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No. 339

REFRIGERATED WIND TUNNEL TESTS ON SURFACE COATINGS FOR PREVENTING ICE FORMATION

By Montgomery Knight and William C. Clay
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Summary

This investigation was conducted in the Refrigerated Wind Tunnel at Langley Memorial Aeronautical Laboratory, Langley Field, Virginia, to determine the effectiveness of various surface coatings as a means for preventing ice formations on aircraft in flight.

The substances used as coatings for these tests are divided into two groups: compounds soluble in water, and those which are insoluble in water.

It was found that certain soluble compounds were apparently effective in preventing the formation of ice on an airfoil model, while all insoluble compounds which were tested were found to be ineffective.

Introduction

The formation of ice on aircraft in flight presents a serious hazard, which is of particular importance to air mail and transport lines. The danger arises partly from the increased weight, but more particularly from the deformation of aerodynamic shapes resulting in decreased lift, increased drag, excessive vibration, and loss of control. Wings, wires, and struts are the parts most seriously affected.

The possible methods for overcoming the ice hazard may be divided into two general classifications. The first is prevention, which includes the use of surface applications and the use of heat. The second is avoidance, which includes adequate weather forecasting over established air routes and the use of suitable instruments to enable pilots to avoid conditions conducive to ice formation.

A study of the various physical and chemical properties of water as a solid, liquid, and vapor, with particular reference to atmospheric conditions, is useful in interpreting phenomena of ice formation. The problem is very complex and still the subject of much research. However, the following references are suggested as giving a general resume of the subject. A discussion of the behavior of water in its various forms may be found in References 1 and 6. The formation of clouds, water, vapor, ice, snow, etc., and associated phenomena are discussed in any good text on meteorology (References 1 to 5).

Free flight information and other material directly applicable to the subject of ice formation may be found in References 7 to 12. In many records, there are apparently conflicting accounts of ice formations and the conditions under which they occur, which may be due to the particular weather conditions encountered and type of aircraft used. Thus far these unrelated reports have been of little technical value, and a definite solution of the problem can be looked for only after a complete study of the subject.

There are three general atmospheric conditions which cause three corresponding types of ice formations on airplanes: namely, temperature inversion, mild and high supercooling.

The first condition, known as temperature inversion, exists during an "ice storm." An ice storm is considered to be any storm which causes ice to form on exposed objects (Reference 2). The structure of the ice formed in such storms is generally smooth and glassy in appearance, but it may be temporarily rough owing to an admixture of snow or sleet. Another kind of roughness may develop if the water freezes slowly after it has fallen, which may cause ridges to form. In practically all cases, this ice has been observed to adhere strongly to the surface. There are numerous temperature combinations of the air, rain, and object which may produce these ice formations, but the most easily recognized condition is the one in which the temperatures of the air and object are below the freezing point and rain is falling from comparatively warm clouds at a higher altitude. Under such conditions, ice will form on any exposed object in this colder region. In the case of an airplane flying in such a region, ice forms and builds up rapidly on all leading edges, giving a very blunt nose which soon breaks up the smooth air flow over the surfaces, thus reducing the lift and increasing the drag and making an immediate landing necessary. It is possible, in some cases, for an airplane to rise above the ice-forming region, but often this region is quite extensive both in altitude and area. Such storms are quite frequent in Northern United States and Canada and generally cause considerable damage, due to heavy formations of ice on telegraph lines and trees.

The second general condition occurs in cloud or mist when the air temperature is 1 or 2 degrees below freezing. In this case, the surface tension of the water particles is great enough to overcome the tendency to freeze. Such a state is relatively unstable, and as soon as an airplane strikes the particles, they freeze. This is a mild form of supercooling, and gives a "glaze" formation similar to that obtained during an ice storm, except that it is generally more moderate and does not deform the surfaces of an airfoil to such an extent. It is, however, a condition that is encountered quite frequently and has caused many forced landings. A pilot may fly in this mist for some time without realizing that the wings are collecting quite a growth of ice until he notices a marked vibration of the airplane, or a sluggishness of the controls which is accompanied by difficulty in maintaining altitude. It is believed that with sufficient warning, a pilot could avoid such a region, as it is generally a local condition.

The third condition is encountered in fog or mist which is several degrees or more below freezing temperature. In such a region, the water particles are highly supercooled. As soon as an airplane comes into contact with these particles, they freeze upon the surfaces instantly and have an appearance somewhat similar to snow. This type of formation is, however, composed of hard, white crystals of ice, which adhere strongly to the surface and which build out forward from all exposed leading edges giving them a sharp-nosed shape. This particular type of condition has not as yet been encountered to a great extent.

Another condition under which ice forms on an airplane when the temperature of both air and rain is slightly above freezing point has been reported occasionally. In such a case, the rain, as it falls on the airplane, may be cooled by evaporation sufficiently to cause freezing. The extent of this evaporative cooling varies inversely with the relative humidity.

Up to this date no effective preventive for ice formation is in use on airplanes. A few instances are known where individual pilots have tried one or two surface applications without success. A few commercial instruments have been made to warn pilots when they are approaching dangerous regions, but this phase of the problem is still relatively undeveloped. In 1925, a small wind tunnel was set up in a refrigerated room at McCook Field for the purpose of studying the effect of ice formation on Pitot tubes, but this research did not include methods of prevention on other airplane parts. The United States Weather Bureau has made a special study of ice-forming weather conditions with the intention of using weather forecasts by radio to warn pilots of approaching danger. Such a system is now in use to a limited extent, and the value of these forecasts cannot be overestimated.

It has been recently announced through the press that a device has been developed by Dr. W. C. Geer and Dr. Merit Scott of Cornell University in cooperation with the Daniel Guggenheim Fund, the B. F. Goodrich Company, and the National Air Transport, which removes ice from the wing as fast as it forms. This device, known as an "overshoe," is laced over the leading edge of the wing. It consists mainly of rubber, impregnated with a special oil which reduces the adhesion between the ice and the rubber. Within the shoe are air ducts to which a pulsating air pressure is applied alternately inflating and deflating the shoe, thus distorting the leading edge of the wing and breaking off the ice as it forms.

The problems of ice formation are being investigated at the Langley Memorial Aeronautical Laboratory, both on airplanes in flight and on models in a refrigerated wind tunnel which was built especially for this purpose. The results of the flight tests that have been conducted thus far have been published in References 8 and 12. The present preliminary report covers tests made in the wind tunnel on means for preventing ice formation by the use of surface coatings. In these tests formations on wings only have been considered, since this represents the most important aspect of the hazard.

Apparatus

A diagram of the refrigerated wind tunnel, which is of the open-throat type with an air stream 6 inches in diameter, is shown in Figure 1. The tunnel proper, which is of metal, is insulated from the outside air by layers of cork and wood. The test chamber is insulated by double glass doors and windows which enable the ice-forming process to be observed and photographed from the outside (Fig. 2). The air temperature in the tunnel is lowered and regulated by the flow of cold brine through the hollow, metal guide vanes, the brine being cooled by a refrigerating apparatus of commercial type (Fig. 3). The circulation of the air in the tunnel is maintained by a propeller driven by an electric motor.

In order to simulate clouds or rain, cold water is injected into the air stream by means of a group of four spray nozzles, which are of the air impingement type and give fine atomization. The location of these nozzles is shown in Figure 1, and the cross section of a nozzle tip is given in Figure 4. The spray water is contained in an insulated, closed reservoir (Fig. 5), which is equipped with a water level gauge and with a brine coil for cooling the water. Compressed air is blown from the "stirring tube" in the reservoir keeping the water in motion so that it will not freeze on the coils. The reservoir is connected to the compressed air supply as shown in the diagram. The quantity of spray water and the size of the drops admitted to the tunnel are regulated by various combinations of the air and water pressures in the nozzles.

The temperature readings during the operation of the tunnel are obtained by resistance thermometer units of a commercial type placed in the water reservoir, spray nozzle inlet tube, and test chamber (Figs. 1 and 6).

The model used in these tests was a 3-inch chord, Clark Y mahogany airfoil. The span of the airfoil was 12 inches, which permitted it to extend entirely across the jet at the center.

In all the tests only half of the airfoil was covered with the substance under consideration, the other half being left bare for comparison. In all accompanying photographs of ice formations, the coated half of the wing is indicated by an arrow.

Tests and Results

Certain preliminary tests were made in the wind tunnel to determine the best form of water spray necessary to produce ice of smooth appearance and which would be similar in structure and form to that observed in flight (Reference 12), in order to make a study of possible preventives. It was found that the character of the formations obtained depended to a great degree on the quantity of water admitted to the tunnel per unit of time. A spray which consisted of large drops was found to use excessive quantities of water which could not be properly regulated without giving very poor dispersion in the jet, and which gave formations of ice on the model of a very different shape from any obtained in flight. A spray, which consisted of very small drops, was found to be quite satisfactory and was used in all the following tests, as it could be easily controlled to give even dispersion across the air stream at any desired rate of water output.

