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Report of the Second 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.

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AEROPLANE AND ARMAMENT EXPERIMENTAL ESTABLISHMENT

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Since this report was printed it has been discovered by Napiers that the figures they had supplied for the calibration of the rotating disc were in error. This means that all the liquid water contents quoted in the report as measured by the rotating disc are some 20% higher than they should be. The parts affected are columns 9 - 12 in table 2 and all the liquid water contents in table 4 and figures 6 and 9. In figure 8 both scales are in error by the same amount. The slope of the line will therefore be the same but the intercept on the t_e axis must be reduced by 20%. This will mean that the formula in para. 5.4.5 will become $n = \frac{400}{V(T + \frac{228}{\theta})}$. In the body of the report the liquid water contents quoted in para. 5.1 should be reduced by 20%.

No general discussion or conclusion is affected but the liquid water contents quoted in conclusion 6.1 and in the summary should be reduced to 0.3 - 0.4 grms/cubic metre and 1.1 grms/cubic metre respectively.

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Summary

The results of the second year's flying in search of natural icing conditions are given in this report. Icing conditions extending over 100 miles have been found in strato cumulus clouds over areas from East Anglia to the English Channel. Average liquid water contents were 0.4 - 0.5 gms./cubic metre but an exceptional value of 1.4 gms/cubic metre is reported. Photographs of ice crystals and liquid water droplets together have been obtained. This advance in sampling technique is being extended to try to measure liquid water content and total water content by timing the exposures. The R.A.E. thermal ice detectors have not yet reached their final form but have been improved considerably. The Smiths ice detector has been calibrated to give liquid water content and, together with the rotating disc has continued to be very valuable. Meteorological Office forecasts of icing conditions have continued to be reliable.

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1. Introduction

Reference 1 describes the first year's work by the A.& A.E.E. in searching for natural icing conditions and trying to measure the parameters on which such conditions depend. The work was undertaken as part of a combined programme with the R.A.E. and the Meteorological Office. The aims of the programme were

(i) To continue the study of the correlation of forecasts of ice 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.

(iv) To develop artificial methods of ice formation in flight.

The present report describes the second year's work by the A.& A.E.E. on items (i)-(iii) of this programme, covering the period from June 1952 to May 1953.

2. Details of test aircraft and its instrumentation

2.1 Aircraft. As described in reference 1 the aircraft used for the work was a Viking twin engined civil airliner with an all up weight of 34,000 lb.

2.2 Instrumentation. The majority of the instrumentation was the same as was used during the previous year. The fixed cylinder, the R.A.E.-Smiths icing indicator, the balanced bridge thermometer, the vortex tube thermometer, the Hussenot A.20 recorder and the automatic observer were virtually unchanged. The rotating disc ice accretion meter was changed for a production model of very similar design and for a short period two instruments were fitted. The following alterations were made to the other instruments.

2.2.1 Rotating cylinders. After a few flights the sampling position was moved to the front end of the cabin and the number of cylinders increased to six ranging from 2" to $\frac{1}{8}$" in diameter but a 3" diameter cylinder was soon introduced instead of one of the intermediate sizes. This made the sizes of the cylinders 3", 2", 1", $\frac{1}{2}$", $\frac{1}{4}$" and $\frac{1}{8}$" diameter. The method of extending the cylinders was improved so that the pole on which the cylinders were mounted passed through two ball bearing races mounted on a small carriage which ran on rails fixed to the front bulkhead of the forward cabin. This can be seen in the first photograph in figure 1. To extend the cylinders the carriage was pushed to the top of the rails and the pole pushed outwards through the bearings until the cylinders were fully extended as shown in the second photograph of figure 1.

2.2.2 Oiled slide sampler and micro camera. The micro camera was modified to enable the microscope stage to be kept at a temperature below freezing. This was done by boxing the stage in with wood and leading a supply of cold air from the atmosphere into the compartment so formed. The lens and slide mounting were carefully shielded and the cold air exit was positioned to prevent water drops from the cold air supply landing on the slide or lens when the aircraft was flying through cloud. A heater was installed near the microscope stage to enable the local temperature to be brought above freezing when required.

A slide storage box was made up consisting of an inner metal container in which the slides were stored and an outer insulating box. Between the two boxes cold air from the atmosphere was allowed to flow to maintain the temperature of the slides below freezing.

2.2.3 R.A.E. thermal ice detector. Several variants of this ice detector as manufactured by Sangamo Weston Ltd and by Teddington Controls Ltd have been fitted to the Viking for short periods, usually for flight trials in the development of the instruments. No final production model has yet been received.

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2.2.4 Observation strut. Due to a modification to the water spray apparatus for artificial icing it was found necessary to remove the cine camera that had been used for measuring rate of ice accretion by photographing the ice as it built up on the observation strut. No serious attempt was made to replace it in any other position as the rotating disc ice accretion meter had become available to give the same information with reasonable reliability.

3. Method of test

3.1 Special tests. As on the previous rotating cylinder installation, tests were made in icing conditions using three cylinders of the same size mounted on the new rotating cylinder position. This was to check the consistency of the droplet distribution in the area sampled from the new rotating cylinder position.

3.2 Period of tests. Throughout the year the aircraft was unserviceable for several spells during which no flights could be made. During the whole month of August the aircraft was on inspection and modifications were being made to the instrumentation. On 10th October an engine failed and there was considerable delay in obtaining a new one. The C. of A. inspection and some modifications to the water spray system for producing artificial ice were made during this period and the aircraft did not fly on test work until early in January. Otherwise apart from a week in March for an inspection and three days in April for water spray modifications the aircraft was available for searching for ice throughout the rest of the year up to 19th May when further inspection became due which was not completed until after the beginning of June.

3.3 Normal tests. The general method of test was the same as in the previous year. Each morning the local meteorological officer was consulted as to the prospects of finding icing conditions. If a suitable forecast was forthcoming the aircraft would be flown to the area and a search made. When icing conditions were found measurements would be taken using all the available instruments. Normally the search would only be discontinued when no further worthwhile icing conditions could be found, but some tests were stopped because the recorder film or sets of instruments were completely consumed.

3.4 Special oiled slide sampling tests. In last year's results the presence of melted ice crystals in a number of samples made the answers unreliable. After the micro camera had been modified to keep the temperature at the microscope stage below freezing, several flights were made with the cabin heating switched off to obtain a cabin temperature below freezing. This enabled the slides to be transferred from the sampler to the microcamera without the ice crystals melting. Oiled slide samples were taken under these conditions and, after an initial photograph of the slide had been taken of those samples that contained ice crystals, the heater in the microcamera was switched on and the ice crystals melted. A series of photographs was taken of the sample during the melting process.

4. Results

4.1 Success in finding ice. During January and again during late February and early March, a large high pressure system developed over the British Isles which prevented any icing conditions coming within reasonable range of the country. This, combined with the fact that the aircraft had been unserviceable during the last part of 1952, meant that the winter season was not as successful as it might have been. In spite of this three good flights were made in February two of which were in the most continuous icing conditions found so far. The rest of the flying was virtually outside the winter season so the majority of the flights were in cumulus type clouds.

The relationship between the meteorological forecasts and the conditions found are given in table 1. Altogether there were 25 encounters with ice in 20 flights and there were two flights on which no ice was found. The failure in the first of these unsuccessful flights was entirely due to ground control

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forbidding the aircraft to enter a cloud layer in which there were several other aircraft some of which were actually reporting icing conditions. In the second case of failure alto cumulus was forecast to build up in unstable air but when the area was investigated it was found that the clouds had not built up above freezing level.

These 22 flights represent the only forecasts of worthwhile icing when the aircraft was serviceable apart from four occasions when no pilots were available, two occasions when the Establishment was closed for flying and one occasion when the weather at base was too bad to allow the aircraft to return. In none of the seven cases was the forecast of sufficiently severe icing to justify the effort that would have been required to overcome the difficulty that prevented the flight or to risk not being able to return to base.

Figure 2 shows the areas where ice was encountered both this year and last year. Different symbols have been chosen so that, as well as showing the icing severity of the encounter, both the type of cloud and the synoptic condition responsible are shown.

On five occasions during the year reports of moderate or severe icing were received when no worthwhile icing condition was forecast.

4.2 <u>Icing conditions missed due to unserviceability</u>. A log was kept of the icing forecasts made throughout the periods when the aircraft was unserviceable and of reports of icing conditions encountered by other aircraft. 24 forecasts were made which would have been investigated, 18 of them between the middle of October and the first week in January. Only 16 reports of aircraft icing conditions were received from service sources during this period but of course aircraft tend to avoid icing conditions and almost certainly did not fly through all areas where icing conditions had been forecast.

4.3 <u>Type of ice formation</u>. Photographs of ice formation in figure 3 give further illustrations of the type of ice found. The effect of run back caused by flying at a temperature very close to freezing is shown in the first set of photographs. The second set shows the type of ice formation caused by a long exposure to a low water concentration of fairly small drops while the last set gives a further comparison between some of the effects of rime ice and glaze ice.

4.4 <u>Instrument readings</u>. The results from the various instruments are given in table 2. There is a direct comparison between the liquid water content as measured by the rotating disc and by the rotating cylinder for almost every rotating cylinder measurement, while in addition, the average liquid water content as measured by the rotating disc is given for the whole period during which values of over 0.1 gms. per cubic metre were obtained. Higher average liquid water contents of shorter duration within these periods are also given.

4.5 <u>Oiled slide results</u>. The droplet sizes as obtained from the oiled slides are included in table 2. Figures 4 and 5 show some of the samples taken at temperatures below freezing together with the melting process when the sample was warmed up. Figure 4 shows a clump of ice crystals when no supercooled liquid water droplets were present and follows the melting process through until only a number of drops remain. Figure 5 shows a mixture of supercooled droplets and ice crystals together with the melting sequence. The presence or absence of supercooled liquid water droplets was confirmed by whether or not ice was forming on the rotating disc at the time the sample was taken.

4.6 <u>Rotating cylinder special test results</u>. The amounts of ice found on the three cylinders of the same size exposed together at the new sampling position are given in table 3.

