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Report of the First Year's Flying on the Development of Flight Testing Techniques for Finding and Measuring Natural Icing Conditions

By

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Report of the first year's flying on the development of flight testing techniques for finding and measuring natural icing conditions

by

G. C. Abel, B.Sc., D.I.C.

Summary

The results of the first year's flying in search of natural icing conditions using a Viking aircraft are given in this report. Special meteorological forecasts of icing conditions have proved to be reasonably reliable. Good photographs of droplets that have been sampled from a cloud can now be obtained at will and they give direct measurement of droplet sizes although, when frozen particles and supercooled droplets are present together, the interpretation of the photograph is still subject to doubt. The rotating disc ice accretion meter, especially when coupled to a Hussenot recorder, has proved, within certain limitations, to be a valuable instrument for measuring both the liquid water content of the cloud and the rate at which ice is building up. The best icing conditions in layer type cloud were found in December 1951 and January, 1952. The immediate programme is outlined and the future programme discussed.

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*Balance bridge thermometer to read Balanced bridge thermometer.

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1. Introduction

Starting in June, 1951, flights have been made in search of natural icing conditions with the object of measuring the parameters on which such conditions depend, and of developing suitable instruments for measuring these parameters. These flights formed the A.& A.E.E. part of the combined programme with the R.A.E. and the Meteorological Office which, apart from work on the production of artificial icing, had three main items in view. These were:-

(i) To continue the study of the correlation of forecasts of icing and its occurrence.

(ii) To find out more about ice formation on aircraft.

(iii) To develop suitable instruments for measuring the parameters on which natural icing depends.

2. Description of test aircraft and its instrumentation

2.1 Aircraft. The aircraft used on the flights was a Viking, a twin engined passenger carrying aircraft with an all up weight of 34,000 lb. The safe duration was over five hours at a cruising speed of 150 knots I.A.S., while the aircraft was equipped with oxygen to allow flights up to 20,000 feet if necessary. A photograph of the aircraft is given in figure 1.

2.2 Instrumentation. The instrumentation was provided almost entirely by the R.A.E. and was fitted as it became available. The instruments used were as follows:-

2.2.1 Rotating cylinders. These consist of several cylinders of different diameters which are exposed to icing conditions. The amount of ice that forms on the cylinders during the time they are exposed depends, among other things, on the diameter of the cylinder, the amount of supercooled liquid water per unit volume of air present in the cloud and the size of the droplets forming the cloud. After bringing the ice coated cylinders back into the aircraft each one is removed from the sampling pole and placed in a container which is tightly corked. On landing the cylinders, the containers and the now melted ice are weighed, after which the water is poured away and, after drying, the cylinders and containers are weighed again. The difference between weighings gives the weight of the water picked up by each cylinder which in turn, after comparison with some standard curves, gives an indication of the median droplet diameter and the liquid water content of the cloud. A photograph of the original set of rotating cylinders using three cylinders only is given in figure 2, while a later set using four cylinders is shown in figure 3 this time with ice on the cylinders.

2.2.2 Fixed Cylinder. This consists of a cylinder $3\frac{1}{2}$" in diameter round the surface of which blue print paper could be fastened. The cylinder with its blue print paper covering is exposed to the icing cloud for from 5-10 seconds and then withdrawn. The water in the cloud changes the colour of the paper over the part of the cylinder which it strikes and the width of this area, which is a band along the leading edge, is a measure of the diameter of the largest water droplet present in appreciable quantity. A photograph of the fixed cylinder equipment is given in figure 4 while a typical record is shown in figure 5.

2.2.3 Heated Cylinders. These consisted of four cylinders of different diameters which could be heated by nichrome ribbon heaters wound round each cylinder. On the leading edge of each cylinder were thermocouples, the readings from which could be taken inside the aircraft. The temperature of the leading edge of each cylinder was observed when flying through icing conditions and from this the drop in temperature due to the evaporation of the water droplets could be obtained by comparison with the temperature found when flying through dry air under corresponding flight conditions. This temperature drop

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gave a measure of the amount of water striking each cylinder and, from this, the droplet diameter and liquid water content could be calculated in a similar manner to the rotating cylinder method of calculation. A photograph of the heated cylinders appears as figure 6.

2.2.4 Oiled slide sampler and micro camera. These pieces of equipment enabled a photograph of cloud droplets to be obtained. A small glass slide $2\frac{1}{2}$" by $\frac{1}{2}$" was coated with a film of oil and placed in a sampling pole. The sampling end of the pole was then held out through a hole in the side of the aircraft and the slide exposed for a fraction of a second. The pole would then be brought in and the slide transferred to the micro camera which would then take a photograph of the exposed sample enlarged approximately 50 times. The original micro camera, although it took good photographs, was awkward to focus and had the slide mounted in a vertical plane so that the oil tended to flow to the bottom. An improved camera was introduced in May, 1952, which overcame these problems and had several other advantages as well. The original sampling pole, although effective in obtaining samples, was comparatively slow in operation, and, because of its size, may well have disturbed the droplet distribution around it so that it caught samples that contained fewer small drops than were actually present. This was not serious as a large change in the number of small drops present makes little difference to the median diameter of most samples. A modified pole is, however, being introduced to get over these difficulties. The oil used on the slide was Shell Spirax 250 and had been specially chosen to catch the water droplets without breaking them up, and to retard their evaporation sufficiently to allow adequate time for a photograph to be taken. Photographs of the original sampling pole, the original and the improved camera are given in figures 7, 8 and 9.

2.2.5 R.A.E. thermal ice detector. This was a prototype instrument working on the principle described in reference 1 where the liquid water content is measured by recording the difference in temperature between two heated elements one of which is exposed to icing conditions while the other is shielded.

2.2.6 R.A.E.-Smiths icing indicator. This instrument has been used as a standard ice detector on several aircraft. The head consists of a small tube mounted outside the aircraft with holes in the front and the back. When no ice is present, the pressure in the tube is greater than static as the area of the forward facing holes is greater than that of the rear holes. When ice starts to form the forward holes become blocked and pressure in the tube becomes less than static, due to the suction from the rear holes. This change of pressure operates a micro switch which switches on a heater element in the head to de-ice it and lights a warning lamp inside the aircraft. When the heater has de-iced the front holes, pressure again becomes greater than static and the heater and lamp are switched off. This cycle continues so long as the aircraft is in icing conditions.

2.2.7 Rotating disc ice accretion meter. This instrument was not fitted until the end of November. It consists of a disc 1/32nd of an inch thick at the edge, mounted outside the aircraft with its edge facing forward. The disc is rotated at about $2\frac{1}{2}$ revolutions per minute and ice can build up on the forward facing edge. The thickness of ice is measured by a feeler that presses on the rear half of the disc and the ice is later removed by a scraper which gives a clean surface for a further build up of ice. The movement of the feeler which is only a few thousandths of an inch is transmitted through a shaft to a transducer unit which gives an output of roughly 1 milliamp for a deflection of .015". A photograph of the disc is shown in figure 10.

2.2.8 Observation Strut. This was not originally intended as a quantitative instrument but was merely a small strut placed outside one of the windows to show when ice was actually forming. Later a cine camera was installed to photograph the ice as it built up, partly with the intention of recording how solid ice particles become frozen on to the aircraft surface along with the ice formed from supercooled water droplets, and partly to record other similar phenomena.

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It was then decided to use the instrument to measure the rate of ice build up in addition to its original purpose. The strut can now be de-iced by an electrical heater of pyrotenax that has been built into the leading edge. An illustration of the ice formed on the leading edge is given in figure 11.

2.2.9 Balance Bridge Thermometer. Outside air temperature is measured by a standard meteorological office balance bridge air thermometer with a modified radiation shield. To prevent ice forming on the bulb of the thermometer the forward end of the standard radiation shield has been closed in. This is shown in figure 12.

2.2.10 Vortex tube thermometer. This consists of a thermometer bulb mounted in the centre of a special tube. The air inlet faces forward and is mounted at one side of the tube causing the air to swirl round inside the tube until it reaches the outlet at one end. It has been found that, by adjusting the ratio of the areas of the air inlet and outlet, a thermometer bulb can be made to give a reading that is independent of air speed. This thermometer was fitted to see whether the results would be consistent when working in clouds and with ice building up on the air inlet. A photograph is given in figure 13.

2.2.11 Hussenot A 20 recorder. This recorder was fitted towards the end of March, 1952. It records a time base, together with air speed, height, the reading from the rotating disc, the cycles of the Smiths icing indicator, air temperature, the operation of the automatic observer and has a spare channel reserved for the new R.A.E. Sangano Weston thermal ice detector. The film speed used is 1 m m. per second and the duration at this speed is approximately $1\frac{1}{2}$ hours. A typical record from the A 20 is shown in figure 14.

2.2.12 Automatic observer. The milliammeter which shows the output from the rotating disc is mounted on the panel of the automatic observer together with an air speed indicator, an altimeter, the vortex tube air thermometer ratiometer, a clock and a counter. These instruments may be observed or photographed when required and space is available for future instruments to be mounted on the panel.

3. Method of test

3.1 Preliminary tests

3.1.1 Boundary layer air flow investigation. The thickness of the boundary layer at various positions where it was intended to mount instruments was investigated. A pitot static head was mounted at the end of a pole which slid through a hole in the side of the aircraft at the position to be checked. The pitot head could thus be pointed into the airstream at any distance from the side of the aircraft. The aircraft was flown at a constant speed and the pitot head pushed out from the side of the aircraft until the air speed indicator on the inboard end of the pole read the same as did the aircraft air speed system. This was repeated for difference speeds and the distance was observed for each position tested. This distance was taken into account when mounting the instruments and when operating the rotating cylinders or when taking oiled slide samples.

3.1.2 Air temperature thermometer calibrations. The outside air temperature thermometers were calibrated over a range of speeds to determine the correction to be applied for the heat rise due to speed.

3.2 Normal tests. The local Meteorological Officer was consulted each morning as to the prospect of finding icing conditions. When a suitable forecast was forthcoming the aircraft was flown to the area and a search made. The search was normally started at a height to give a temperature only a few degrees below freezing as this should produce glaze ice which is normally considered to be the more dangerous of the two main types. If ice could not be found at this height the search was carried to progressively greater heights and lower temperatures until either satisfactory icing conditions were found, or the area was abandoned as unproductive. When icing conditions were found, measurements were taken on

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all available instruments and later photographs were taken of the ice formation on several parts of the aircraft structure. Occasionally photographs were taken of the clouds flown through either before or after flying through them, but this was normally only possible for cumulus type clouds. Records and measurements were normally taken for as long as satisfactory icing conditions lasted but on one or two occasions tests were abandoned after using up all the sets of rotating cylinders, or all the frames in a camera magazine. For almost all the flights the aircraft was based at Boscombe Down although flights 28 and 29 both started from Paris.

3.3 Special tests. Because of scatter of the results from the rotating cylinder measurements, tests were made in icing conditions using three cylinders of the same diameter to check the consistency of droplet distribution at the normal sampling position which was that described in reference 2.

4. Results

4.1 Success in finding ice. The relation between the meteorological forecasts and the conditions found has been dealt with in reference 3 for the first 26 flights, but for completeness the conditions for these flights are included in table 1, together with the details for the remaining 11 flights. A map showing the areas where ice was found during the whole period is given in figure 15. As explained in reference 3 no flights were made in search of ice during August to November. The aircraft was under inspection and being fitted with a water spray system during August and September while no suitable forecast of icing conditions was received during October and November. The 37 flights made represented almost all the forecasts of reasonable icing conditions during the year, apart from August and September. On three occasions icing conditions were forecast when the weather at base was extremely bad and the chance of finding ice was not thought to justify the risk of taking off with the probability of not being able to get back On one occasion ice was forecast when the station was closed for flying but the forecast was not sufficiently good to justify the trouble of organising the necessary facilities. On four further occasions the aircraft or the instrumentation was unserviceable when icing conditions were forecast. At least four occasions are recorded when other aircraft found ice when icing conditions were not forecast, but on only two of these occasions is it known that a reasonable build up of ice was obtained on the aircraft.

4.2 Type of ice formation. A number of photographs of the ice formation on various parts of the aircraft are given in figures 16 - 18. These are representative samples of the different types that have been found during the year. The water droplet diameter, the liquid water content and the air temperature are given in each sample.

4.3 Instrument readings. For a variety of reasons that are discussed in the following paragraphs a number of the results from some of the instruments are not regarded as reliable. For the sake of completeness some of these results are included in table 2 together with the results that are believed to be more reliable. Examples of the photographs of cloud droplets caught by the oiled slides are given in figures 19 to 24. They cover the range of liquid water drop sizes found, while some show the presence of melted ice particles. The results of the measurements made using three rotating cylinders of the same size are given in table 3.

The balance bridge thermometer proved to have a co-efficient giving approximately 0.6 of the normal adiabatic heat rise while the vortex tube thermometer readings were practically unaffected by air speed.

5. Discussion of results

5.1 Success in finding ice. This has been discussed in reference 3 so

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far as the first 26 flights are concerned. On all the remaining 11 flights some ice was found bringing the total number of successful flights up to 34. On these 11 flights the icing conditions were found approximately where forecast, so alternative areas were not investigated. It is interesting to note that 5 of these 34 encounters took place in December and 6 were in January, in spite of the aircraft being unserviceable for over a week on inspection. The remaining flights were fairly evenly distributed either 3 or 4 per month. This gives an indication that winter is the best period of the year for this type of work.

5.2 Duration of icing conditions. In table 1 both the time in measurable ice and the number of successful rotating cylinder measurements made are quoted for each flight. The time in measurable ice is the time during which observations were being taken of the ice building up on the aircraft. In some cases it is the summation of a number of short periods that could only be measured on the instantaneous reading instruments. The number of successful rotating cylinder measurements made is, for layer type clouds, a better guide to the continuity of the icing conditions. Samples were not normally taken on the rotating cylinders unless ice was forming fairly steadily, but if it obviously stopped forming the sample was discontinued, and, if insufficient ice to give a good reading had been collected, it was scrapped. A scrapped sample would prevent the taking of rotating cylinder measurements in more continuous conditions soon after the abortive attempt as several minutes are needed for reloading, but, though this is one of the reasons for apparent discrepancies between time in ice and the number of samples taken, it did not happen very often.

Over the whole 34 flights only 2 or less than 2 satisfactory rotating cylinder measurements were taken on each of 18 flights, while 3 or more than 3 measurements were taken on 12 flights. On the remaining 4 flights the icing conditions were sufficiently good to allow 3 or more measurements to have been taken but due to some unavoidable reason this could not be done. These flights are fairly evenly divided between cumulus type cloud and layer type cloud. The lack of success in the 9 flights in cumulus type cloud is mainly due to the short time during which such conditions last. These 9 are all among the earlier flights and later a satisfactory technique to overcome this difficulty was worked out, where the cylinders were exposed before entering cloud and timed from the start of ice forming until leaving the cloud. The 9 relatively unsuccessful types in layer type cloud were mainly made in intermittent conditions when periods of 5 minutes at a time were rare. On the remaining flights two had to be abandoned despite good icing conditions as ice built up on the spray mast used for producing artificial ice and caused serious vibration. In one case the mast was thermally de-iced but the system proved to be inadequate to deal with the severe icing that was encountered. On two further flights no rotating cylinder measurements were taken due to lack of observers.

Of the 12 more successful flights 5 were made in layer type cloud, 6 in cumulus cloud and 1 partly in each type. During 3 in layer type cloud over 1" of ice built up on the wings and tail plane, while on the remaining flights in this type of cloud the build up was of the order of $\frac{3}{4}$" and $\frac{1}{2}$" respectively. The aircraft de-icing system was purposely not used so as to allow the ice to build up. Normally less than 1" of ice built up during the flights through cumulus type clouds, but this could usually have been increased with ease by merely flying more often through the clouds. The duration in this type of cloud is very short as will be seen from the times over which the average liquid water content was measured in table 2. The shortest quoted is 11 seconds, while the longest is only $2\frac{1}{2}$ minutes.