Having satisfactorily produced ice formations, tests were then made on various surface coatings to find their effect in preventing or delaying ice formation. These tests were divided into two series. In the first, the spray was made dense to impose extreme weather conditions on the coatings. However, it was not sufficiently dense to prevent the water from freezing very soon after it deposited on the model, thus eliminating the formation of icicles and other deformations on the leading edge which would be misleading. In the second series, the spray was made very much lighter and, as is explained later, the results were different in several respects from those obtained with the heavy spray.

Under the first series of tests the following substances were tested at an air temperature of -1°C, which is about the average temperature encountered in an ice storm, and at an air stream velocity of 70 m.p.h. (31 meters per second) with the airfoil set at zero angle of attack.

Insoluble compounds:

Light lubricating mineral oil.

Heavy lubricating mineral oil.

Cup grease.

Vaseline.

Paraffin.

Simonize wax.

Soluble compounds:

Glycerine.

Glycerine and calcium chloride.

Molasses and calcium chloride.

Hardened sugar solution

Hardened glucose solution.

All the above compounds, except the sugar and glucose, were brushed on the airfoil so as to form a thin coat. The sugar and glucose solutions were boiled down, applied about 1/16 inch thick with a brush while hot and allowed to harden. When in the hardened condition they had about the consistency of taffy candy.

In these first tests, oils, greases, and waxes showed no tendency towards prevention or even hindrance of the formation of ice, and actually, in some cases they augmented it as shown in Figure 7. It was originally believed that the drops would not remain on these substances, since they are supposed to shed water, but this action did not take place. The drops adhered to the surface, especially at the stagnation point of the leading edge, and froze quite as readily as on the bare wing.

Tests on the soluble substances likewise did not show a marked preventive tendency. It was believed that these substances would dissolve with the water as fast as it struck the surface, and thus lower the freezing point so that ice would not form. Owing to the low viscosity of the glycerine and calcium chloride solutions, they immediately blew back from and exposed the leading edge on which ice then formed. Tests made on the sugar solution did not show this tendency to blow back. The solution, however, was not easily dissolved, consequently ice formed readily on the leading edge on top of the coating. It was difficult to distribute this sticky substance evenly on the wing and some of it crystallized upon cooling, showing that it was a rather impractical coating at the best. In tests on a hardened glucose solution (Fig. 8), made at the suggestion of the U.S. Bureau of Standards, the same general process took place as in the case of the sugar, except that for the first two minutes of the test the formation of ice on the coated side was hindered. However, after the formation had once started, it built up rapidly showing apparently that there was too much water falling on the surface for the glucose to have much effect.

The formations obtained under this first series appeared to be exaggerated. During the first two minutes of each test the formation was apparently similar in proportion to those obtained in actual flight, but after that it merely built up and exceeded in proportions any probable full-scale formation. Figures 7 and 8 show such formations after tests of 15 minutes each, in which heavy oil and glucose were used as coatings. In Figure 8 there appears to be a larger formation on the coated than on the uncoated half of the wing, but actually there was very little difference in the weight of ice. After the original leading edge formation became large, some of the wet solution which remained on the back part of the wing was carried forward by a reversal of air flow. This melted some of the back part of the leading edge formation and altered the profile, making it thinner in the vertical dimension and causing it to build out forward, thus giving an extended formation as seen in the plan view. It is doubtful if such an action has any importance in this study, as an airplane probably could not remain in flight long enough to collect such a formation on a wing, since the lift would be greatly reduced.

Assuming that the conditions under which the first series of tests was made were too severe and probably not representative of flight conditions, a second series of tests was made which gave less exaggerated formations. These second test conditions were obtained by reducing the quantity of spray water admitted to the tunnel per unit of time to one-fifth of the previous amount, and by reducing the duration of the tests to nine minutes. A few preliminary tests under these altered conditions appeared to indicate that the formations obtained were more moderate and approximated more nearly those of full scale.

It was believed, since ice had been observed to form only on the leading edge of the model airfoil, that any preventive compound need be applied only to that part of the wing to be effective. Subsequent tests which were made on that basis proved this assumption to be correct. The drops of water which strike the leading edge and are prevented from freezing by the preventive compound, blow back on the airfoil and remain in the liquid state.

Under the less exaggerated conditions additional tests were made on the glucose, as this was the only substance used thus far that had any noticeable preventive effect on the formation. It was expected that these new test conditions would amplify the preventive effect noticed during the first two minutes of the previous test.

The first glucose test of this second series was made at an air temperature of $-0.5^{\circ}C$, and, as can be seen in Figure 9, the formation obtained was considerably more moderate than those shown in Figures 7 and 8. During the first eight minutes the glucose entirely prevented the growth of ice, but by the end of the ninth minute, all of it had dissolved from the leading edge and ice began to form as can be seen in Figure 9. Similar tests were then made, gradually lowering the air temperature. At temperatures above $-2^{\circ}C$, the structure of the ice on the uncoated half of the airfoil was that of a clear solid, giving a bluntnosed shape such as is formed in a temperature inversion ice storm. The glucose, which can be distinctly seen on the leading edge in Figure 10, completely prevented this type of formation. Below -2°C, the structure of the ice which formed on the uncoated half of the model was similar to that known as "rime," which indicated the presence of supercooled particles of water in the air. This "rime" formation was composed of hard, white crystals which built out forward from the leading edge towards the direction of the air stream, giving a sharp-nosed shape which was distinctly different from the blunt type obtained at higher temperatures. The preventive action of the glucose with this type of ice structure decreased with temperature until at -6°C (Fig. 11), it was practically negligible.

The temperature of -2°C recorded in these tests as the point of change between the formation of "glaze" and "rime" does not necessarily mean that "glaze" will not form below that temperature nor "rime" above it, as that depends on various weather conditions.

A solution of "White Karo" corn syrup was then tested. This was applied in the same manner as the glucose solution. It made a coating very similar to that of the glucose, except that when in the hardened condition, it was slightly softer. This "Karo" coating entirely prevented all formations of ice from 0°C to the lowest limit tested, which was -4°C. Figure 12 shows very clearly the preventive effect of the "Karo" on a "rime" formation at -4°C.

A coating of honey applied in the same manner as the glucose completely prevented the formation at $-1^{\circ}C$, but only hindered it at the lower temperatures. The honey appeared to dissolve from the wing much faster than did any of the other boiled-down solutions, which, of course, shows that it has a short life as a preventive.

A test made on an application of glycerine soap showed no tendency whatever to prevent or hinder the formation. While this is distinctly a soluble compound, the solution formed evidently did not lower the freezing point sufficiently.

It was not considered necessary to retest under the altered conditions all the insoluble compounds previously tried, as at no time did any of them show any tendency to prevent or hinder the formation. However, for comparison, tests were made with heavy oil and, as expected, no preventive action was indicated (Fig. 13).

Tests on a commercial paint and on goose oil, recently suggested because of their "ice-adhesion" properties (Reference 11), failed to prevent the formation of ice on the model. Several other tests on various commercial products for ice prevention have also failed to show any such tendency.

A list of all surface coatings tested and their degree of effectiveness is given in Table I.

Discussion

The value of the results of this research depends upon the successful reproduction in the refrigerated wind tunnel of actual ice-forming weather conditions encountered in flight. This has proved very difficult, since there are a large number of possible conditions upon which but little flight information is available.

Information on various flight tests has been carefully studied and compared with the wind tunnel results on the uncoated airfoil. For comparison with wind tunnel formations, a photograph of an actual ice formation obtained in a test flight at this laboratory is given in Figure 14. This particular example was obtained during a sleet and rain storm at a recorded air temperature of about -0.5°C. The formation was collected in about 15 minutes, and though very light, had a characteristic shape and structure.

The amount of water present in the wind tunnel jet was measured roughly to determine the actual density of the spray used in the tests. These measurements were compared with meteorological tables, and indicate that the spray density used in the first series of tests, which was about 2000 milligrams of liquid water per cubic meter of air, corresponds to an excessive rain. Similarly, the density used in the second series, which was about 500 milligrams per cubic meter, corresponds with figures for a moderate to heavy rain. It is believed that the latter density represents more closely average ice-forming weather conditions.

It is doubtful whether any insoluble compound would ever be effective in preventing ice formation on airplane wings. The adhesive properties alone between the water and the substance do not appear to affect the formation of ice. Hence, there is nothing to prevent the small drops from lodging and freezing on the leading edge.