5. <u>Discussion of results</u>

5.1 <u>Most suitable types of weather for finding ice</u>. In figure 2 the various encounters with ice are classified as to the type of cloud and synoptic conditions. In table 4 the two types of encounter with ice on which the greatest

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amount of information is available are itemised to give the duration of various severities found. The corresponding data for encounters in other synoptic conditions were felt to be too scanty to justify their inclusion. Unfortunately the number of encounters is still far too small to allow more than a few generalisations to be drawn from them. The most profitable synoptic condition for the Viking flights has undoubtedly been an unstable airstream. In the winter when the freezing level was very low there have been four or five occasions when in a North Easterly air stream either with instability or considerable turbulence a layer of strato cumulus cloud some 3-4,000 feet thick has extended for over 100 miles in the area from East Anglia to the English Channel. The greatest duration found in this condition was on flight 46 when an average of 0.4 grms. per cubic metre was measured over 115 miles. Even then the flight was abandoned because the recorder film had run out and not because the end of the cloud had been reached. Throughout the 35 minutes taken to fly this distance the liquid water content varied between 0.2 and 0.6 grms. per cubic metre, the first third averaging about 0.25 while the last third averaged about 0.5. On flight 45 the cloud was less consistent but a stretch of 30-40 miles length gave an average liquid water content of over 0.2 grms. per cubic metre. On one of the earlier flights, flight 20, before the recorder was installed, over 60 miles of cloud were flown through before turning back due to the proximity of an air lane. The rotating cylinder measurements indicated that the liquid water content throughout the cloud at that level was of the order of 0.5 grms per cubic metre while several of the peak readings from the rotating disc suggested that it was higher still. Ice built up continuously throughout the period but never sufficiently rapidly to be called more than light icing. In a cloud of this type that was known to extend for over 100 miles the Meteorological Research Flight measured consistent liquid water contents of the order of 1.4 grms. per cubic metre over two three minute runs at different altitudes and 1.0 grms. per cubic metre at a lower height. There is no reason to suppose that water concentrations of this order may not have extended throughout the whole cloud. This is the highest liquid water content the author has heard of as measured in a strato cumulus cloud and the rate of ice accretion on the aircraft is understood to have been correspondingly severe.

This type of cloud, though rare, is the most suitable for testing aircraft de-icing systems but it suffers from the geographical disadvantage that if not found early in its existance it will be in an area so full of the air lanes radiating from the London control zone that difficulty will be experienced in making use of it.

The more common type of cloud found in an unstable air stream is the cumulus. This can be found all the year round but in summer when the freezing level is higher the cloud droplets have time to grow to a larger size before they ascend through the freezing level and become supercooled. On the average about three or four times a month numbers of cumulus clouds have been found to extend well above freezing level and, if flown through while they are still building, moderate and often severe icing can be found although always of short duration. Intercepts of from half a mile to six or seven miles have been found in individual clouds although the greater distances were usually made up of centres about three miles in extent so close together in the same cloud that the rotating disc did not return to zero between them. Peak values of over 2 grms. per cubic metre have been measured with averages of 1.7 grms. per cubic metre or so over half a minute. A considerable build up of ice may be obtained by flying through such clouds a number of times if it is desired to test the behaviour of the aircraft with ice on it. Severe turbulence may be avoided by selecting clouds at a stage when their growth is not too vigorous if the strength factors of the aircraft are not high.

Although individual cumulus clouds seldom extend for much more than six or seven miles it is possible to find "streets" of cumulus clouds. Much more continuous icing conditions can be found in these clouds and, although so far in the Viking the water concentrations found have been nearer those found in layer type clouds, there is no reason to suppose that high water contents should not be found at frequent intervals when progressing along such a "street". Normally these "streets" of cumulus clouds are easily seen before entering them but under

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certain conditions it would be possible for the "street" to be embedded in a layer of strato cumulus type clouds so that visual warning of its proximity might not be obtained. This might be the case, for instance, in a cold front that had been subject to orographic lift from a range of hills.

There are still too few successful icing encounters in other synoptic conditions to draw any further conclusions as to the relative suitability of these other types of weather for finding ice.

5.2 Severity of icing conditions. Table 5 shows that again the meteorological forecasts of icing severity were very good. The overestimated severity when no ice was found would probably have been correct if the cumulus clouds had built up sufficiently high in the area while in the other cases it is possible that the severities were present in some part of the area that the aircraft did not find.

The actual severities quoted in table 1 were based purely on observers' opinions. The values of rate of ice accretion quoted in the same table may be compared directly with them as may the values of liquid water content measured by the rotating disc quoted in tables 2 and 4. The rotating cylinder results have been compared with the severities by a different method as used in the past by calculating the rate of ice build up (Rg) on a standard ice collector under standard conditions. The values of Rg calculated from the liquid water content and droplet size of the rotating cylinder results are given in table 6 together with the observer's severities from table 1. Previous results had suggested that the dividing line between moderate and severe lay somewhere between values of Rg of 4 and 6 while between light and moderate the value of Rg lay between 2 and 3. It will be seen that 40 of the 49 results fall within those limits. There are five cases where values of over 6 were obtained when the severity was quoted as moderate but four of these are under 7, while there are two values of Rg over 3 when the severity was quoted as light. The only other discrepancies were two underestimates which were obviously due to the measurements having been made when only light icing conditions were present although moderate icing was found during some part of the flights. As the observers had had considerable experience of flying in icing conditions they were apt to underestimate severity rather than to overestimate it so it seems probable that the divisions between severe and moderate and moderate and light given above would be quite reasonable for normal use.

5.3 Ice formation. The first photographs in figure 3 taken on flight number 40 show an unusual ice formation in that the area covered is very much larger than normal. Ice was found at a height of about 9,500 feet where the static outside air temperature was -5 to -6°C but, due to the kinetic heat rise, the temperature on the aircraft was only about -2°C. The aircraft, climbing slowly up to this height and descending below it, occasionally flew at a height where the temperature on the wings was very close to freezing, thereby allowing some of the water, which was present in fairly large droplets, to run back before it finally froze. This can be seen clearly by comparing the areas over which the ice formed on corresponding parts of the aircraft on flights 40 and 46, both of which are shown on the same figure. One most unusual feature of the ice formation is the way in which it built up inside the engine cowling and, in fact, had such an effect on the flow of cooling air that, even with the gills fully open, it was not possible to keep the cylinder head temperatures within limitations. Under normal cruising flight, including almost all flights in icing conditions, the gills would have been fully closed so the magnitude of this effect can be appreciated. This flight was the only one on which such an effect was obtained.

The four photographs of flight 46, apart from giving a useful comparison with those of flight 40, in themselves show an interesting build up of ice. Most of the droplet sizes measured were of the order of 15 microns and the aircraft had flown for almost an hour through an average water concentration of nearly 0.3 gms. per cubic metre. The ice has broken off the engine cowling and from part of the leading edge of the tailplane. On the centre of the

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leading edge of the tailplane it is still an inch thick while on the lips of the engine air intake the build up has reached almost four inches.

The last two photographs of ice on the test strut show how faithfully rime ice can follow the contour of the object on which it forms as on flight 58, while glaze ice, as it becomes thicker, does not retain the shape of the strut so exactly as shown on flight 56. The formation on flight 58 was made by flying through a number of cumulus clouds and it is possible to see that the ice is made up of at least three layers.

5.4 Readings of individual instruments

5.4.1 Rotating cylinders. The figures in table 3 show that the new rotating cylinder position is very much better than the old one but they also indicate that it is still not possible to get completely consistent results every time. Rotating cylinder measurements made in icing conditions bore this out as, on several occasions, the points did not all lie on a smooth curve. From some such results it was possible to estimate liquid water contents differing from each other by as much as 40%. This possible error may well account for some of the scatter shown in figure 6 where the liquid water contents as measured by the rotating cylinders are compared with those obtained from the rotating disc. A more important reason for much of the scatter is believed to have been blow-off from the larger cylinders. This phenomenon is due to there being a limiting liquid water content for any set of conditions beyond which all the water present will not freeze but a fraction of it will be blown off. This was first shown by Ludlam[2] and further work on the subject is reported in reference 3. In figure 7 approximate extreme Ludlam limits for the smallest and the largest cylinders used are plotted together with the liquid water contents calculated from the rotating cylinder measurements. It will be seen that with the exception of the values of liquid water content less than about 0.25 gms. per cubic metre almost all the points lie between the extreme Ludlam limits. The points lying near the upper limit would tend to be underestimates of the true liquid water content and so would lie above the mean line in figure 6. For the points nearer the lower limit only the larger cylinders would be in error so the true value of liquid water content might be overestimated or underestimated depending on the curvature of the plot and the droplet distribution assumed. The limits in figure 7 do however show that the majority of the rotating cylinder measurements are subject to some doubt.

5.4.2 Fixed cylinder. This instrument has continued to give a useful idea of the maximum size of water droplet present in a preciable quantity. It is, however, of more value as a check to show if the results from the other instruments are wildly out than as a quantitative instrument itself. As other methods of measuring droplet size become more reliable the use of the fixed cylinder will eventually be discontinued.

5.4.3 Oiled slide sampler and micro camera. Figures 4 and 5 prove conclusively that the oiled slide sampling technique as it has been used in the past is completely unreliable if ice crystals are present in the icing cloud. To enable liquid droplets to be measured correctly by this technique in all types of icing cloud, samples must be taken and photographed at a temperature below freezing. This has been achieved to a limited extent when taking the photographs in figures 4 and 5 and other similar samples that have been obtained but the technique used involved reducing the temperature in the aircraft cabin to below freezing and this required a low outside air temperature of the order of -15°C. Efforts are being made to produce a simple and satisfactory technique that will keep the slide below freezing temperature and so enable reliable samples to be taken in any type of icing cloud.

5.4.4 R.A.E. thermal ice detector. Although no results from this instrument are quoted in this report there has been a considerable improvement during the year and designs made by both Sangamo Weston Ltd and Teddington Controls Ltd have shown reasonable promise of becoming successful ice detectors.

