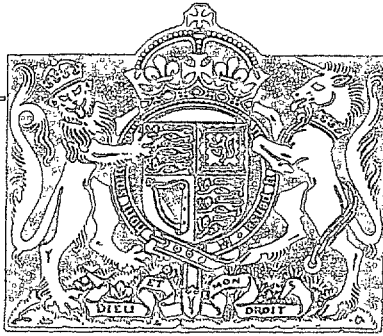


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for Visual Indications of Boundary-layer
Transition in Air and Water

By

J. D. MAIN-SMITH

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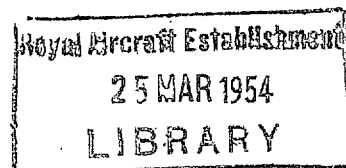
Chemical Solids as Diffusible Coating Films for Visual Indications of Boundary-layer Transition in Air and Water

By

J. D. MAIN-SMITH

COMMUNICATED BY THE PRINCIPAL DIRECTOR OF SCIENTIFIC RESEARCH (AIR),
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Summary.—Experimental investigations have been made on various chemical solids as diffusible coating films for visual indication of boundary-layer transition in air and water. Originally, the method was applicable only at low speeds in wind tunnels and water tanks, and the indications were somewhat transient. More durable coating materials have now been made available, admitting of use at subsonic and supersonic wind-tunnel speeds from 30 to 1350 m.p.h., and at ship-hull speeds from $2\frac{1}{2}$ to 20 kt. The method has also proved capable of extension to aircraft in flight at speeds from 100 to 445 m.p.h. at temperatures down to -22 deg C and at altitudes up to 20,000 ft. The diffusible-solid-coating method, with its advantages of autographic indication and simplicity and rapidity of operation, has thus become a versatile technique in investigations on fluid flow in aerodynamics and hydrodynamics.

1. *Introduction.*—1.1. *General.*—The diffusible-solid-coating method (to which this report is restricted) for visual indication of aerodynamic and hydrodynamic boundary-layer transition was originally devised in 1945 at the Royal Aircraft Establishment by Pringle and Main-Smith (Refs. 1 and 2 and R. & M. 2079³ and 2267⁴) and was suitable only for low speeds in wind tunnels and seaplane tanks. Often the indications were developed somewhat too rapidly to ensure that steady fluid flow conditions had been attained; the coatings tended to have rough spots bringing about undesired areas of local transition (wakes); and the indications obtained in wind tunnels were transient.

Despite these defects, the method had the advantages of simplicity, rapidity, cheapness in operation, and capacity to give an autographic record of the general and local transitions from laminar to turbulent flow over the whole of the coated surface.

The principles underlying the method were by no means clear, and it appeared desirable to overcome the foregoing defects as well as to extend the method to higher wind-tunnel and water-tank speeds, and, if possible, to aircraft in flight.

1.2. *Transition in Aerodynamic Flow.*—The basis of the method for indicating transition from laminar to turbulent flow in air was to coat the surface of the model with a smooth, thin white film of a volatile chemical solid, expose it to the airflow, and develop areas in which the film had been removed by differential evaporative diffusion (solid sublimation). It was expected that the thin body of laminar-flowing air close to the surface would rapidly become more or less saturated with the diffusing chemical and that the rate of evaporation would greatly decrease in flowing over the coated surface before the position of transition to turbulent flow was reached. At the position of transition, the ensuing turbulence was expected to increase the rate of

* R.A.E. Report Chem. 466, received 2nd May, 1950.

evaporation so as to remove the white coating before much of it had evaporated in the laminar area. These expectations were fulfilled for the few chemical solids tested¹, in particular, for camphor, urethane (ethyl carbamate) and naphthalene.

The general form of the picture obtained was a white area (laminar-flow region), followed by a dark area (turbulent-flow region) from which the white coating had disappeared, the line of demarcation (position of transition) being sharply defined and nearly at right-angles to the direction of flow. Excrescences on the surface in the laminar-flow region formed the apices of acute-angled triangular dark areas diverging backwards into the dark area of general turbulent flow. These wakes of localised turbulent flow, set up by surface imperfections often less than half a thousandth of an inch in height, varied considerably in their angle of divergence but the latter was usually between 5 deg and 20 deg. If the excrescences were close together, the divergent wakes joined one another so that the position of general transition was obscured.

1.3. *Transition in Hydrodynamic Flow.*—The method used was similar to that for aerodynamic flow, except that the chemical coating-solid was required to diffuse by dissolving in the water flow. The position of general transition was indicated by the sharply defined boundary between the white areas of laminar flow and the dark areas of turbulent flow. Surface excrescences in the laminar region were similarly indicated as heads of dark wakes diverging backwards into the dark area of general turbulent flow.

Most of the chemical solids tested as indicating coatings had low adhesion to the polished surfaces of the models, and large areas of coating tended to flake off on immersion in water. This was finally overcome², in the case of the indicating material acetanilide, by dissolving in the spraying solution a small amount of dibutyl phthalate, a colourless, non-volatile liquid, insoluble in water. The coatings thus obtained were somewhat fragile, but had sufficient adhesion to admit of speeds round about 6 kt. As acetanilide is almost insoluble in dibutyl phthalate, the coatings were sufficiently white to give good contrast for indicator purposes. The turbulent area, immediately aft of the white laminar area, was still coated (after the test) with a thin transparent liquid film of dibutyl phthalate, which allowed the dark surface of the model to be seen. Water drops, on the surface of the water laminar area, were removed by a jet of air. If the drops were allowed to remain, dark spots formed in the laminar area, owing to solution of the acetanilide in the water drops.

Many of the chemical solids, tested as indicating materials, were too soluble in water and were completely dissolved before the model had attained a speed of more than a few knots. Some were too insoluble to effect any indication of transition in the time of traversing the length of the water tank. Others were too insoluble in spraying solvents to yield coatings of sufficient thickness.

Indication of hydrodynamic transition from laminar to turbulent flow was thus limited to the use of acetanilide in the small range of speeds, near 6 kt, permitted by varying the thickness of coating.

2. *Discussion on Indicating Coatings.*—2.1. *General.*—In view of the restricted usefulness of the transition indicators available, it was decided to institute search for improved indicating materials, and, in particular, for such as could be used at high speeds of flow in air and water. It was also considered desirable to devise laboratory methods of determining suitability, to avoid the great labour and expenditure necessitated by direct trials in wind tunnels, seaplane tanks, and aircraft in flight.