In general, all soluble substances when dissolved in a liquid cause a lowering of the freezing temperature. This phenomenon appears to be the greatest factor in the study of surface applications for ice prevention. Some solutes are, of course, more effective than others, depending on their solubility, molecular weight, and degree of ionization. Another phenomenon produced by some substances is that they decrease the rate of growth of crystals that may be precipitating from a solution in which they are present even in small quantities. Glucose and Karo corn syrup are good examples of substances having this effect. It is likely that this property aids in effecting ice prevention by suppressing the precipitation of ice crystals, and although this latter phenomenon may not be as important as the first, it may have a bearing on the selection of suitable compounds.

There are limitations to the practical use of surface coatings. Many effective agents are physically unsuitable in that they are quickly washed away. This fact at once eliminates the use of liquids and soft soluble coatings unless a means of continuous application is provided. Some of the soluble materials which can be applied so as to produce a fairly hard coating are satisfactory as long as they last, but these, too, will wash away after a limited time. The durability of these soluble substances depends on the hardness, while their effectiveness which decreases with the temperature depends on the softness of the application. Hence, the consistency of such applications, which must be determined by experimentation, must be a suitable compromise depending on the requirements for their use.

Conclusions

Within the scope of these tests which consisted only in investigating the ability of certain substances when applied to an airfoil surface to prevent the formation of ice, none of the compounds showed any appreciable preventive action with the heavy spray. The following conclusions may be drawn from the results of tests in which the lighter spray was used:

1. Insoluble compounds, such as oils, waxes, greases, and paints, are ineffective in preventing the formation of ice.
2. Soft soluble compounds, such as mixtures of molasses and glycerine with calcium chloride, which do not have a strong tendency to keep their shape and to adhere to the surface, blow away from the leading edge and do not prevent the growth of ice.

3. Hard soluble compounds, such as glucose and Karo syrup, which hold their shape and adhere strongly to the surface, prevent ice formations within certain temperature limits, depending on their solubility.

4. Coatings need only be applied to the leading edge of an airfoil as far back as the maximum ordinate.

5. Other methods of applying substances to the wing surfaces may prove to be effective, such as the continuous application of a liquid soluble compound to the leading edge.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., March 7, 1930.

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TABLE I

Surface Coatings Tested

Insoluble Compounds	Soluble Compounds
X Light oil	P Glycerine
X Heavy oil	P Glycerine and calcium chloride
X Cup grease	P Molasses and calcium chloride
X Paraffin	I Hardened sugar solution
X Vaseline	F Hardened glucose solution
X Simonize wax	G Hardened "Karo" syrup solution
X Commercial preparations	F Hardened honey
X Commercial paint	X Soap
X Goose grease	

X = Not a preventative

P = A possible preventive, but could not be made to stay in place on the wing

I = Prevention indicated

F = Prevention fair

G = Prevention good

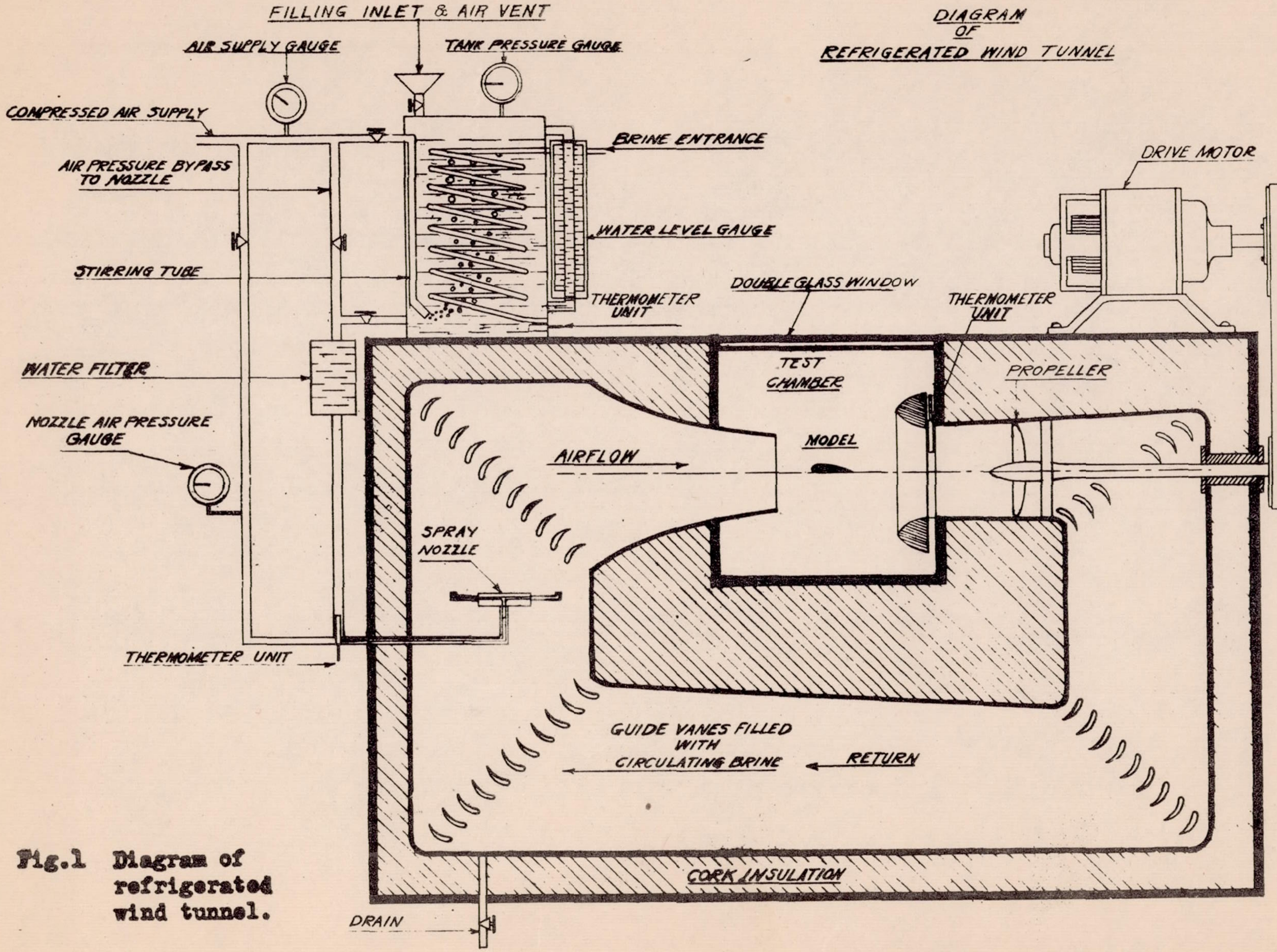


Fig.1 Diagram of refrigerated wind tunnel.