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5.4.5 R.A.E. Smiths icing indicator. This indicator has continued to give reliable indications of the presence of icing conditions, and, thanks to work in the N.A.E. icing tunnel in Canada[4], it is now possible to compare its results with those from the rotating disc. Figure 8 is a calibration of the off time of the Smiths indicator against liquid water content measured by the rotating disc made by plotting t_e the "equivalent sensitivity", which is virtually the thickness of ice required to block the holes and is defined as $1.2 \times 10^{-5} \frac{EmVT}{\sigma}$, against $\frac{Rg}{\theta}$, where E is the efficiency of catch taken as 1, m is the liquid water content in grms. per cubic metre, V is the true air speed in feet per second, T is the off time between Smiths indicator signals in seconds, σ is the specific density of ice taken as 0.8, and 1.2×10^{-5} is a conversion factor to bring t_e to inches. Rg is the rate of ice accretion in grms. per cm.^{2} per hour obtained from the rotating disc readings and θ is the air temperature in degrees C. It should be noted that these values of Rg do not correspond with those used for the rotating cylinder calculations in para. 5.2 and table 6 as the ice collector is different. From figure 8 the liquid water content has been deduced by the method described in reference 4. For the type of Smiths indicator used on the Viking, this formula becomes

$$m = \frac{510}{V(T + \frac{228}{\theta})}$$

where V is the true air speed in knots and m, T and θ are as defined above.

Using this formula the liquid water content was calculated from the Smiths detector results and compared with the values obtained from the rotating disc. About 85% of the results agreed to within 0.2 grms. per cubic metre while 60% were within 0.1 grms. per cubic metre. On the other hand nearly 5% of the 90 odd points gave unreasonably high values of liquid water content as the value of 228/θ approached the value of T. This measure of agreement, although not yet satisfactory for universal use, is encouraging and confirms the Canadian suggestion that this type of instrument is fundamentally sound for use both for statistical work and for controlling de-icing systems.

5.4.6 Rotating disc. This instrument has continued to be the main method of obtaining liquid water content. Its records have given a good insight into the variation of the liquid water content throughout the clouds flown through and it has been simple to compare their values with those of any other instrument for measuring liquid water content. As the edge of the disc is half the thickness of the Canadian rotating disc edge, the Ludlam limit is somewhat higher and it will be seen from figure 9 that there are only 6 results from the 141 measured this year that are sufficiently close to the limit to be in doubt. The slope of the Ludlam limit does however show that this version of the rotating disc will not measure the higher values of liquid water content at temperatures just below freezing. Too few results have been obtained with two rotating discs operating at the same time to make any useful comparison but such records as have been obtained do not give any reason to doubt their reliability.

5.4.7 Observation strut. Now that the cine camera has been removed the observation strut has lost much of its value but it is still useful for assessing the severity of icing conditions that have been flown through. By de-icing after each icing encounter a constant datum is available for checking the ice build up with time.

5.4.8 Vortex tube thermometer. The reading from the vortex tube thermometer has normally been within 2 or 3 degrees of the corrected reading from the balanced bridge thermometer. As the vortex tube thermometer reading is taken from ratiometer this may well be as good agreement as can normally be expected from this particular installation. It is not thought that the present design of vortex tube justifies a manually balanced bridge instrument particularly in view of the other commitments of the observers.

5.4.9 Hussenot A.20 recorder. The continuous record of the various instruments has been invaluable throughout the year. Apart from giving a clear

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picture of the variation of liquid water content throughout a cloud, it has been possible to compare the rotating cylinder values of liquid water content with the averages over the same time from the rotating disc. It has also been possible to compare the readings from the Smiths ice detector with those from the rotating disc.

5.4.10 Automatic observer. Throughout the year various thermal ice detector indicators have been fitted in the automatic observer as they came for trial. Direct comparison with the rotating disc indicators has thus been possible and, as a continuous trace of the rotating disc record was also available, a reasonable picture of the functioning of the thermal ice detector could be obtained. In addition the automatic observer has continued to be used for synchronising the various samples and records that were taken.

6. Conclusions

6.1 More information is being amassed on the best type of synoptic conditions for finding natural icing conditions over this country. The greatest durations have been found over the area from East Anglia to the English Channel where in a north easterly airstream strato cumulus cloud sheets 3-4,000 feet thick have given continuous icing conditions for over 100 miles with liquid water contents of the order of 0.4 - 0.5 gms/cubic metre but up to 1.4 gms/cubic metre in one exceptional case.

6.2 Successful photographs have been obtained of ice crystals and super-cooled water droplets together on cooled oiled slides. This has led to a better understanding of previous failures using the oiled slide technique.

6.3 The signals from the Smiths ice detector may now be used to give liquid water content and they compare reasonably well with the corresponding results from the rotating disc. The measure of agreement obtained confirms the Canadian suggestion that this type of instrument is fundamentally sound for use for statistical measurements and for controlling de-icing systems.

6.4 Although not yet completely developed the designs of R.A.E. thermal ice detector have advanced considerably during the year and should soon be reaching their final form.

6.5 The meteorological office forecasts have continued to be very reliable in directing the aircraft to icing conditions. The greatest difficulty appears to be in forecasting the extent to which cumulus clouds will build on some occasions due to lack of current air soundings.

The only failure this year was due to there being no cumulus cloud tops above freezing level at the time when the aircraft searched the area.

6.6 In the future more difficulty is likely to be experienced in searching for icing conditions below about 12,000 feet due to the increasing number of air lanes and the increase in ground control being exercised over the country.

7. Further developments

7.1 The oiled slide sampling technique has still to be advanced and exposures timed to give a measure of liquid water content. It may then be able to measure droplet diameter in any type of cloud, liquid water content, and where ice crystals are present, total water content, together with an indication of the shape and size of any ice crystals in the cloud.

7.2 Further measurements of the extent and severity of icing conditions are required. In particular, streets of cumulus clouds should be investigated from this aspect.

7.3 Improved designs of the thermal ice detectors and the rotating disc meter must be tried out in flight to enable suitable icing severity meters to be chosen both for research purposes and for use with aircraft protection systems particularly on jet engines.

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8. References

1	A&AEE/Res/272	Report of the first year's flying on the development of flight testing techniques for finding and measuring natural icing conditions. C.P. 221.	G. C. Abel.
2	Quarterly Jrnl. Royal Met. Soc. v77 no. 334 pp.663-666, Oct. 1951	The heat economy of a rimed cylinder.	F. H. Ludlam
3	N.A.E. LR-32	Thermodynamic limitations of ice accretion instruments.	D. Fraser C. K. Rush D. Baxter
4	N.A.E. LR-71	Characteristics of an orifice type icing detector probe.	D. Fraser

9. Acknowledgement

Acknowledgement is made to the Meteorological Research Flight for allowing some of their unpublished results to be quoted.

Table 1

Comparison of Meteorological Forecasts and Conditions Encountered

Flight No.	Date	Meteorological Forecast				Found on Flight				Flying time hrs-min.		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 ft.	Type of Cloud	Icing Severity	Height at which ice was found ft.	Air temp. °C	Flight	Total on which ice was found	Flight	Total		Peak	Average	
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
38	18.6.52	Cumulus	Unstable air with minor troughs.	Moderate	4,000	Cumulus	Moderate and severe	12,000	-7	1.20	95.05	0.05	9.30	1	0.24	0.18	Only one cumulus cloud found above freezing level.
39	1.7.52	Cumulus Castel-latus	Thundery low	Moderate	13,000	Cumulus Castel-latus	Moderate	17,000	-10	2.30	97.35	0.10	9.40	4	0.19	0.14	Not many cumulus castellatus clouds found.
40	16.7.52	Strato Cumulus	Depression	Moderate	6,000 - 10,000	Strato Cumulus	Light	9,500	-5	2.40	100.15	0.15	9.55	3	.06	.05	Tip of Depression went much further north than forecast. Ice found on warm front. Very interesting build up due to runback. (see Fig. 3)
41	8.9.52	Cumulus	Unstable Northerly Airstream	Moderate	5,000	Cumulus	Moderate	11,000	-8	1.35	101.50	0.10	10.05	4	-	-	Had to fly at 11,000 ft. to clear air lanes. Few cumulus tops at this height.
42	17.9.52	Alto Cumulus	Two cold fronts.	Moderate	10,000 - 5,000	Alto Cumulus	Light	14,000	-12	2.25	104.15	0.10	10.15	0	.07	.06	Only short periods of light icing found.
43	26.9.52	Cumulus	Unstable W.N.W. Airstream.	Moderate-Severe	4 - 5,000	Cumulus	Moderate-Severe	8,000	-5	2.00	106.15	0.25	10.45	4*	.14	.09	Good number of cumulus clouds found. 1 Inch of ice built up on tailplane.
44	29.9.52	Cumulus	Unstable N.W'ly. Airstream.	Moderate-Severe	5,000	Strato Cumulus	Light	9,500	-8			0.15		2*	-	-	Three areas tried. Only one without some success.
		Cumulus	Depression		5,000		Nil	-	-			-					
		Cumulus	Unstable S.W'ly. Airstream.		5,000	Cumulus	Moderate	10,000	-8	5.00	111.15	0.10	11.05	2*	-	-	

* During these flights sets of three cylinders of the same diameter were tried. So 4 is the maximum number that could be taken. Conditions were such that more could have been taken if the cylinders had been available.

