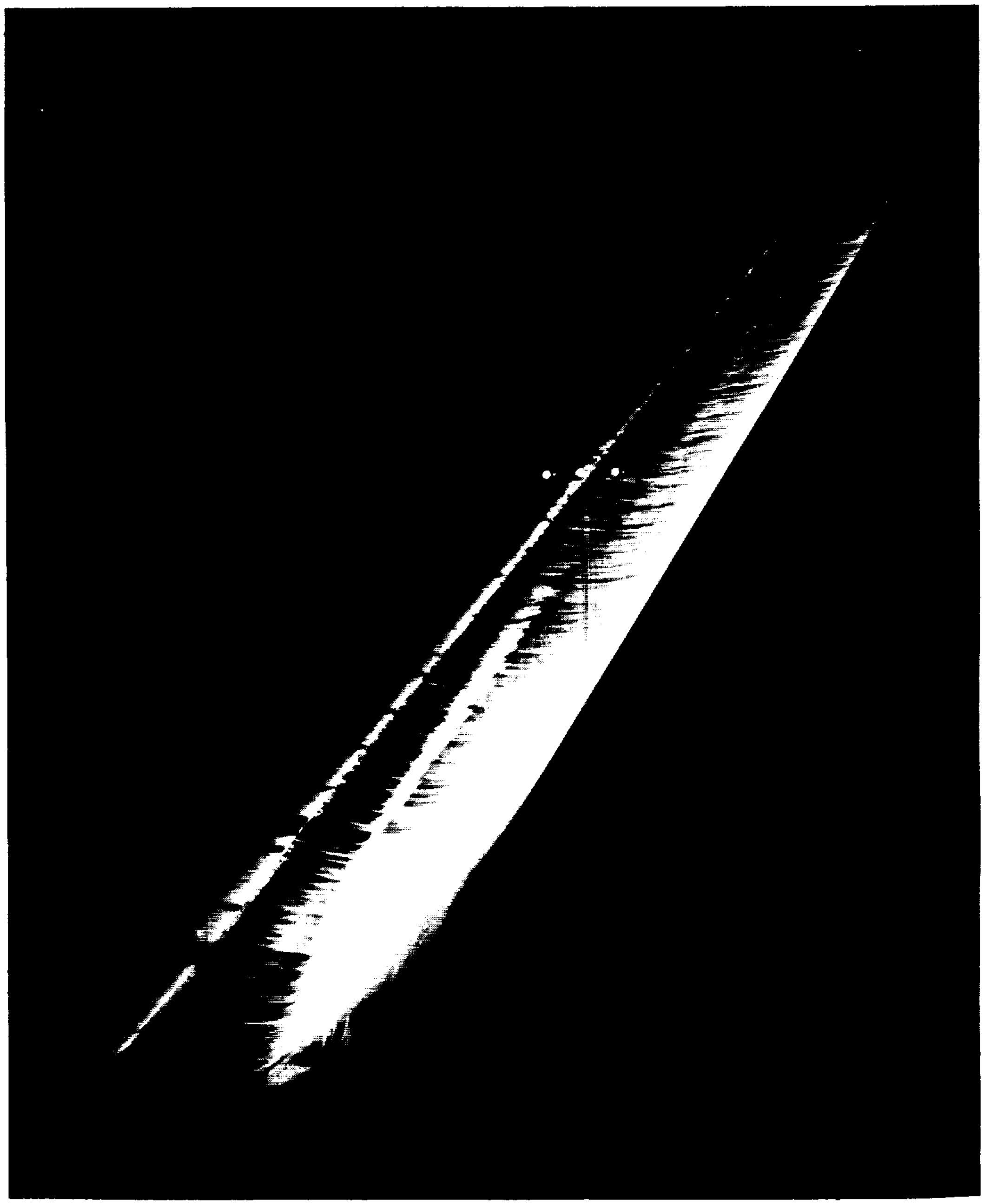
(a) Angle of attack, 1°; Mach number, 0.70; transition natural.

Figure 1.- Fluorescent-oil film pattern on surface of cambered and twisted 40° sweptback-wing model in the Langley high-speed 7- by 10-foot tunnel.

L-58-144a

(b) Angle of attack, 0°; Mach number, 0.90; transition natural.