5.3 Severity of icing conditions. The definitions in table 1 for the icing conditions found on the flight were based on the observers' opinions rather than on quantitative measurements, although in the last part of the table such quantitative measurements have been given. It will be seen from table 5 that meteorological forecasts of severity were very good in that 26 of the 34 made and investigated were correct, while, apart from the two failures to find any appreciable amount of ice, the main disagreements were in the 6 cases where only light ice was found, although moderate or moderate to severe had been

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forecast. The fact that the severity forecast was not found does not necessarily mean that the forecast was wrong, as it may have been that the aircraft failed to find the area which contained the more severe conditions.

To try to link up the severity of the icing conditions as judged by the aircrew with the droplet size and water content measured, the value of Rg, the rate of ice accretion on a "standard" ice collector, has been calculated for each of the rotating cylinder results. The "standard" ice collector has been taken as that used in reference 5, a 3 inch diameter cylinder flying at 200 mph at a height of 3 kilometers (nearly 10,000 feet) in the international standard atmosphere. These values are given in table 4 together with the type of cloud and the icing severity encountered.

It will be seen that, although two values of Rg when the severity is quoted as moderate are over 6, all but two of the others are between 4 and 2. Similarly all but two of the values of Rg for light icing are 3 or less, while the values for light to moderate and moderate to severe icing come within these limits with only one exception. From this it may be argued that the values of Rg, calculated from rotating cylinder measurements, that are above somewhere between 4 and 6, represent severe icing while the division between the light and moderate icing would appear to come between values of Rg of 2 and 3. This is not in exact agreement with the values suggested in references 5 and 6 where the divisions between light and moderate and moderate and severe were given as 1 and 4 in reference 5 and 1 and 6 in reference 6 but the disagreement is not serious. In view of the doubts of the accuracy of the rotating cylinder measurements taken from the old sampling position, it would be better to wait for confirmation of these values from more reliable results it is hoped to obtain in the future from the new sampling position before placing too much reliance on these values of Rg.

5.4 <u>Ice formation</u>. The photographs in figures 16 - 18 illustrate three main points. The first is the way in which the area of the aircraft on which ice forms is affected by the diameter of the drops. All three figures show clearly the larger area on which ice forms when large drops are present. This is, of course, a well known and predictable occurrence but the photographs illustrate it very clearly. The second point is also well known and is directly related to the first. It is that the build up of ice on small objects such as aerials or the small test strut is relatively greater than on larger objects such as the wings and tail plane. This can be seen by comparing the corresponding photographs in figures 17 and 18. The reason for the greater build up on small objects is that their influence on the airflow ahead of them is not very great. Only the smallest drops are deflected along a streamline and miss the object. Large objects affect the airflow well in advance of themselves and the mean curvature of the streamlines is less so the larger drops are accelerated sideways and pass the object without striking it. Thus a larger proportion of the total number of drops per unit area are caught by the smaller object than by the larger object. This is, of course, the principle upon which the rotating cylinders operate. The third point is more complicated and concerns the type of ice formation. The two main types of ice, namely glaze ice and rime ice, are described in reference 4 together with the main reasons for their difference.

Briefly, glaze ice forms when the water concentration is sufficiently high and the temperature is sufficiently close to freezing to allow the supercooled water droplets to flow a little after impact before they freeze. This gives a well knit layer of ice which, depending on its thickness and stage of development, may be clear and smooth as on flights 20 and 21 in figure 16, or rough and uneven as on flight 23 in the same figure. It may also be milky in appearance due to the inclusion of air bubbles, as at the edges of the ice formation on flights 20 and 21 in figure 16.

Rime ice forms when the water concentration and temperature are sufficiently low to allow each droplet to freeze on impact without flowing appreciably. This gives a white porous structure with a matt surface, as shown on flight 28 in figure 16, 17 and 18. With small drops and particularly when frozen particles

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are present in the cloud at the same time as supercooled water droplets, the structure is loose and almost powdery as in flight 32 in figure 17. This last sample was obtained when flying through a succession of small cumulus clouds. When the liquid water content in such clouds is higher and drop sizes are larger, hail stones may well be included in the ice formation as in figure 3. This phenomenon has been found several times but was not photographed successfully.

The way in which the ice has built up on the aerials in figure 18 is quite interesting. On flight 28 the droplet sizes were small and temperatures low giving a comparatively narrow band of ice. On flight 21 on the other hand droplet sizes and water concentrations were larger with a higher temperature, and the ice had built up with a very much wider area in front than on the aerial itself. This glaze type of ice is obviously going to have a greater aerodynamic effect than rime ice that does not spread itself quite so widely. This is, of course, well known but the figure gives a further illustration of the point.

The greatest amount of ice that has so far been collected on the aircraft during these trials caused a considerable reduction in speed due to the increased drag, but apart from this increase in drag which, of course, reduced the range, no serious difficulties have been found in flying the aircraft with ice on it. A much larger build up of ice might well increase the drag and decrease the lift beyond the point where the aircraft could maintain height, even with full power, but such a build up has not yet been experienced.

5.5 Readings from individual instruments

5.5.1 Rotating cylinders. The figures in table 3 show that the distribution of liquid water droplets at the sampling position that has been used is not uniform. Some of this scatter may be because distribution throughout the cloud is uneven, but the fact that the inboard cylinder collected the lowest weight of ice on each occasion gives a clear indication that the airflow round the fuselage is at least partly responsible for the error. This is in spite of the fact that all the cylinders were outside the boundary layer as measured by the travelling pitot head. It is obvious that the presence of the aircraft disturbs the distribution of droplets, to the extent that such drops as do not strike the aircraft are deflected sideways so that there is a region outside the fuselage where there are more water droplets, particularly small ones, than there would have been in the undisturbed air. This region will presumably be wider and further from the fuselage near the tail than near the front of the fuselage, so apart from any boundary layer problems, the ideal sampling position will be as far forward as possible. The results of this test will cast doubt on all rotating cylinder readings taken from this position.

On several occasions there was less ice on the 2" diameter cylinder than on the 1" diameter cylinder of the same length. Although this is theoretically possible if the cloud consists of very small droplets, it is believed that it is more likely to have been due to the uneven droplet distribution at the sampling position. The effect of the reduced amount of ice on the larger cylinder would be to give a droplet size that is too small and a liquid water content that is too large.

Apart from any errors due to the incorrect distribution, it is known that rotating cylinders suffer from the phenomenons known as blow off. Under certain conditions some of the supercooled drops that strike the cylinder are blown off again before they have time to freeze, so the amount of ice that forms on each cylinder under these conditions is not a true measure of the amount of water that should have been collected.

Yet a further point that casts doubt on some rotating cylinder results is illustrated in figure 3. It will be seen that, in addition to normal ice on the cylinders, a number of particles that were already frozen before they reached the cylinders have been frozen into the ice. As these particles were

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not round this is going to upset the theory on which the reduction for the rotating cylinder method is based (reference 7) in cases where solid particles are picked up on the cylinders. This appears to happen when frozen particles are present in the cloud in appreciable quantities as is particularly the case in convective type clouds. According to reference 8 the majority of icing clouds are a mixture of solid ice particles and supercooled liquid water droplets, so this trouble may well be fairly widespread.

5.5.2 Fixed cylinder. The fixed cylinder has proved to be a reliable instrument within its practical limitations. When the temperature was not too low, as was the case in the majority of flights, water running back from the leading edge of the cylinder made the record clear and unmistakable as may be seen in figure 5. The value of the maximum droplet diameter could be determined very quickly. The true edge of an overexposed record was not, however, always easy to distinguish, as many, if not all of the lines caused by water running back had joined together. At lower temperatures all the water froze on impact and again the record contained no individual lines caused by water running back. It was usually difficult to distinguish between these two types of record so, when runback was not present, the results were often less reliable than usual.

5.5.3 Heated cylinders. No worthwhile results are available from the heated cylinders. The readings took some time to obtain and so required a considerable time in consistent icing conditions. The cylinders were originally mounted underneath the fuselage and they received mechanical damage from stones thrown up by the wheels. This damage was sufficiently serious to make them unserviceable and it was decided that the effort required to repair them was hardly justified.

5.5.4 Oiled slide sampler and micro camera. Good photographs of cloud droplets as shown in figures 19 - 24 can be obtained relatively easily. Their interpretation may however be considerably more difficult. When it is known that only liquid water drops were present as in figures 19 and 20 the assessment of the median drop diameter presents no great difficulty but when a mixture of frozen particles and liquid droplets is present as in figures 23, 24 and possibly 22, the interpretation of the record is far from simple. Normally by the time photographs are taken the solid particles have melted and the supercooled droplets, which presumably froze on impact, are also liquid again. It is hoped that a technique may be worked out using the new camera whereby solid particles may be differentiated from liquid droplets. Until such a technique is available only the larger frozen particles can be clearly identified by virtue of their size, and so droplet counts remain unreliable, giving what is probably a much larger answer than the truth, unless it is known that no frozen particles were present in the atmosphere.

5.5.5 R.A.E. Thermal ice detector. No reliable results have so far been obtained from this instrument when mounted on the Viking. Experience with it has shown up the more obvious major faults which have been rectified in later designs, which should be available for test in the near future.

5.5.6 R.A.E. Smiths icing indicator. The results from this instrument are not directly comparable with any of the other instruments, although there is no doubt that a measure of the icing severity may be obtained from the records of this instrument alone. It has proved to be quite reliable and sensitive and, only the rotating disc gives a better indication of when ice is actually forming on the aircraft.

5.5.7 Rotating disc. Apart from initial teething troubles the rotating disc has proved to be the most satisfactory instrument so far available for both indicating the presence of ice, and for measuring reasonably quantities of it. Small quantities of ice have been found to pass unnoticed by the instrument, working at its present speed, but this could be overcome by reducing the rate of rotation when the measurement of such small quantities is required. The records from the instrument can be interpreted into both the measurement of the

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rate of ice build up in inches per minute, and the liquid water content of the icing cloud. At first the values of liquid water content measured were believed to be too high and the position of the disc on the aircraft was changed from about the middle of one side to as far forward as possible, as shown in figure 1. Further records taken in this position did not confirm the belief that the readings were too high. Many of the readings were peak values that seldom lasted for more than a few seconds, and it was not until the A 20 recorder was installed that a clearer understanding of the disc readings was obtained. In table 2, peak values are quoted throughout, but where they are available, average values are also given, together with the time over which the average was taken. Very few of these average values exceed 1 gm. per cubic meter and there is no reason to suppose that they are greatly in error. Like the rotating cylinders, the rotating disc is subject to blow off which limits its accuracy, although the results are unlikely to be over statements.

5.5.8. Observation strut. Some trouble has been experienced in obtaining satisfactory photographs of white particles striking the white ice on the strut, against a background of the white cloud in which the aircraft was flying. Figure 11 shows that reasonable results can now be obtained. Since suitable photographic arrangements have been made no conditions have been encountered when ice particles have been observed striking the aircraft and sticking for only a short time, or else being frozen into the normal ice build up. It is intended to photograph these phenomena when they are again encountered. It has, however, been possible to obtain measurements of the rate of ice build up partly from photographs of the strut taken by a hand held camera, and partly by pictures from the cine camera record taken every 5 or 10 seconds. This latter arrangement is not ideal as the cine camera is set to photograph the front face of the strut rather than the side view.

5.5.9 Balance bridge thermometer. This thermometer has operated satisfactorily throughout the tests and no reason has been seen to doubt its readings.

5.5.10 Vortex tube thermometer. Several teething troubles were encountered with the thermometer bulb, but after these had been overcome, fair agreement was obtained between this instrument and the balance bridge thermometer, as can be seen in the last part of table 2. The agreement is not yet completely satisfactory and it is hoped that it may still be improved.

5.5.11 Hussenot A 20 recorder. The records from the rotating disc were of far more use than the spot readings that had been all that could be obtained before, while a useful comparison with the Smiths icing indicator was readily available. The continuous recorddof the readings also proved to be of considerable value when compared to the previous results that had been obtained.

5.5.12 Automatic observer. The automatic observer was of considerable value in co-ordinating records from the various icing instruments with flight conditions as a photograph could be taken at the time of each observation. Even after flight 27 when the A 20 recorder was fitted, the automatic observer was still very useful for synchronising records.

5.6 Comparison of results from different instruments

5.6.1 Liquid water content. Values of liquid water content were obtained from two different sources, the rotating cylinders, and after flight No. 10 from the rotating disc. The records of these instruments in the first part of table 2 are not directly comparable as the rotating disc readings were peak values and the rotating cylinder readings were averages. Later in the table when averages are given for both instru ents, readings are more comparable, but there are insufficient to draw any reasonable comparisons. Better synchronisation between the two records is now being obtained and future results should be more directly comparable. In addition, records of liquid water content from the new Sangamo Weston instrument should be available on future flights.

/5.6.2.....

5.6.2 Droplet size. There are three methods by which the droplet size was obtained. The rotating cylinders, the oiled slides, and the fixed cylinder. The possible inaccuracies in the values obtained from each method have been discussed in previous paragraphs, so the discrepancies between readings can more easily be understood. The larger sizes usually given by the oiled slides are undoubtedly in many cases due to the presence of melted ice particles in the sample. The individual disagreements between the results from the fixed cylinder records are commented on in the table.

5.6.3 Outside air temperature. As mentioned in paragraph 5.5.10 the only records from the vortex tube thermometer that are believed to be reliable are confined to the last few flights and these do not differ widely from the reading from the standard balance bridge thermometer. Discrepancies of the order of 2°C are still common, but it is hoped that this will be improved. The vortex tube type of thermometer should then be of value in giving readings of outside air temperature directly at least over the speed range covered by the tests on the Viking.

6. Conclusions

6.1 Considerable advances have been made in the technique of measuring the parameters on which natural icing conditions depend. Several new instruments have been and are being developed, and the method of using some of the older ones has been improved.

6.2 The rotating disc ice accretion meter, especially when combined with a Hussenot A 20 recorder, has proved to be a very satisfactory instrument for indicating the presence of ice in worthwhile quantities, and for measuring the liquid water content of the cloud. Its record may be interpreted to give rate of build up of ice in addition to the value of the liquid water content. The value of liquid water content may however be in error under certain conditions, due to blow off.

6.3 Photographs of liquid water droplets sampled from an icing cloud may be obtained at will. From these photographs direct measurements of droplet size may be made. So far, difficulty has been experienced in differentiating between the frozen particles that have been caught in the sample and supercooled water droplets, as both were liquid at the time the photograph was taken. It is hoped to overcome this difficulty in the future.

6.4 Special meteorological forecasts made by an experienced forecaster can be relied upon to direct an aircraft to the vicinity of conditions that will produce at least some ice. Although protracted periods of severe or even moderate icing cannot be guaranteed, there is a good chance of being able to find conditions that will enable a reasonable build up to be obtained on an aircraft. Such conditions were found five times in layer type cloud during one month in the winter. They occur much less frequently during the rest of the year, although reasonable build up may be obtained by flying repeatedly through suitable cumulus clouds. These clouds were found on the average 2 - 3 times per month throughout most of the rest of the year.

6.5 A number of examples of the types of ice that build up under various conditions were obtained and have been related to the values of the parameters measured at the time. They will be useful in the study of the formation of artificial ice using the same aircraft.

7. Further developments

7.1 Immediate programme

7.1.1 No instrument yet tested on the Viking has given an absolutely reliable answer of either droplet diameter or liquid water content. The oiled slide sampling and photographing technique must be developed to a stage where, when measuring liquid water droplet diameter, it is possible to exclude from the

/drops......

drops that are counted, drops that are formed from particles that were not in the supercooled liquid state immediately before reaching the slide.

7.1.2 Although it is very satisfactory within its limitations, the rotating disc ice accretion meter is subject to errors due to blow off, and may also be unreliable under conditions when frozen particles would be trapped in the ice that forms on rotating cylinders. An instrument that is not subject to these limitations is needed to measure liquid water content. The new R.A.E. Sangamo Weston thermal ice detector may meet these requirements, but this has to be tested.