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
45	2.2.53	Strato Cumulus	Cold moist unstable N.N.E'ly, Airstream	Moderate	1,000 1,500	Strato Cumulus	Light with a little moderate.	6,000	-10	2.35	113.50	0.35	11.40	2+	.05	.04	+Loss of taper pin early in flight prevented more cylinders being taken. Conditions were suitable for several more sets.
46	3.2.53	Strato Cumulus	Cold unstable N.E.'ly Airstream.	Moderate	500 - 1,000	Strato Cumulus	Light with patches of moderate.	4,500	-8	2.45	116.35	1.00	12.40	9	0.19	0.07	Over an inch of ice built up on wings and tail. Speed reduced by about 20 knots. (See Fig. 3)
47	10.2.53	Strato Cumulus Alto Cumulus	Deep Depression	Moderate	2 - 3,000	Strato Cumulus	Light with patches of moderate.	7,000	-6	3.05	119.40	0.25	13.05	4	0.09	0.02	½ inch of ice on tailplane.
48	13.2.53	Strato Cumulus	Cold Mois. N.E.'ly Airstream.	Moderate	1,000 1,500	Strato Cumulus "	Light "	3,000 7,000	-	1.30	121.10	0.10	13.15	Nil		-	The ice was in an area with several busy air lanes among which an adequate search could not be made.
49	20.3.53	ALTHOUGH SEVERE ICING HAD BEEN REPORTED AND AIRCRAFT WERE STILL REPORTING ICING CONDITIONS WHEN THE TEST AIRCRAFT WAS OVERHEAD, GROUND CONTROL WOULD NOT PERMIT THE VIKING TO DESCEND INTO THE CLOUD TO TAKE MEASUREMENTS.																
50	23.3.53	Alto Cumulus Castel-latus	Ridge of high pres-sure. Air unstable aloft.	Moderate	7,000	Alto Cumulus Castel-latus	Light and Moderate	11,500	-11	1.30	122.40	0.15	13.30	5	0.17	0.03	Not many icing clouds found. ½ inch of ice on tailplane.
51	24.3.53	Alto Cumulus	Ridge of high pres-sure. Air unstable in medium levels.	Moderate	6,000	Nil	Nil	-	-	1.30	122.40	-	-	-	-	-	No clouds above freezing level in area forecast.
52	26.3.53	Medium	Cold front.	Moderate	5,000	Medium	Light and moderate	9,000	-6	3.20	126	0.25	13.55	4	0.07	0.05	

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
53	27.3.53	Alto Cumulus	Warm Front	Light - Moderate	3,000	Strato Cumulus	Light	6,500	-7	5.00	131	0.30	14.25	2	0.07	0.02	Front less active than anticipated.
54	30.3.53	Strato Cumulus. Cumulus.	Cold Front "	Moderate locally severe	5,000 3,000	Strato Cumulus. Cumulus	Light Light with a little moderate.	7,000 9,500	-7 -11	2.00	133	0.20	14.45	1	0.1	0.06	Only very scattered patches of icing found.
55	31.3.53	Cumulus	Unstable N.W.'ly Airstream	Moderate locally severe	2,500	Strato Cumulus. Cumulus	Light Light and Moderate	6,500 8,000	-8 -9	2.30	135.30	0.30	15.15	3	0.26	0.1	Main Cumulus development less than expected.
56	8.4.53	Alto Cumulus Cumulus	Cold front Unstable N'ly Airstream, Behind cold front.	Light or Moderate	3,500	Strato Cumulus. Cumulus	Light Moderate	5,000 6,000	-7 -4	5.15	140.45	0.40	15.55	6	0.10	0.06	Over an inch of ice on wings and tailplane. (See Fig. 3)
57	13.4.53	Cumulus	Cold Unstable N.W.'ly Airstream.	Moderate to severe.	3,000	Cumulus	Moderate and severe	8 - 9,000	-12 - -13	2.00	142.45	0.20	16.15	9	0.3	0.19	Samples of ice crystals on oiled slide photographed
58	14.4.53	Cumulus	Cold Unstable N.N.W.'ly Airstream.	Moderate Locally Severe.	3,500	Cumulus	Light	8 - 10,000	-11 - -16	1.45	144.30	0.25	16.40	4	0.16	0.04	Further samples of ice crysta's photographed.
59	18.5.53	Alto Cumulus	Thundery low	Moderate	8 - 9,000	Alto Cumulus	Very light	10,000	-4	2.05	146.35	0.10	16.50	Nil	-	-	Only very light patches of ice found. Too much wooly cloud in front to see best areas to search.

Table 2

Summary of measurements made in icing conditions

Flt. No.	Date	Time of Day	Height (feet)	I.A.S. (knots)	Static O.A.T. °C: Balance Bridge	Static O.A.T. °C: Vortex Tube	Rot. Cyls.	Liquid Water Content (Grams/Cubic Metre): Port Rot. Disc. Peak	Port Rot. Disc. Ave.	Stbd. Rot. Disc. Peak	Stbd. Rot. Disc. Ave.	Time over which ave. taken (Secs.): Rot. Cyls.	Port Disc.	Stbd. Disc.	Med. Drop Dia. (Microns): Rot. Cyls.	Oiled Slide	Max. Drop Dia. (Microns): Fixed Cyl.	Oiled Slide	Remarks
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
33	18.6.52	1227	11,650	116	-5	-	1.8	1.75	1.45	1.35x	1.0	17	20	20	22	-	-	-	xOn max. stop for 12 seconds.
		1228	12,000	115	-	-	-	1.05	0.95	1.0	0.9	-	11	11	-	-	-	-	-
		1228	11,700	144	-	-	-	0.80	0.65	0.80	0.6	-	15	15	-	-	-	-	-
		1234 (30)	11,830	123	-6.5	-	-	>1.7+	1.30	1.2x	0.8	-	34	62	-	40	25	65	+On max. stop for 20 seconds xOn max. stop for 32 seconds. Some ice crystals appear to have melted on the oiled slide.
		1235	11,200	130	-	-	-	1.3	0.95			-	20		-	-	-	-	
39	1.7.52	12.00	17,230	105	-10	-	-	1.4	0.5	1.15	1.0	-	39	39	-	-	20	-	
		1205	17,750	124	-10	-	-	0.35	0.3	0.25	0.2	-	12	20	-	-	-	-	
		1206	17,500	130	-10	-	-	0.4	0.35	0.65	0.35	-	38	80	-	-	-	-	
		1208	17,000	129	-	-	-	0.45	0.4	0.4	0.25	-	43	90	-	-	-	-	
		1208	17,000	129	-10	-	0.65	0.45	0.35	0.4	0.4	50	50	50	14	16	-	20	
		1216	15,400	140	-6	-	0.5	-	-	-	-	38	-	-	12	-	15	-	
		1219	13,700	140	-4	-	-	1.05	0.55	0.95	0.8	-	55	65	-	-	-	-	
		1303	14,900	122	-5.5	-	0.55	-	-	-	-	65	-	-	9	23	17	45	Some ice crystals on oiled slide.
		1314	13,350	135	-4	-	-	-	-	-	-	-	-	-	-	18	18	50	

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
40	16.7.52	1824	9,760	153	-6	-4	-	-	-	-	-	-	-	-	-	-	25	-	
		1824	9,800	135	-6	-	-	-	-	0.2	0.15	-	-	14	-	-	-	-	
		1824	9,800	135	-6	-	-	-	-	0.25	0.2	-	-	13	-	-	-	-	
		1828	9,750	140	-5.5	-	-	-	-	0.15	0.15	-	-	10	-	-	-	-	
		1829	9,750	145	-5.5	-	-	-	-	0.2	0.2	-	-	9	-	-	-	-	
		1830	9,740	142	-5.5	-4	0.3	0.4	0.3	-	-	150	150	-	11	-	25	-	
		1831	9,750	139	-5.5	-	-	0.4	0.35	0.45	0.2	-	16	33	-	-	-	-	
		1831.32	9,720	136	-5.5	-4	-	0.4	0.35	0.35	0.25	-	55	54	-	-	-	-	
		1834	9,750	150	-5.5	-	-	0.15	0.1	0.15	0.15	-	14	12	-	-	-	-	
		1835	9,800	120	-5.5	-	-	0.4	0.35	-	-	-	50	-	-	-	-	-	
		1852	9,720	127	-5	-4	-	-	-	-	-	-	-	-	-	-	40	-	
41	8.9.52	1441	10,950	120	-6	-	-	-	-	-	-	-	-	-	-	-	18	-	
		1449	10,850	124	-8	-	-	-	-	-	-	-	-	-	-	15	15	20	
		1459	10,000	120	-9	-	1.1	-	-	-	-	44	-	-	11	-	14	-	
42	17.9.52	1221	15,200	135	-13	-8	-	-	-	0.45	0.25	-	-	28	-	-	-	-	
		1223	14,400	140	-12	-11	-	-	-	1.0	0.3	-	-	56	-	-	-	-	
		1234	14,100	139	-12	-10	-	-	-	-	-	-	-	-	-	19	-	30	
		1235	14,180	139	-12	-10	-	-	-	0.65	0.4	-	-	126	-	22	-	35	
43	26.9.52	1441	7,710	165	-5	-6	-	-	-	0.65	0.5	-	-	24	-	23	22	40	
		1442	7,640	166	-5	-6	-	-	-	0.55	0.35	-	-	34	-	-	-	-	
		1443	7,500	145	-5	-	-	-	-	0.95	0.4	-	-	78	-	-	-	-	

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
		1444	7,450	145	-5	-5	-	-	-	0.75	0.35	-	-	52	-	-	-	-	
		1446	7,450	147	-5	-4	-	-	-	1.1	0.5	-	-	19	-	-	-	-	
		1447	7,500	140	-5	-	-	-	-	0.6	0.4	-	-	13	-	-	-	-	
		1448	7,480	133	-5	-	-	-	-	0.4	0.2	-	-	7	-	-	-	-	
		1448	7,480	141	-5	-4	-	-	-	0.5	0.25	-	-	13	-	-	-	-	
		1449	7,410	142	-5	-4	-	-	-	0.7	0.45	-	-	20	-	-	-	-	
		1450.14	7,550	135	-5	-	-	-	-	1.9	0.65	-	-	39	-	-	-	-	
		1450.43	7,700	137	-5	-	-	-	-	0.75	0.55	-	-	22	-	-	-	-	
		1504	7,670	149	-5	-1	-	-	-	0.65	0.5	-	-	31	-	-	-	-	
		1505	7,650	146	-5	-2	-	-	-	0.2	0.1	-	-	14	-	-	-	-	
		1506	7,570	140	-5	-3	-	-	-	-	-	-	-	-	-	-	22	-	
		1511	7,300	130	-	-3	-	-	-	0.35	0.25	-	-	10	-	-	-	-	
		1511	7,800	130	-	-	-	-	-	0.9	0.65	-	-	87	-	-	-	-	
		1513	7,750	132	-	-	-	-	-	0.3	0.2	-	-	12	-	-	-	-	
		1514	7,700	130	-5	-	-	-	-	0.5	0.3	-	-	27	-	-	-	-	
		1515	7,750	135	-5	-2	-	-	-	0.35	0.25	-	-	10	-	22	24	30	
		1517	7,980	135	-6	-3	-	-	-	0.6	0.35	-	-	22	-	-	-	-	
		1513	7,900	125	-	-	-	-	-	1.35	1.25	-	-	85	-	-	-	-	
		1519	7,900	124	-	-	-	-	-	0.4	0.2	-	-	13	-	-	-	-	
44	29.9.52	1552	10,150	160	-8	-8	0.65	-	-	0.9	0.6	110	-	30	14 - 18	-	14	-	