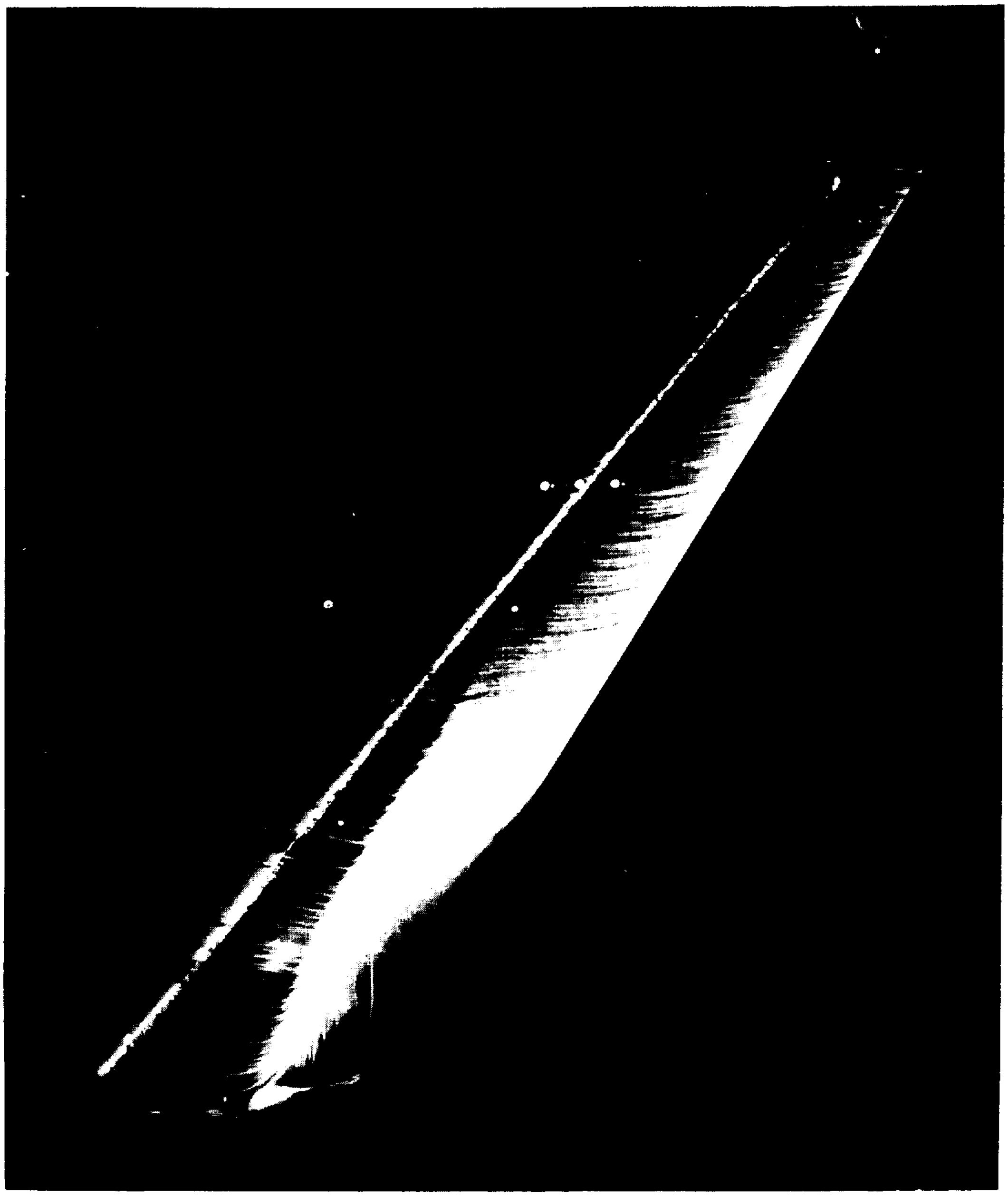
Figure 1.- Continued.



L-58-145a

(c) Angle of attack, 0°; Mach number, 0.90; transition fixed at 30-percent-chord line.

Figure 1.- Continued.



L-58-146a

(d) Angle of attack, 0°; Mach number, 0.90; transition fixed at 30-percent-chord line. (Photograph taken a few minutes later than photograph in fig. 1(c).)

Figure 1.- Concluded.