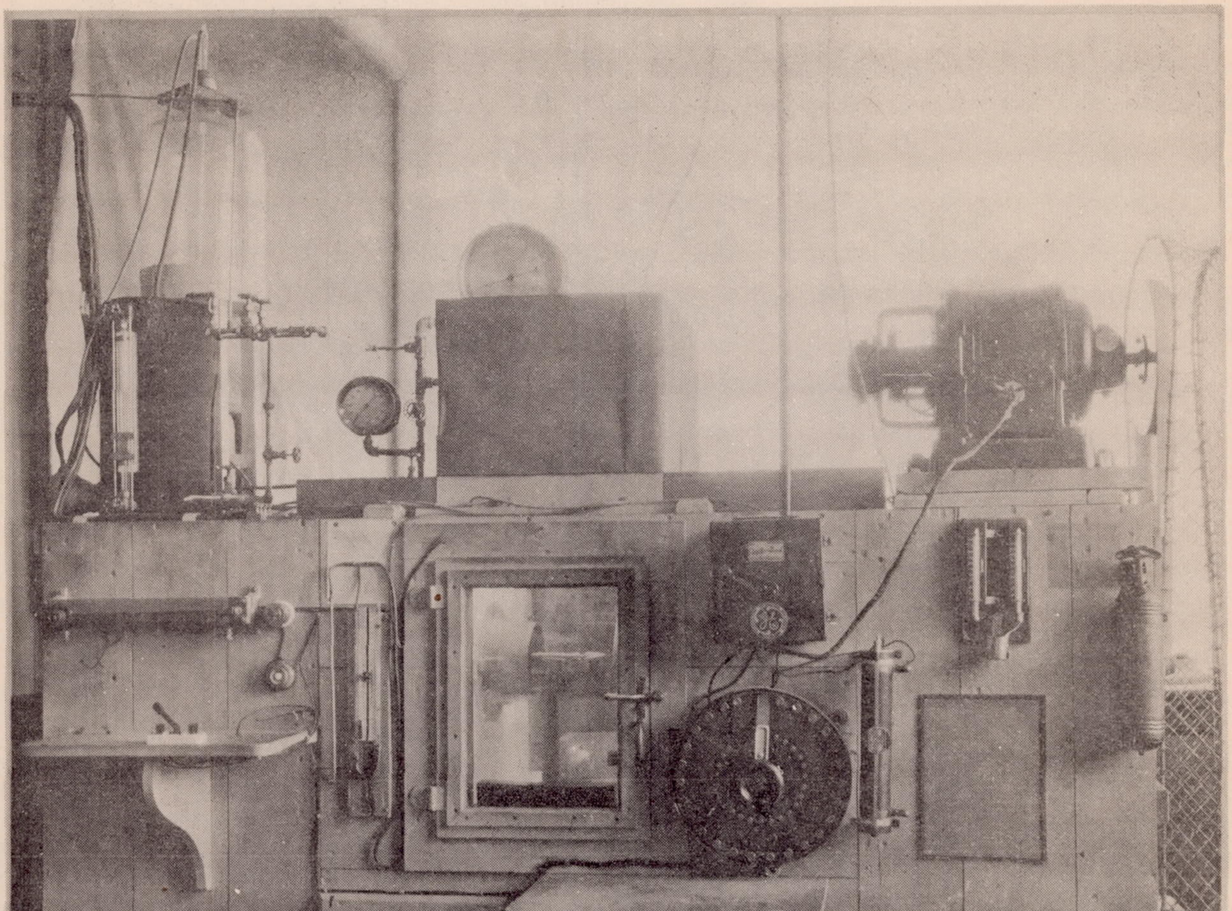


Fig.2 General view of refrigerated wind tunnel.

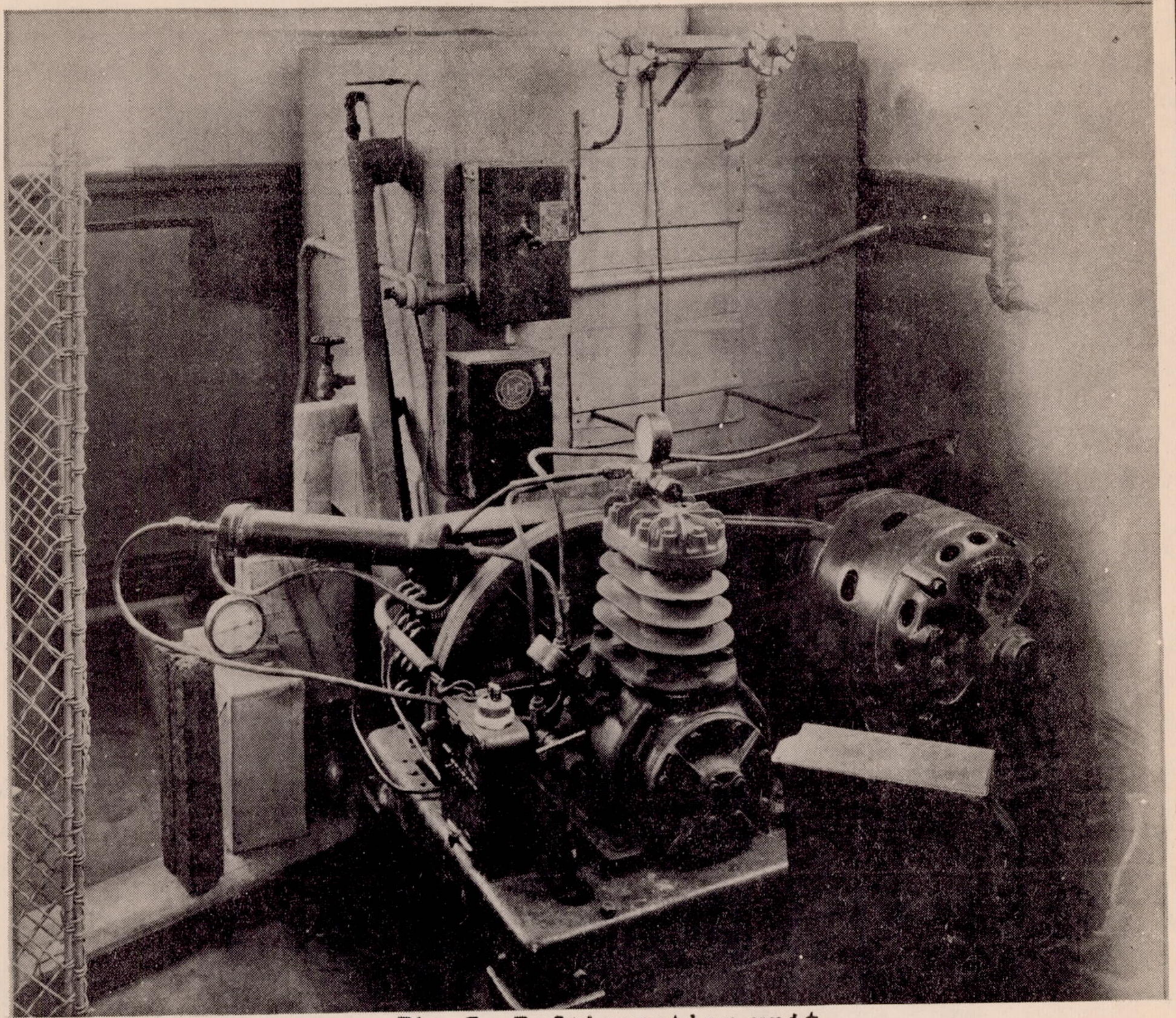


Fig.3 Refrigerating unit.

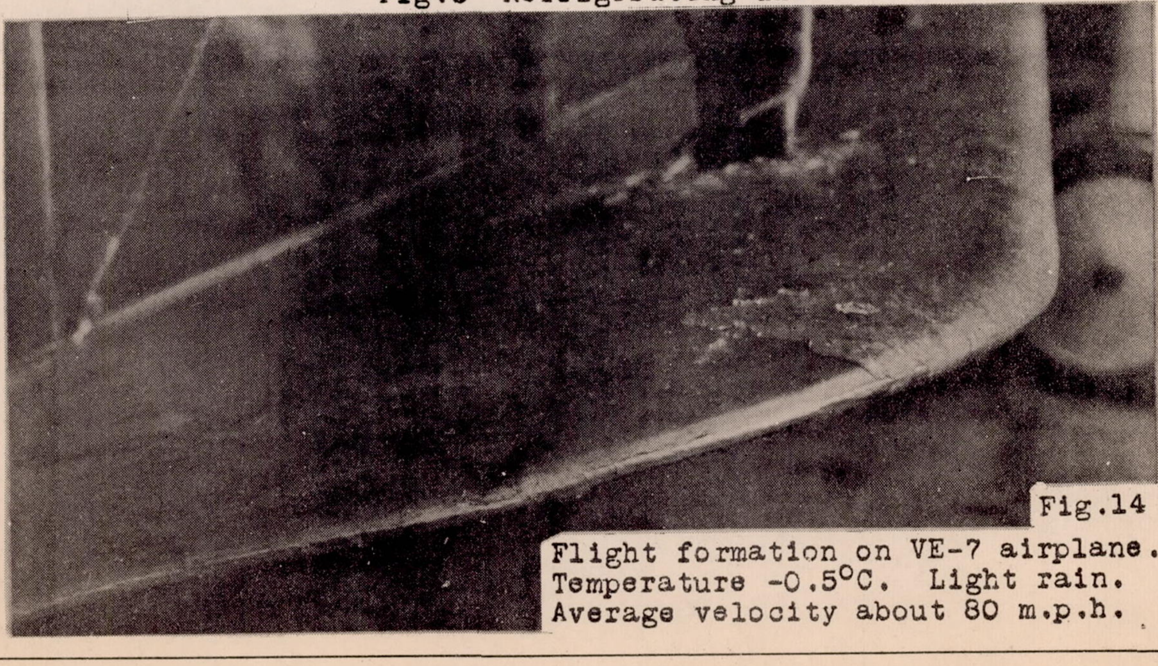


Fig.14

Flight formation on VE-7 airplane.
Temperature -0.5°C. Light rain.
Average velocity about 80 m.p.h.