Chemical substances for use as diffusible solid coatings must be capable of yielding opaque films on model surfaces, and such films must remain solid, opaque, and durable at temperatures at which transition indications are obtained and examined. In general, coating materials must have high melting points and, for use in airflows, must be sufficiently resistant to moisture and give good indications in damp atmospheres.

The materials must have no adverse effects on metals and surface finishes; they must also be free from substances which may cause discomfort or injury to operators during or after application.

These considerations limit the classes of possible indicating compounds to the less reactive solids with melting points about 50 deg C or higher. For aerodynamic use, suitable substances must have small but not negligible vapour pressures at and below ordinary temperature, and are thus likely to be found only among compounds of low or medium molecular weight, containing much hydrogen.

The types of solid compounds, likely to be suitable for indication of air-transition, are therefore hydrocarbons, esters, alcohols, ethers, ketones, acylamines, and azohydrocarbons.

For water-transition, indicating substances must be sparingly soluble in water, and, as long-lasting indications are desirable, the substances should have low volatility. This restricts the classes of chemical substances likely to be useful to solids of fairly high molecular weight, such as esters, ethers, ketones, acids, phenols, alcohols and amides.

2.2. Substances for Air-transition Indication.—Substances for use as indicators of air-transition must possess, not only low reactivity and high melting point, but also low vapour pressure at the temperature of the airflow, ranging from 40 deg C to the lowest atmospheric temperatures.

The vapour pressures necessary for the detection or indication of boundary-layer transition in air are unknown, even for camphor, urethane (ethyl carbonate) and naphthalene. It is probable that the required vapour pressures are much less than a thousandth of an atmosphere, and are likely to lie between 10^{-1} and 10^{-6} mm of mercury. Vapour pressures of these low orders are not on record for organic solids, though they can be extrapolated from measurements of higher vapour pressure and temperatures for the commoner compounds.

It follows from the integration of the simplified Clapeyron-Clausius equation that

$$\ln p = A - \frac{L}{RT} .$$

This assumes that the vapour pressure p is sufficiently small for the vapour to behave as a perfect gas, and that the latent heat of evaporation L is constant in the range of temperature and vapour pressure. These conditions must be very nearly true for such slightly volatile substances as are considered here. It is therefore reasonable to make straight-line extrapolations of the curves of $\ln p$ against $1/T$ for some distance.

The data on vapour pressures of 1 mm and upwards, for a number of substances likely to be of use as air-transition indicators, plotted against the reciprocals of the absolute temperatures are shown in Fig. 1. Extension of these straight-line plots to regions of vapour pressure less than 1 mm and greater than 760 mm, yields an extrapolated graph in which the lines converge towards regions of high vapour pressure and high temperature. The convergence of this pencil (or rather series of pencils, one for each type of chemical structure) is a feature of the Cox Chart Method⁶ for determining boiling points at various pressures.

From the point of view of transition indication, however, the more interesting feature of Fig. 1 is the divergent region of vapour pressure below 1 mm of mercury, and, in particular, the region of very low vapour pressure at atmospheric temperatures.

The three air-transition indicators, camphor, urethane (ethyl carbonate) and naphthalene are in the region of highest vapour pressure at room temperature, in agreement with their well-known capacity to sublime to the upper parts of storage bottles.

The vapour pressures of the various substances, on the line of 20 deg C in Fig. 1, constitute a series of progressively decreasing volatility from dimethyl oxalate with the high vapour pressure of 1 mm of mercury to phenanthrene with the very low vapour pressure of 0.001 mm of mercury.

The substances shown in Fig. 1 are separately listed in Table 1 with their melting points and their probable vapour pressures at 20 deg C. This list includes most if not all the known solids of melting point about 50 deg C or above, likely to be of use as air-transition indicators at present-day wind-tunnel and aircraft speeds.

Included in this list, for comparative purposes only, are dimethyl oxalate and iodine, both of which are too toxic and corrosive for indicator use. Also included are hexachlorethane and camphor, both of which are somewhat toxic when sprayed in confined spaces. With camphor may be included its alcohol, borneol, with similarly high melting point but lower volatility and more objectionable odour.

Though the substances in Table 1, with the exceptions noted, are probably all of some use as air-transition indicators, no means exists of determining, in advance, their utility as indicators in various aerodynamic conditions, particularly as regards speed of airflow, time of exposure and atmospheric temperature and pressure. It therefore became necessary to devise laboratory methods of evaluating their utility as indicators in any given set of aerodynamic conditions, so as to obtain the required information without recourse to laborious and expensive full-scale trials. Details of the laboratory methods of evaluation are given in section 3.

2.3. Substances for Water-transition Indication.—In addition to general chemical unreactivity, opacity in film form and the possession of melting point about 50 deg C or above, substances for use as indicators must be sparingly soluble in water at the temperatures common in hull-testing tanks, *i.e.*, about 20 deg C.

The solubilities necessary for indication of boundary-layer transition in water are unknown except in the case of acetanilide, which, with the recorded solubility of 0.563 per cent, at 25 deg C, is known to be a successful indicator² only for speeds of about 6 kt. It can probably be assumed, for equal times and temperature of exposure, that substances having a solubility less than 0.5 per cent in water are likely to be of use as transition indicators for speeds greater than 6 kt.

Unlike aerodynamic tests in wind tunnels and in aircraft in flight that may extend from some minutes to several hours, hydrodynamic tests in tanks have usually to be made in a few seconds. For example, a 200-ft test run in a water tank would last less than 5 sec at 25 kt. Moreover, it is impossible to forecast, even approximately, to what extent the decreased amount of coating dissolved at lower speed will be compensated by increased time of exposure to the water.

The number of organic substances that are sparingly soluble in cold water is limited and, excluding a few in pharmaceutical use, the solubilities in water are not on record. Most of these substances are inadmissible as transition indicators by reason of low melting point, insolubility in spraying solvents, corrosiveness, toxicity, or objectionable odour. The remainder are few enough in number to admit of direct testing as indicators.

It was found, however, that determinations of solubility and direct testing in full-scale water tanks were unnecessary, the required information on probable suitability as water-transition indicators being obtainable by very simple laboratory tests. Details of the method are given in sections 3.8 and 3.9.