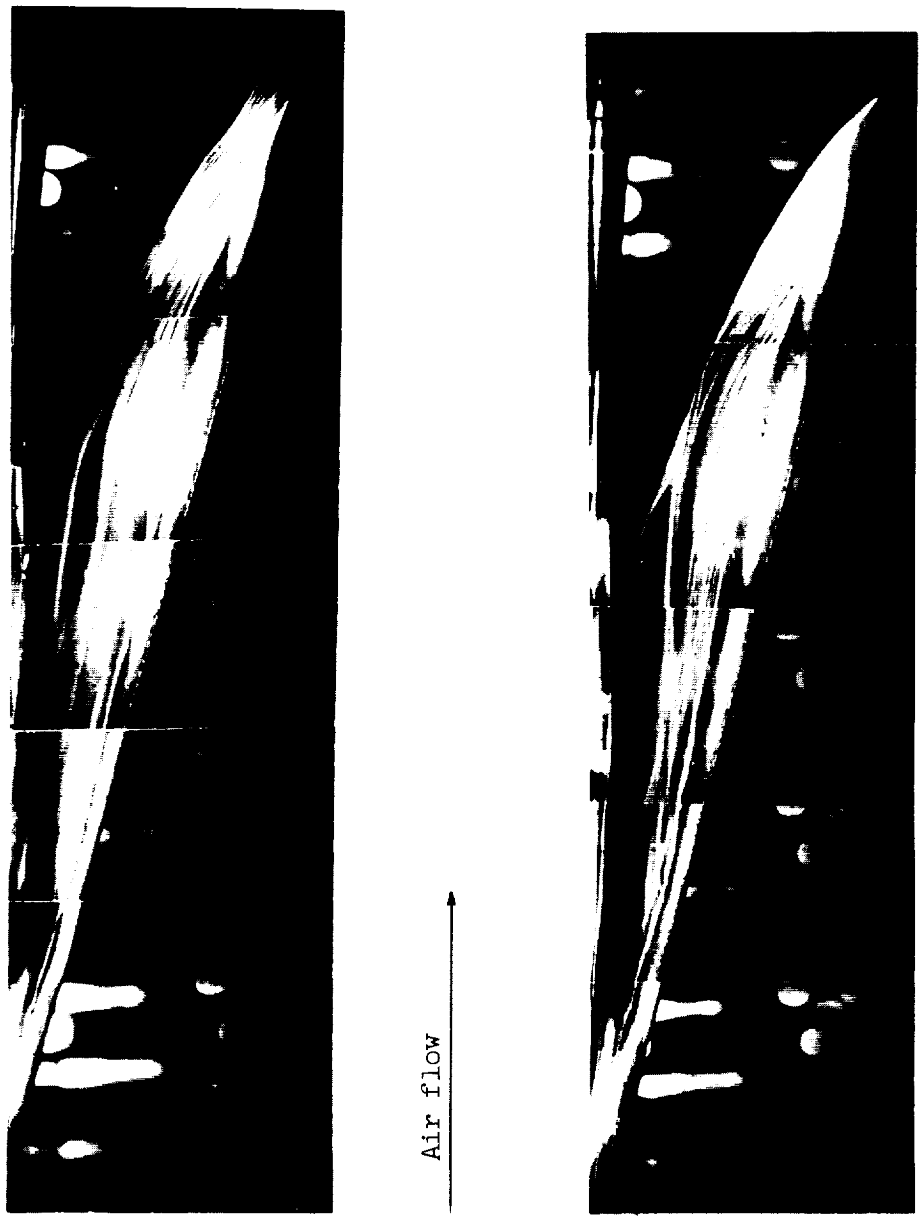
L-58-147a

(a) Original wing.

Figure 2.- Fluorescent-oil film pattern on surface of cambered 35° sweptback-wing model in the Langley 8-foot transonic pressure tunnel. Angle of attack, 3.7°; Mach number, 0.90; transition fixed at 10-percent-chord line.

(b) Bodies added to wing. L-58-148a

Figure 2.- Concluded.