7.1.3 Only a relatively small number of icing conditions have so far been found during the present tests. Considerably more must be found and the parameters measured to give a greater knowledge of icing conditions from which improvements may be made in the present icing standards.

7.2 Future programme. Measurements must be made and instruments must be tested at higher speeds, greater heights and lower temperatures than can be attained by the Viking. In addition information of icing conditions is required in other parts of the world besides Europe, which is all that is being covered by the immediate programme.

The next problem that has not yet been seriously investigated is the build up of ice caused by water running back from inadequately heated leading edges and freezing further back on the wing. Its effect on aircraft performance must be studied. The rate of sublimation of ice from unprotected aircraft surfaces at various speeds and various temperatures below freezing is another important problem that should be investigated.

8. References

1.	R.A.E. Tech. Memo Eng. 47	Note on thermal ice detector	F.J. Bigg
2.	AAEE/Tech/56	Fluid de-icing tests. A.R.C. 12,624.	G.A. Rogers
3.	AAEE/Res/266	Preliminary comparison of meteorological forecasts of natural icing conditions with conditions encountered.	G.C. Abel
4.	R.A.E. S.M.E.3380	Protection of aircraft against ice. A.R.C. 10,034	J.K. Hardy
5.	Meteorological Office Professional Note No106	Occurrence of high rates of ice accretion on aircraft.	A.C. Best
6.	N.A.C.A. Tech. Note 1393	A flight investigation of the meteorological conditions conducive to the formation of ice on airplanes. A.R.C. 11,014.	W. Lewis
7.	AAF Tech. Report 5418, 1946	A mathematical investigation of water droplet trajectories.	I. Langmuir K. B. Blodgett
8.	A paper of the Meteorological Research Committee (London) M.R.P. No.679 A copy is available in the library of the Meteorolgical Office.	The present position regarding meteorological aspects of ice accretion on aircraft. A.R.C. 14,644.	A.C. Best

Table 1

Comparison of Meteorological Forecasts and Conditions Encountered

Flight No.	Date	MET. FORECAST				FOUND ON FLIGHT				FLYING TIME		TIME IN MEASURABLE ICE		No. of rotating cyl. measurements made	Remarks
		Type of Cloud	Synoptic Condition	Icing Severity	Freezing Level	Type of Cloud	Icing Severity	Height at which ice was found	Air Temp. °C	Individual flight	Total of successful icing flights	Flight	Total		
1	8.6.51	Stratocumulus	Occlusion	Moderate	8-9,000	Nil	-	-	-					1	Front had petered out.
		Stratocumulus	Occlusion	Moderate	8-9,000	Strato-cumulus	Light	11,500	-6	3.15	3.15	5 mins	5 m.		Alternative point on Occlusion.
2	19.6.51	Cumulus Cumulo-nimbus.	Unstable S.W.'ly air stream.	Moderate-severe.	6,000	Cumulus	Light-moderate.	9,000	-6	1.15	4.30	5 m.	10 m.	2	
3	20.6.51	Cumulus	" " "	Moderate	6-7,000	Nil	-	-	-	2.40	4.30	-	10 m.	-	No clouds above freezing level. Cold pool had moved East.
4	22.6.51	Cumulo-nimbus Alto Cumulus Castellatus.	Thundery low	Moderate-severe.	8,000	Cumulus, Cumulo nimbus	Moderate-severe.	12,000	-5	2.05	6.35	15 m.	25 m.	2	Very short period of severe icing.
5	26.6.51	" "	Cold trough	Moderate	5,000	Thin Alto-cumulus	Light	10,000	-5	4.05	10.40	15 m.	40 m.	1	Long search for little ice.
6	2.7.51	Alto stratus	Weak cold front	Moderate	11,000	Thin medium c-300' thick	Light	12,500	-4	4.10	14.50	20 m.	1.00	-	Very thin cloud.
7	4.7.51	Alto stratus	Wave depression	Light-moderate.	10,000	Alto stratus	Light with small period of moderate.	10,500	-3	3.35	18.25	15 m.	1.15	2	Radio message directed aircraft to icing area.
8	11.7.51	Alto stratus cululo-nimbus	Cold trough	Moderate	9,000	Thick medium	Practically nil	-	-	1.50	18.25	-	1.15	-	Cloud mainly iced up. Oil pressure failed so returned on one engine.
9	23.7.51	Cumulo-nimbus	Occlusion	Light-moderate	9,000	Cumulus	Light with small period of moderate.	12,000	-5	4.20	22.45	15	1.30	2	Large proportion of clouds iced up.
10	31.7.51	Cumulo-nimbus	Thundery low	Moderate	12,500	Almost nil	Almost nil	-	-	3.55	22.45	-	1.30	-	Lack on information. Met teleprinter breakdown.

Table 1 continued

Flight No.	Date	MET. FORECAST: Type of Cloud	Synoptic Condition	Icing Severity	Freezing Level	FOUND ON FLIGHT: Type of Cloud	Icing Severity	Height at which ice was found	Air Temp. °C	FLYING TIME: Individual flight	Total of successful icing flights	TIME IN MEASURABLE ICE: Flight	Total	No. of rotating cyl. measurements made	Remarks (including rate of ice build up (ins/min)
11	3.12.51	Strato-cumulus Alto-stratus	Weak warm front	Light-moderate	3,500	Thick medium	Light	12,000	-8	1.20	24.05	10m	1.40	1	Cloud iced up below 12,000 ft.
12	7.12.51	Nimbo stratus	Warm front	Moderate-severe	5,5-6000	Alto stratus	Moderate-severe	7,000	-5	4.20	28.25	10m	1.50	-	Had to disengage as spray mast iced up and vibrated seriously.
13	18.12.51	Alto stratus	Wave on cold front	Moderate-severe.	6,500	Thin alto-stratus.	Light	11,000	-6					2	Moderate conditions for short time in front.
						Thick alto-stratus.	Light-moderate	12,000	-7	3.10	31.55	20 m	2.10		
14	28.12.51	Cumulo-nimbus	Unstable W'ly air stream.	Moderate	2,500	Cumulus	Moderate	6,000	-8					1	Duration of flight in cloud very short but moderate icing found.
15	28.12.51	Cumulus	" "	Moderate-severe	"	"	Moderate	6,500	-10	4.30	36.05	25 m	2.35	2	
16	2.1.52	Alto stratus	Wave on cold front.	Moderate	2,500	Thick alto-stratus.	Light	6,500	-6	2.15	38.20	15 m	2.50	-	Cloud mainly iced up. Small cumulus gave good readings on instantaneous instruments, otherwise too small.
						Small cumulus.	Light	"	"						
17	16.1.52	Cumulo-nimbus	Unstable N.W.'ly air stream.	Moderate-severe.	3,000	Cumulus	Moderate-severe.	6,000	-10	2.05	40.25	25 m	3.15	-	Short duration in Cu. ¾" build up.
18	16.1.52	Cumulus	" "	"	"	"	Moderate	4,000	-5	1.15	41.40	10 m	3.25	-	Short duration in Cu. Rather late in day.
19	18.1.52	Cumulus	Unstable N.W.'ly air stream.	Moderate	1,5-2000	Cumulus	Moderate	6,000	-10	3.05	44.45	30 m	3.55	6	Numerous large Cu. (0.1)
20	21.1.52	Strato cumulus	Cold N.E.'ly air stream	Light-moderate.	1,000	Strato cumulus	Continuous light	4,000	-6	2.40	47.25	45 m	4.40	6	1 in. build up on wings. (0.07) (0.04)
21	22.1.52	Strato cumulus Alto-stratus.	Warm sector & occlusion.	Moderate	2-3,000	Strato cumulus.	Moderate	8,000	-12					6	1 in. build up in depression forming beyond occlusion. Smaller build up in occlusion.
							Light-moderate.	5,500	-	5.10	52.35	25 m	5.05		

Table 1 continued

Flight No.	Date	MET. FORECAST: Type of Cloud	MET. FORECAST: Synoptic Condition	MET. FORECAST: Icing Severity	MET. FORECAST: Freezing Level	FOUND ON FLIGHT: Type of Cloud	FOUND ON FLIGHT: Icing Severity	FOUND ON FLIGHT: Height at which ice was found	FOUND ON FLIGHT: Air Temp. °C	FLYING TIME: Individual flight	FLYING TIME: Total of successful icing flights	TIME IN MEASURABLE ICE: Flight	TIME IN MEASURABLE ICE: Total	No. of rotating cyl. measurements made	Rate of ice build up ins/min.	Remarks
22	28.1.52	Strato cumulus.	Occlusion	Light-moderate	2,5-3000	Strato Cumulus.	Light	6,000	-4	2.40	55.15	10 m	5.15	2		Short patches of light ice only.
23	31.1.52	Strato cumulus.	Cold front.	Light-moderate.	2,500	Strato cumulus.	Light	7,000	-7	3.45	59.00	20 m	5.35	3	0.05	Did not reach front but found ice behind it.
24	11.2.52	Strato cumulus.	Cold front	Moderate-severe *	2,5-3000	Strato cumulus.	Light	7,500	-13 -7	2.50	61.50	15	5.50	3		Front had moved more rapidly than expected.
25	14.2.52	Strato cumulus	Warm front	Light-moderate.	2,000	Strato cumulus	Light	4,500	-6	2.55	64.45	10	6.00	2		Much of the cloud was iced up.
26	14.2.52	Cumulus	Occlusion	Moderate	2,000	Cumulus	Moderate	8,500	-13	0.45	65.30	15	6.15	-		Several short period of moderate icing ½" built up on port of the aircraft.

* This forecast was made by a relief forecaster when the regular forecaster was on leave.

Before March 1952 the rate of ice build up was obtained from photographs of the test strut. After then the rate of ice build up was obtained from the record of the rotating disc.

Table 1 continued

Flight No.	Date	METEOROLOGICAL FORECAST				FOUND ON FLIGHT				FLYING TIME		Time in Measurable Ice		No. of Rotating Cylinder Measurements made	Rate of Ice Build Up Ins. per minute		Remarks
		Type of Cloud	Synoptic Condition	Icing Severity	Freezing Level	Type of Cloud	Icing Severity	Height at which ice was found	Air Temp. °C	Individual Flight	Total of Successful Icing Flights	Flight	Total		Peak	Average	
27	25.3.52	Strato cumulus	Occlusion	Light-Moderate	3,500-5,500	Thin strato cumulus	Light	6,000	-4	2,00	67,30	0.10	6.25	Nil			Partly transit flight to Paris as good icing conditions were expected near Paris next day.
28	26.3.52	Strato cumulus				Strato cumulus	Nil	-						-			Forecast obtained from French Met. Office.
		Cumulus				Cumulus	Light-Moderate	8,500	-14	3,30	71.00	0.25	6.50	4			Whip aerial broken by vibration due to ice build up.
29	27.3.52	No icing forecast given				Very thin strato cumulus	Light	5,000	-9	1.25	72.25	0.05	6.55	1			Mainly return flight from Paris.
30	1.4.52	Strato cumulus	Depression	Moderate	0-1,000	Strato cumulus	Light	6,500	-10	5.20	77.45	1.00	7.55	5			
31	7.4.52	Strato cumulus	Waving cold front	Light-Moderate	6,000-6,500	Strato cumulus	Light	7,500	-5								
		Cumulus				Cumulus	Light-Moderate	7,000	-6	3.50	81.35	0.15	8.10	5	0.1	0.05	Several patches of short duration
32	22.4.52	Cumulus Cumulo-nimbus	Unstable airstream with minor troughs.	Moderate Locally severe in Cu Nb tops.	3,500	Cumulus	Moderate	7,500	-6	1.30	83.05	0.10	8.20	4	0.11	0.07	
33	30.4.52	Alto-cumulus Castellatus.	Unstable air mass	Moderate-severe	9,000	Alto-cumulus Castellatus.	Severe	12,500	-9	2.35	85,40	0.10	8.30	3			
34	7.5.52	Cumulus	Unstable S.W.'ly airstream	Moderate-severe	3,500-4,000	Cumulus	Severe	7,000	-7	2.55	88.35	0.15	8.45	1	0.15	0.10	Ice built up on spray mast in spite of anti-icing. Flight was abandoned due to spray mast vibration but was resumed after mast had been removed. Although it was only noon G.M.T. the cumulus were subsiding and very little ice was found.

Table 1 continued

Flight No.	Date	METEOROLOGICAL FORECAST				FOUND ON FLIGHT				FLYING TIME		Time in Measurable Ice		No. of Rotating Cylinder Measurements made	Rate of Ice Build Up ins. per minute		Remarks
		Type of Cloud	Synoptic Condition	Icing Severity	Freezing Level	Type of Cloud	Icing Severity	Height at which ice was found	Air Temp. °C	Individual Flight	Total of Successful Icing Flights	Flight	Total		Peak	Average	
35	9.5.52	Cumulus	Unstable S.SW'ly airstream	Moderate-severe.	6,000-6,500	Cumulus	Severe	9,000	-7	2.05	90.40	0.15	9.00	4	0.13	0.09	
36	19.5.52	Cumulus	Unstable humid air mass	Moderate-severe	10,000	Cumulus Congestus	Severe	13,000-15,000	-9	1.15	91.55	0.10	9.10	Not in use		0.2	Aircraft caught in up current and forced up 2,000 ft.
37	6.6.52	Cumulus	Complex frontal trough	Light-Moderate	9,000	Cumulus	Moderate	12,000	-6	1.50	93.45	0.15	9.25	4			

Table 2

Summary of Measurements made in Icing Conditions

Flight No.	Date	Time of Day L.M.T.	Height feet	Speed (I.A.S.) knots	Static outside air temperature balance bridge °C	Liquid water content GMS/Cubic Metre		Time over which average was taken (secs) (Rotating Cylinder)	Median Drop Diam. Microns		Maximum Drop Diam. Microns		Remarks
						Rotating Cylinder	Rotating Disc		Rotating Cylinder	Oiled slide	Fixed Cylinder	Oiled slide	
1	8.6.51	1430	11,300	157	-6	-	-	-	-	-	9^{ϕ}	-	
2	19.6.51	1637	9,300	127	-6	0.72	-	99	9	-	20	25	
4	22.6.51	1205	12,100	148	-4	-	-	-	-	-	21	-	
		1212	12,400	128	-5	1.01	-	61	9	-	-	-	
		1216	13,100	143	-5	-	-	-	-	-	22	-	
5	26.6.51	1427	10,400	154	-5	-	-	-	-	35	19	50	The large drop size from the oiled slide is probably due to melted ice particles.
6	2.7.51	1425	12,300	138	-4	-	-	-	-	-	42	-	Photographs in figs. 16 & 18 show that large drops were present during some of the flight.
		1442	12,300	143	-4	-	-	-	-	-	24	-	
7	4.7.51	1219	10,500	153	-3	0.22	-	90	9	-	-	-	Photographs of ice formation on aircraft show that large drops were present.
		1223	10,750	153	-3	-	-	-	-	40	50	70	
9	23.7.51	1412	12,100	160	-5	-	-	-	-	20	30	-	
		1412	12,100	160	-5	-	-	-	-	48	-	-	Large drop size due to melted ice particles.
11	3.12.51	1528	12,150	150	-8	0.22	0.2	75	10	-	$40^{\dagger}$	-	
		1534	12,100	130	-8	0.39	0.65	60	13	-	20^{ϕ}	-	
		1537	12,090	170	-8	-	0.65	-	-	-	-	-	
12	7.12.51	1245	7,000	166	-5	-	0.52	-	-	-			
		1330	7,000	160	-5	-	-	-	-	26 π 55	-	35 80	One drop over 200 microns excluded.
13	18.12.51	1050	10,800	162	-6	-	-	-	-	-	$23^{\dagger}$	-	
		1128	11,150	166	-7	-	1.0	-	-	26	-	45	Frozen particles are believed to have been caught in all drop samples in this flight.
		1131	10,950	158	-7	-	0.44	-	-	-	-	-	
		1131	10,950	157	-7	-	0.72	-	-	-	-	-	
		1132	10,950	158	-7	-	0.44	-	-	36	35^{ϕ}	55	
		1132	11,000	156	-7	-	0.80	-	-	22	-	35	
		1207	12,500	154	-8	0.08^{++}	0.50	88	10^{++}	24	22	35	
		1203	12,500	156	-8	-	0.10	-	-	30	-	40	
		1212	12,300	150	-8	-	0.40	-	-	32	18^{ϕ}	45	