2.4. Solvents for Indicating Materials.—In the confined spaces of wind tunnels and rooms with experimental wind tunnels and water tanks, the use of solvents of low toxicity and corrosiveness and of unobjectionable odour is essential. This restricts the solvents that may be used to water, petroleum hydrocarbons and the lower alcohols and ketones. Some of the lower esters, ethyl

acetate for example, have suitably low toxicity, but on long continued use they proved corrosive to metals, particularly brass and copper, their powerful odours tended to be objectionable, and they had insufficient solvent capacity for many of the types of transition-indicating solids.

The method of obtaining aerodynamically suitable coatings of transition-indicating solids by 'dry-spraying' (see section 3.4) necessitated the use of solvents sufficiently volatile to evaporate almost completely before the spray had time to wet the surface to be coated. Owing to the high latent heat of evaporation of water and the lower alcohols (water 540, methyl alcohol 263 and ethyl alcohol 204 cal/gm at the boiling point), these solvents had insufficient vaporising power for successful 'dry-spraying.' Petroleum hydrocarbons and the lower ketones have suitably low latent heats of evaporation (octane 71, cyclohexane 86, and acetone 124 cal/gm at the boiling point).

The solvents found most suitable for dry-spraying were acetone (boiling point 56 deg C) and light petroleum fractions ('petroleum ethers' of boiling ranges 40 deg to 60 deg, 60 deg to 80 deg, 80 deg to 100 deg, and 100 deg to 120 deg C).

Though wetting of the surface is to be avoided in spraying coatings, small amounts of solvents do reach the surface and remain in the coating for some time and may soften oil or cellulose finishes to the point of rendering them unsuitable for aerodynamic and hydrodynamic investigations. This objection does not apply to petroleum solvents, but is important where acetone is used alone or mixed with petroleum solvents. If acetone has to be used, the model surface should be finished with stoving-enamel or Bakelite-type varnishes.

The main advantage of acetone over petroleum solvents lies in its greater solvent power, enabling more concentrated solutions to be used in spraying without danger of saturation being attained. Saturated or nearly saturated solutions can be used in dry spraying only with the utmost difficulty, amounting to impossibility with very volatile solvents. Solid tends to separate and accumulate on the spray-gun nozzle, only to be blown off from time to time and deposited as lumps on the coating. Surface imperfections, due to such deposits, invariably bring about local transitions in the form of divergent wakes during development of the transition indication, and may completely obscure the position of general transition. It is possible to remove these deposits by lightly wiping the surface from end to end with the side of the hand or a soft pad of cotton wool, but they can be avoided by care in the choice of solvents, the concentration of solution and the technique of spraying.

3. *Laboratory Testing of Transition-indicating Materials.*—3.1. *Outline of Method.*—The procedure, for laboratory testing of suitability of materials for indicating boundary-layer transition in air and water, was as follows

- (a) preparation of 5 to 10 per cent solutions of the solid material in a selected solvent;
- (b) application of a thin, smooth coating of the solid to the surface of a model by spraying the solution from a spray-gun;
- (c) exposure of the coated model to a flow of air at the desired speed in a small suction-type wind tunnel or to a stream of water in a tank already full of water;
- (d) examination of the coating during and after development of the transition indication.

3.2. *Laboratory Wind tunnel.*—The suction-type wind tunnel used for the laboratory tests was about 36-in. in overall length, the working-section being a cylindrical 'Perspex' tube 4-in. in diameter and 15-in. in length. Steady airflows from 20 to 120 m.p.h., as shown on a calibrated pitot gauge, were readily obtained within a few seconds of starting the suction.

Laminar-flow conditions in the working-section were confirmed by means of a fine textile filament about 12-in. in length, held at one end. In steady conditions of airflow, the filament streamed freely along the axis of the wind tunnel, and remained horizontal and almost motionless throughout its length. Any turbulence, set up by leaks in the working-section or by obstruction to flow inside or outside near the mouth of the wind tunnel, caused strong undulations in the filament.

3.3. *Model Wing-sections.*—The models used in the wind tunnel were small wing-sections (slightly less than 4-in. in width and about 9 in. from leading edge to trailing edge). The upper edges of the sides of the model were chamfered to a shape enabling the models to be passed into the wind tunnel in close contact with the side walls. The models fitted the Perspex tube sufficiently tightly for supports to be dispensed with. The sides of the models were shaped so that, with the thicker end in front, the slope of the top surface was slightly downwards to the rear, whereas, with the thinner end in front, the slope was slightly upwards to the rear. In the first position transition occurred towards the front of the model, and, in the second case, towards the rear of the model.

Open-sided models were made from polished brass sheet (1/32-in. in thickness) bent to shape, the upper surface being finished with glossy, black stoving-enamel. Solid models were made from wood finished with dark brown, cold-setting, Bakelite-type enamel.

3.4. *Coating the Models.*—A 5 to 10 per cent solution of the test substance was made in a suitable solvent (*see* section 2.4) and sprayed on the upper surfaces of the model by means of an ordinary paint spray-gun, with an air pressure from 10 to 25 lb/sq in. and a gun nozzle distance of 12 to 18 in. It was found essential so to adjust the spraying pressure and nozzle distance that dry spraying was attained, practically complete evaporation of the solvent occurring before the spray reached the surface. The best effect was obtained by the use of a flat vertical spray, *i.e.*, with the side air holes of the gun in use. The spray was passed steadily to-and-fro over the surface with a slow horizontal movement of the arm. By this procedure, uniformity of coating was readily attained with three or four passages of the gun, the coating being finely crystalline, uniformly greyish-white, and of aerodynamic smoothness. The usual thickness, based on the weight of a measured area and the density of the substance, was from 5 to 12 microns (0.0002 to 0.0005 in.), but coatings of twice this thickness or more were easily obtained.

During spraying, if the surface was allowed to become visibly wet in any part, areas of coarse crystallisation were formed, the resultant roughness and unequal thickness of coating being detrimental to good indication of transition. Though wetting of the surface is to be avoided, it is equally necessary to avoid very dry spraying with the gun nozzle further away from the surface than just sufficient to prevent visible wetting. In very dry spraying, the solvent was evaporated from the spray too early, and the resultant coating was 'fluffy' and insufficiently durable for use in high-speed wind tunnels, aircraft in flight, or water tanks.

