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THE USE OF A LUMINESCENT LACQUER FOR THE VISUAL
INDICATION OF BOUNDARY-LAYER TRANSITION

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SUMMARY

A method is presented for the visual indication of boundary-layer transition by use of a luminescent lacquer. The method consists of spraying a thin, uniform film of lacquer containing a phosphor pigment on the model and irradiating the model with ultraviolet light. The phosphor used has the property of fluorescing with a bright yellow, light when dry and remaining dark when wet. Since the drying time (or evaporation rate) is different for laminar and turbulent boundary layers, patterns of light and dark areas are established which identify the type of boundary layer and, consequently, the location of transition from laminar to turbulent flow. The contrast between the light and dark regions is pronounced and good photographs of the patterns may be obtained. Usually, special preparation of the model surface is not required.

INTRODUCTION

In many wind-tunnel investigations it is necessary, or at least desirable, to be able to determine visually the type of boundary-layer flow (laminar, turbulent, or separated) and the location of the region of transition from one type of boundary-layer flow to another. There are various methods for visual indication of boundary-layer transition that have been used successfully. It is the object of this report to present a new method that has been developed by the Ames Aeronautical Laboratory.

Most methods of indicating boundary-layer transition depend on the differences in mass-transfer rates (evaporation rates) through laminar, turbulent, and separated boundary layers. When a thin, uniform layer of a volatile liquid is deposited on a surface and air flow established over it, the liquid will evaporate at different rates in different areas with the result that certain areas become dry, while others remain wet.

Interpretation of the patterns thus established requires knowledge of the relative mass-transfer rates with various kinds of boundary-layer flow.

According to the analogy between mass, momentum, and heat transfer, all three quantities are proportional to each other (reference 1). Thus, the observer need be familiar only with heat transfer or momentum transfer to analyze the film patterns established by the mass-transfer process. As an example, consider a flat plate in parallel flow with a laminar boundary layer existing to the 50-percent chord where transition to a turbulent boundary layer occurs. The relative local mass-transfer rates would be of the form shown in figure 1. The local heat-transfer or momentum-transfer rates would be of the same form. Thus, the film would dry first at the leading edge and a short time later at the point of transition. The drying would proceed toward the rear of the plate with the turbulent portion drying more quickly than the laminar portion.

In the china-clay lacquer method developed by Richards and Burstal (reference 2), a thin layer of china clay suspended in lacquer is sprayed on the model which, when dry, gives a smooth white absorbent film. The white film becomes transparent when sprayed with a volatile liquid having the same index of refraction as the china clay. As the liquid evaporates, the china-clay film once more becomes white. This method is relatively simple and apparently good visual contrast between laminar and turbulent regions may be obtained when a flat, black finish is applied to the model surface prior to the application of the china-clay lacquer.

A method using the sublimation of a solid, rather than the evaporation of a liquid, has been used by Holder (reference 3). The solid (e.g., camphor) is first dissolved in a solvent, then deposited on a model surface by spraying. The method requires exceptional care in obtaining a smooth surface and the sublimation time is apparently relatively short.

The liquid-film method has been used and reported first by Gray (reference 4). The description which follows is an adaptation of the method used at the Ames Aeronautical Laboratory (reference 5). The model is first covered with a smooth, dull, black lacquer and then sprayed with a liquid mixture consisting of glycerin, alcohol, and a liquid detergent in the volume ratio of 1:9:2. Glycerin is the indicating agent, while the alcohol is used to achieve proper spraying consistency and the liquid detergent facilitates wetting of the surface. Visual indication of the wet and dry regions is satisfactory, but photographs require additional contrast. This may be obtained by dusting the model with talcum powder. The talcum adheres to the wet regions and may be blown off the dry regions. Care, of course, is required in application of the liquid film to assure an excess amount is not applied that would run and ripple when air flow is established over the model. Several representative photographs of the results of liquid-film

tests in the Ames 1- by 3-foot supersonic wind tunnel are shown in reference 5.

The luminescent-lacquer method reported herein has the advantages of simple application, excellent visual contrast between the light and dark regions, and drying times sufficiently long for practical use in most wind tunnels - either subsonic or supersonic.