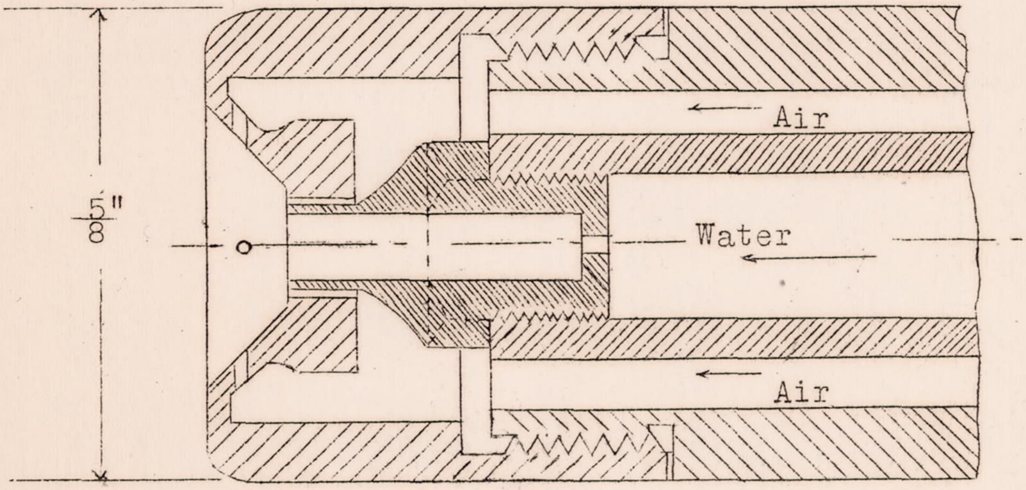


Fig.4 Spray nozzle tip.

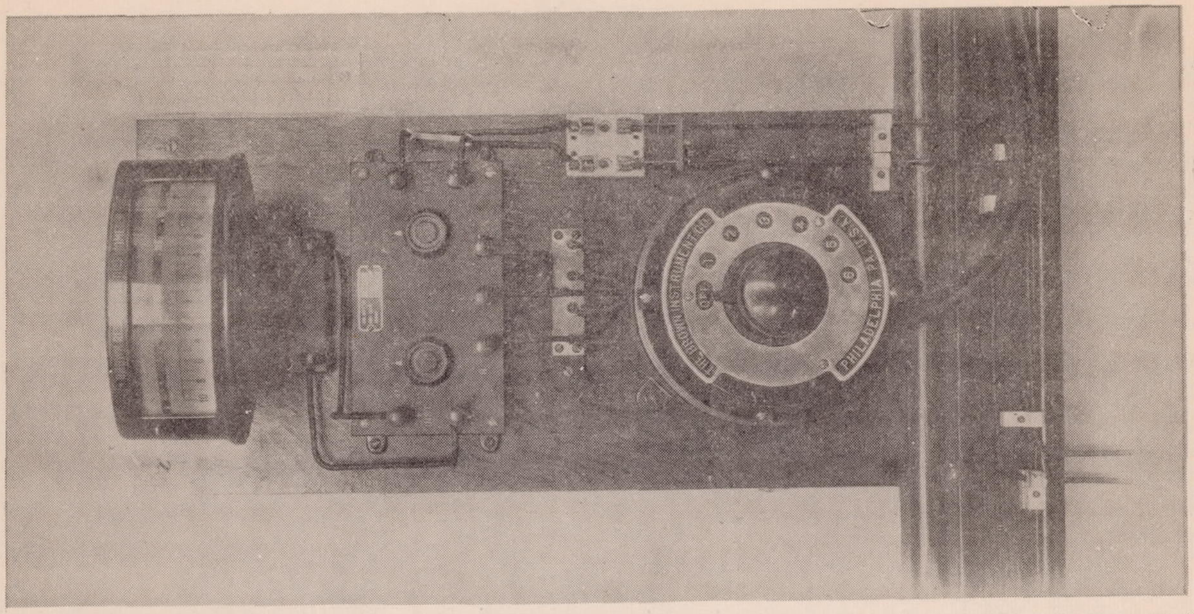


Fig.6 Resistance thermometer panel.

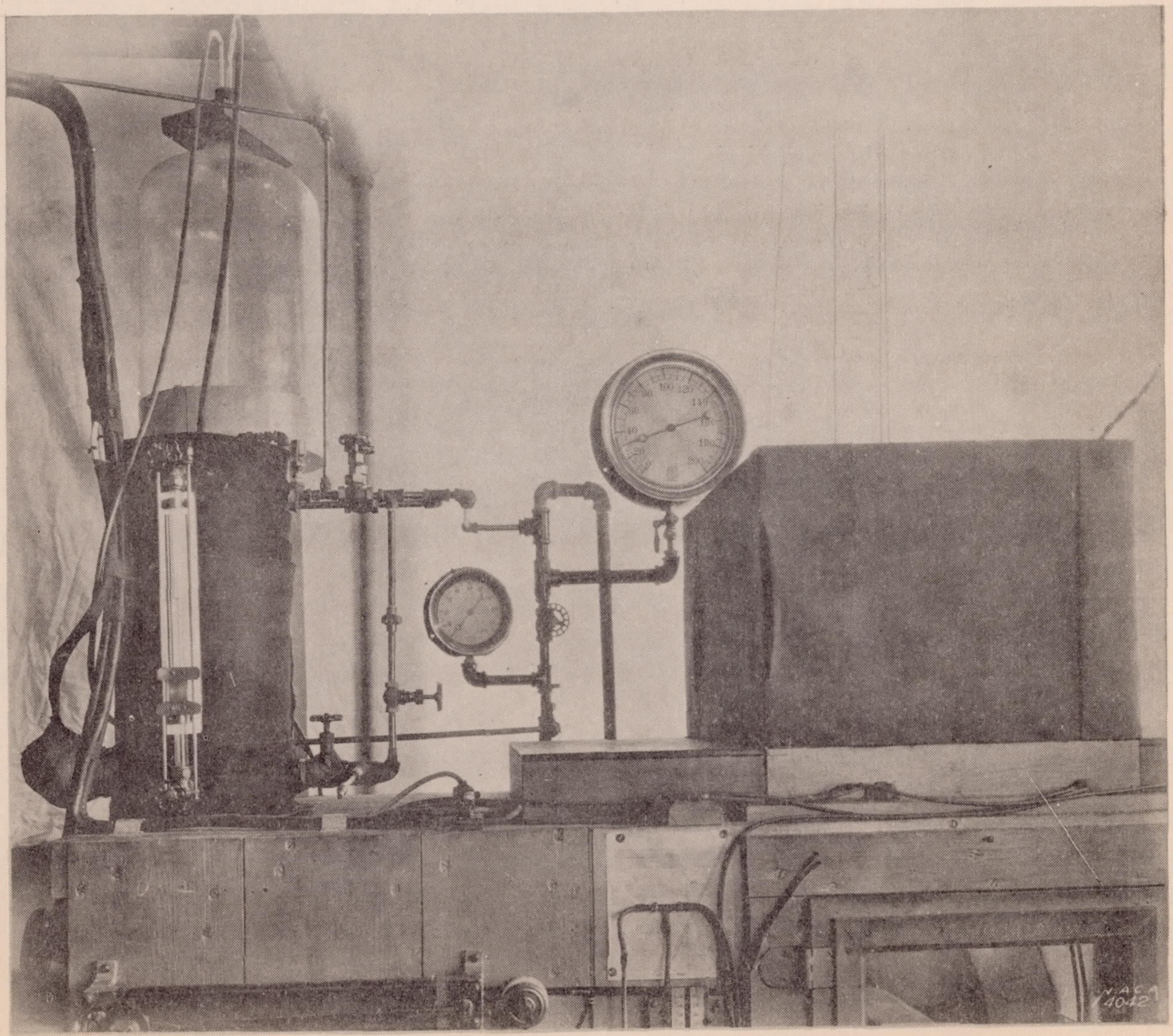
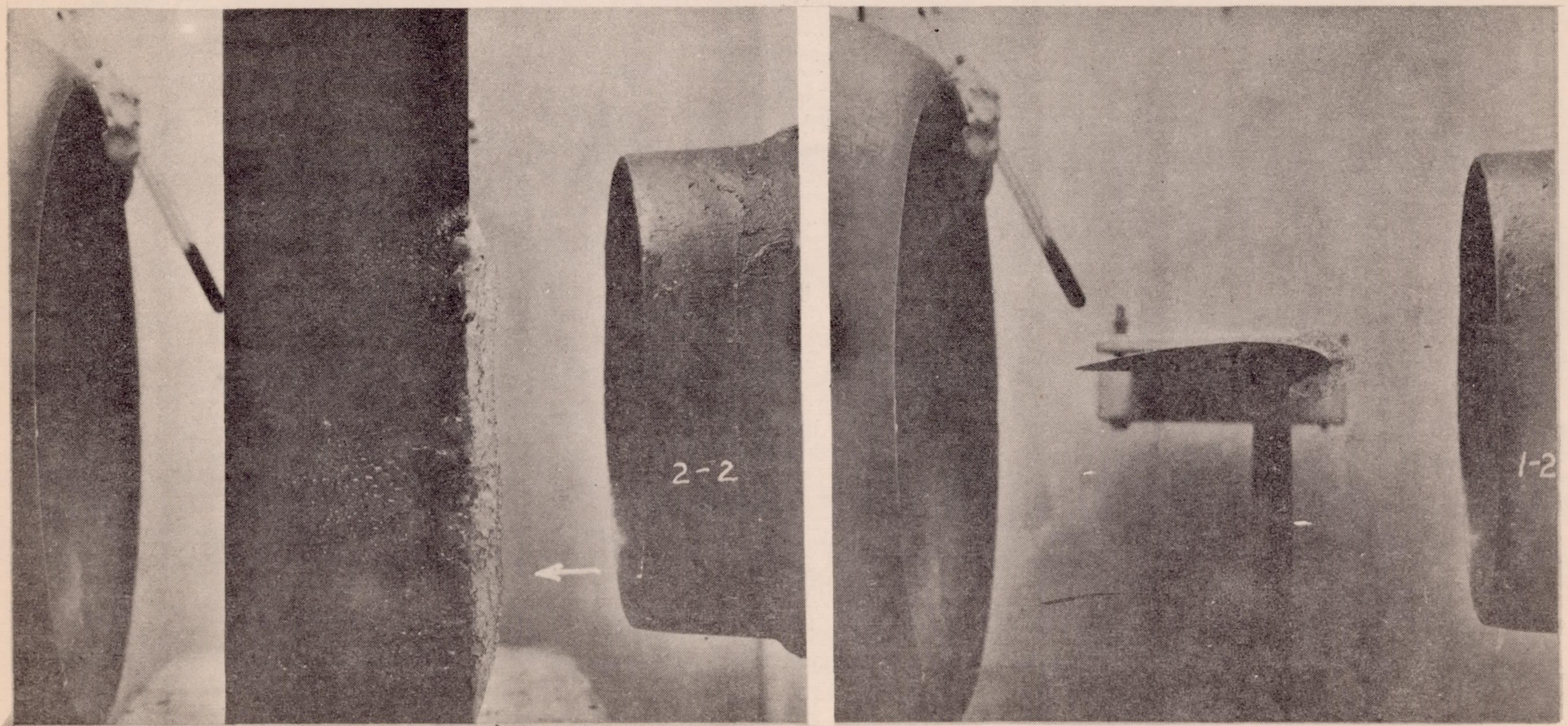