3.5. *Simultaneous Tests on Two Indicating Substances.*—It was possible to make simultaneous tests on two different substances, thus avoiding the effects of variation in speed and temperature of airflow, by the following method. One half of the model was covered by a closely applied strip of thin aluminium foil, carried round leading edge and trailing edge and fixed by paper clips. The uncovered half was dry sprayed in the usual way. The strip of foil was then removed and carefully fixed over the coated half, and the other uncovered half was dry sprayed with a solution of the second substance. By using the same number of passages of the spray-gun, it was not difficult to attain substantially equal thickness of coating on the two halves of the model. The model was immediately placed in the wind tunnel and the development of the transition indications observed. With substances of nearly equal volatility, the indication developed on both halves at about the same time. With substances of different volatility, the indication developed first on the half with the more volatile substance, and later on the other half, the second indication being in the same line across the model as the first indication. With substances differing greatly in volatility, the first indication developed and disappeared before the second indication was visible.

This method was valuable in testing air-transition indicators of unknown volatility against others for which vapour pressure data were available, and was found indispensable in testing water-transition indicators, for most of which solubility data were not available.

A variant of this method of simultaneous testing was used as a rapid sorting test where many substances of unknown volatility had to be considered as air-transition indicators. Instead of waiting for the indication of general transition to develop, use was made of the much more rapid development of the wake caused by an excrescence placed near the leading edge of the line of junction of the two coated halves (*see* section 3.7) each half of the wake developing at different times with substances of different volatility.

3.6. Development of Air-transition Indications.—Immediately after application of the coating, the model was inserted firmly in the wind tunnel with its leading edge about 2 in. from the mouth of the wind tunnel. The air blast was then turned on rapidly until the required air speed was shown on the pitot gauge.

As the airflow continued, the white coating at the leading edge rapidly disappeared leaving a dark band which spread backwards at a rate dependent on the volatility of the coating chemical and on the speed and temperature of the airflow. While this front dark area was spreading backwards, a similar dark area began to develop near the trailing edge and spread forwards at first rapidly, then progressively more slowly until finally it ceased to spread forwards, the rear edge of the white area in front then remaining in a fixed position as a more or less straight line across the width of the model. This line marked the position of general transition from laminar to turbulent airflow, and constituted the transition indication. That this line was the position of transition (sometimes referred to as the 'front of turbulent flow') was readily shown by introducing a filament as described in section 3.2. The filament streamed back and lay rigid and motionless along the surface of the model as far as the rear end of the white band, while from there to the trailing edge it was in violent undulation. Little or no undulation occurred in the dark area immediately behind the leading edge, indicating that this dark area and the white area together constitute the region of laminar flow.

On continuance of the airflow, the white area steadily decreased, the rear edge of this area, however, continuing fixed in position. Ultimately the entire white area vanished, the front dark area then merging with the rear dark area and the transition indication disappearing. Often the position of transition remained marked for a time as a narrow white band, after all trace of the white coating elsewhere had evaporated.

In the early stages of the backward spread of the front dark area, and usually prior to the development of the rear dark area, two other dark areas rapidly developed on each side of the model adjacent to the wind-tunnel walls. Each of these areas consisted of an acute-angled band diverging from the point where the leading edge touched the wind-tunnel wall. These lateral dark areas were usually fully developed before the transition indication, with the result that the latter extended only part way across the width of the model and was cut off at each side by the lateral dark areas. Filament exploration showed that these dark areas were regions of turbulent flow. With the model removed from the wind tunnel, it was shown that the air flow was laminar near the wind-tunnel walls. The lateral areas were thus wakes of turbulence set up by the obstructions of the corners of the leading edge of the model. The width of the wakes shown on the model surface may be interpreted as the 'height' to which the turbulence extends from the wind-tunnel walls.

The usual course of development of an air-transition indication is illustrated by the curve shown in Fig. 2 in which the distance of the front and rear edges of the white coated area from the leading edge of the model is plotted against time. As evaporation proceeds, the white coating begins to be removed at each end of the model, the retreat of the front and rear edges of the white area being at first very rapid, then slower. The retreat of the rear edge ceases at the position of transition (PP), this rear straight edge constituting the indication, which remains fixed for a considerable time while the front edge is still retreating. Ultimately, the front edge also reaches the position of transition (PP), the indication then vanishing with the last trace of the white area. Just prior to disappearance of the indication, the rear white edge moves slightly forward of the position of transition. If, owing to over exposure in the tunnel, measurement of the position of the indication is delayed to this stage, the position of transition may be slightly in error, usually much less than 5 per cent.

3.7. *Effect of Surface Inequalities.*—A model, with a small excrescence (a tiny blob of sealing wax) fixed about 2 in. behind the leading edge, was placed in the wind tunnel. The four dark areas (front, rear and sides) developed as usual, but a fifth dark area rapidly developed as an acute angle diverging backwards from the excrescence. Filament exploration showed that this was a region of turbulence—a wake of turbulent flow created by the excrescence. Usually this wake developed before the indication of general transition, and when the indication did develop, it was seen to be cut into two parts by the wake. Similar wakes were developed behind isolated rough spots of deposit caused by faulty technique of spraying.

With a model having a small pit in the forward surface, in place of an excrescence, a wake was either not developed at all or developed much more slowly than the indication of general transition, and the indication was thus usually not split into two parts.

With an open-sided model, having a small hole cleanly drilled through to establish air communication between the upper and lower surfaces of the top of the model, a strong wake was rapidly developed, usually before the transition indication, which was thus cut in two, as in the case of a model with an excrescence. Using the same model, with the hole drilled through and bearing also an excrescence to one side of the hole, two wakes rapidly developed, sometimes that from the excrescence and sometimes that from the hole developing first. If the hole was blocked, by placing a piece of adhesive paper over the underneath opening of the hole, either no wake or only a feeble wake developed, the blocked hole thus acting similarly to a pit in the surface.

3.8. *Laboratory Equipment for Water-transition Testing.*—No attempt was made to construct a water channel for tests on water transition on the laboratory scale. Since successful indications of transition had been obtained with acetanilide on models in the seaplane tank, it was therefore assumed that the behaviour of a proposed indicator could be predicted by comparing its rate of solution (from a coated surface into a fast-moving stream of water) with that of acetanilide. Materials selected by this simple method behaved as expected when later tested on the large scale.