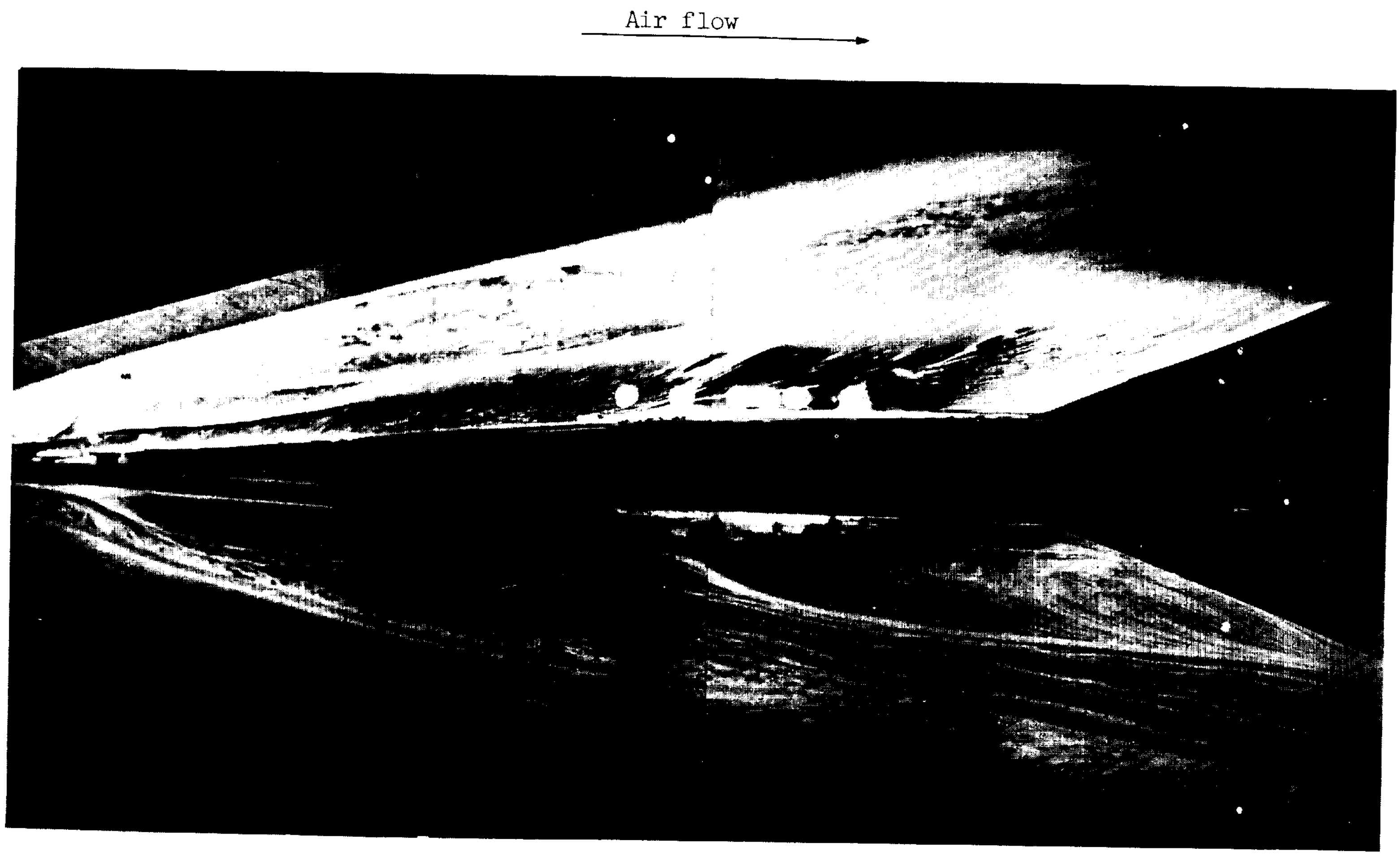


Mach number, 2.36 Mach number, 2.87

L-58-149a

(a) Oil on left wing panel; transition fixed near leading edge.