Table 2 continued

Flight No.	Date	Time of Day L.M.T.	Height feet	Speed (I.A.S.) knots	Static outside air temperature balance bridge °C	Liquid water content GMS/Cubic Metre		Time over which average was taken (secs) (Rotating Cylinder)	Median Drop Diam. Microns		Maximum Drop Diam. Microns		Remarks
						Rotating Cylinder	Rotating Disc		Rotating Cylinder	Oiled slide	Fixed Cylinder	Oiled slide	
14	28.12.51	1112	7,000	165	-8	0.49	0.80	120	12	28	-	40	x
15	28.12.51	1301	7,450	167	-11	-	0.70	-	-	23	25	35	x
		1311	6,600	150	-9	-	0.75	-	-	-	-	-	
		1312	6,700	150	-9	-	1.75	-	-	-	-	-	
		1312	6,700	152	-9	0.17	1.20	90	28	23	-	30	
16	2.1.52	1146	5,850	148	-6	-	0.95	-	-	-	-	-	
		1148	5,950	138	-6	-	0.50	-	-	-	-	-	
		1300	5,600	162	-7	-	0.80	-	-	-	-	-	
17	16.1.52	1124	6,100	130	-10	0.9	-	35	8	-	-	-	
		1136	6,000	120	-9	0.49	-	16	7	-	-	-	
18	16.1.52	1525	4,100	125	-5	-	0.55	-	-	-	-	-	
		1526	4,100	125	-5	-	1.5	-	-	13	-	15	
		1541	4,500	120	-6	-	0.85	-	-	-	-	-	
		1610	5,600	125	-9	-	1.25	-	-	-	-	-	
19	18.1.52	1205	6,700	150	-11	-	1.8	-	-	36	-	50	x
		1207	6,500	155	-11	0.19	2.0	220	9	27	-	50	
		1208	6,300	153	-11	-	0.2	-	-	29	-	40	
		1225	5,500	150	-9)	0.55	(0.95)	44	18	(34	-	45	
		1226	5,700	145	-9)		(1.0)			(28	-	40	
		1226	5,650	155	-9	-	0.3	-	-	23	-	35	
		1227	5,800	140	-9	-	0.4	-	-	24	-	35	
		1228	5,900	147	-9	-	2.2	-	-	25	-	40	
		1251	6,200	140	-9	0.73	2.0	11	14	28	27ø	40	
		1252	6,400	140	-10	-	1.1	-	-	24	-	40	
		1252	6,200	148	-10	-	1.3	-	-	28	-	45	
		1301	6,400	140	-10	0.33	2.2	32	17	29	-	45	
		1300	6,300	142	-10	-	0.5	-	-	34	-	50	
		1306	6,100	150	-10	0.13	0.5	32	21	37	-	45	
		1309	5,900	145	-9	-	1.1	-	-	-	-	-	
		1310	5,900	142	-9	0.06	1.9	22	22	-	-	-	
		1311	5,800	135	-9	-	1.3	-	-	-	-	-	

Table 2 continued

Flight No.	Date	Time of Day L.M.T.	Height feet	Speed (I.A.S.) knots	Static outside air temperature balance bridge °C	Liquid water content GMS/Cubic Metre		Time over which average was taken (secs) (Rotating Cylinder)	Median Drop Diam. Microns		Maximum Drop Diam. Microns		Remarks
						Rotating Cylinder	Rotating Disc		Rotating Cylinder	Oiled slide	Fixed Cylinder	Oiled slide	
20	21.1.52	1155	3,800	145	-6	-	0.7	-	-	-	12 ø	-	
		1208	3,900	145	-6	0.45	0.8	60	15	-	20	-	
		1209	3,900	140	-6	-	1.5	-	-	-	-	-	
		1219	4,000	139	-6	0.55	1.7	35	6	-	25	-	
		1222	4,000	137	-6	-	1.2	-	-	-	-	-	
		1223	3,900	133	-6	0.64	0.9	30	10	-	15	-	
		1231	4,100	142	-6	0.43	1.1	45	13	-	-	-	
		1234	4,100	143	-6	-	0.7	-	-	-	17	-	
		1242	4,200	143	-7	0.16	0.5	35	12	-	17	-	
		1245	4,100	142	-6	-	0.6	-	-	-	10	-	
21	22.1.52	1336	7,900	148	-12	-	0.35	-	-	29	-	45	x
		1337	8,100	153	-12	0.14	0.4	120	24	35	-	45	
		1338	8,100	155	-12	-	0.45	-	-	-	22	-	
		1339	8,200	158	-12	-	0.4	-	-	27	-	40	
		1347	8,500	147	-13	-	0.45	-	-	30	-	40	
		1347	8,700	147	-13	-	0.65	-	-	30	32?	40	
		1348	8,400	158	-12	0.27	0.85	120	20	-	-	-	
		1349	8,500	148	-12	-	0.85	-	-	35	35 ø	50	
		1353	7,700	138	-11	-	0.5	-	-	-	22 ø	-	
		1356	7,500	148	-11	-	0.5	-	-	-	25 ø	-	
		1415	8,000	140	-12	-	0.4	-	-	-	35 ø	-	
		1436	7,700	158	-10	-	0.8	-	-	-	25 ø	-	
22	28.1.52	1248	5,500	132	-3	0.10	0	311	16	-	-	-	x
		1250	5,400	127	-3	-	0	-	-	45	25	60	
		1346	6,100	143	-5	0.11++	0	88	5++	48	20 ø	70	
23	31.1.52	1143	8,700	172	-11	-	0.7	-	-	48	20	60	
		1146	7,600	175	-8	0.9	0.7	45	8	-	24	-	
		1148	7,200	141	-8	-	0.2	-	-	14	-	15	
		1154	6,400	157	-7	-	1.2	-	-	37	19	50	
		1158	6,800	131	-7	-	0.9	-	-	19	-	25	
		1224	7,200	126	-7	-	0.3	-	-	32	29 ø	60	
		1228	7,200	148	-8	-	0.7	-	-	32	-	60	

Table 2 continued

Flight No.	Date	Time of Day L.M.T.	Height feet	Speed (I.A.S.) knots	Static outside air temperature balance bridge °C	Liquid water content GMS/Cubic Metre		Time over which average was taken (secs) (Rotating Cylinder)	Median Drop Diam. microns		Maximum Drop Diam. Microns		Remarks
						Rotating Cylinder	Rotating Disc		Rotating Cylinder	Oiled slide	Fixed Cylinder	Oiled slide	
24	11.2.52	1149	10,000	155	-11	-	0.48	-	-	26	-	40	
		1156	9,050	142	-13	0.14	0.11	68	12	29	30 Ø	40	
		1159	9,050	132	-12	-	0.25	-	-	37	-	60	
		1200	9,050	131	-13	-	1.25	-	-	-	-	-	
		1208	7,650	173	-8	0.32	0	167	12	38	-	60	
		1209	7,500	159	-7	-	1.05	-	-	-	30 Ø	-	
		1210	7,450	136	-7	-	0.14	-	-	24	-	40	
		1211	7,550	127	-7	-	0	-	-	24	-	30	
		1303	6,000	170	-7	-	0.19	-	-	22	-	30	
25	14.2.52	1059	3,100	158	-3	-	0	-	-	22	-	35	x
		1108	4,400	162	-6	0.19	0.8	159	9	31	15	40	
		1108	4,400	159	-6	-	0.5	-	-	24	-	35	
		1116	4,450	163	-6	-	1.5	-	-	20	-	40	
		1136	4,900	172	-6	0.07	0.3	304	7	-	8	35	
		1137	4,900	162	-6	-	0.4	-	-	28	-	40	
		1247	6,300	163	-8	-	1.5	-	-	-	-	-	
26	14.2.52	1624	8,300	170	-12	-	1.6	-	-	36	-	50	x
		1627	9,100	148	-13	-	0.9	-	-	-	-	-	
		1632	8,650	164	-13	-	1.1	-	-	31	18 Ø	40	
		1642	8,350	161	-12	-	0.9	-	-	32	-	50	
		1645	8,350	160	-12	-	1.2	-	-	30	15 Ø	35	
		1649	8,300	167	-12	-	0.9	-	-	24	-	30	
27	25.3.52	1801	5,900	163	-4	-	-	-	-	32	-	45	
		1812	6,800	155	-4	-	-	-	-	25	-	45	
28	26.3.52	1159	5,400	150	-9	-	-	-	-	17	-	25	x
		1201	5,400	152	-9	-	-	-	-	20	11	35	

Table 2 continued

Flight No.	Date	Time of Day L.M.T.	Height feet	Speed Knots (I.A.S.)	Static outside air temperature °C: Balance bridge	Static outside air temperature °C: Vortex tube	Liquid water content GMS/Cubic metre: Rotating Cylinder	Liquid water content: Rotating Disc Peak	Liquid water content: Rotating Disc Average	Time over which average was taken (secs): Rotating Cylinder	Time over which average was taken (secs): Rotating Disc	Median Drop Diam. Microns: Rotating Cylinder	Median Drop Diam. Microns: Oiled slide	Maximum Drop Diam. Microns: Fixed Cylinder	Maximum Drop Diam. Microns: Oiled slide	Remarks
28 contd	26.3.52	1204	5,400	140	-9		-	-	-	-	-	-	16	-	20	Droplet samples shown in figures 20, 24 & 25 were taken on this flight. Where possible the large drops that were originally frozen particles have not been counted.
		1326	5,000	145	-9		-	-	-	-	-	-	32	-	35	
		1352	4,700	145	-7		-	-	-	-	-	-	8	8	10	
		1353	4,700	150	-7		-	-	-	-	-	-	8	-	10	
		1401	8,750	-	-14		1.05	-	-	88	-	9	29	12^Ø	60	
		1408	8,700	149	-14		0.35	-	-	81	-	10	13	-	20	
		1416	8,150	165	-14		0.25	-	-	132	-	10	27	-	50	
		1416	8,250	154	-13		-	-	-	-	-	-	16	-	25	
		1427	8,400	146	-14		-	-	-	-	-	-	-	13	-	
29	27.3.52	1545	5,400	155	-9		-	-	-	-	-	-	15	-	20	
		1550	5,100	150	-9		0.34	-	-	95	-	7	20	-	30	
		1551	5,130	150	-9		-	-	-	-	-	-	18	-	25	
30	1.4.52	.349	5,300	154	-9		-	-	-	-	-	-	29	20	35	x
		1651	5,700	126	-10		0.04++	-	-	50	-	7++	32	-	40	
		1707	6,300	168	-9		-	-	-	-	-	-	-	-	-	
		1714	6,700	115	-9		-	-	-	-	-	-	-	16	-	
		1724	6,650	160	-10		-	-	-	-	-	-	10	12	15	
		1736	6,700	160	-10		-	-	-	-	-	-	25	-	60	
		1741	6,650	162	-10		0.07	-	-	120	-	7	-	-	-	
31	7.4.52	1129	7,550	147	-4		-	0.59	0.35	-	42	-	21	19	25	
		1152	9,450	148	-7		-	-	-	-	-	-	10	15	20	
		1346	7,100	126	-6		-	0.71	0.24	-	27	-	-	-	-	
		1347	7,050	128	-6		-	-	-	-	-	-	14	14	20	
		1351	7,100	135	-6		-	-	-	-	-	-	24	-	35	
		1352	7,450	140	-7		-	0.74	0.33	-	66	-	-	-	-	
		1354	7,450	129	-7		-	1.9	1.67	-	30		32	25	40	
		1359	6,800	-	-		-	-	-	-	-	-	23	-	30	) Air speed system frozen.
		1401	7,650	-	-		-	0.81	0.30	-	20	-	24	-	30	)
		1405	6,650	-	-		-	1.2	0.56	-	16	-	18	-	25	)
32	22.4.52	1055	7,750	130	-7	-5	-	1.33	0.70	-	33	-	38	23	50	
		1105	7,800	137	-6	-4	0.2	0.78	0.51	150	17	8	-	-	-	
		1116	7,750	124	-7	-5	-	0.73	0.63	-	50	-	32	27	45	
		1133	7,250	130	-6	-5	-	1.2	0.82	-	12	-	-	-	-	
		1138	7,000	144	-5	-5	-	1.15	0.56	-	63	-	29	16	40	

Table 2 continued

Flight	Date	Time of Day L.M.T.	Height feet	Speed knots (I.A.S.)	Static outside air temperature °C Balance Bridge	Vortex tube	Liquid water content GMS/Cubic Metre Rotating Cylinder	Rotating Disc Peak	Rotating Disc Average	Time over which average was taken (secs) Rotating Cylinder	Rotating Disc	Median Drop Diam. Microns Rotating Cylinder	Oiled slide	Maximum Drop Diam. Microns Fixed Cylinder	Oiled slide	Remarks
33	30.4.52	1223	12,350	137	-9	-13	0.05	-	-	63	-	8	-	-	-	x
		1232	12,900	137	-9	-12	0.23	-	-	54	-	9	40	$40^{Ø}$	50	
		1243	12,650	144	-9	-12	-	-	-	-	-	-	31	26	45	
34	7.5.52	1321	7,000	132	-7	-9	-	0.31	0.21	-	16	-	-	-	-	
		1326	7,200	153	-7	-9	-	0.74	0.38	-	28	-	-	-	-	
		1342	6,800	141	-6	-6	-	0.77	0.39	-	34	-	-	-	-	
		1346	6,550	142	-6	-8	-	0.65	0.54	-	18	-	-	-	-	
		1348	6,500	147	-6	-8	-	0.37	0.16	-	16	-	-	-	-	
		1356	6,500	144	-6	-9	-	0.36	0.26	-	10	-	-	-	-	
		1400	7,100	140	-7	-10	-	0.54	0.35	-	23	-	-	-	-	
		1403	6,550	140	-6	-10	-	0.66	0.29	-	26	-	-	-	-	
		1407	6,750	144	-6	-10	-	0.34	0.30	-	11	-	-	-	-	
		1419	7,300	143	-	-15	-	1.3	0.68	-	88	-	-	-	-	Balance bridge thermometer reading not taken.
35	9.5.52	1418	9,800	135	-8	-6	-	1.03	0.38	-	30	-	-	-	-	
		1420	9,700	127	-8	-5	-	1.82	0.69	-	19	-	-	-	-	
		1421	9,750	131	-8	-5	-	1.88	0.71	-	23	-	44	-	60	
		1423	9,450	128	-8	-4	-	1.81	0.68	-	44	-	-	25	-	
		1429	9,100	140	-7	-5	1.15	0.85	0.29	19	21	20	-	-	-	
		1431	9,000	150	-7	-5	-	1.0	0.41	-	33	-	-	-	-	
		1432	8,650	139	-6	-5	-	0.9	0.11	-	4	-	36	-	50	
		1438	9,400	131	-6	-	0.64	0	0	94	-	24	-	-	-	
		1452	9,050	138	-7	-10	0.17	0.68	0.29	60	16	18	44	-	60	
		1530	8,500	147	-7	-7	-	0.64	0.28	-	9	-	-	34	-	
36	19.5.52	1540	13,450	114	-	-	-	-	-	-	-	-	-	18	-	x
		1542	13,650	124	-9	-9	-	-	-	-	-	-	17	-	20	
		1604	12,700	120	-5	-8	-	-	-	-	-	-	28	14	35	
		1620	12,600	129	-5	-5	-	-	-	-	-	-	23	-	30	
37	6.6.52	1556	12,350	119	-6	-	0.5^{++}	-		80	-	12^{++}	27	-	35	
		1603	11,850	118	-5	-	0.48	-	-	42	-	12	39	20	60	
		1606	11,600	125	-5	-	-	-	-	-	-	-	37	27	60	

Ø)
++) See next page.
x)

Notes on Table 2

ø These fixed cylinder records are not as clear as usual mainly because there was no runback. The answer may be a slight overestimate but it will not be an underestimate.