For the laboratory tests, the tank used was a large sink (30-in. in length, 18-in. in width, and 12-in. in depth) with an overflow near the top at one end. The model was a flat plate of polished dark brown Bakelite (10-in. in length, 6-in. in width, and $\frac{1}{4}$ -in. in thickness). Fixed on the middle of one of the short ends of the plate was a copper pipe ($\frac{1}{8}$ in. bore) connected at the outer end by rubber pressure tubing to the water main (80 lb/sq in. pressure), the inner end of the copper pipe being soldered to the middle of a U-shaped pipe of similar bore. The piping was mounted over the plate so that, with the water on, the jets of water delivered from the open ends of the U-tube were parallel to the surface and sides of the plate. The optimum distance of the U-tube above the plate was found by trial, and was usually about $\frac{3}{16}$ in. The object of the two water jets was to allow simultaneous tests to be made on different indicator substances sprayed on the two halves of the plate (see section 3.5).

3.9. *Developing Water-transition Indications.*—After spraying the plate (see sections 3.4 and 3.5), the attached piping was connected to the water main. The plate was then placed in the tank already filled with water, and securely fixed on the bottom of the tank at the end furthest from the overflow. The water pressure was turned on and the plate kept under observation.

After a time depending on the temperature of the water and the speed of flow from the jets, a dark band appeared under each jet. Each band had the same shape as the jet, *i.e.*, diverging from $\frac{1}{8}$ in. wide at the jet to about 1 in. wide at the far end of the plate. With the plate coated with a single substance, the two dark bands developed simultaneously or within a few seconds of one another. With a different substance on each half of the plate one band invariably developed much before the other.

Though the water flowing in the jets was apparently turbulent, the water elsewhere over the plate appeared to be flowing steadily as judged by complete transparency. This was confirmed by liberating particles of sawdust at the bottom of the tank in rear of the jets, the particles moving rapidly in nearly straight lines over the white coated plate. Owing to the high speed of the flow in the jets, the particles could not be observed in the water composing the jets.

The dark bands on the plate appeared to be areas of artificial turbulence induced by the water jets overhead and were thus unlike regions of natural turbulence ensuing at transition from laminar to turbulent flow. Nevertheless, it was expected that substances capable of developing an indication by forced turbulence would be capable of developing an indication of the natural turbulence of transition, and further, that the time to develop the indication by forced turbulence would bear a close relation to the time to develop an indication of natural transition. These expectations were confirmed later (*see* sections 4.6 and 4.7).

4. *Experimental Results.*—4.1. *Laboratory Results with Air-transition Indicators.*—Tested in the laboratory wind tunnel at air speeds about 90 m.p.h., the substances listed in Table 1 (among some hundreds tested) were found to give good indication of boundary-layer transition. The order of rate of development of indication closely agreed with the order of probable volatility at 20 deg C given by the vapour pressure extrapolations of Fig. 1.

Two other substances, ethers of hydroquinone, were also found to give good transition indications, the dimethyl ether (melting point 56 deg, boiling point 213 deg C) giving its indication in nearly the same time as naphthalene. The diethyl ether (melting point 71 deg, boiling point 246 deg C) was much less volatile, giving its indication quicker than acenaphthene but slower than diphenyl. Both ethers yielded translucent coatings, rendering indications somewhat difficult to observe under the artificial lighting conditions of wind tunnels. This objection does not hold in broad daylight, and the ethers thus appear to be specially suitable for use on aircraft in flight. The dimethyl ether, however, had a powerfully pungent odour, nauseating on spraying, and its use offers no advantage over the equally volatile naphthalene. The diethyl ether had only a slight, sweetish odour, and its volatility was of a useful order between those of diphenyl and acenaphthene.

Many of the substances listed in Table 1 are somewhat rare chemicals. In view of the expense involved in the use of the large amounts required for full-scale trials, a selection was made of the more readily available substances to cover the air-speed range from 100 to 1400 m.p.h. The six substances chosen were naphthalene, diphenyl, hydroquinone diethyl ether, acenaphthene, fluorene, and azobenzene.

In laboratory tests at about 90 m.p.h. in winter, the times to develop the transition indication averaged 10 minutes for naphthalene, 15 minutes for diphenyl, 15 to 30 minutes for hydroquinone diethyl ether (the shorter times for commercial material containing much dimethyl ether as impurity), 60 minutes for acenaphthene, 90 minutes for fluorene, and 300 minutes for azobenzene. In summer, at a room temperature about 10 deg C higher, these times were nearly halved. After development in the wind tunnel, the indications in still air at room temperature lasted about 2 hours for naphthalene, 2 days for acenaphthene and 4 days for azobenzene.

4.2. *Rapid Demonstrations of Air-transition.*—The highly volatile substance, hexachlorethane, was found particularly convenient for rapid laboratory demonstrations of transition, wakes, etc. Its high solubility in acetone permitted the use of 10 per cent solutions, for spraying dense, matt white coatings on black polished surfaces. At air speeds from 30 to 80 m.p.h., clear-cut indications of considerable pictorial effect were easily obtained in 30 to 120 seconds. After removal from the wind tunnel, the indications lasted sufficiently long for demonstration purposes, and evaporated completely in 2 or 3 minutes. As the substance is somewhat toxic, particularly when repeatedly sprayed into the air, prolonged exposure in confined spaces should be avoided.

4.3. *Results in Subsonic Wind Tunnels.*—Naphthalene, diphenyl, and acenaphthene proved to be good transition indicators at air speeds from 100 to 450 m.p.h. A photograph of the indication obtained with acenaphthene on a swept-back model wing at a wind-tunnel speed of 330 m.p.h. at an equivalent altitude of 35,000 ft is shown in Fig. 3, the position of transition from laminar to turbulent flow being clearly shown as the straight rear edge of the white area extending from root to tip of the wing.

At air speeds near 150 m.p.h., the indications were developed somewhat too rapidly with naphthalene. Addition of about 5 per cent of the less volatile diphenyl enabled the tests to be prolonged to the more convenient period of about 15 minutes. Larger additions, though giving more opaque white coating, tended to produce diffuseness of indication.

4.4. *Results in Supersonic Wind Tunnels.*—Acenaphthene coatings yielded good transition indications in about 10 minutes at air speeds near 1,200 m.p.h. At 1100 m.p.h., the coating evaporated uniformly without development of a line indication such as was obtained at the higher speed. This was attributed, at first, to failure of acenaphthene to act as an indicator at the lower speed. Later, it was found that the airflow was turbulent at this speed. No failure of the material as an indicator had in fact occurred, there being no transition from laminar to turbulent flow to be recorded.