Acknowledgment is made to Mr. Marcel Vogel of the Vogel Luminescence Corporation, San Francisco, California, for his development and formulation of the phosphor pigment used in this technique.

DESCRIPTION OF METHOD

Visual determination of the boundary-layer transition is achieved by means of a phosphor pigment mixed with a lacquer, which has the property of fluorescing with a bright yellow color under irradiation by ultra-violet light when dry and exhibiting no fluorescence when wet. A body that has been sprayed with the phosphor-pigmented lacquer and has air flow established over its surface will, at first, appear uniformly dark when irradiated by ultra-violet light. As the solvents leave the film and it dries, the areas that become dry commence to fluoresce while the areas that are still wet remain dark. A pattern thus established is indicative of the types of boundary-layer flow and the location of transition from one type to another. The phenomenon is a transient one and, of course, after a sufficient time has elapsed, the film will be dry and will fluoresce over the entire body.

The lacquer solution consists of three components: Ethocel as the film base, phosphor mixture, and solvents. The phosphor mixture is Calcozine Yellow Ox and a special slow drying vehicle; this is mixed one part to four parts Ethocel by volume. Stronger concentrations may be used if a brighter fluorescence is desired. Solvents are added to the lacquer to control spraying and film properties and to control the drying time. The solvent solution found to give best results consisted by volume of 15-percent Cellosolve, 15-percent butanol, 15-percent ethanol, and 55 percent of a solvent that controlled the drying time. The following are solvents that may be used to control the drying time listed in the order of decreasing evaporation rate:

1. Diacetone alcohol
2. Butyl Cellosolve
3. Butyl Cellosolve acetate
4. Glycol diacetate
5. Carbitol
6. Butyl Carbitol

The lacquer and solvent solution were mixed in equal amounts by volume. The resulting solution had satisfactory spraying qualities and the thin film that was deposited on the models did not run nor ripple due to the forces exerted by the air stream. Some variation in these proportions may be necessary for different test conditions. A tendency for the film to run or ripple when the air flows over it may be due to spraying on too heavy a layer of the lacquer or to the use of an insufficient proportion of the fast-drying alcohols which leave the film very rapidly and allow it to partially set up. It is to be expected that some practice will be required to develop skill in spraying and to determine the proper mixture for each different set of test conditions.

For visual inspection of the flow patterns a spot ultraviolet light source is satisfactory. For photographing it is necessary to provide uniform ultraviolet irradiation over the portion to be photographed. This may be obtained by use of several spot sources or a flood-type light source.

For photographing the patterns, it is advised that filters be used on the camera to filter out ultraviolet and visible blue light that might reach the camera directly from the ultraviolet lamp or by reflections. For the tests performed so far, the patterns have persisted sufficiently long to allow photographing without undue haste. In several cases it has been found possible to stop the wind tunnel soon after the patterns were established without the patterns being altered during the stopping period. It was then possible to make detailed and prolonged studies of the patterns which persist in still air almost unchanged for several hours.

The model usually requires no special preparation for application of the lacquer. The color of the model is unimportant. It should not, however, have a surface coated with a material that will be dissolved by the solvents in the lacquer as this material will then mix partially with the lacquer film and may deaden the fluorescence. The dried film is removed easily with acetone, alcohol, or lacquer thinners.

RESULTS AND DISCUSSION

The fluorescent-lacquer method of indicating boundary-layer transition has been used in three wind tunnels at the Ames Aeronautical Laboratory: the 1- by 3-foot supersonic wind tunnel, the 1- by 3-1/2-foot high-speed wind tunnel, and the 6-inch heat-transfer wind tunnel. The Mach numbers ranged from 0.7 to 2.45. In these tests Butyl Carbitol was used as the solvent for controlling the drying time of the film. The supersonic tunnels required considerable time for starting - up to 20 minutes - as it was necessary to evacuate the tunnels to an absolute pressure of approximately 5 pounds per square inch before starting. It then took from 3 to 5 minutes to reach the desired test conditions.

During this starting time the film remained sufficiently wet so that the desired flow conditions were established before any of the film began to fluoresce with the exception of the extreme leading edge of the models. The pattern once established remained distinct for approximately 5 minutes.