++ These rotating cylinder results are not very reliable. The experimental points did not fit very well on to the theoretical curves.

* Both droplet samples on flight No.12 are from the same oiled slide. They included some very large drops that were caught as frozen particles and melted before being photographed. The larger drop diameter is incorrect for the median drop diameter of the liquid water, as the large drops have been counted. The smaller diameter is more nearly correct as the obvious larger drops have been excluded from the count.

On the other flights marked * the large drops that could readily be identified as probably coming from frozen particles have, where possible, been discarded from the drop samples. Many less outstanding large drops that had probably been frozen particles have had to be included in the count. On several other flights frozen particles are believed to have been present when the oiled slide sample was taken but it has not been possible to exclude them as they could not be identified with absolute certainty.

Table 3

Weight of ice (gms) caught on three rotating cylinders of the same size

Cylinder Position \ Run No.	1	2	3	4	5	6
Inboard	1.96	6.64	7.25	0.11	0.14	5.71
Middle	2.31	6.78	9.87	0.19	0.18	6.57
Outboard	2.19	7.31	8.32	0.58	0.17	-
True air speed (knots)	155	165	165	170	system frozen	145

Table 4

Values of Rg calculated from the Rotating Cylinder Measurements compared with observed icing severity

Flight No.	Liquid water content gms/metre^3	Median droplet diameter microns	Rg gms/cm^2/hours	Observed icing severity	Type of Cloud
2	0.72	9	2.4	Light-moderate	Cumulus
4	1.01	9	3.3	Moderate-severe	Cumulus
7	0.22	9	0.75	Light with small amount of moderate	Alto-stratus
11	0.22	10	1	Light	Thick medium
"	0.39	13	3	"	"
14	0.49	12	3.3	Moderate	Cumulus
15	0.17	28	3.4	Moderate	Cumulus
17	0.9	8	2	Moderate-severe	Cumulus
"	0.49	7	0.75	"	"
19	0.19	9	0.6	Moderate	Cumulus
"	0.55	18	7	"	"
"	0.73	14	6.5	"	"
"	0.33	17	4	"	"
"	0.13	21	2	"	"
"	0.06	22	1	"	"
20	0.45	15	4.4	Light	Strato-cumulus
"	0.55	8	1.3	"	"
"	0.64	10	2.8	"	"
"	0.43	13	3.5	"	"
"	0.16	12	1.0	"	"
21	0.14	24	2.5	Moderate	Strato-cumulus
"	0.27	20	4	"	"
22	0.10	16	1	Light	Strato-cumulus
23	0.9	8	2	Light	"
24	0.14	12	0.9	Light	"
"	0.32	12	2.2	"	"

Table 4 continued

Flight No.	Liquid water content gms/metre^3	Median droplet diameter microns	Rg gms/cm^2/hours	Observed icing severity	Type of Cloud
25	0.19	9	0.6	Light	Strato-cumulus
"	0.07	7	0.1	"	"
28	1.05	9	3.5	Light-moderate	Cumulus
"	0.35	10	1.5	"	"
"	0.25	10	1	"	"
29	0.34	7	0.6	Light	Strato-cumulus
30	0.07	7	0.1	Light	"
32	0.2	8	0.5	Light-moderate	"
33	0.05	8	0.1*	Severe	Alto cumulus castellatus
"	0.23	9	0.75*	"	"
35	1.15	20	16	Severe	Cumulus
"	0.64	24	11	"	"
"	0.17	18	2.1	"	"
37	0.48	12	3.3	Moderate	Cumulus

* These measurements were obviously not taken in the part of the cloud where the icing severity corresponded to "severe."

Table 5

Comparison of severity of icing forecast, with severity of icing observed

Observed / Forecast	Correct forecasts			Overestimated forecasts (degree)		
				1		2
	Light	Moderate	Severe	Nil	Light	Nil
Light-moderate	6	4		-		
Moderate		5			5	2
Moderate-severe		4	7		1	-
	6	13	7	-	6	2
Totals	26			6		2

FIG. 1. THE TEST AIRCRAFT.

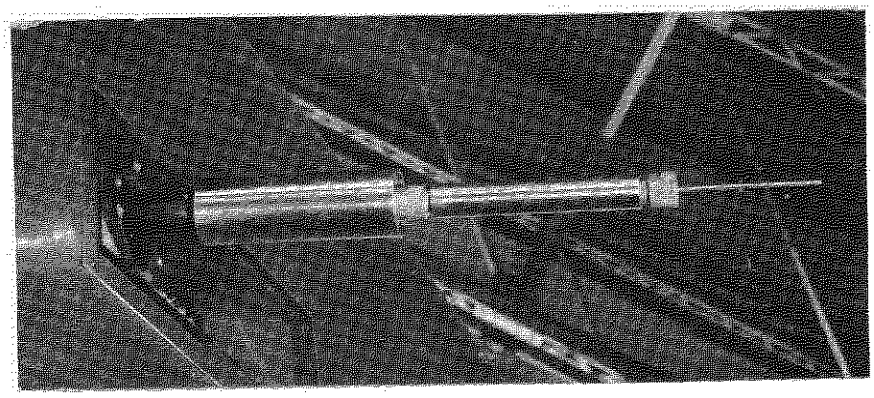


FIG. 2. ROTATING CYLINDERS EXTENDED.

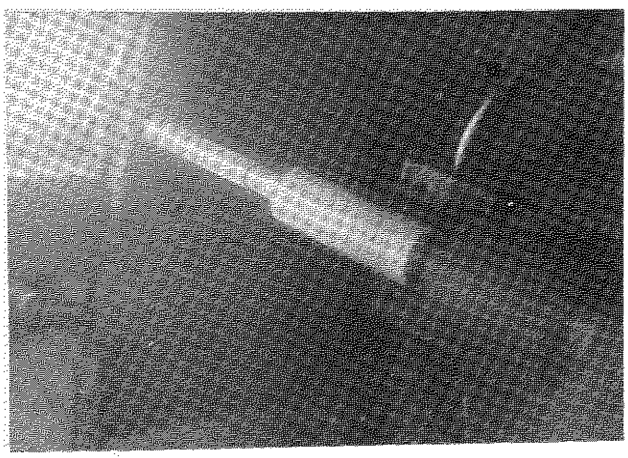


FIG. 3. ROTATING CYLINDERS RETRACTED WITH ICE ON.

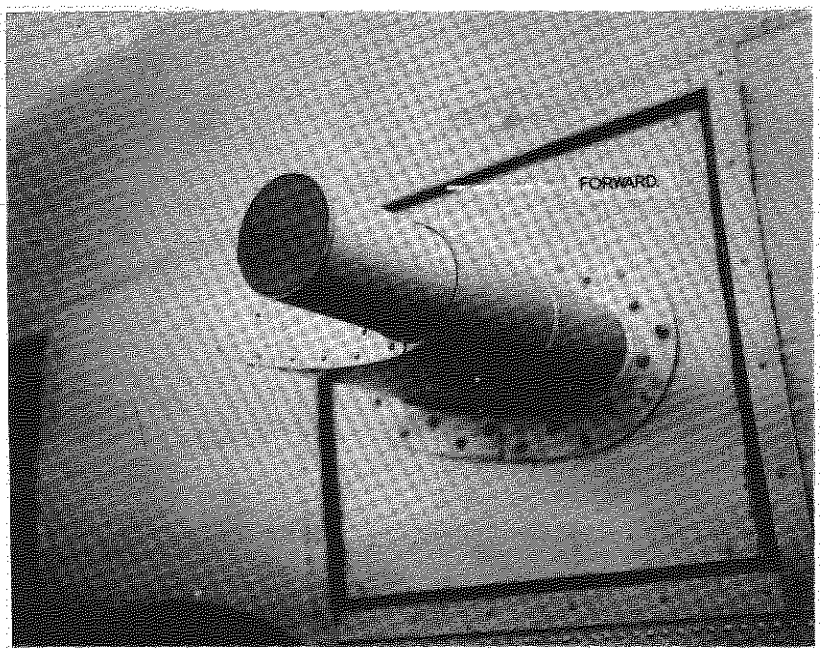


FIG. 4. FIXED CYLINDER.

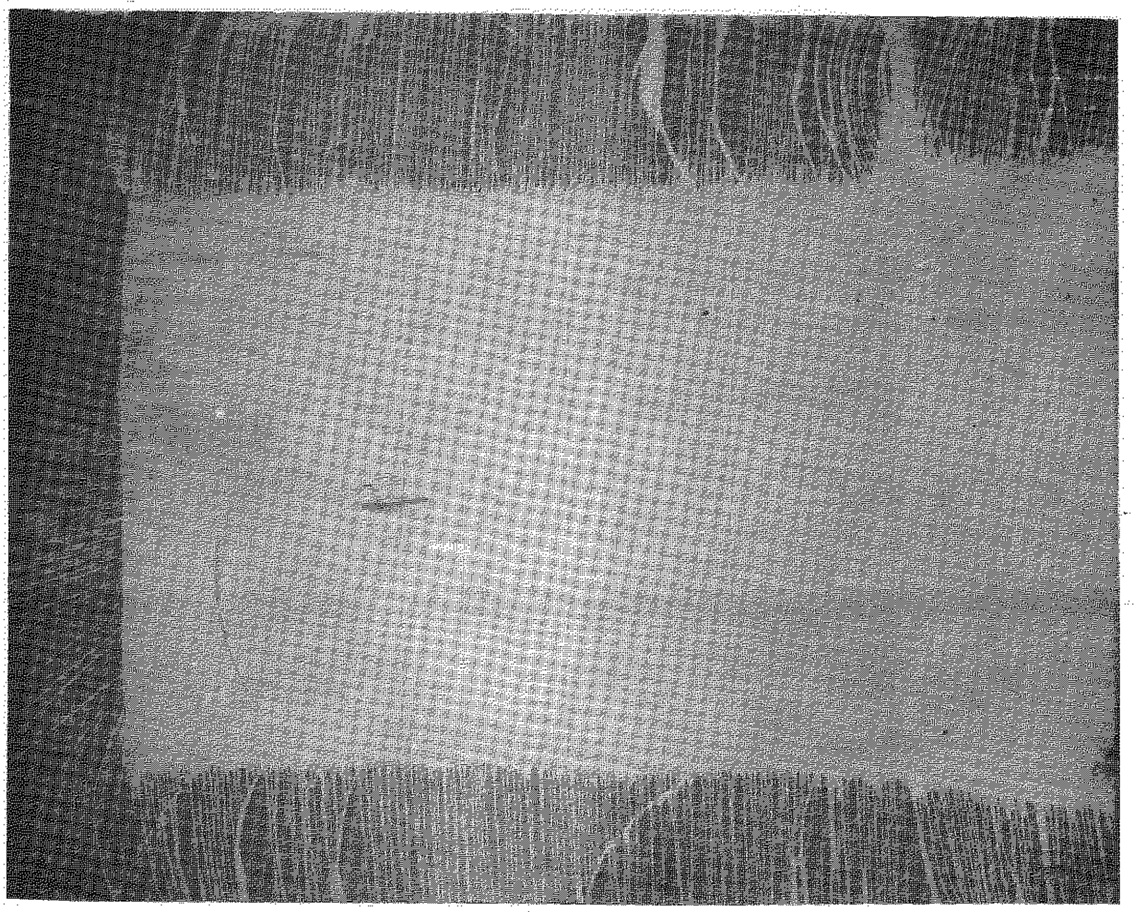


FIG. 5. FIXED CYLINDER RECORD. DROPLET DIAMETER 23 MICRONS.

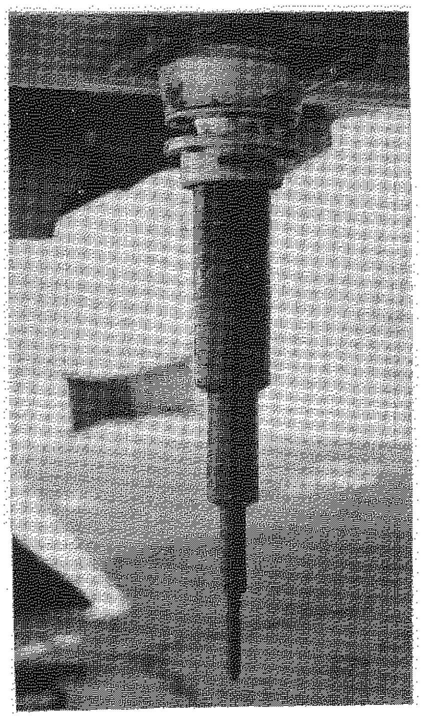


FIG. 6. HEATED CYLINDERS

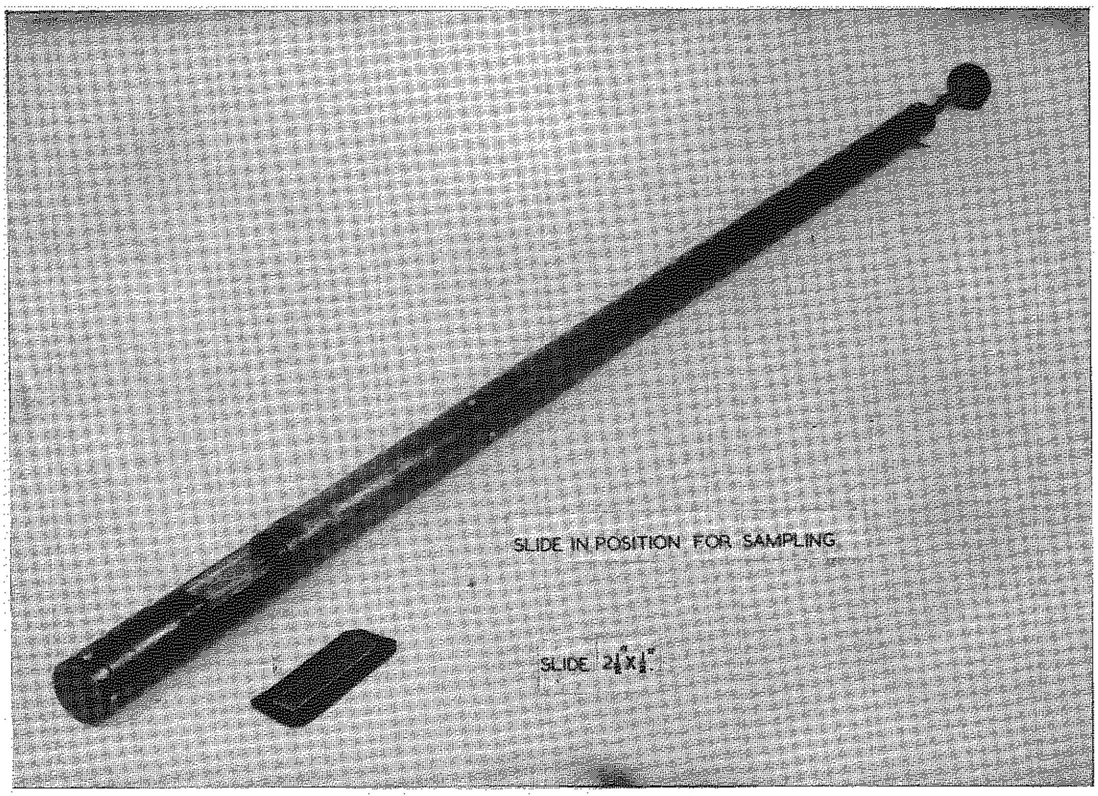


FIG. 7. OILED SLIDE SAMPLING POLE.