Azobenzene, an orange-coloured substance giving yellow coatings on a white-surfaced model, yielded a somewhat diffuse indication in about 20 minutes at an air speed of about 1,350 m.p.h. The diffuseness was attributed to a slight turbulence in the airflow at this speed. On a black surface heavily coated with azobenzene, a good transition indication was obtained in 90 minutes at an air speed of 1260 m.p.h. After 3 days much of the thinner parts of the coating had evaporated, leaving the indication shown in the photograph Fig. 4.

4.5. *Results of Aircraft Trials.*—A series of trials (R & M. 2079³) of transition indicators, comprising over 70 flights, was carried out over a period of some months with *Hurricane*, *Meteor* and *Vampire* aircraft at speeds from 130 to 445 m.p.h. Details of some of these trials are given in Table 2.

Hydroquinone diethyl ether was used chiefly at the lower speeds, the indications developing in 10 to 45 minutes depending on speed temperature and altitude of flight. Acenaphthene and fluorene were used for speeds from 250 to 445 m.p.h., the indications developing in 8 to 32 minutes, depending on the flight conditions.

In general, the materials tested were successful indicators at temperatures down to -22 deg C and at altitudes up to 20,000 ft.

The transition indication obtained with hydroquinone diethyl ether on the wing of a *Hurricane* aircraft after a flight of 25 minutes at 180 m.p.h., altitude 35,000 ft and temperature 10 deg C, is shown in the photograph Fig. 5. In similar conditions, a transition indication was obtained with fluorene on the wing of a *Vampire* aircraft in 12 minutes at 400 m.p.h., and is shown in the photograph Fig. 6. In both photographs, the divergent dark areas are wakes of turbulence set up by roughnesses close to the leading edge of the wing. The position of transition is obliterated in the foreground of Fig. 5 by coalescence of the wakes.

4.6. *Laboratory Results with Water-transition Indicators.*—The following materials, among a large number tested, were placed in the order of rate of development of indication in water at 15 deg C, acetoacetanilide, exalgin, acetanilide, phenacetin, hydroquinone diacetate, para-acetotoluidide, benzoin, and stearic acid. Of these, the first two were extremely fast, and the last two extremely slow indicators. A few other substances were also found suitable as indicators, such as the aromatic acids and their amides, but were sternutatory or otherwise objectionable in spraying, and required special solvents.

4.7. *Results in Full-scale Water Tanks.*—In full scale trials, hydroquinone diacetate proved to be the most generally suitable water-transition indicator. Recording of stagnation points on models in seaplane-tanks was found possible with acetanilide, but not with the slower indicators, phenacetin and hydroquinone diacetate.

Though adherent coatings of acetanilide were originally obtained (*see* section 1.3) only by admixture with dibutyl phthalate, it was found that very adherent, white coatings of acetanilide could be obtained by spraying a 4 or 5 per cent solution in acetone, or in a mixture of acetone and light petroleum (boiling point 60/80 deg C) in about equal parts by volume.

Hydroquinone diacetate, sprayed from 5 per cent solution in acetone, was found⁷ to be specially suitable on large models of ship hulls for indication of natural transition and artificially produced turbulence. Wakes deliberately produced by small excrescences fixed at various points on the hull were also found of value in indicating the direction of flow of water over the hull, thus providing a means of determining the optimum position of bilge-keels on ship bottoms. The photograph (Fig. 7) shows the indication obtained in water on a model at $2\frac{1}{2}$ kt (corresponding to $10\frac{1}{2}$ kt on a 400 ft ship at deep load draught). The white area on the lower part of the hull is the region of laminar flow, in which appear two dark wakes of turbulence caused by small excrescences placed on the surface.

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Acknowledgement is also made to Mr. W. P. Walker of Messrs W. Denny & Bros. Ltd., Leven Ship Yard, Dumbarton, for permission to use the photograph Fig. 7.

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TABLE 1

*Melting Point and Probable Vapour Pressure at 20 deg C of
Chemical Substances for Air-transition Indication*

Substance	Melting point deg C	Vapour pressure at 20 deg C, mm Hg
dimethyl oxalate	54	1.0
camphor	178.5	0.7
hexachlorethane	186.6	0.7
iodine	112.9	0.6
urethane (ethyl carbamate)	50	0.4
durene	79.5	0.3
naphthalene	80.2	0.2
1.2.3.5—tetrachlorobenzene	54.5	0.1
propyl carbamate	53	0.1
isobutyl carbamate	65	0.08
thymol	51.5	0.05
diphenyl	69.5	0.04
exalgin (N-methylacetanilide)	102	0.03
acenaphthene	95	0.02
fluorene	113	0.01
phenyl benzoate	70.5	0.008
benzhydrol	68.5	0.004
azobenzene	68	0.003
phenanthrene	99.5	0.002

TABLE 2

Tests of Transition Indicators on Aircraft in Flight

Indicator (5% sol.)	Aircraft	Speed m.p.h.	Altitude ft	Temp. deg C	Time min	Indication
H	<i>Hurricane</i>	130	2500	+ 7	25	Average
„	<i>Meteor</i>	170	4000	+ 2	30	Good
„	<i>Hurricane</i>	180	3500	+ 10	25	Very good
„	„	190	10000	0	15	Good
„	„	210	8000	- 5	45	„
„	„	230	10000	0	15	„
„	„	230	1000	+ 6	11	Very good
A	<i>Vampire</i>	250	3000	+ 10	12	Good
H	<i>Hurricane</i>	280	13000	- 2	10	„
A	<i>Vampire</i>	300	20000	- 19	30	„
F	„	300	20000	- 19	30	Faint
„	„	300	20000	- 22	32	„
A	„	300	3600	+ 11	20	Very good
F	„	350	3000	+ 10	10	Good
„	<i>Meteor</i>	370	3000	+ 5	15	„
„	„	370	3000	+ 2	25	„
„	<i>Vampire</i>	400	3500	+ 11	10	Very Good
„	„	400	3500	+ 11	12	„
HH	„	400	8000	+ 4	12	Good
„	„	400	8000	+ 5½	12	„
A	„	400	3500	+ 8	12	Very good
F	„	445	3500	+ 11	10	Good