Figure 2 is a photograph of a wing-body configuration being tested at a Mach number of 2.0 in the Ames 1- by 3-foot supersonic wind tunnel. This picture was taken using four 100-watt ultraviolet spotlights with no filter on the camera. Laminar flow exists over the wings and the front half of the body. The bright regions on the wings along the leading edges and 50-percent chord lines are regions of high-mass transfer rates and do not indicate the presence of a turbulent boundary layer. It can be seen that turbulent boundary-layer flow originates at the wing roots, spreads over the body toward the rear, and covers the whole body aft of the center of the wings at the root. No significance should be attached to the patterns on the tail as flow over this region was not of primary interest; thus, care was not observed in applying the lacquer there.

Figure 3 is a photograph of a flat-plate model mounted horizontally in the Ames 6-inch heat-transfer wind tunnel operating at a Mach number of 2.45. The flat-plate model spans the closed test section of the tunnel and is 10 inches long. This picture was taken using four 100-watt ultraviolet spotlights and a minus blue filter on the camera. When the desired flow conditions had been established and the pattern clearly defined, the tunnel was stopped and the windows removed so that a more detailed study of the flow pattern could be made. The pattern did not change when the tunnel was stopped nor for a considerable time afterwards. The flow over the center of the plate is laminar. The bright streamers originating 1 inch and 2 inches aft of the leading edge on the near and far sides, respectively, are regions of turbulence caused by transient air flow through static pressure orifices located at those two points. The bright regions originating at the two edges and spreading toward the center indicate the spread of turbulence due to wall interference.

The results of this investigation on the flat-plate model were of important practical value since it was necessary to know the extent of the influence of the side-wall boundary layer and the pressure orifices on the boundary layer of the flat plate. The photograph shows distinctly these effects and their extent.

Figure 4 is a photograph of a second flat-plate model mounted horizontally in the Ames 6-inch heat-transfer wind tunnel operating at a Mach number of 2.2. The flow over the forward central portion of the plate is laminar. The bright streamers originating at the corners of the plate and spreading toward the center are again regions of

turbulence induced by side-wall interference. The two streamers near the center of the plate are regions of turbulence induced by the transient flow of air out of static pressure orifices. The streamer on the near side of the plate originates from a speck of lint that could be observed by the unaided eye upon close inspection. The dark band across the plate is a strip of lamp black used to cause boundary-layer transition. It was applied to assure turbulent flow over the whole rear portion of the plate. It developed that the device was unnecessary as turbulence originating from other disturbances, upstream, spread until the boundary-layer flow was turbulent at about the position of the lamp-black strip. The lamp-black band was masked during the spraying and thus remains dark. The photograph was taken using a minus Blue filter and four ultraviolet spotlight sources. The variation in brightness between the turbulent streamers and the turbulent flow region aft of the lamp-black strip is due to the plate surface not being evenly irradiated by the four ultraviolet spotlights.

Figure 5 is a photograph of a wing model mounted horizontally in the Ames 1- by 3-1/2-foot high-speed wind tunnel operating at a Mach number of 0.7. Only a portion of the model can be seen as the window through which the photograph was taken is only 2-1/2 inches in diameter and is located in the top of the tunnel near the tunnel side wall. The two streamers originating near the leading edge indicate spreading turbulence originating from two small dust or lint particles which came from the air stream and adhered to the lacquer film. When the tunnel was stopped and the model inspected, these particles could be seen with the naked eye. The bright portion at the left is turbulence due to wall interference. The flow over the wing is laminar back to approximately 90 percent of the chord where transition to turbulent flow is indicated by the light band. The bright trailing edge is due to ultraviolet and visible blue light reflecting from a white material used for filling and smoothing counter-sunk screws. This picture was taken using one 100-watt ultraviolet spotlight and no filter on the camera. It can be seen that the irradiation, and thus the fluorescence, is not uniform and that some ultraviolet or visible blue light was reflected into the camera from the side window.

CONCLUSIONS

The conclusions resulting from the tests using the fluorescent lacquer method for detecting boundary-layer transition are:

1. The method was satisfactory for visually distinguishing the transition from laminar to turbulent boundary-layer flows.