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
45	2.2.53	1124	5,830	162	-10	-12	0.2	-	-	-	0.25	60	-	11	13	23	17	45	Disc not switched on till part of way through cloud
		1125	5,700	170	-	-	-	-	-	0.6	0.2	-	-	381	-	-	-	-	
		1126	5,670	175	-10	-12	-	-	-	-	-	-	-	-	-	22	-	48	
		1130	5,600	167	-10	-11	-	-	-	-	-	-	-	-	-	31	28	45	
		1133	5,630	161	-10	-12	0.25	-	-	0.3	0.25	108	-	108	18	24	-	35	
		1133	5,700	164	-	-	-	-	-	0.35	0.2	-	-	143	-	-	-	-	
		1142	5,600	168	-	-	-	-	-	0.15	0.1	-	-	271	-	-	-	-	
		1143	5,640	169	-10	-12	-	-	-	-	-	-	-	-	-	12	-	25	
		1145	5,680	170	-10	-12	-	-	-	-	-	-	-	-	-	18	-	30	
		1149	5,700	170	-	-	-	-	-	0.65	0.3	-	-	402	-	-	-	-	
		1152	5,670	169	-10	-12	-	-	-	-	-	-	-	-	-	26	17	35	
		1158	6,200	161	-	-	-	-	-	1.15	0.35	-	-	98	-	-	-	-	
		1159	6,190	162	-10	-11	-	-	-	-	-	-	-	-	-	28	28	45	
		1210	6,250	160	-	-	-	-	-	0.75	0.3	-	-	103	-	-	-	-	
46	3.2.53	1133	5,030	172	-10	-10	-	-	-	-	-	-	-	-	-	24	15	35	
		1137	4,730	168	-9	-10	0.15	-	-	0.25	0.15	86	-	86	12	-	-	-	
		1139	4,720	178	-9	-10	-	-	-	0.65	0.2	-	-	201	-	-	-	-	
		1139	4,720	178	-9	-10	-	-	-	0.65	0.15	-	-	348	-	23	16	35	
		1147	4,540	172	-8	-9	0.35	-	-	0.85	0.25	67	-	67	15	12	12	25	
		1150	4,560	173	-8	-8	-	-	-	1.0	0.25	-	-	174	-	21	-	30	
		1157	5,170	144	-9	-9	0.3	-	-	0.75	0.35	96	-	96	17	-	-	-	

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
		1157	5,170	144	-9	-9	-	-	-	0.75	0.3	-	-	129	-	19	12	25	
		1201	5,000	160	-	-	-	-	-	0.25	0.15	-	-	41	-	-	-	-	
		1206	4,280	163	-7	-8	0.2	-	-	0.3	0.15	100	-	104	11	22	17	35	
		1216	5,350	155	-	-	-	-	-	0.5	0.3	-	-	64	-	-	-	-	
		1218	5,270	157	-9	-9	0.15	-	-	0.35	0.15	99	-	99	15	-	14	-	
		1222	4,900	156	-	-	-	-	-	0.65	0.35	-	-	271	-	-	-	-	
		1224	4,630	152	-9	-9	-	-	-	-	-	-	-	-	-	18	13	35	
		1226	4,560	153	-9	-8	0.15	-	-	0.2	0.15	152	-	152	18	19	-	30	
		1229	4,450	150	-	-	-	-	-	1.3	0.3	-	-	334	-	-	-	-	
		1232	4,460	139	-8	-9	-	-	-	0.8	0.5	-	-	97	-	29	18	40	
		1236	4,450	140	-	-	-	-	-	0.45	0.2	-	-	372	-	-	-	-	
		1240	4,400	140	-8	-8	0.45	-	-	0.7	0.45	96	-	96	20	29	16	45	
		1241	4,400	138	-	-	-	-	-	0.9	0.55	-	-	378	-	-	-	-	
		1241	4,340	141	-8	-8	-	-	-	-	-	-	-	-	-	28	-	40	
		1248	4,230	139	-8	-7	0.6	-	-	1.0	0.65	100	-	100	18	31	17	40	
		1249	4,450	142	-	-	-	-	-	1.5	0.45	-	-	87	-	-	-	-	
47	10.2.53	1145	7,800	166	-	-	-	-	-	0.45	0.2	-	-	49	-	-	-	-	
		1149	8,300	165	-	-	-	-	-	0.4	0.15	-	-	76	-	-	-	-	
		1152	8,200	170	-	-	-	-	-	0.75	0.25	-	-	54	-	-	-	-	
		1200	7,200	172	-7	-8	0.25	-	-	0.35	0.15	96	-	96	9	-	-	-	
		1205	6,100	180	-4	-7	-	-	-	-	-	-	-	-	-	25	-	35-	

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
		1219	6,700	150	-	-	-	-	-	0.8	0.4	-	-	121	-	-	-	-	
		1220	6,720	150	-6	-6	0.15	-	-	0.45	0.2	57	-	57	9	-	15	-	
		1223	6,900	163	-6	-6	-	-	-	0.45	0.2	-	-	201	-	-	-	-	
		1228	6,700	159	-	-	-	-	-	0.4	0.2	-	-	17	-	-	-	-	
		1230	6,880	161	-6	-6	-	-	-	0.35	0.01	-	-	92	-	-	-	-	
		1242	8,090	152	-9	-9	-	-	-	1.4	0.35	-	-	175	-	-	12	-	
		1245	8,080	154	-8	-8	0.4	-	-	0.6	0.25	139	-	139	15	22	-	40	
		1246	8,100	154	-	-	-	-	-	0.65	0.3	-	-	137	-	-	-	-	
50	23.3.53	1453	11,300	158	-	-	-	-	-	0.4	0.25	-	-	52	-	-	-	-	
		1518	11,400	142	-11	-14	0.1	-	-	0.4	0.10	161	-	161	16	-	-	-	
		1527	11,450	143	-	-14	0.15	-	-	0.9	0.25	107	-	107	16	-	-	-	
		1534	11,300	143	-11	-13	0.2	-	-	1.15	0.20	101	-	101	14	-	21	-	
		1543	11,100	146	-11	-13	-	-	-	-	-	-	-	-	-	-	10	-	
		1544	11,200	141	-	-	0.1	-	-	1.0	0.1	180	-	180	15	-	-	-	
52	26.3.53	1426	8,800	160	-5	-7	-	-	-	-	-	-	-	-	-	25	-	40	
		1426	8,800	158	-5	-8	0.15	-	-	0.35	0.1	253	-	253	15	-	21	-	
		1428	8,800	137	-6	-8	-	-	-	-	-	-	-	-	-	23	-	35	
		1430	9,000	144	-6	-8	-	-	-	0.8	0.3	-	-	84	-	23	-	35	A few ice crystals present on oiled slide.
		1438	9,200	145	-	-	-	-	-	0.9	0.45	-	-	302	-	18	-	40	
		1443	9,200	144	-7	-6	-	-	-	-	-	-	-	-	-	9	-	20	
		1519	7,800	155	-	-6	0.6	-	-	0.5	0.3	266	-	266	13	-	-	-	

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
		1523	7,650	138	-5	-5	-	-	-	0.55	0.45	-	-	36	-	-	-	-	
		1527	8,000	136	-	-	-	-	-	0.4	0.25	-	-	48	-	-	-	-	
53	27.3.53	1536	6,600	160	-	-	-	-	-	0.5	0.2	-	-	118	-	-	-	-	
		1540	6,580	139	-	-	-	-	-	0.85	0.15	-	-	688	-	-	-	-	
		1548	6,670	147	-8	-8	0.3	-	-	0.5	0.1	173	-	173	20	-	20	-	
		1612	6,600	152	-	-	-	-	-	0.25	0.1	-	-	153	-	-	-	-	
		1613	6,660	152	-6	-6	-	-	-	-	-	-	-	-	-	25	18	40	
		1615	5,580	150	-	-6	0.1	-	-	0.15	0.05	149	-	149	19	21	13	20	
		1138	9,600	154	-	14	0.5	-	-	0.65	0.4	127	-	127	17	-	-	-	
		1231	8,350	174	-	-	-	-	-	0.45	0.25	-	-	15	-	-	-	-	
		1232	8,100	175	-	-	-	-	-	0.35	0.25	-	-	26	-	-	-	-	
55	31.3.53	1431	6,400	142	-	-	-	-	-	0.5	0.3	-	-	19	-	-	-	-	
		1435	6,250	150	-	-	-	-	-	0.25	0.15	-	-	20	-	-	-	-	
		1439	7,100	150	-	-	-	-	-	0.45	0.15	-	-	130	-	-	-	-	
		1508	6,200	154	-	-	-	-	-	0.3	0.25	-	-	11	-	-	-	-	
		1523	7,800	150	-	-	-	-	-	0.9	0.35	-	-	34	-	-	-	-	
		1524	7,800	130	-9	-	-	-	-	0.35	0.25	-	-	13	-	21	-	30	
		1525	8,150	118	-10	-	0.25	-	-	1.0	0.3	160	-	160	17	16	-	30	
		1528	8,200	130	-	-	-	-	-	0.8	0.5	-	-	47	-	-	-	-	
		1532	7,600	130	-	-	-	-	-	0.9	0.4	-	-	88	-	-	-	-	
		1535	7,600	120	-	-	-	-	-	0.3	0.15	-	-	66	-	-	-	-	