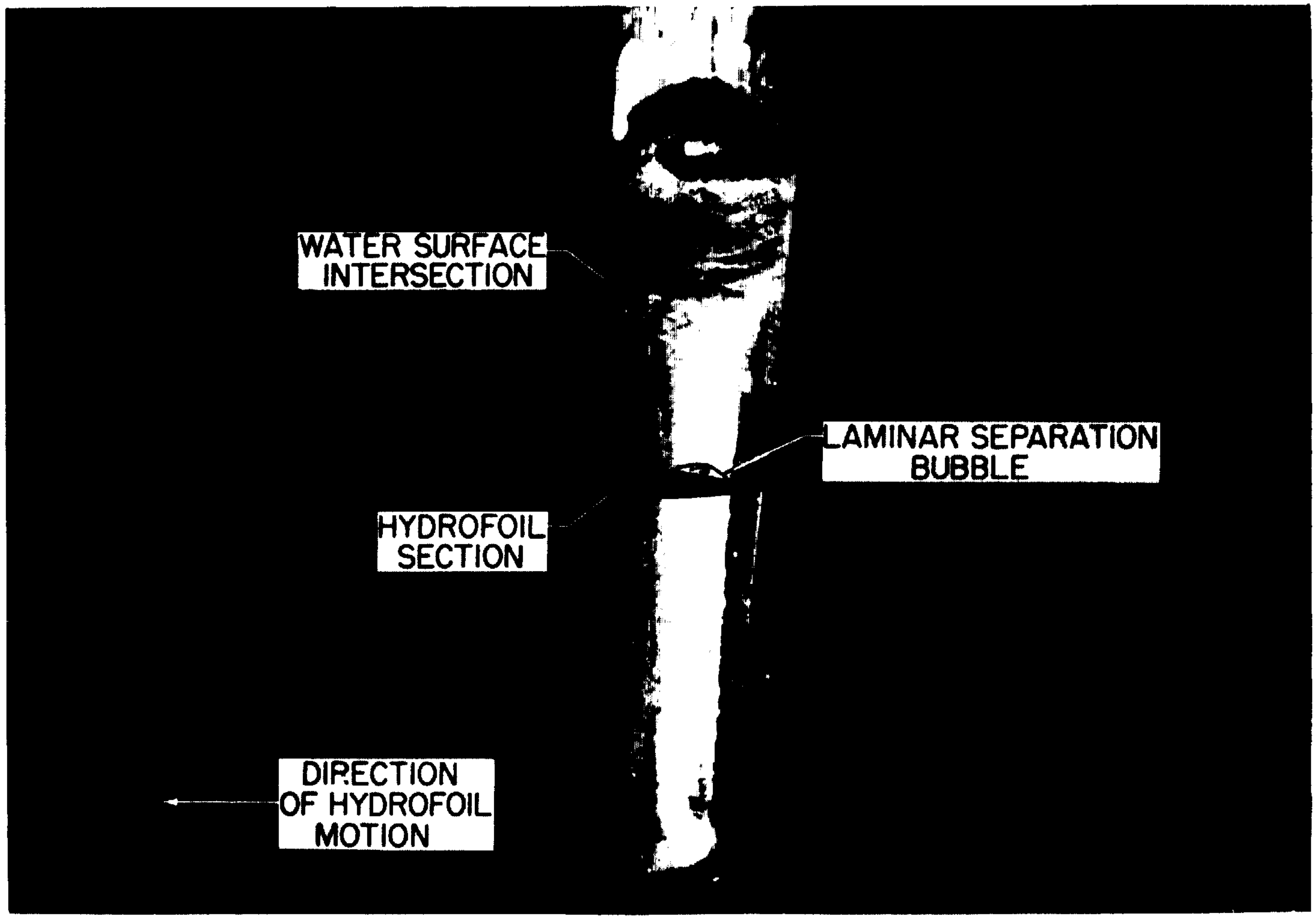
Figure 3.- Fluorescent-oil film pattern on surface of cambered and twisted 70° sweptback-wing model in the low-speed test section of the Langley Unitary Plan wind tunnel.