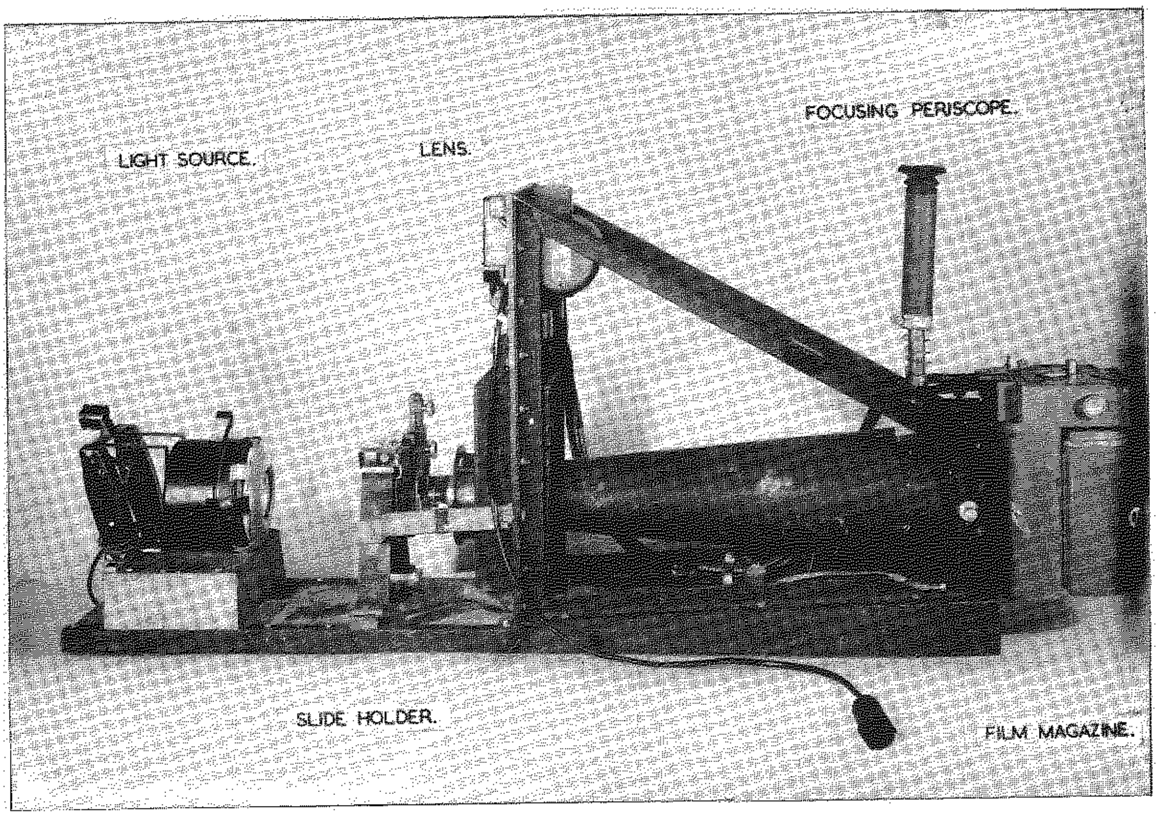


FIG. 8. ORIGINAL OILED SLIDE MICRO CAMERA.

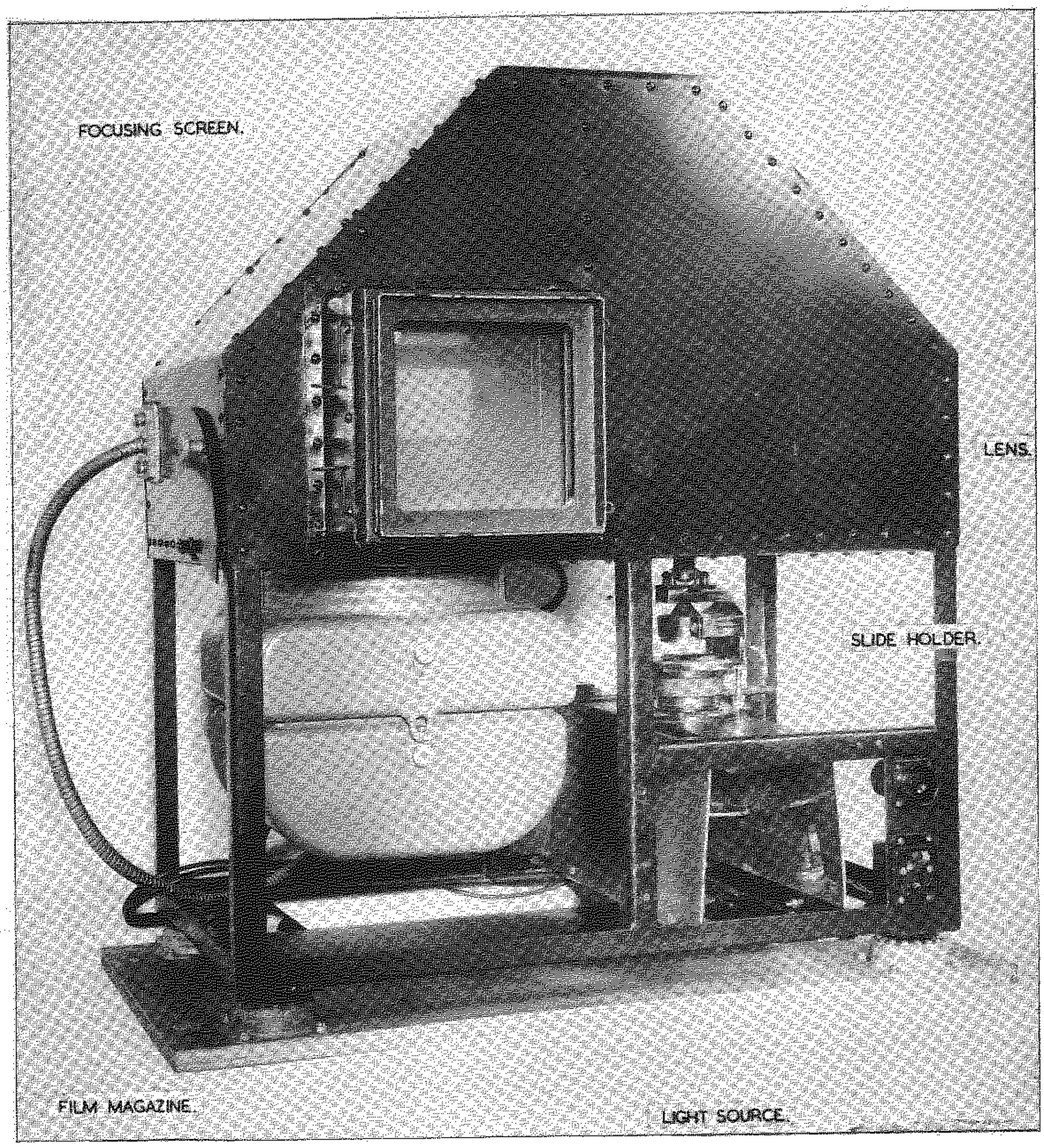


FIG. 9. IMPROVED OILED SLIDE MICRO CAMERA.

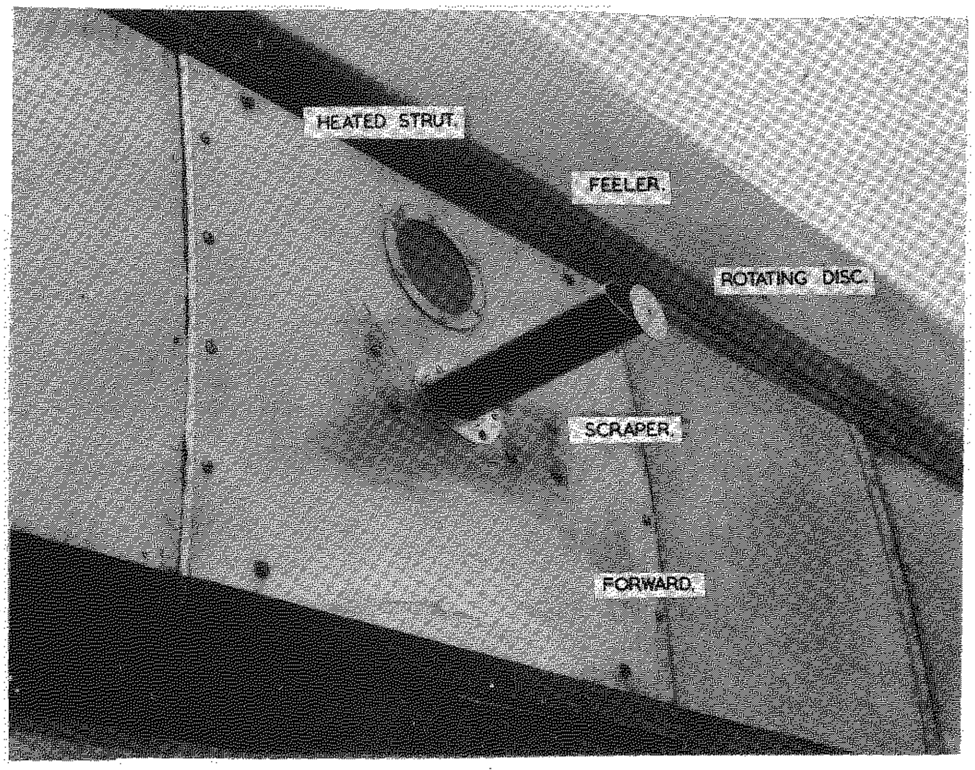


FIG. 10. ROTATING DISC.

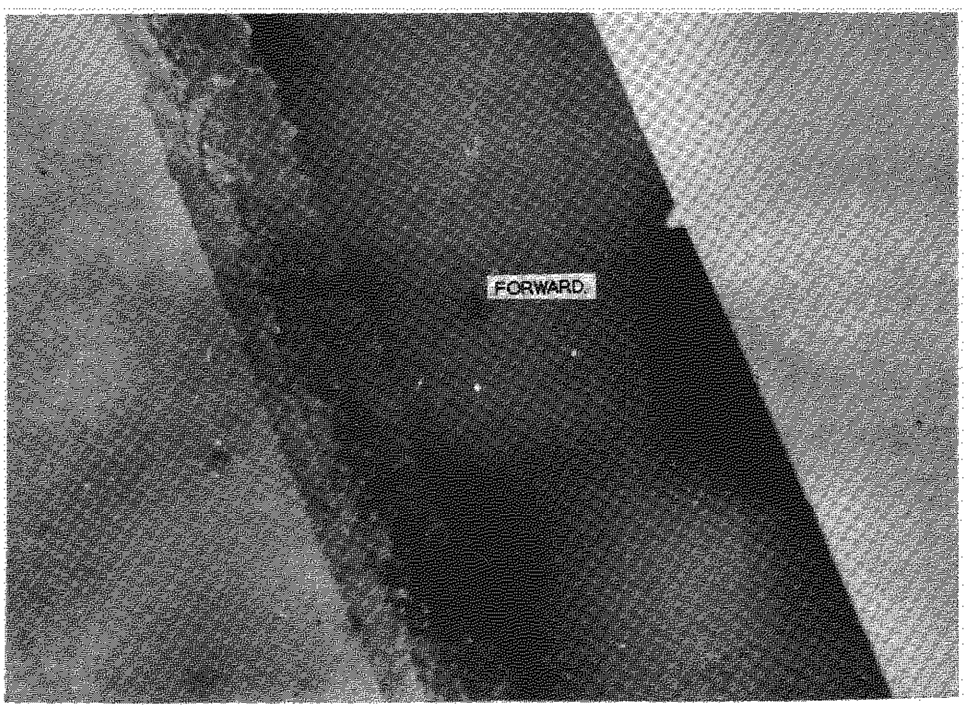


FIG. 11. ICE FORMATION ON THE OBSERVATION STRUT.

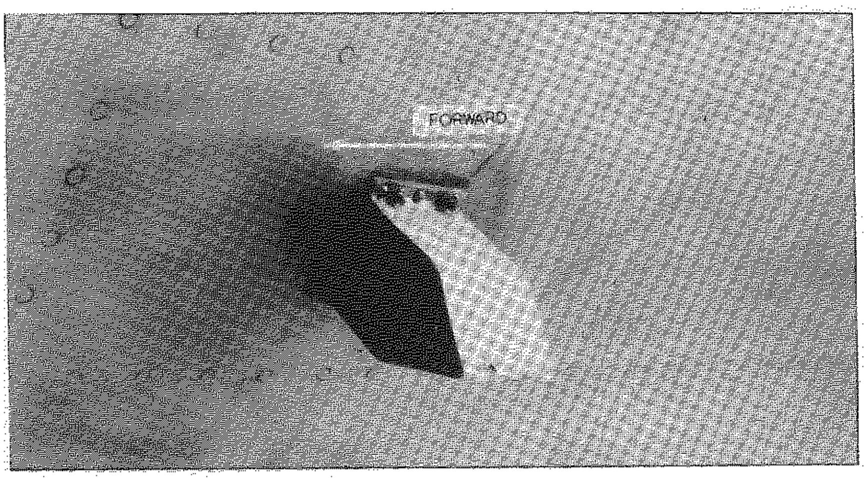


FIG 12. MODIFIED AIR THERMOMETER BULB RADIATION SHIELD.

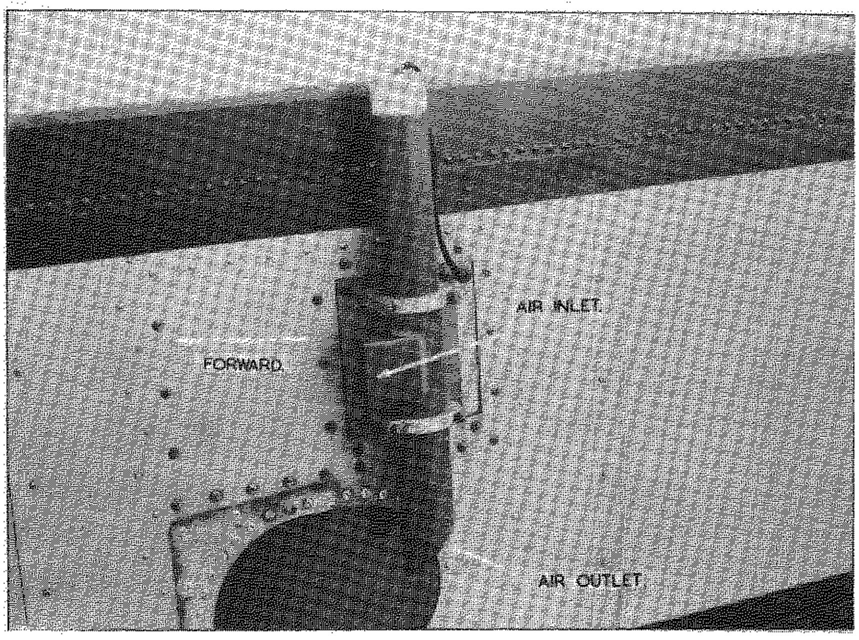


FIG. 13. VORTEX TUBE THERMOMETER.