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
		1554	8,000	140	-	-	-	-	-	1.75	0.7	-	-	129	-	-	-	-	
		1554	8,300	151	-9	-	0.5	-	-	1.75	0.7	120	-	120	19	-	-	-	
		1555	8,100	130	-10	-	-	-	-	-	-	-	-	-	-	30	-	50	) Probably some
																			) ice crystals
		1556	8,100	129	-10	-	-	-	-	-	-	-	-	-	-	32	-	55	) on oiled slide.
		1557	8,200	140	-	-	-	-	-	1.35	0.5	-	-	47	-	-	-	-	
		1600	7,100	140	-	-	-	-	-	0.55	0.25	-	-	24	-	-	-	-	
		1601	7,100	135	-	-	-	-	-	1.85	0.5	-	-	124	-	-	-	-	
		1601	7,050	135	-7	-7	0.45	-	-	1.85	0.55	117	-	117	20	-	-	-	
56	8.4.53	1432	5,000	167	-	-	-	-	-	0.65	0.3	-	-	936	-	-	-	-	
		1434	4,700	175	-5	-6	-	-	-	-	-	-	-	-	-	19	20	30	Some ice crystals appear to have
		1436	4,550	165	-5	-6	0.6	-	-	0.65	0.35	202	-	202	10	19	-	35	been present on several of the
		1439	5,000	147	-	-	-	-	-	0.5	0.35	-	-	289	-	-	-	-	oiled slides on this flight.
		1442	4,900	150	-7	-7	-	-	-	-	-	-	-	-	-	23	19	35	
		1444	4,900	147	-7	-7	0.2	-	-	0.3	0.2	204	-	204	13	23	-	45	
		1515	5,750	150	-	-	-	-	-	0.65	0.3	-	-	831	-	-	-	-	
		1518	5,600	165	-11	-	0.4	-	-	0.5	0.4	203	-	203	15	25	-	40	
		1519	5,600	161	-10	-8	-	-	-	-	-	-	-	-	-	27	32	40	
		1526	5850	143	-9	-8	0.25	-	-	0.35	0.2	137	-	137	13	-	-	-	
		1540	6,900	145	-8	-6	-	-	-	-	-	-	-	-	-	26	-	45	
		1549	5,800	146	-3	-4	-	-	-	0.25	0.1	-	-	43	-	21	-	35	
		1552	6,250	150	-	-	-	-	-	0.5	0.3	-	-	32	-	-	-	-	

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
		1552	6,200	150	-	-5	0.35	-	-	0.7	0.35	166	-	166	17	31	-	55	
		1553	6,150	154	-	-	-	-	-	0.35	0.2	-	-	26	-	-	-	-	
		1554	6,500	150	-	-	-	-	-	0.7	0.4	-	-	116	-	-	-	-	
		1555	6,430	130	-5	-5	-	-	-	-	-	-	-	-	-	14	-	25	
		1601	6,150	160	-	-	-	-	-	0.35	0.2	-	-	81	-	-	-	-	
		1601	6,200	160	-4	-5	-	-	-	-	-	-	-	-	-	11	-	20	
57	13.4.53	1110	8,100	124	-12	-12	1.5	-	-	-	-	40	-	-	10	-	-	-	
		1116	8,250	109	-12	-12	0.65	-	-	1.45	0.6	59	-	59	16	-	21	-	
		1139	9,100	140	-14	-16	-	-	-	1.95	0.85	-	-	37	-	-	27	-	
		1142	9,250	130	-12	-15	0.6	-	-	1.8	0.3	52	-	52	20	-	-	-	
		1149	9,150	128	-13	-15	-	-	-	2.0	1.1	-	-	36	-	-	-	-	
		1151	9,100	124	-13	-14	0.9	-	-	1.9	1.1	35	-	35	19	-	25	-	
		1156	9,200	135	-	-	-	-	-	2.25	1.5	-	-	38	-	-	-	-	
		1159	9,250	133	-13	-14	-	-	-	1.9	1.35	-	-	28	-	-	29	-	
		1201	8,900	135	-	-	-	-	-	1.55	0.45	-	-	69	-	-	-	-	
		1206	9,750	125	-14	-15	1.05	-	-	2.25	1.35	54	-	54	24	-	28	-	
		1215	8,600	127	-12	-14	1.0	-	-	-	-	32	-	-	14	-	-	-	
		1215	8,700	125	-	-	-	-	-	0.25	0.2	-	-	35	-	-	-	-	
		1217	9,200	120	-	-	-	-	-	1.1	0.35	-	-	84	-	-	-	-	
		1223	9,400	132	-	-	-	-	-	1.5	0.95	-	-	31	-	-	-	-	
		1223	9,400	132	-13	-14	1.0	-	-	1.5	1.0	26	-	26	10	25	12	35	

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
		1229	9,450	134	-14	-14	-	-	-	1.75	0.65	-	-	39	-	-	-	-	
		1230	9,400	136	-13	-14	0.85	-	-	1.75	0.95	30	-	30	13	-	12	-	
58	14.4.53	1423	8,500	138	-	-	-	-	-	0.55	0.25	-	-	36	-	-	-	-	
		1425	8,500	135	-	-	-	-	-	0.5	0.2	-	-	50	-	-	-	-	
		1428	8,300	132	-	-	-	-	-	0.7	0.3	-	-	54	-	-	-	-	
		1437	8,350	132	-	-	-	-	-	0.85	0.55	-	-	48	-	-	-	-	
		1437	8,700	130	-12	-14	0.3	-	-	1.2	0.3	60	-	60	8	25	12	35	
		1443	9,200	130	-	-	-	-	-	0.5	0.3	-	-	37	-	-	-	-	
		1444	9,000	130	-	-	-	-	-	0.55	0.4	-	-	10	-	-	-	-	
		1447	9,450	140	-	-	-	-	-	1.0	0.5	-	-	25	-	-	-	-	
		1449	9,200	136	-	-	-	-	-	0.65	0.45	-	-	30	-	-	-	-	
		1457	9,850	135	-	-	-	-	-	0.65	0.45	-	-	15	-	-	-	-	
		1458	9,850	139	-16	-17	0.05	-	-	0.25	0.1	32	-	33	12	10	-	15	
		1501	9,650	130	-	-	-	-	-	0.25	0.15	-	-	20	-	-	-	-	
		1502	9,950	132	-16	-17	-	-	-	0.5	0.25	-	-	63	-	-	13	-	
		1507	8,400	125	-	-	-	-	-	0.5	0.25	-	-	13	-	-	-	-	
		1511	8,950	128	-14	-14	-	-	-	1.25	0.6	-	-	132	-	-	13	-	
		1514	8,900	121	-	-	-	-	-	1.55	0.65	-	-	25	-	-	-	-	
		1515	8,900	120	-13	-14	0.05	-	-	0.55	0.1	112	-	112	9	-	-	-	
		1522	7,800	130	-	-	-	-	-	0.7	0.3	-	-	38	-	-	-	-	
		1522	8,000	131	-11	-12	0.8	-	-	1.05	0.2	89	-	89	7	-	-	-	
		1528	8,900	130	-13	-14	-	-	-	1.55	0.65	-	-	72	-	-	11	-	
		1529	8,800	135	-	-	-	-	-	0.95	0.55	-	-	14	-	-	-	-	

Table 3

Comparison of ice formed on three rotating cylinders of the same diameter exposed at the new sampling position

Cylinder position	Weight of ice - gms.		
Inner	14.11	5.07	10.57
Middle	12.76	5.01	10.81
Outer	13.36	5.07	9.90 *

* A small quantity of ice was lost on removing the cylinder

Table 4

Duration of various average liquid water contents in different types of cloud in an unstable airstream

STRATO CUMULUS TYPE CLOUDS

Liquid water content gms/Cubic metre	Duration miles	Remarks
1.4	> 7, > 7	(Meteorological research flight tests. (Only short runs measured. Cloud (extended for over 100 miles so the (water concentration may well have (extended over 100 miles also
1.1	~ 7	
0.6	> 1.3, > 1.5	(Only rotating cylinder measurements (available. Ice was forming for over (60 miles, probably with similar water (concentrations, and may have continued (in the cloud which extended further (Flight No.20)
0.5	> 2.9	
0.4	115, 5	
0.3	24, 7, 6, 6	
0.2	36, 10	

CUMULUS TYPE CLOUDS

Liquid water content gms/cubic metre	Duration miles	Remarks
1.5	1.7	
1.4	2.5, 1.4	
1.3	1.8	
1.2	3.8	
1.1	1.7, 1.6	
1.0	1.3, 0.5	
0.9	1.5, 1.5, 1.0	
0.8	1.9	
0.7	6.6*, 4, 1.9, 1.9, 0.3	* Triple peaks without coming down to zero
0.6	2.4, 1.8	
0.5	6*	≠ Double peak without returning to zero
0.4	14.4+, 11.4+, 6.1+, 4.1≠, 3.7*, 1.8, 1.1, 1.0, 0.7, 0.7, 0.7	+ Measurements in a street of cumulus without values coming down to zero
0.3	4.8+, 4.3+, 8.7+, 1.7 0.9, 0.6	
0.2	11.8+, 6.8+, 1.6, 1.2, 0.7	

Table 5

Comparison of severity of icing forecast with severity of icing observed

Observed / Forecast	Correct forecasts			Overestimated forecasts degrees 1		Overestimated forecasts degrees 2
	Light	Moderate	Severe	Nil	Light	Nil
Light-moderate	1	-		-		
Moderate		12			6*	1
Moderate-severe		-	2		-	-
Totals	1	12	2		6	1
	15				6*	1

* In one case the search for ice had to be discontinued as the area was in air lanes. Further search in the area might have found the severity forecast.

In a second case the tip of the depression went further north than forecast and so the area where the moderate icing was probably present was not investigated.