A acenaphthene
 F fluorene
 H hydroquinone diethyl ether
 HH „ „ „ (heavy coating)

	mp. in C°		mp. in C°
PHENANTHRENE	99.5	PROPYL CARBAMATE	53
AZOBENZENE	68	1235-TETRACHLOROBENZENE	54.5
BENZHYDROL	68.5	NAPHTHALENE	80.2
PHENYL BENZOATE	70.5	DURENE	79.5
FLUORENE	113	ETHYL CARBAMATE	50
ACENAPHTHENE	95	IODINE	112.9
EXALGIN	102	HEXACHLORETHANE	186.6
DIPHENYL	69.5	CAMPHOR	178.5
THYMOL	51.5	DIMETHYL OXALATE	54
ISOBUTYL CARBAMATE	65		

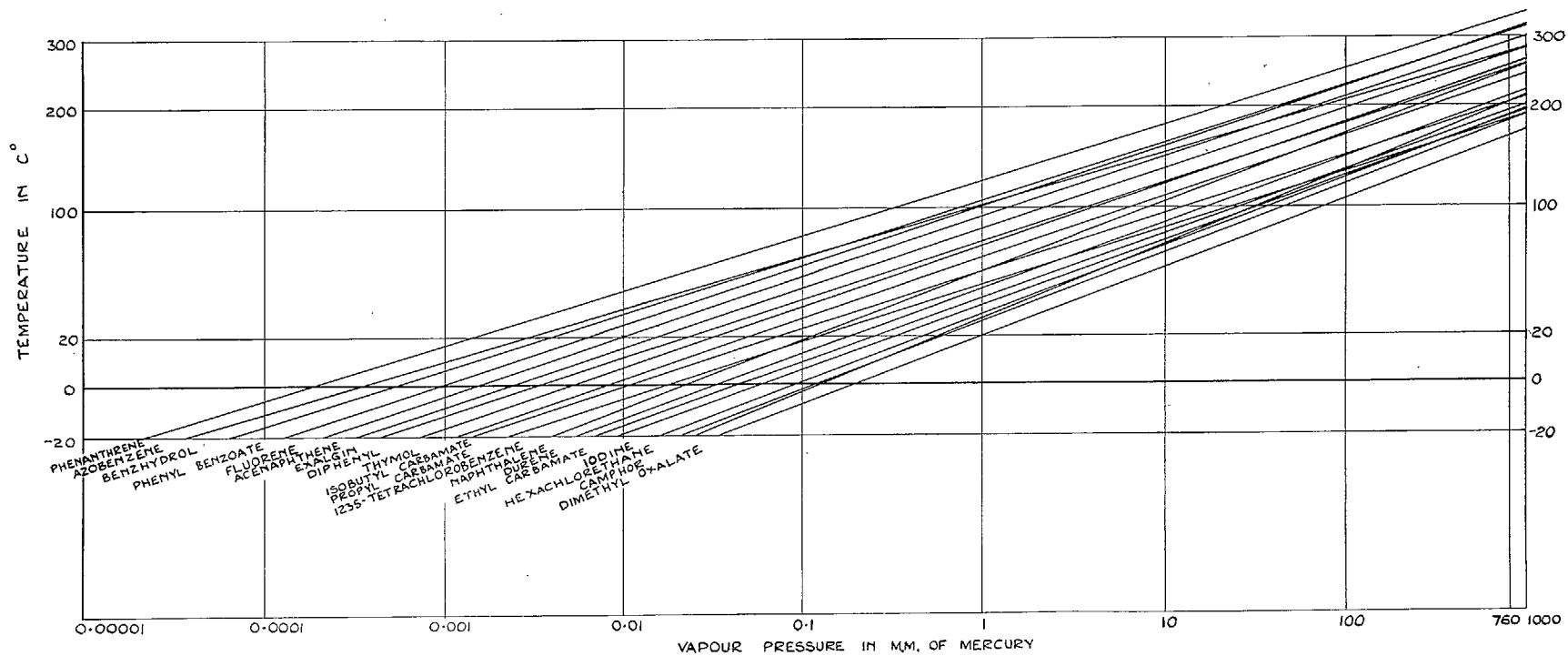
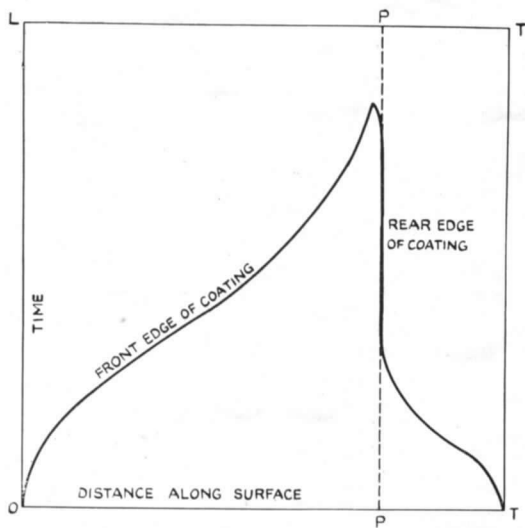


FIG. 1. Vapour pressures of sublimable solids having melting-points of over 50 deg C.



OL TO TT, DIRECTION OF AIR FLOW
 OLPP, AREA OF LAMINAR FLOW
 PP, POSITION OF TRANSITION
 PPTT, AREA OF TURBULENT FLOW

FIG. 2. Development of transition indication.

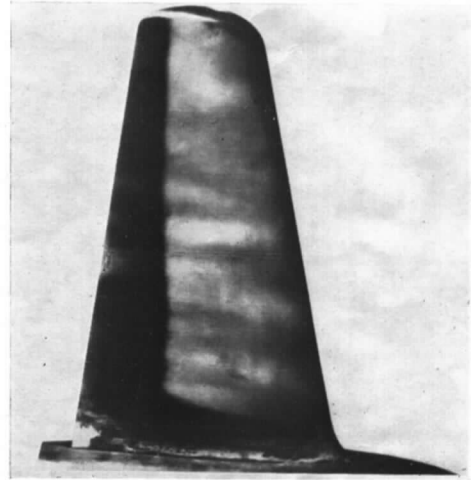


FIG. 3.