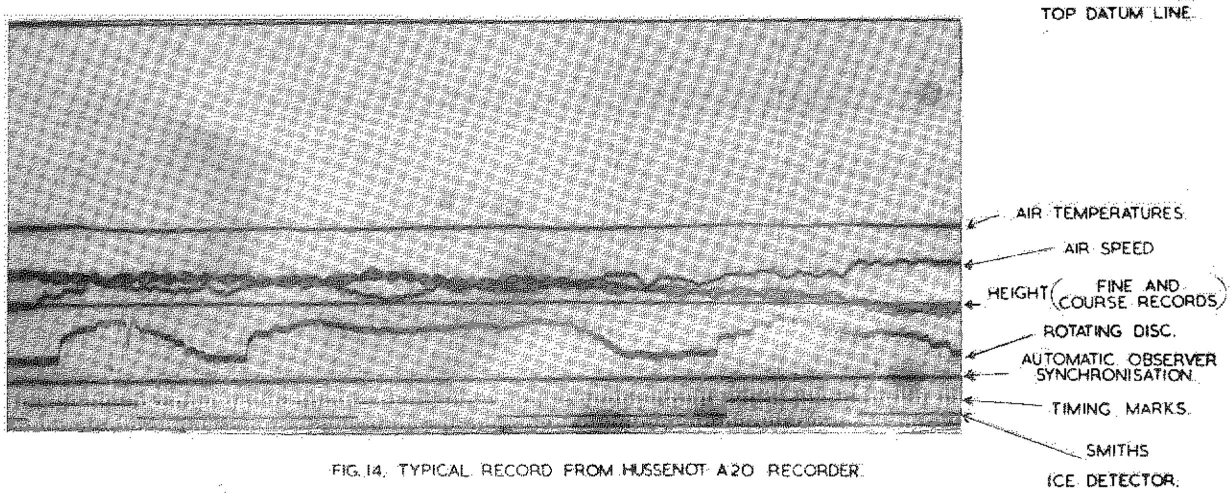
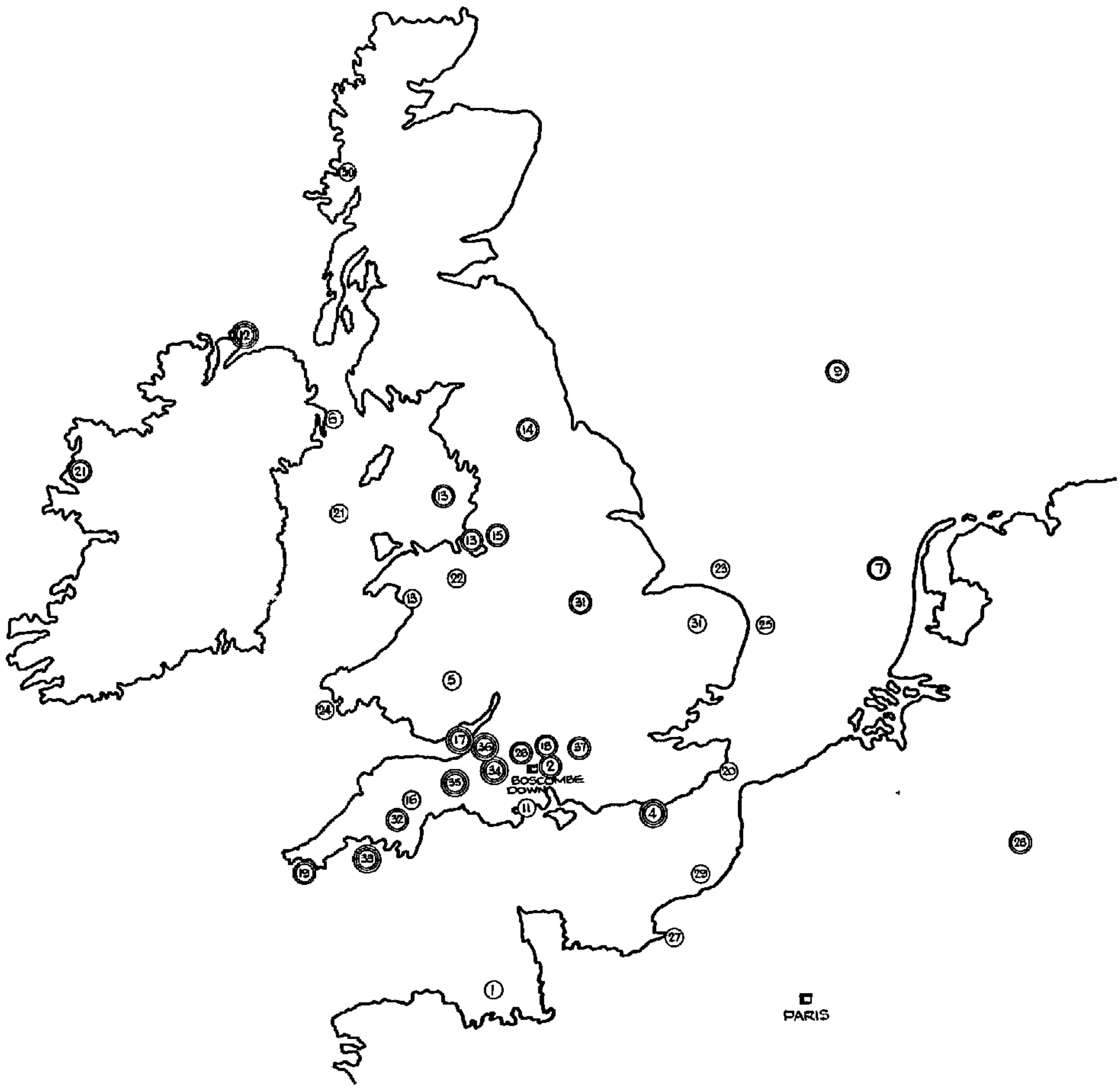


FIG. 14. TYPICAL RECORD FROM HUSSENOT A20 RECORDER.

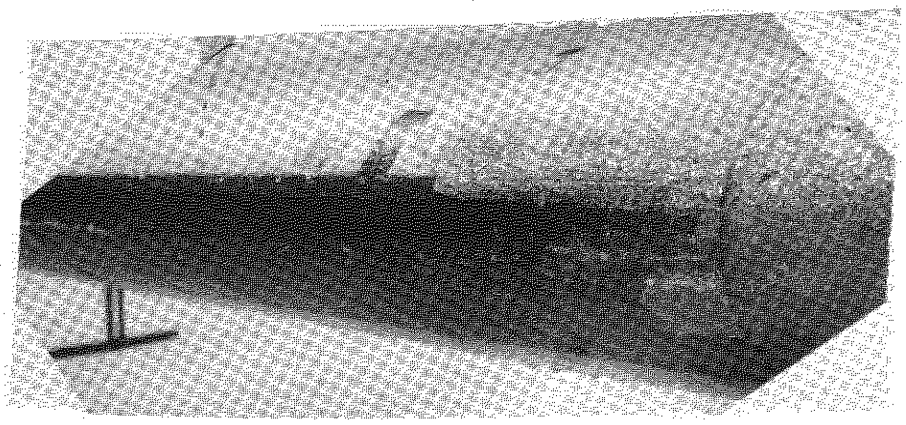
FIG. 15

LIGHT	LIGHT-MODERATE MODERATE	MODERATE-HIGH HIGH
○	○	◎

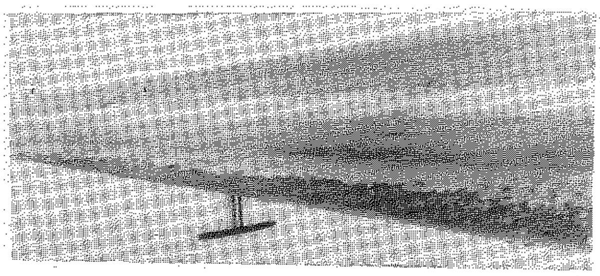
THE NUMBERS GIVEN IN EACH AREA CORRESPONDS TO THE FLIGHT NUMBERS IN TABLE I



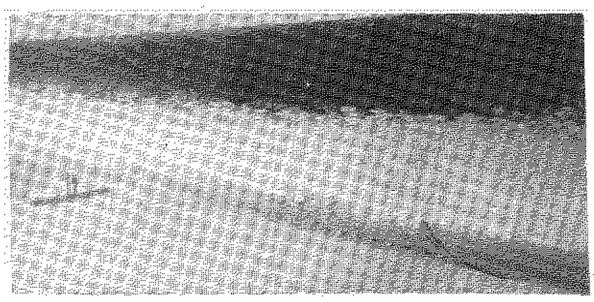
AREAS WHERE NATURAL ICING CONDITIONS HAVE BEEN FOUND DURING 1951-52.



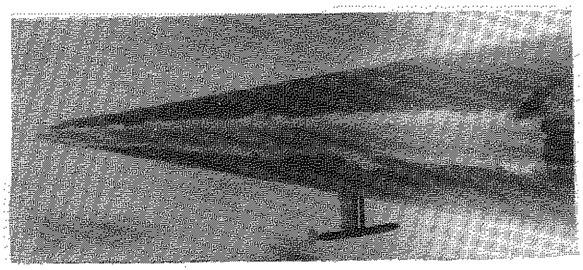
FLIGHT Nº 6.
MEDIAN DROP DIAMETER 40 MICRONS.
OUTSIDE AIR TEMPERATURE – 3°C.



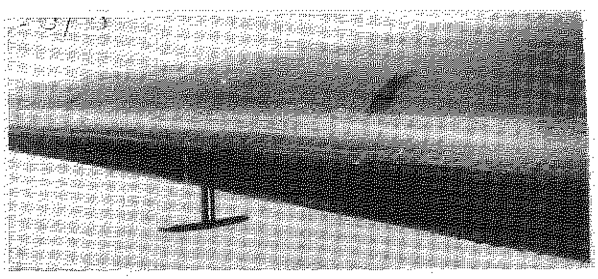
FLIGHT Nº 21.
MEDIUM DROP DIAMETER. 20 MICRONS.
LIQUID WATER CONTENT 0·7 GMS/CU. METRE
OUTSIDE AIR TEMPERATURE –12°C.



FLIGHT Nº 23.
MEDIAN DROP DIAMETER. 20 MICRONS
LIQUID WATER CONTENT 0· 0·9 GMS/CU.METRE
OUTSIDE AIR TEMPERATURE. – 7°C.

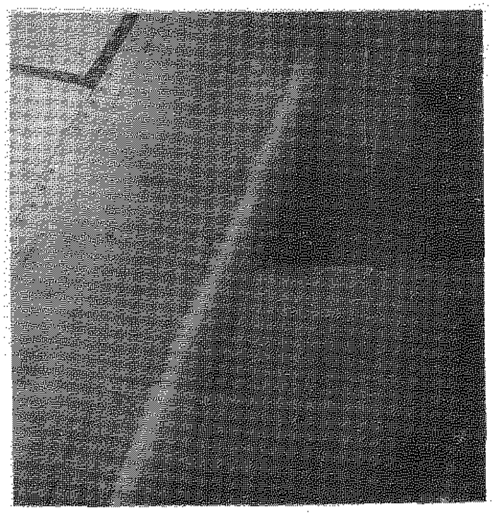


FLIGHT Nº 20.
MEDIAN DROP DIAMETER. ; 10 MICRONS
LIQUID WATER CONTENT 0· 0·5 GMS/CU. METRE
OUTSIDE AIR TEMPERATURE –6°C.



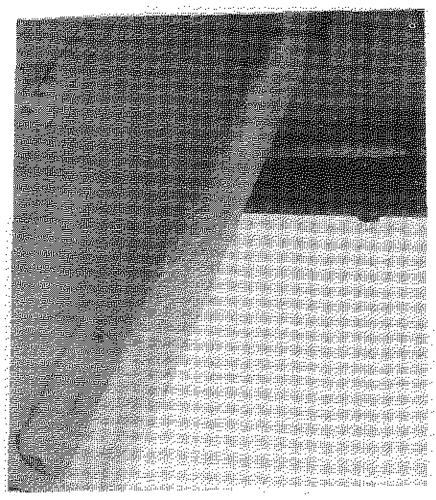
FLIGHT Nº 28.
MEDIAN DROP DIAMETER. ; 10 MICRONS
LIQUID WATER CONTENT 0· 0·3 GMS/CU. METRE
OUTSIDE AIR TEMPERATURE –7 TO –15°C.

FIG. 16. ICE FORMATION ON TAILPLANE.



FLIGHT Nº 21.

MEDIAN DROP DIAMETER. 20 MICRONS.
LIQUID WATER CONTENT O·7 GMS/CU. METRE
OUTSIDE AIR TEMPERATURE -12°C.

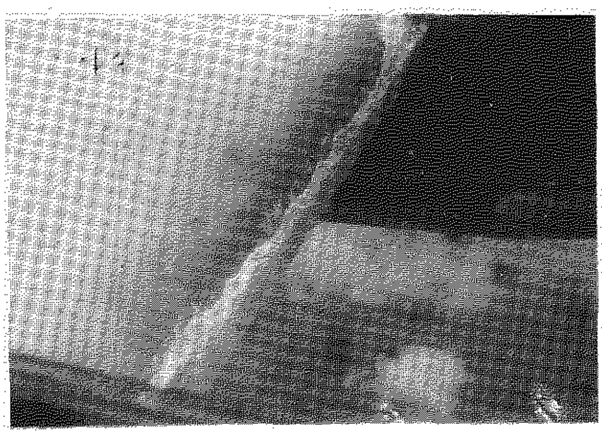


FLIGHT Nº 23.

MEDIAN DROP DIAMETER. 20 MICRONS
LIQUID WATER CONTENT O· O·9 GMS/CU. METRE
OUTSIDE AIR TEMPERATURE -7°C.

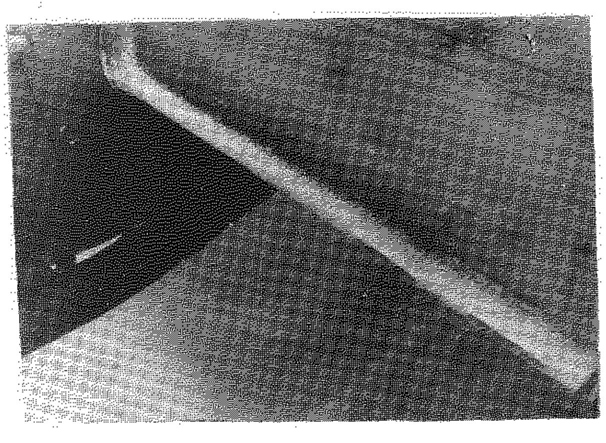
FLIGHT Nº 20.

MEDIAN DROP DIAMETER. 10 MICRONS
LIQUID WATER CONTENT O·O·5 GMS/CU. METRE
OUTSIDE AIR TEMPERATURE -6° C.



FLIGHT Nº 32.

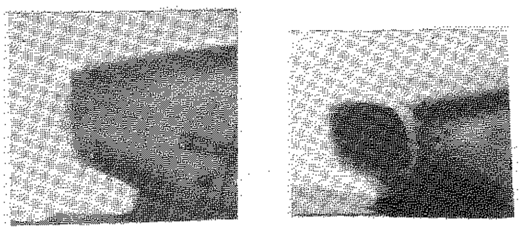
MEDIAN DROP DIAMETER. 10-15 MICRONS
LIQUID WATER CONTENT O· O·2 GMS/CU. METRE
OUTSIDE AIR TEMPERATURE -6°C.



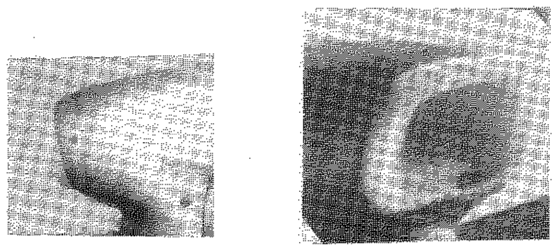
FLIGHT Nº 28.

MEDIAN DROP DIAMETER. 10 MICRONS
LIQUID WATER CONTENT O· O·3 GMS/CU. METRE
OUTSIDE AIR TEMPERATURE -7 TO -15°C.

FIG. 17. ICE FORMATION ON MAIN PLANE.

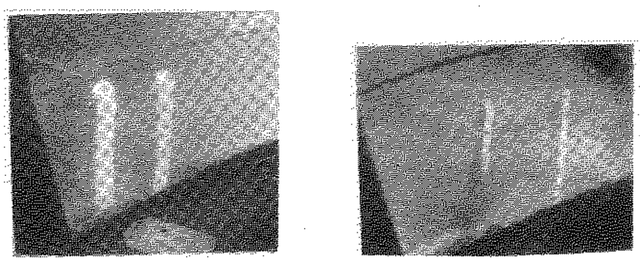


AIR INTAKE FLIGHT Nº 6.
MEDIAN DROP DIAMETER 40 MICRONS.
OUTSIDE AIR TEMPERATURE − 3°C.



AIR INTAKE FLIGHT Nº 20.
MEDIAN DROP DIAMETER. 10 MICRONS
LIQUID WATER CONTENT 0 · 0·5 GMS/CU. METRE
OUTSIDE AIR TEMPERATURE − 6° C.

ICE

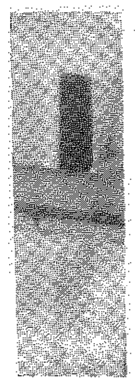


FLIGHT Nº 21. FLIGHT Nº 28.