L-58-150a

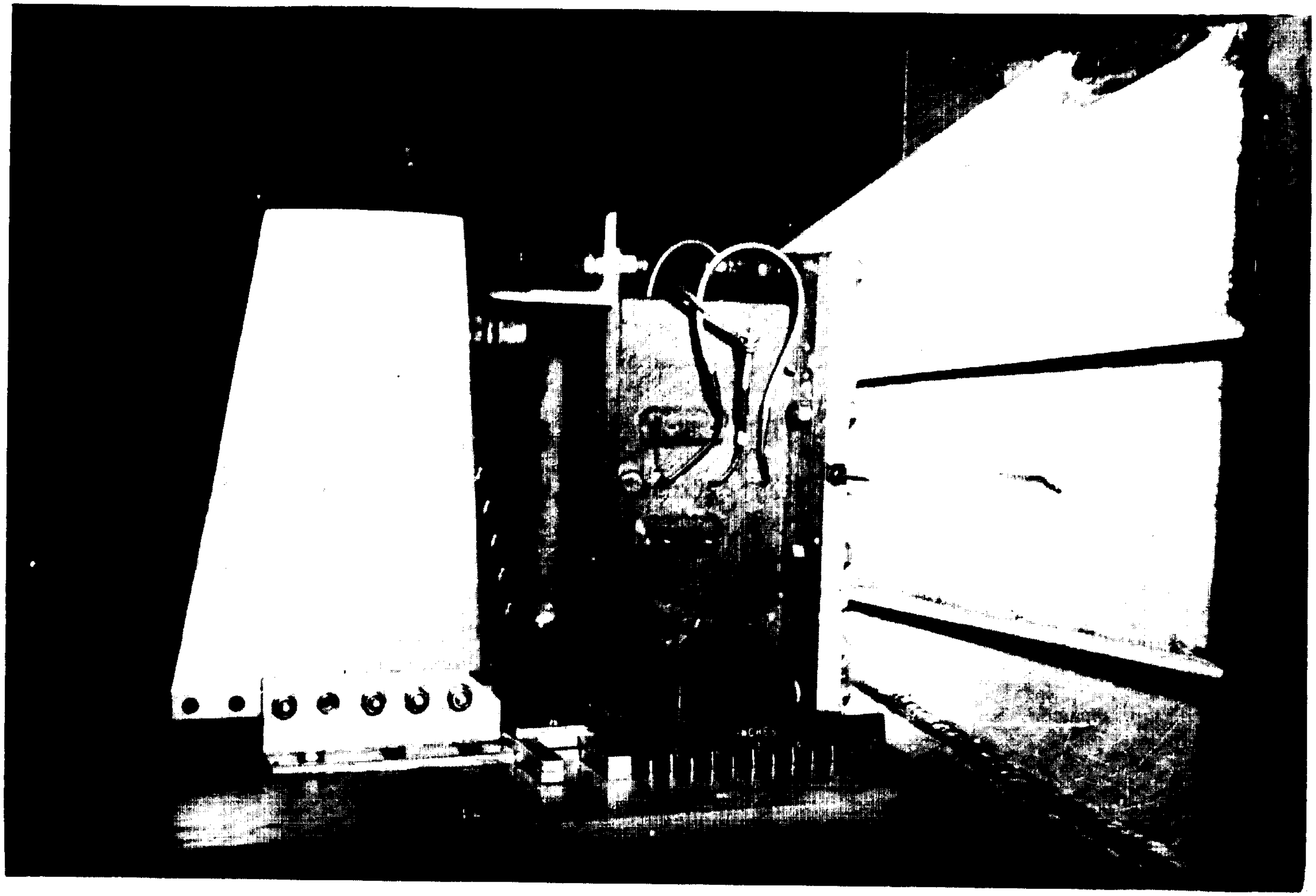
(b) Mach number, 2.87; oil on left wing panel; silicone fluid on right wing panel; transition natural.

Figure 3.- Concluded.



L-58-151a

Figure 4.- Fluorescent-oil film pattern on surface of cambered and twisted $12^{\circ}22'$ sweptforward-hydrofoil model with 33° of negative dihedral after underwater test in the Langley tank no. 2. Angle of attack, 5°; velocity, 13 ft/sec; transition natural.



L-96711
Figure 5.- Removable spray bar and wing model mounted in a 4- by 8-inch open jet.

L-58-156a

(a) Angle of attack, -4°; Mach number, 1.0; transition fixed at 10-percent-chord line; wing being sprayed from extended spray bar. (Shaded area near midspan is caused by spray-bar shadow.)

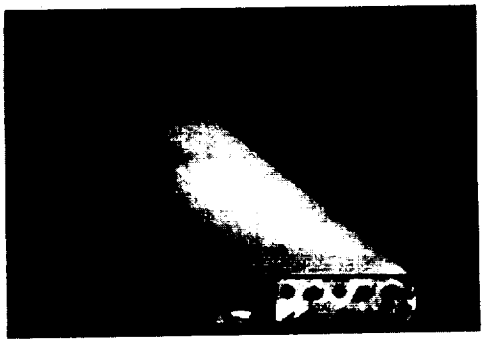
Figure 6.- Use of retractable spray bar in Langley 8-foot transonic tunnel.

Air flow

L-58-157a

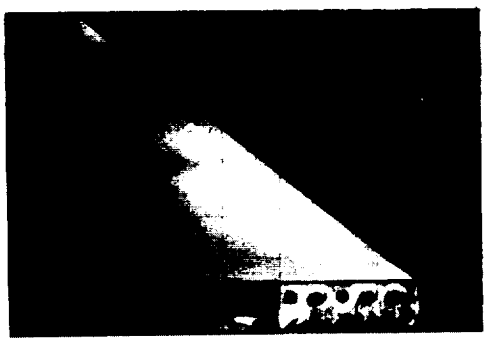
(b) Angle of attack, 6°; Mach number, 0.90; transition fixed at 10-percent-chord line; fluorescent-oil film pattern on surface of wing after model was sprayed and spray bar retracted.

Figure 6.- Concluded.



Approximate Mach number, 0.65

Approximate Mach number, 0.80



Approximate Mach number, 0.70

Approximate Mach number, 0.85

Approximate Mach number, 0.75

Approximate Mach number, 0.90

(a) Interval between successive Mach numbers, 6.5 seconds.