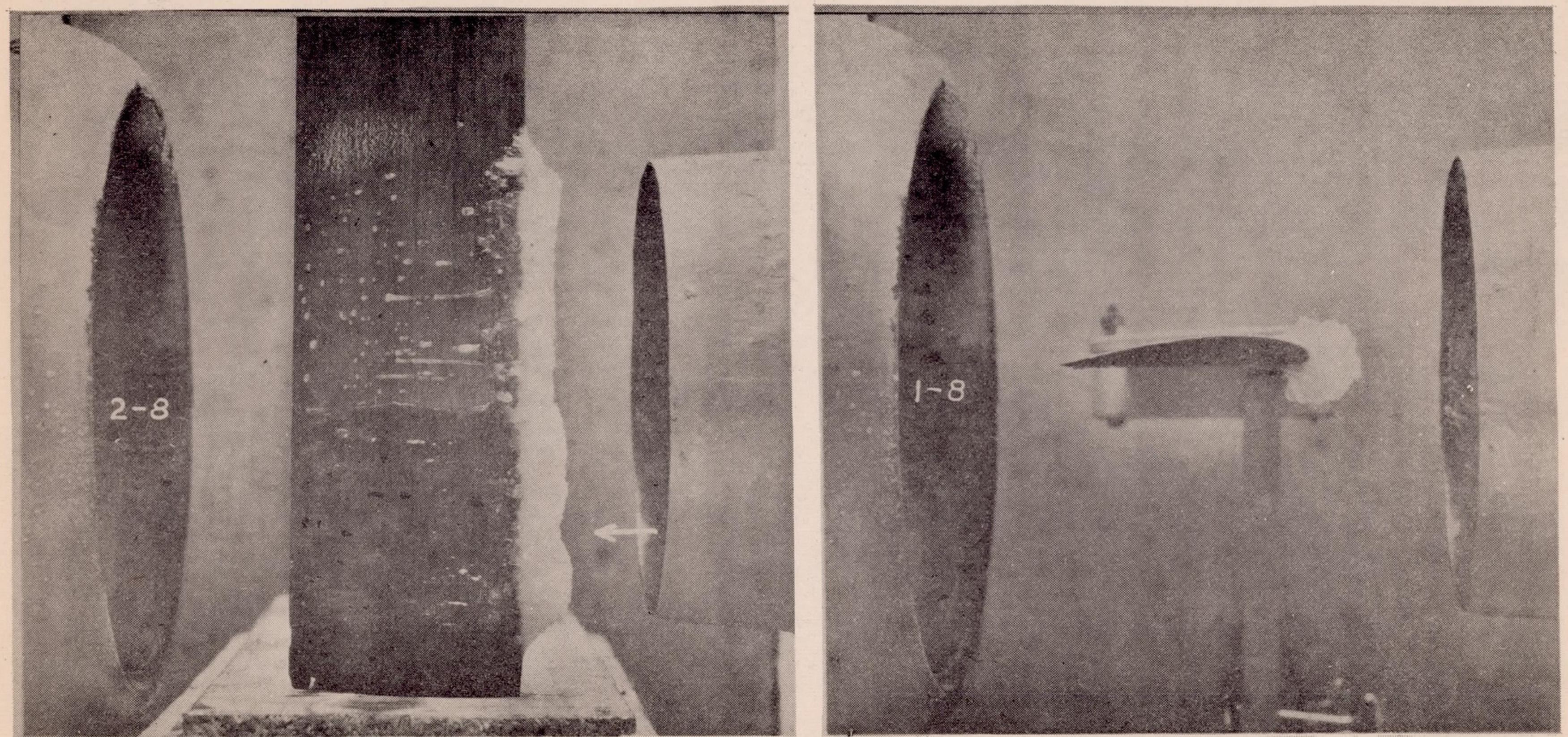
Fig.5 Spray water reservoir assembly.



Upper surface Profile

Test on heavy oil coating. Heavy spray.
Temperature -1°C. Air speed 70 m.p.h.

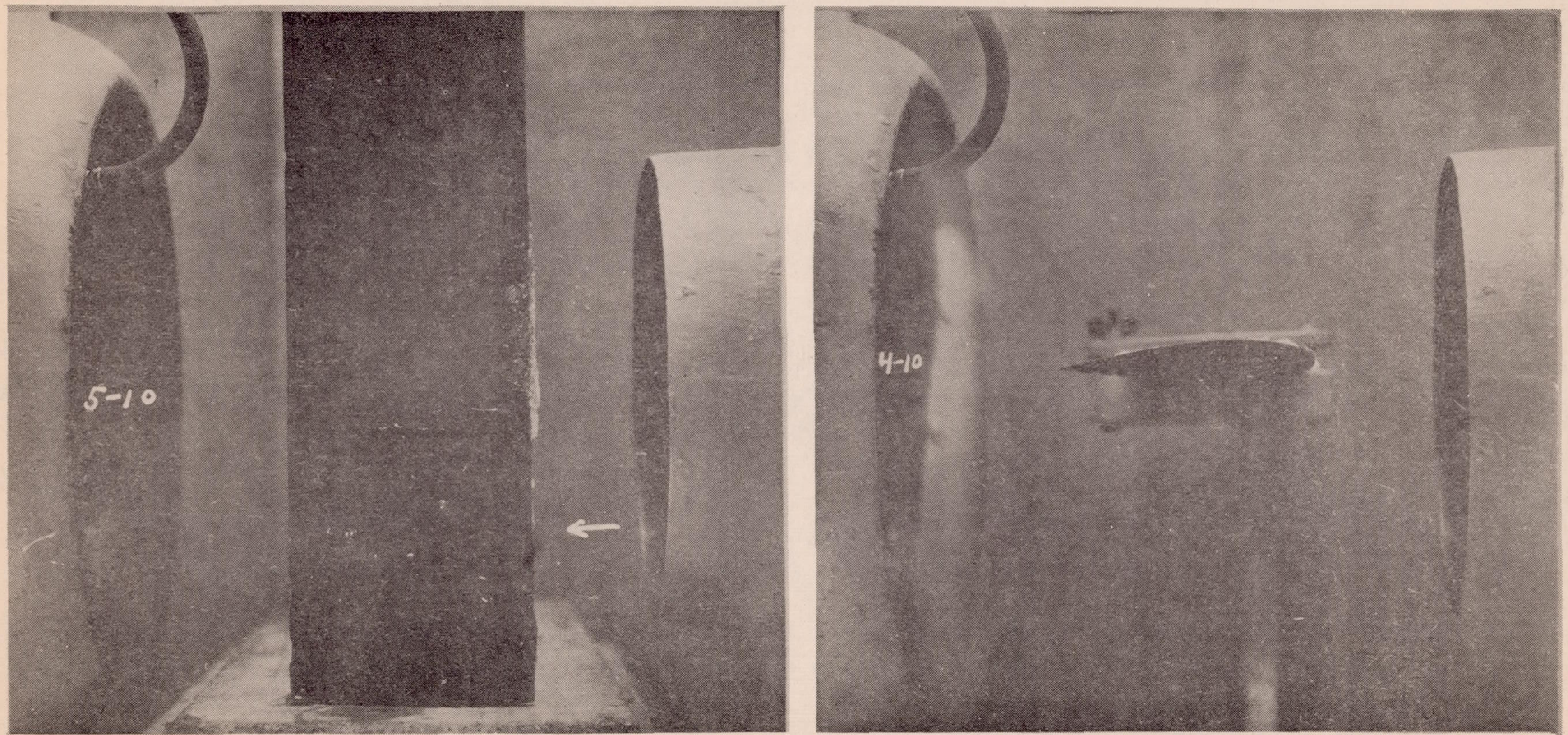
Fig.7



Upper surface | Profile

Test on glucose coating. Heavy spray.
Temperature -1°C. Air speed 70 m.p.h.