2. The technique is simple and only inexpensive equipment is required for its use.

Ames Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Moffett Field, Calif., Oct. 6, 1950.

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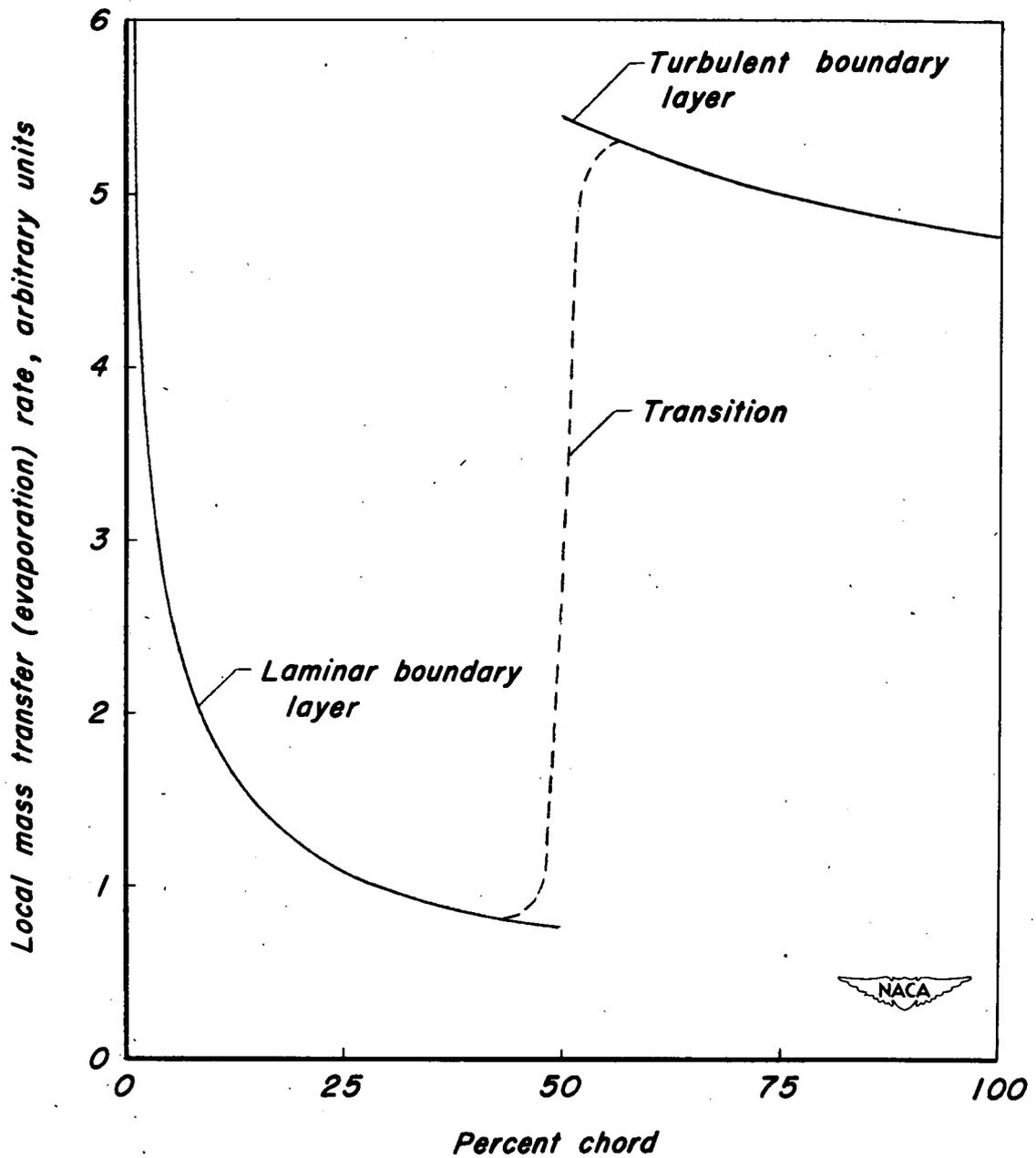


Figure 1.-Variation of mass transfer rates over a flat plate.