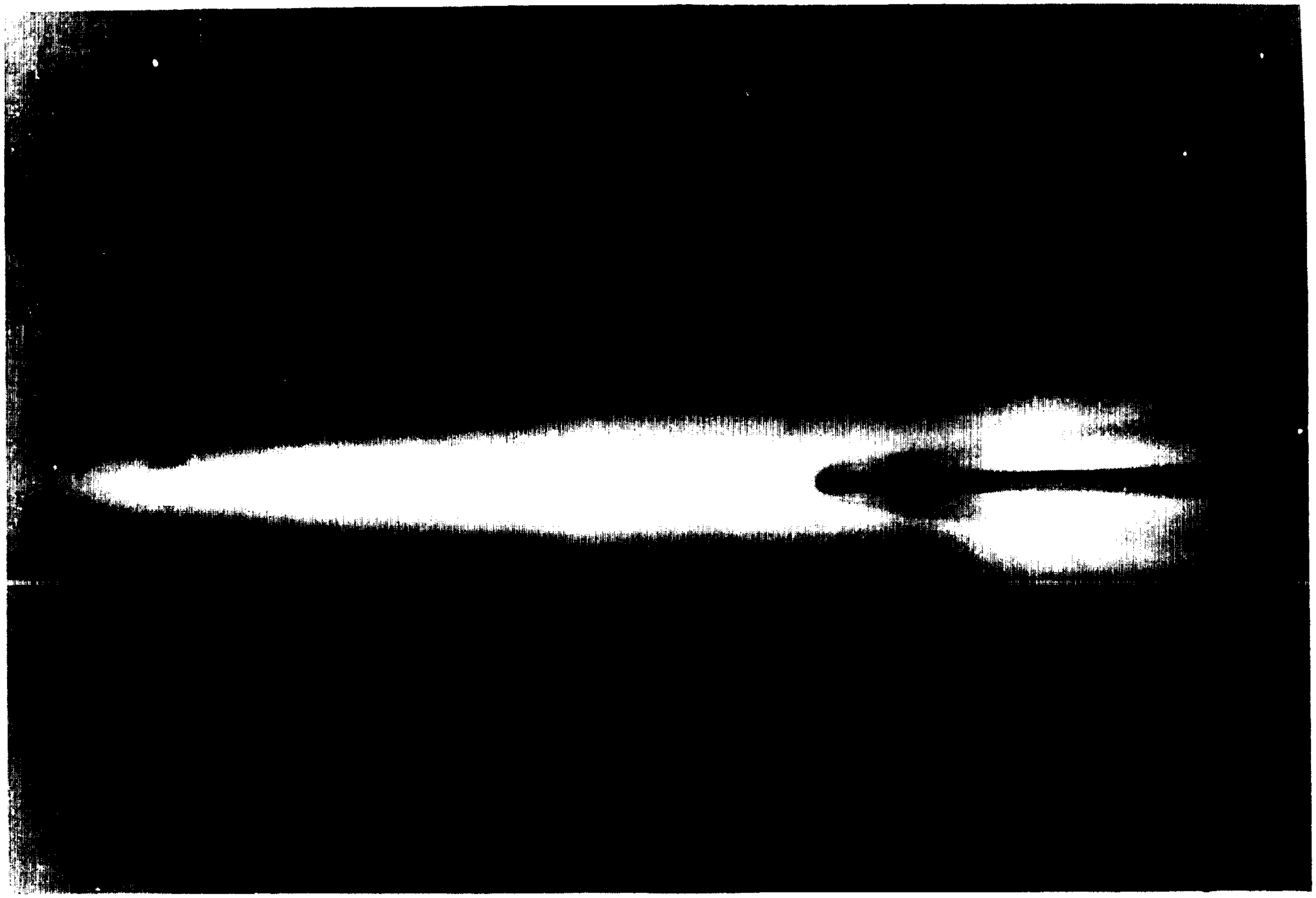
L-58-152a

Figure 7.- Sequence photographs of transition patterns in temperature-sensitive fluorescent paint on lower surface of 45° sweptback-wing model in a 4- by 8-inch open jet. Angle of attack, 2°; transition natural.

L-58-153a

(b) Approximate Mach number, 0.80. Interval between successive frames (beginning at top left photograph and reading down), 0.5 second.

Figure 7.- Concluded.