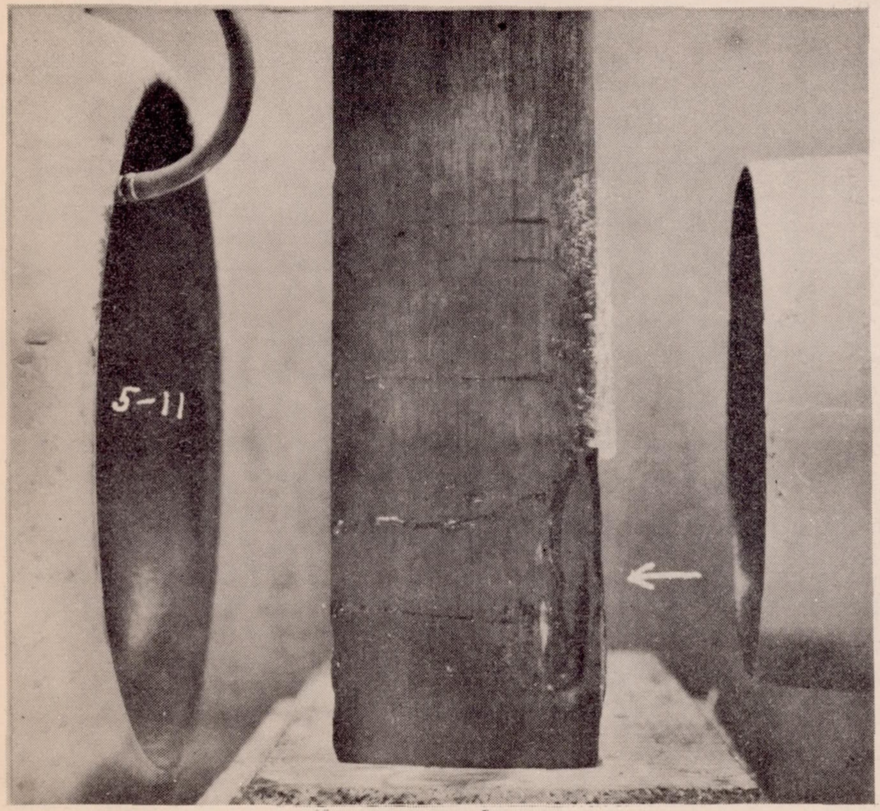
Fig.8



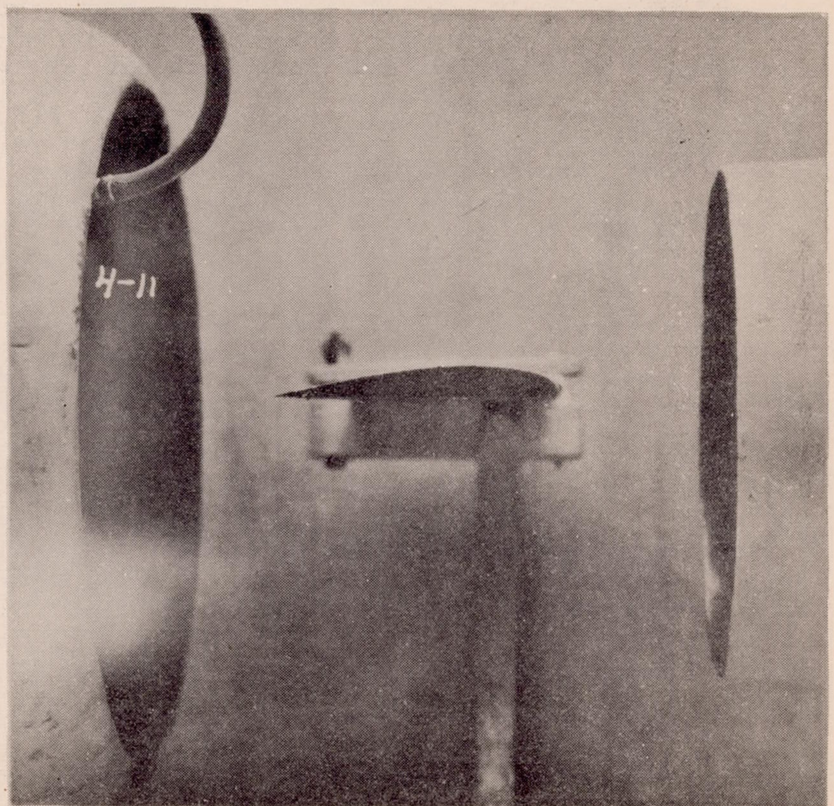
Upper surface　　　　　　　　　　Profile

Test on glucose coating. Light spray.
Temperature 0.5°C. Air speed 70 m.p.h.

Fig.9



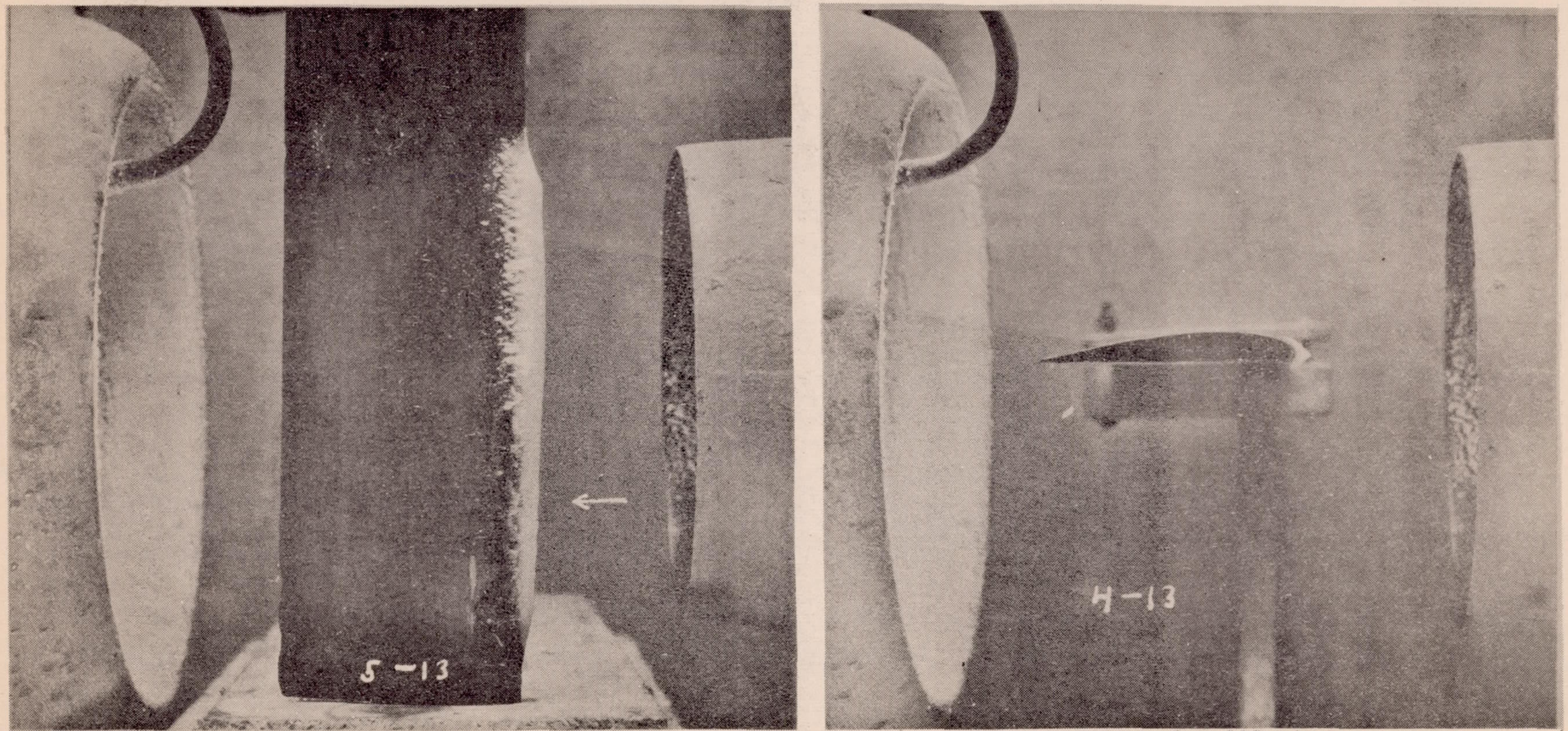
Upper surface



Profile

Test on glucose coating. Light spray.
Temperature -1°C. Air speed 70 m.p.h.