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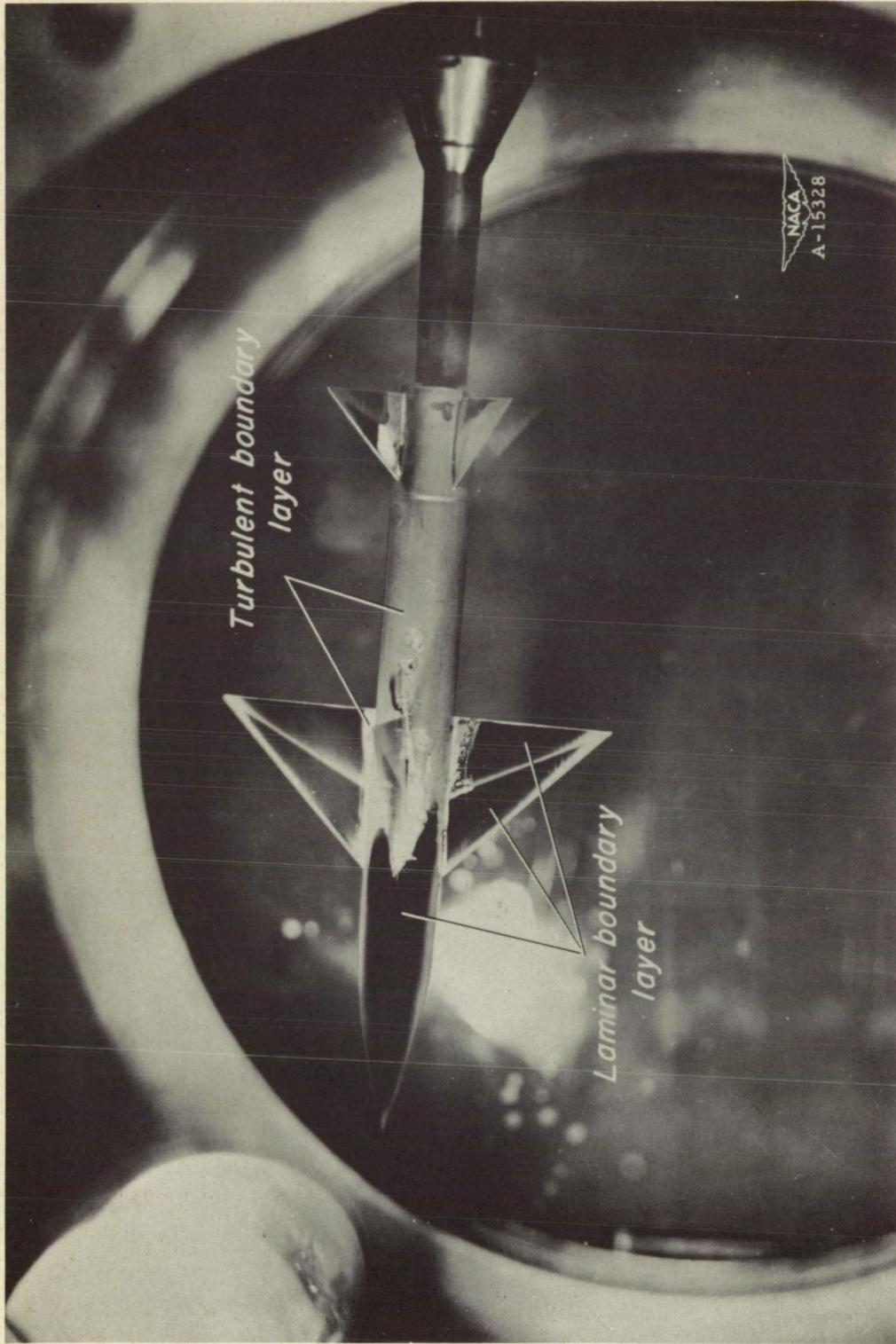


Figure 2.- Luminescent lacquer technique used on a wing-body combination in the Ames 1- by 3-foot supersonic wind tunnel.