L-58-154a

Figure 8.- Temperature-sensitive fluorescent paint patterns on surface of a missile model with four highly sweptback fins in the Langley Unitary Plan wind tunnel. Angle of attack, 0°; Mach number, 2.30; transition natural.

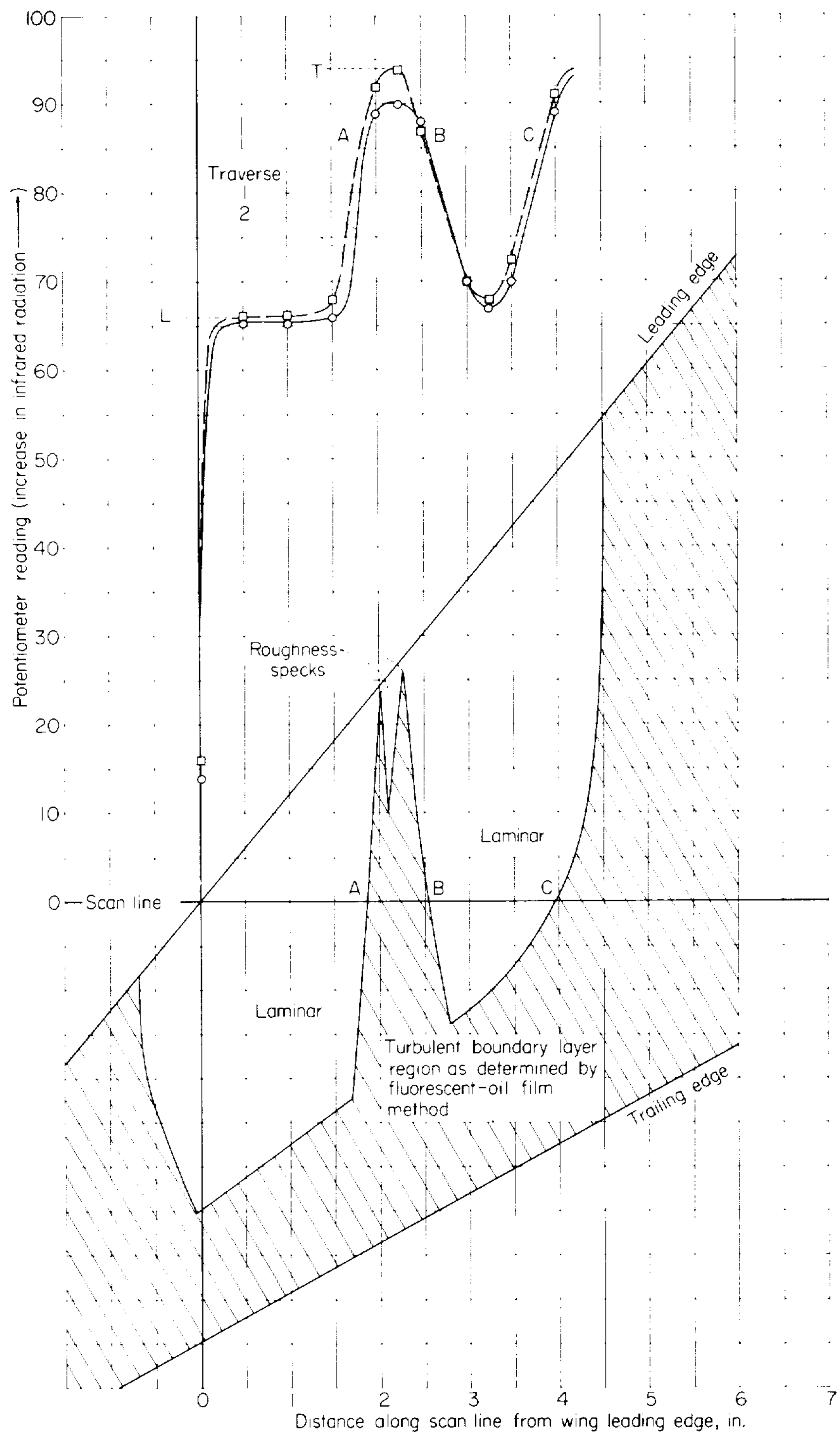


Figure 9.- Sketch of transition pattern on wing model (fluorescent-oil film method) and radiometer traverse records for one scan line. Lower surface of 45° sweptback-wing model in a 4- by 8-inch open jet. Angle of attack, 2°; Mach number, 0.90; stagnation temperature, 195° F. L and T indicate readings that correspond to radiation from laminar and turbulent areas, respectively.