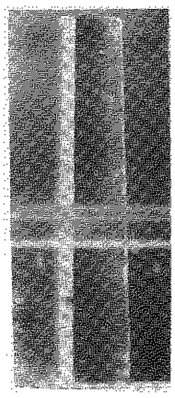
REBECCA AERIAL STRUT

ICE

ICE ON PERSPEX

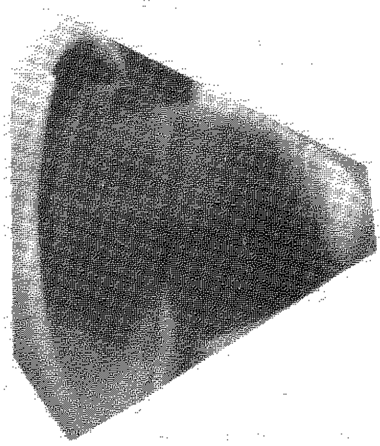


FLIGHT Nº 36.
DROP DIAMETER. 20 MICRONS.
AIR TEMPERATURE − 9°C.

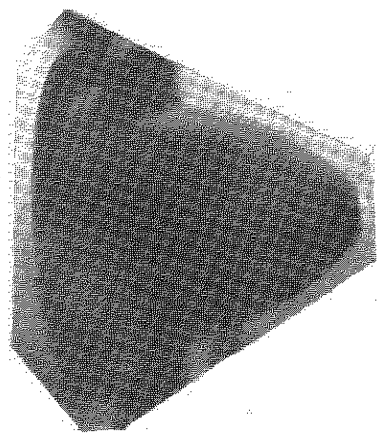


FLIGHT Nº 28.

TEST STRUT

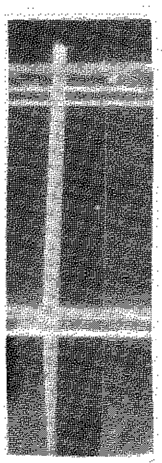


PROPELLER SPINNER FLIGHT Nº 21.
MEDIAN DROP DIAMETER. 20 MICRONS.
LIQUID WATER CONTENT 0·7 GMS/CU. METRE
OUTSIDE AIR TEMPERATURE − 12°C.



PROPELLER SPINNER FLIGHT Nº 28.
MEDIAN DROP DIAMETER. 10 MICRONS
LIQUID WATER CONTENT 0 · 0·3 GMS/CU. METRE
OUTSIDE AIR TEMPERATURE − 7 TO − 15°C.

ICE



OUTBOARD

TEST STRUT

INBOARD

TEST STRUT SHOWING REDUCTION OF ICE BUILD UP INSIDE THE BOUNDARY LAYER.

FIG. 18. ICE FORMATION ON ENGINE AIR INTAKE, AERIALS, TEST STRUT AND PROPELLER SPINNERS.

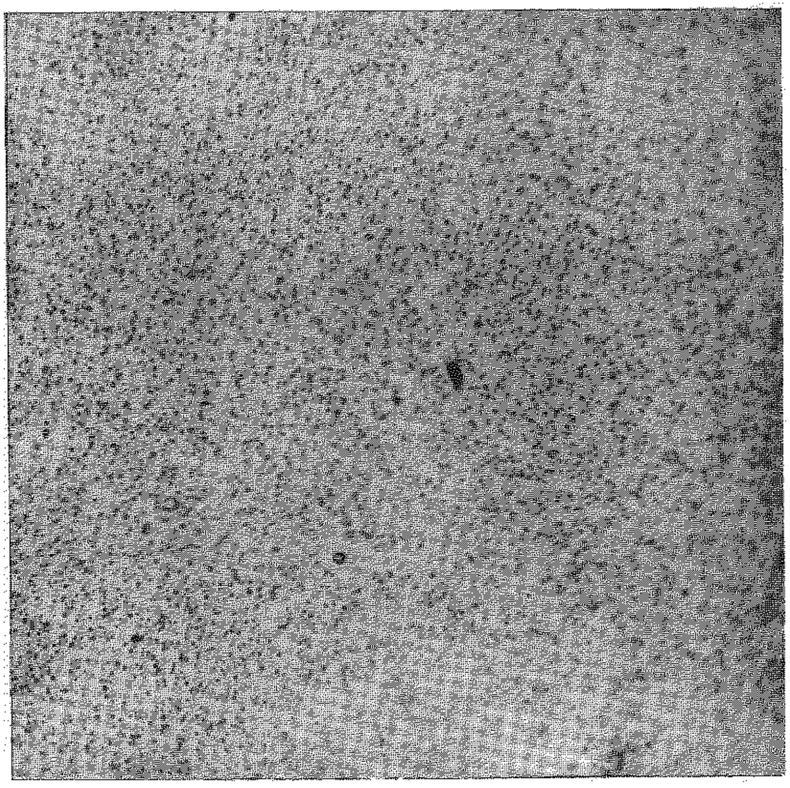


FIG. 19. CLOUD DROPLET SAMPLE
MEDIUM DIAMETER 8 MICRONS.

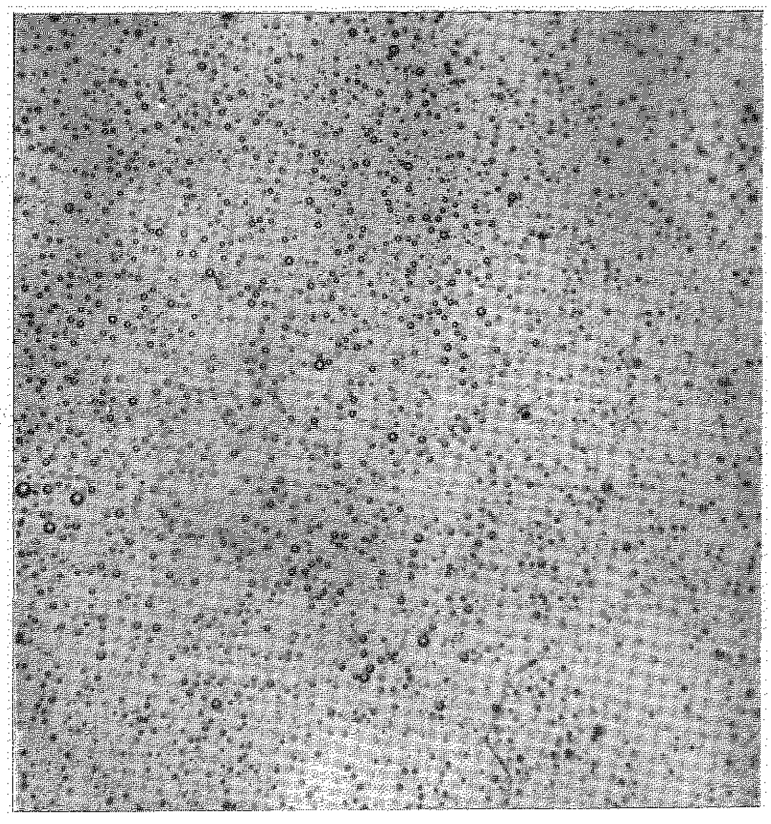


FIG. 20. CLOUD DROPLET SAMPLE
MEDIAN DIAMETER 16 MICRONS.

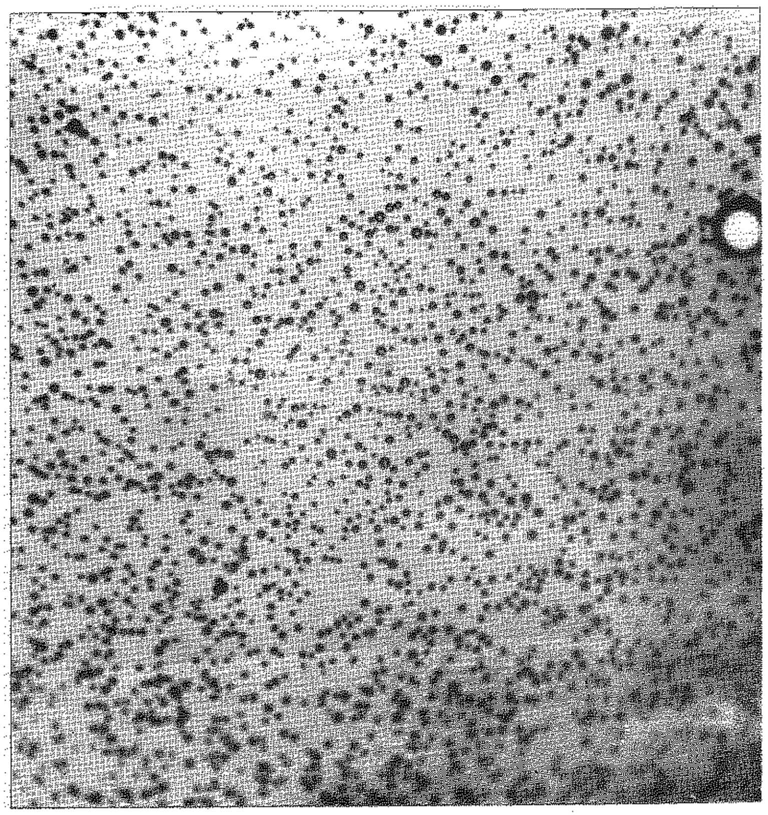


FIG. 21. CLOUD DROPLET SAMPLE
MEDIAN DIAMETER 22 MICRONS.

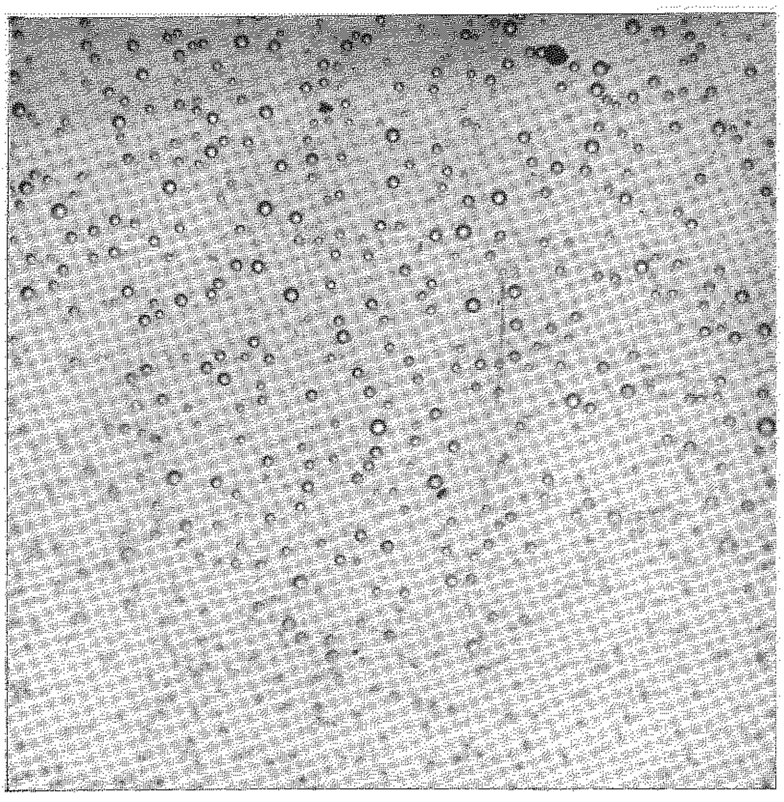


FIG. 22. CLOUD DROPLET SAMPLE
MEDIAN DIAMETER 32 MICRONS.

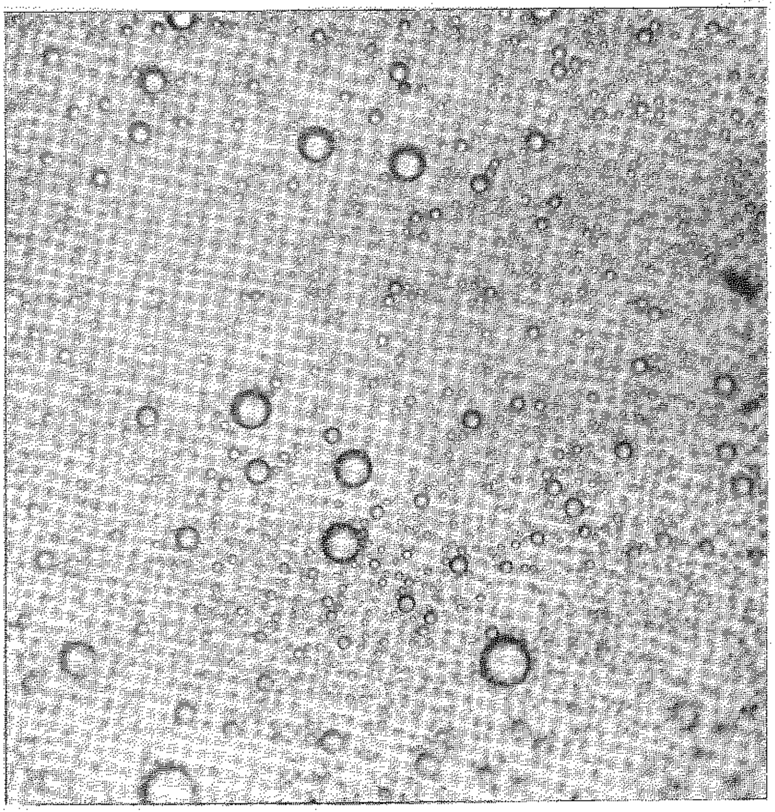


FIG. 23. CLOUD DROPLET SAMPLE
MEDIAN DIAMETER 20 MICRONS EXCLUDING DROPS
OVER 35 MICRONS ASSUMED TO HAVE BEEN FROZEN PARTICLES.

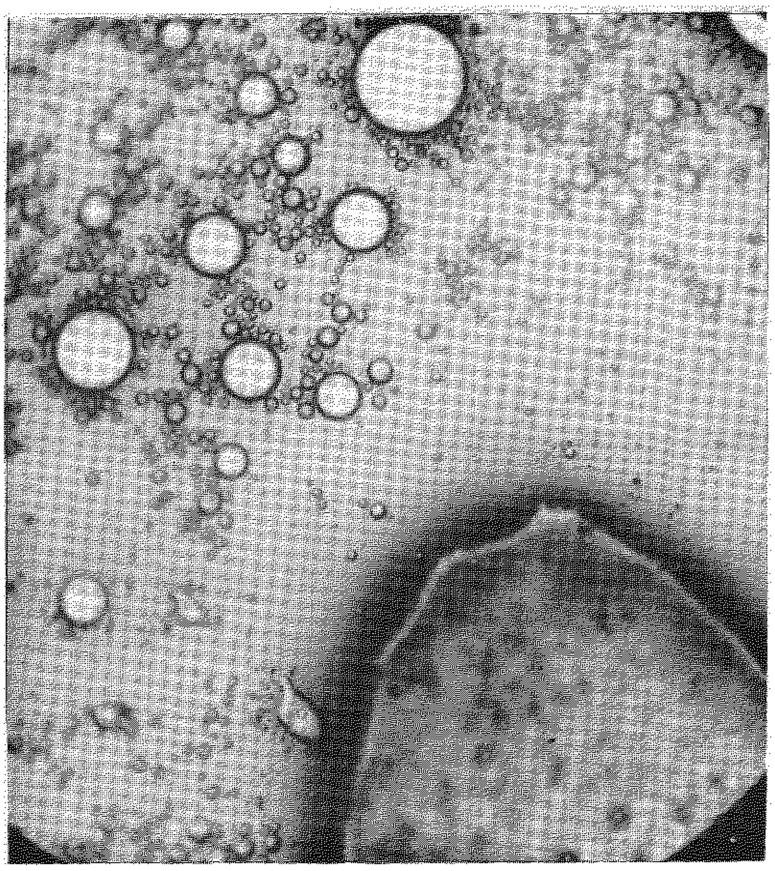


FIG. 24. CLOUD DROPLET SAMPLE SHOWING FROZEN PARTICLES
MOST OF WHICH HAVE MELTED.

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