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Figure 3.- Luminous lacquer technique used on a flat plate model in the Ames 6-inch heat-transfer tunnel.

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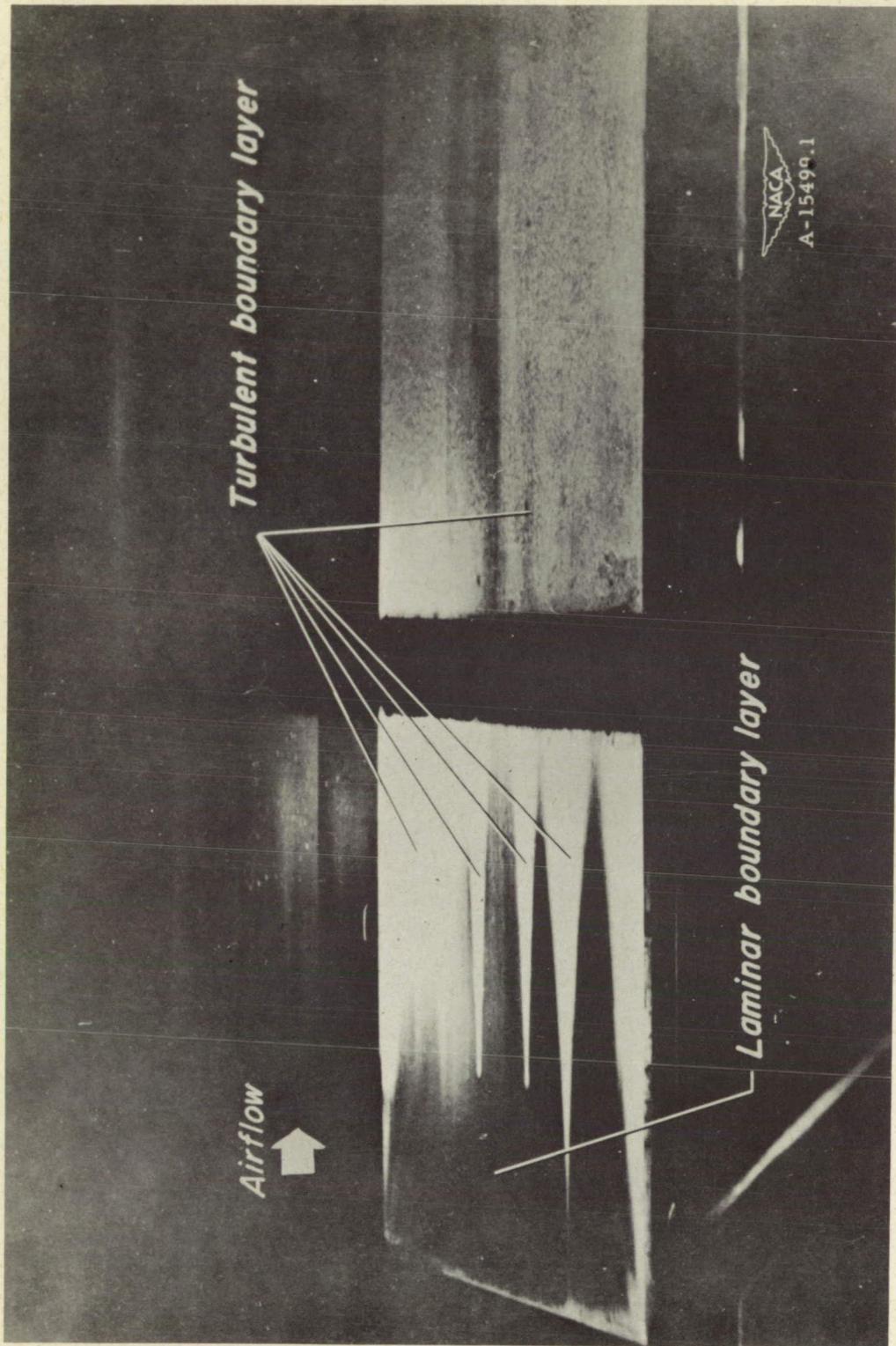


Figure 4.- Luminescent lacquer technique used on a flat plate model in the Ames 6-inch heat-transfer tunnel.