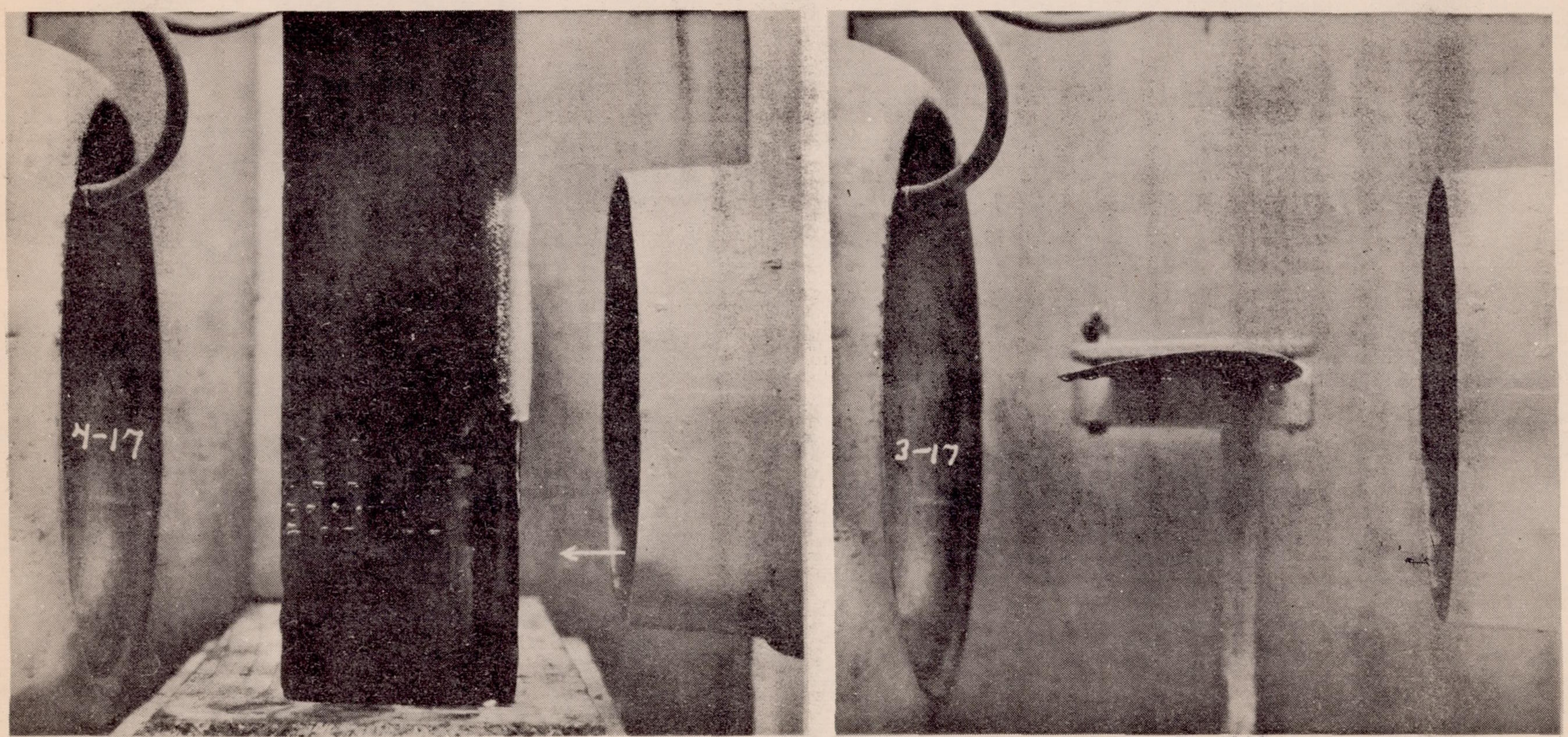
Fig.10



Upper surface Profile

Test on glucose coating. Light spray.
Temperature -6.3°C. Air speed 70 m.p.h.

Fig.11

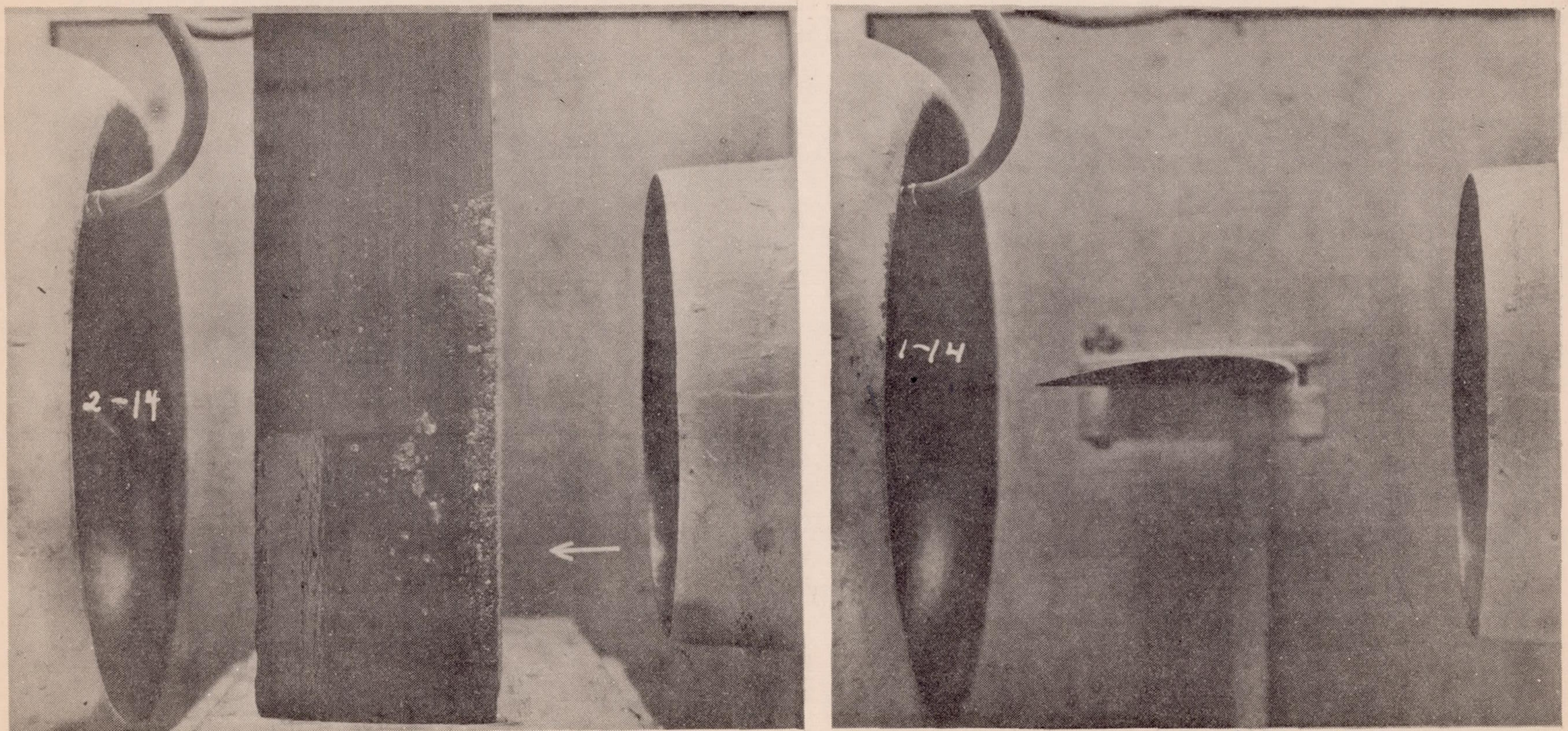


Upper surface

Profile

Test on "karo" syrup coating. Light spray
Temperature -4°C.   Air speed 70 m.p.h.

Fig.12



Upper surface — Profile

Test on heavy oil coating. Light spray.
Temperature 0.5°C. Air speed 70 m.p.h.

Fig.13