Table 6

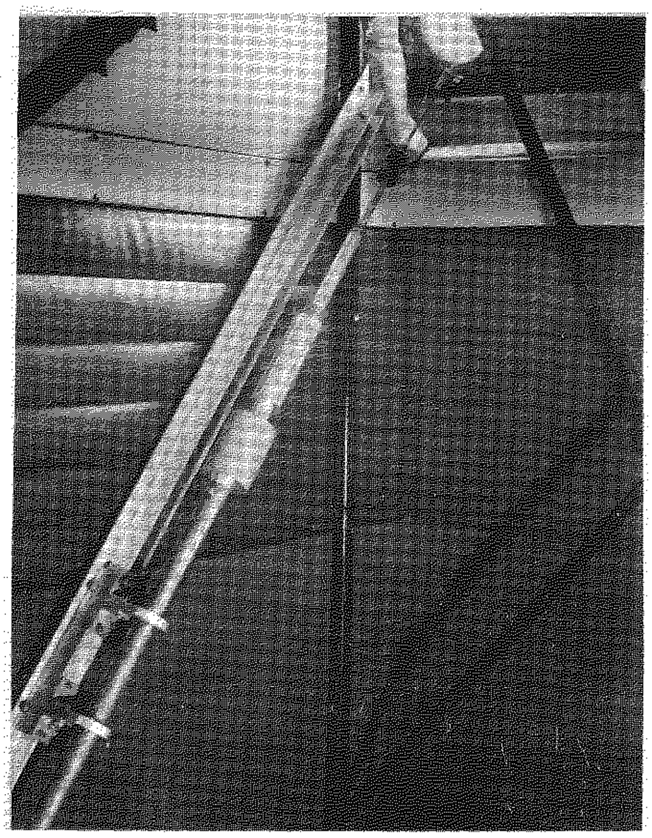
Values of Rg calculated from the rotating cylinder measurements compared with observed icing severity

Flight No.	Liquid water content (gms/metre^3)	Median droplet diameter (microns)	Rg gms/cm^2/hours	Observed icing severity	Type of cloud
38	1.8	22	30.0	Moderate & severe	Cumulus
39	0.65	14	5.8	Moderate	Cumulus castellatus
"	0.5	12	3		
"	0.55	9	1.8		
40	0.3	11	1.65	Light	Strato cumulus
41	1.1	11	0.625	Moderate	Cumulus
44	0.65	14	6.2	Light & moderate	Strato cumulus and cumulus
45	0.2	18	2.4	Light with a little moderate	Strato cumulus
"	0.25	18	2.9		
46	0.15	12	0.9	Light with patches of moderate	Strato cumulus
"	0.35	15	3.3		
"	0.3	17	3.5		
"	0.2	11	1.0		
"	0.15	15	1.5		
"	0.15	18	2.0		
"	0.45	20	6.7		
"	0.6	18	8.0		
47	0.25	9	0.85	Light with patches of moderate	Strato cumulus
"	0.15	9	0.45		
"	0.4	15	3.8		
50	0.1	16	0.9	Light and moderate	Alto-cumulus castellatus
"	0.15	16	1.6		
"	0.2	14	1.75		
"	0.1	15	1.0		
52	0.15	15	1.3	Light and moderate	Medium
"	0.6	13	0.5		
53	0.3	20	3.8	Light	Strato-cumulus
"	0.1	19	1.2		
54	0.5	17	6.25	Light	Strato-cumulus
55	0.25	17	3.1	Light and	Strato cumulus and cumulus
"	0.5	19	6.5	Light and moderate	
"	0.45	20	6.5		
56	0.6	10	3.3	Light and moderate	Strato-cumulus and cumulus
"	0.2	13	1.5		
"	0.4	15	4.3		
"	0.25	13	1.75		
"	0.35	17	4.5		

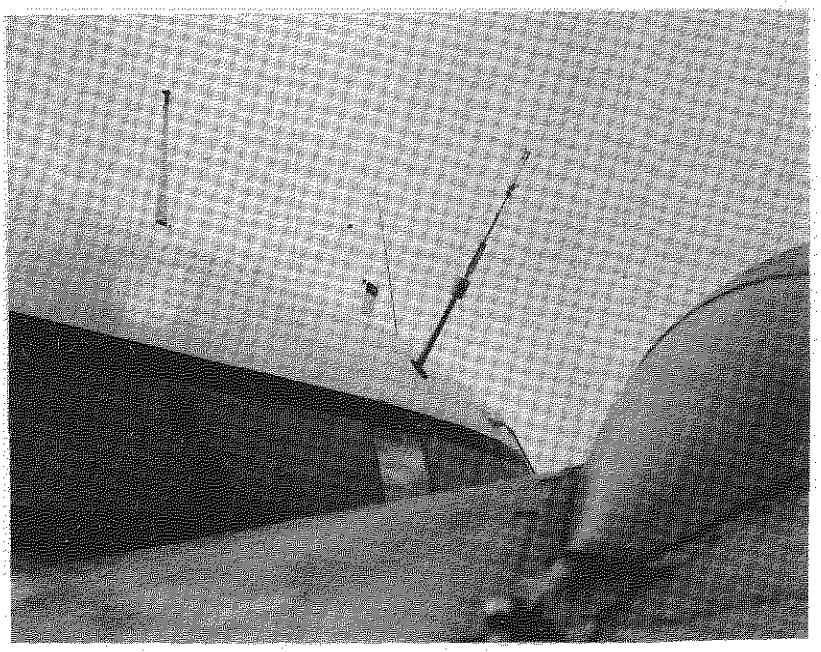
/contd

Table 6
(contd)

Flight No.	Liquid water content (gms/metre^3)	Median droplet diameter (microns)	Rg gms/cm^2/hours	Observed icing severity	Type of cloud
57	1.5	10	7.5	Moderate and severe	Cumulus
"	0.65	16	7.5		
"	0.6	20	8.5		
"	0.9	19	12.0		
"	1.05	24	17.0		
"	1.0	14	8.3		
"	1.0	10	2.4		
"	0.85	13	6.8		
58	0.3	8	0.75	Light	Cumulus
"	0.05	12	0.35		
"	0.05	9	0.1		
"	0.8	7	0.2		



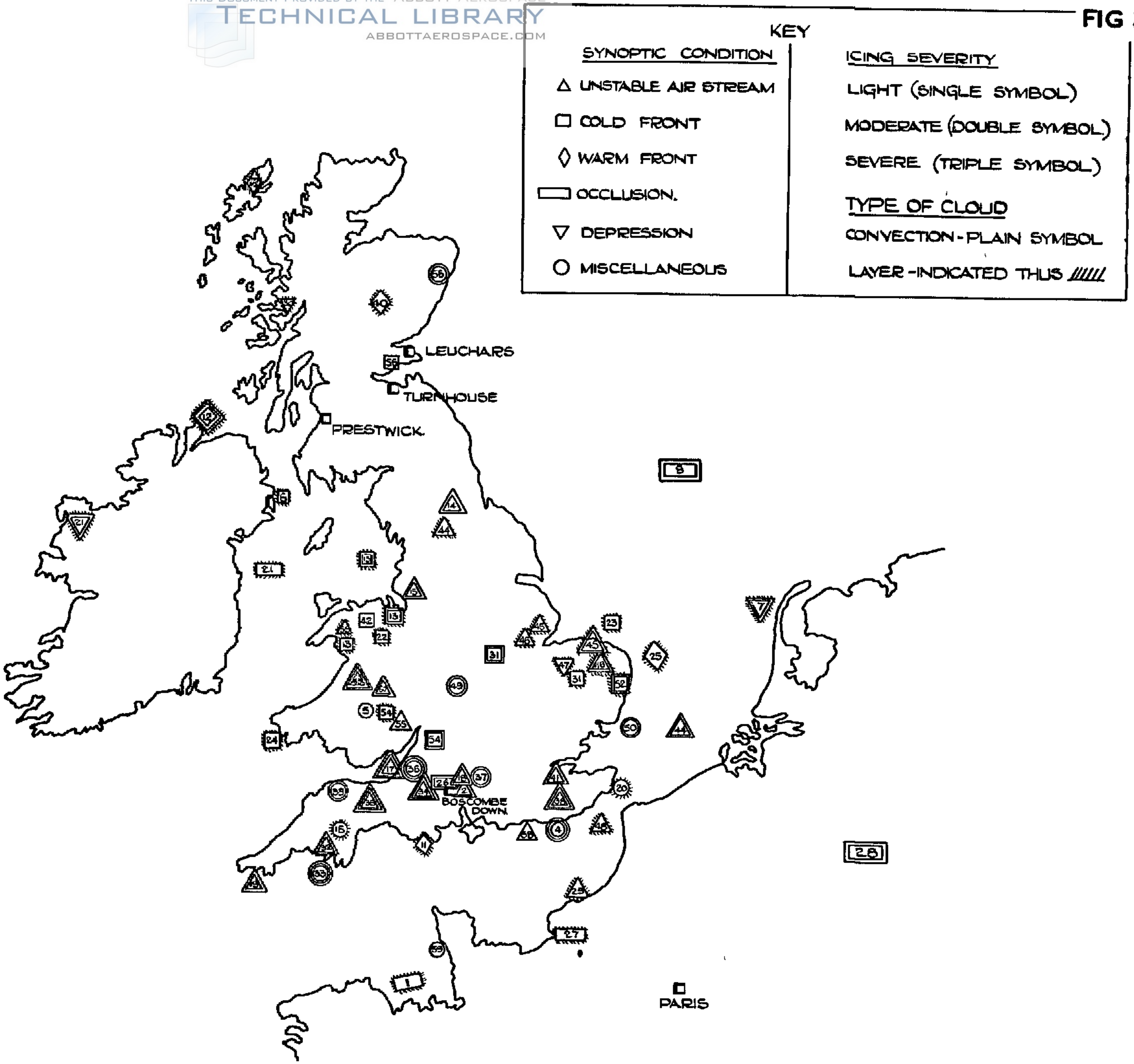
Rotating cylinders retracted showing rails & carriage.



Rotating cylinders extended.

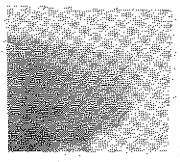
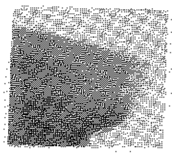
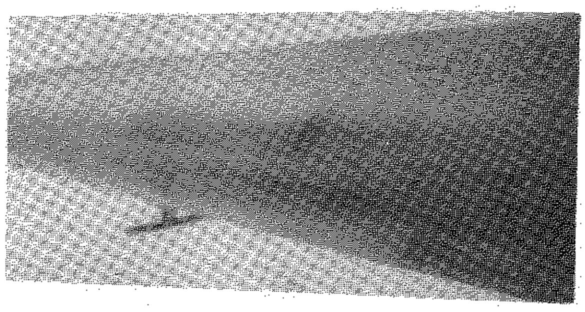
Improved rotating cylinder Installation.

FIG 2.

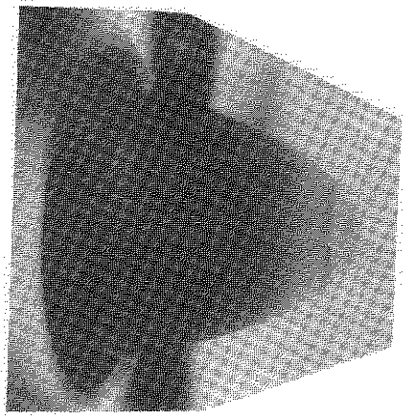


AREAS WHERE NATURAL ICING CONDITIONS HAVE BEEN FOUND DURING 1951-53.