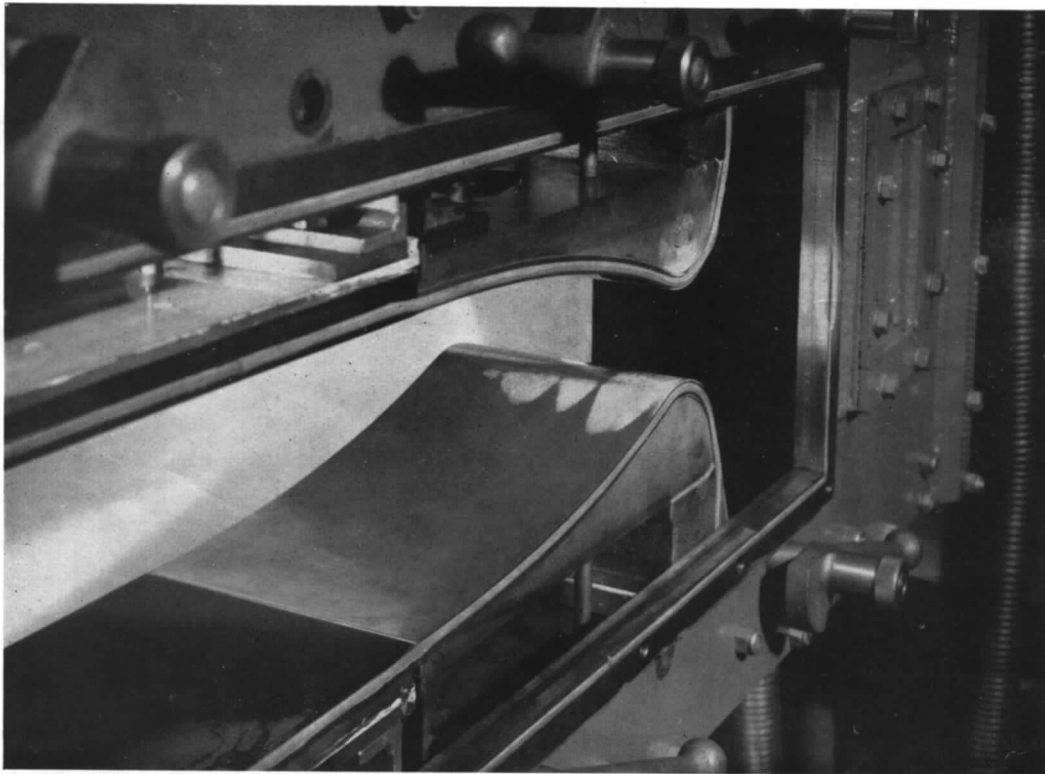


FIG. 4.

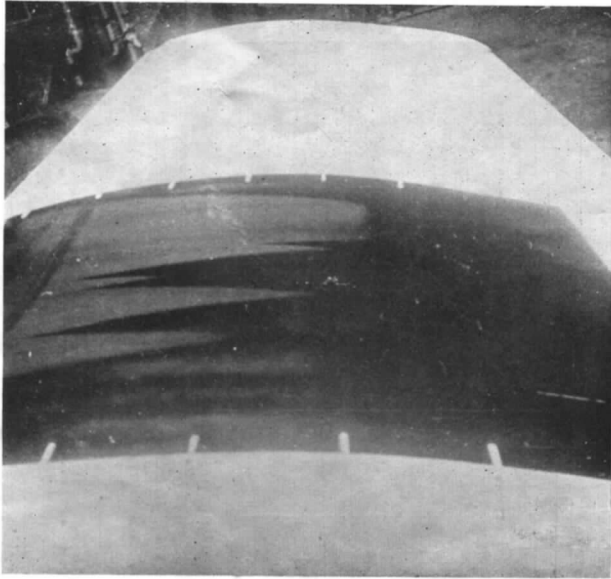


FIG. 5.

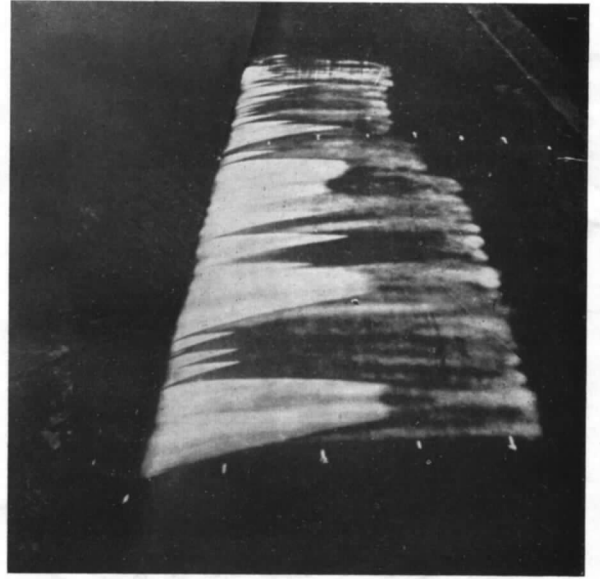


FIG. 6.

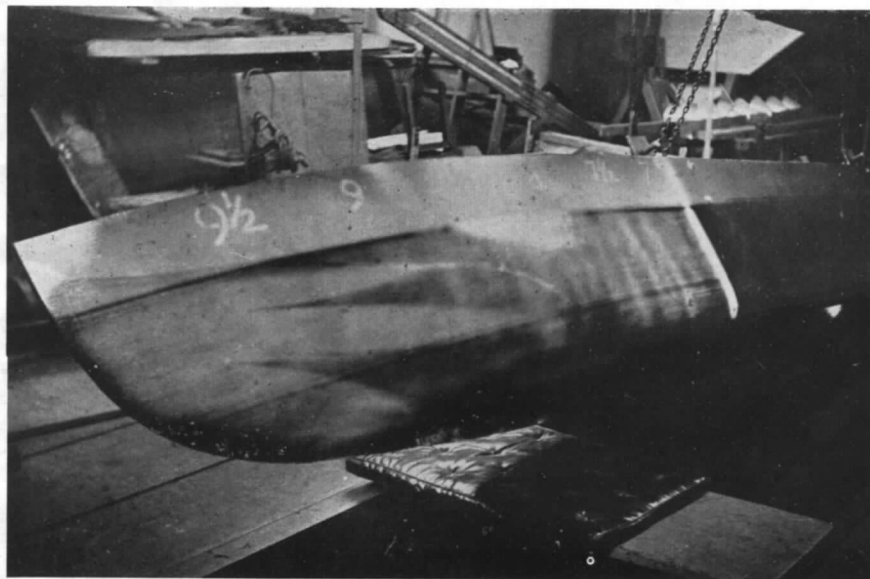


FIG. 7.

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