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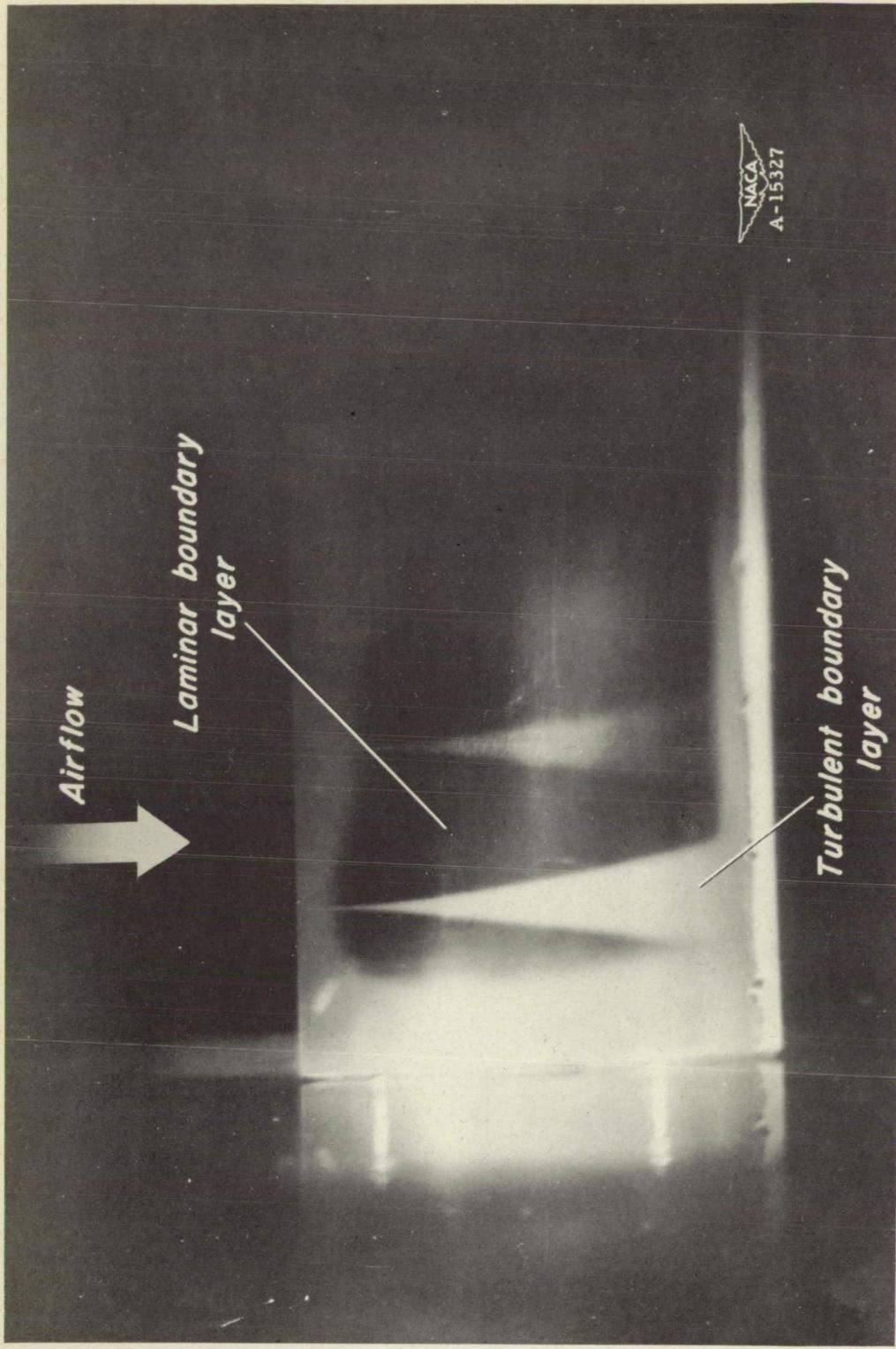


Figure 5.- Luminescent lacquer technique used on an airfoil model in the Ames 1- by 3-1/2-foot wind tunnel.