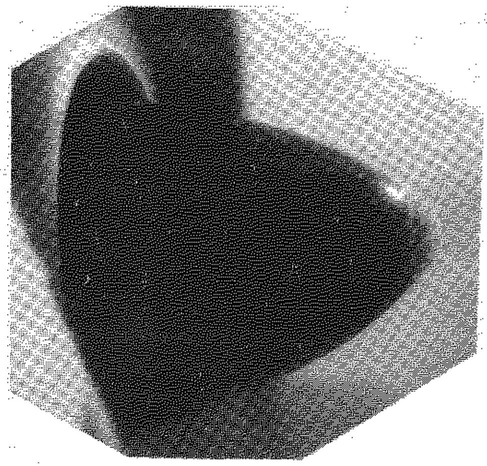
FIG.3.

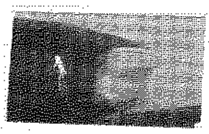
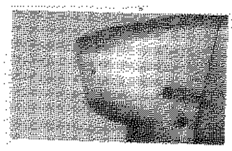




Flight No 40

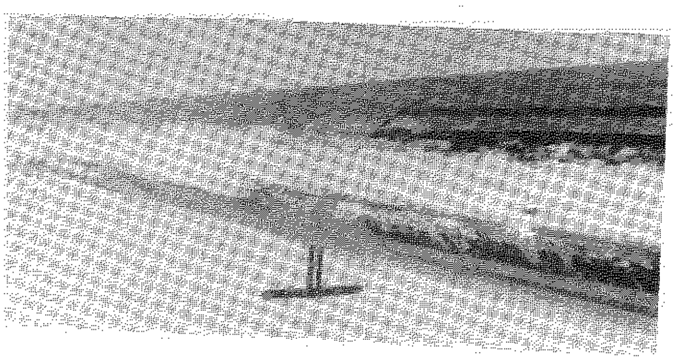


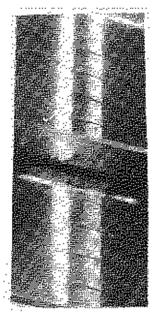
Median drop diameter 25-30 microns
Liquid water content 0·2-0·3 gms/cu. metre
Outside air temperature - 5°c



Flight No 46
Average median drop diameter 15 microns
Average liquid water content 0·3 gms/cu metre
Outside air temperature -8°c





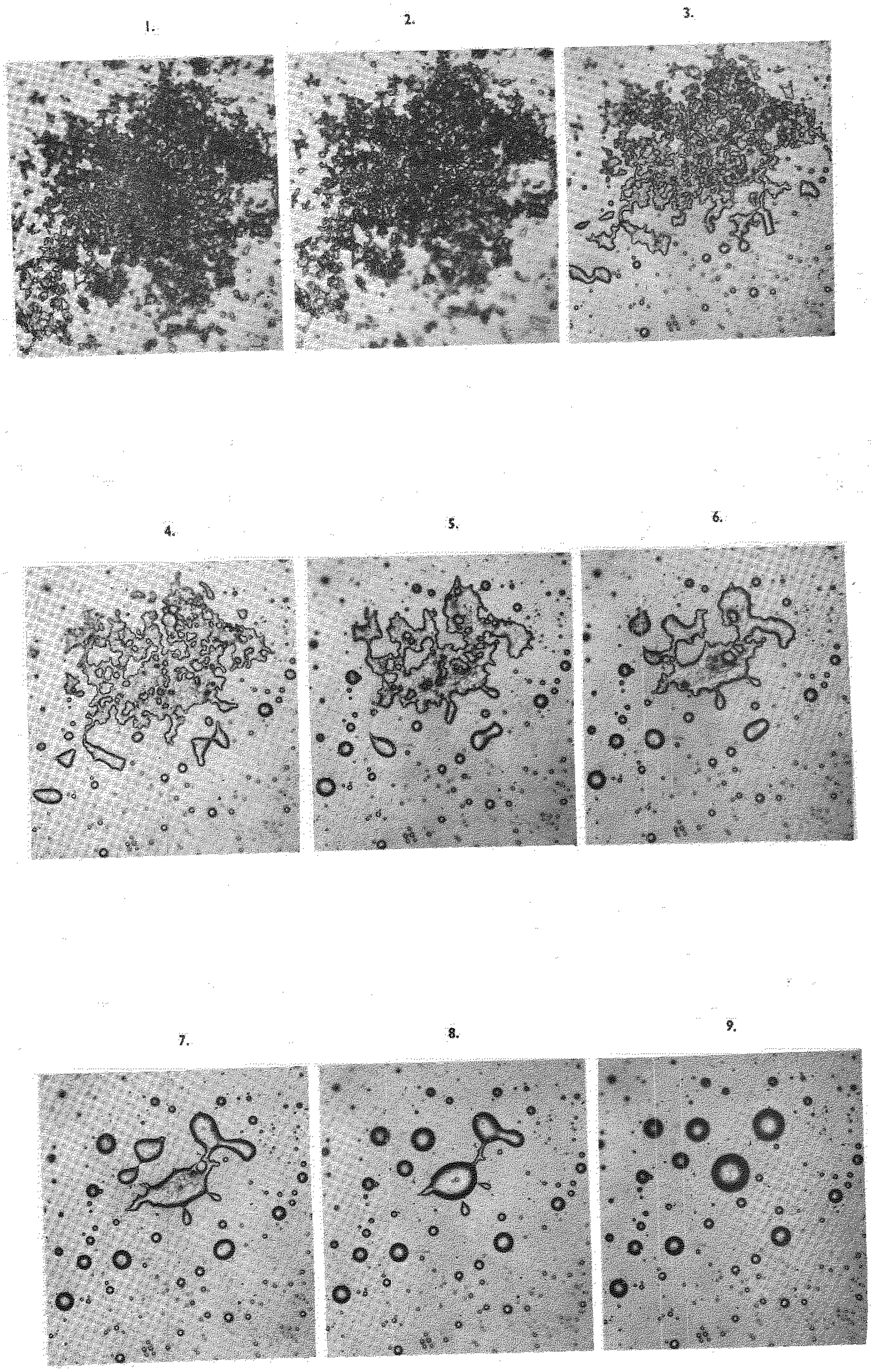
Flight No 58
Median drop diameter 10 microns
Liquid water content 0·1-0·3 gms/cu. metre
Outside air temperature - 15°c

← wire bound test strut →

Flight No 56
Median drop diameter 15-20 microns
Liquid water content 0·2-0·4 gms/cu. metre
Outside air temperature - 4 to - 8°c

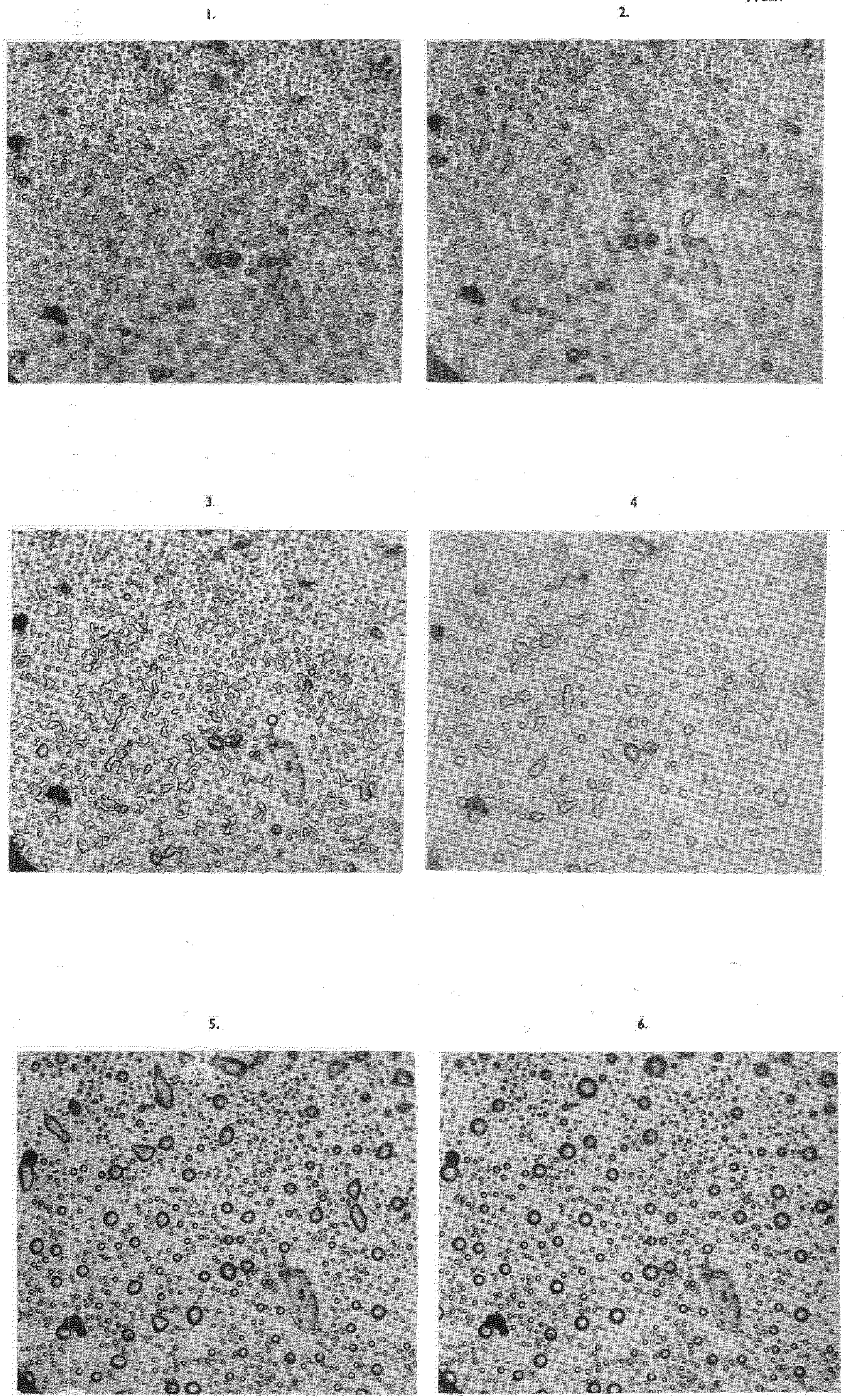
Ice formation on parts of the aircraft.

FIG.4.



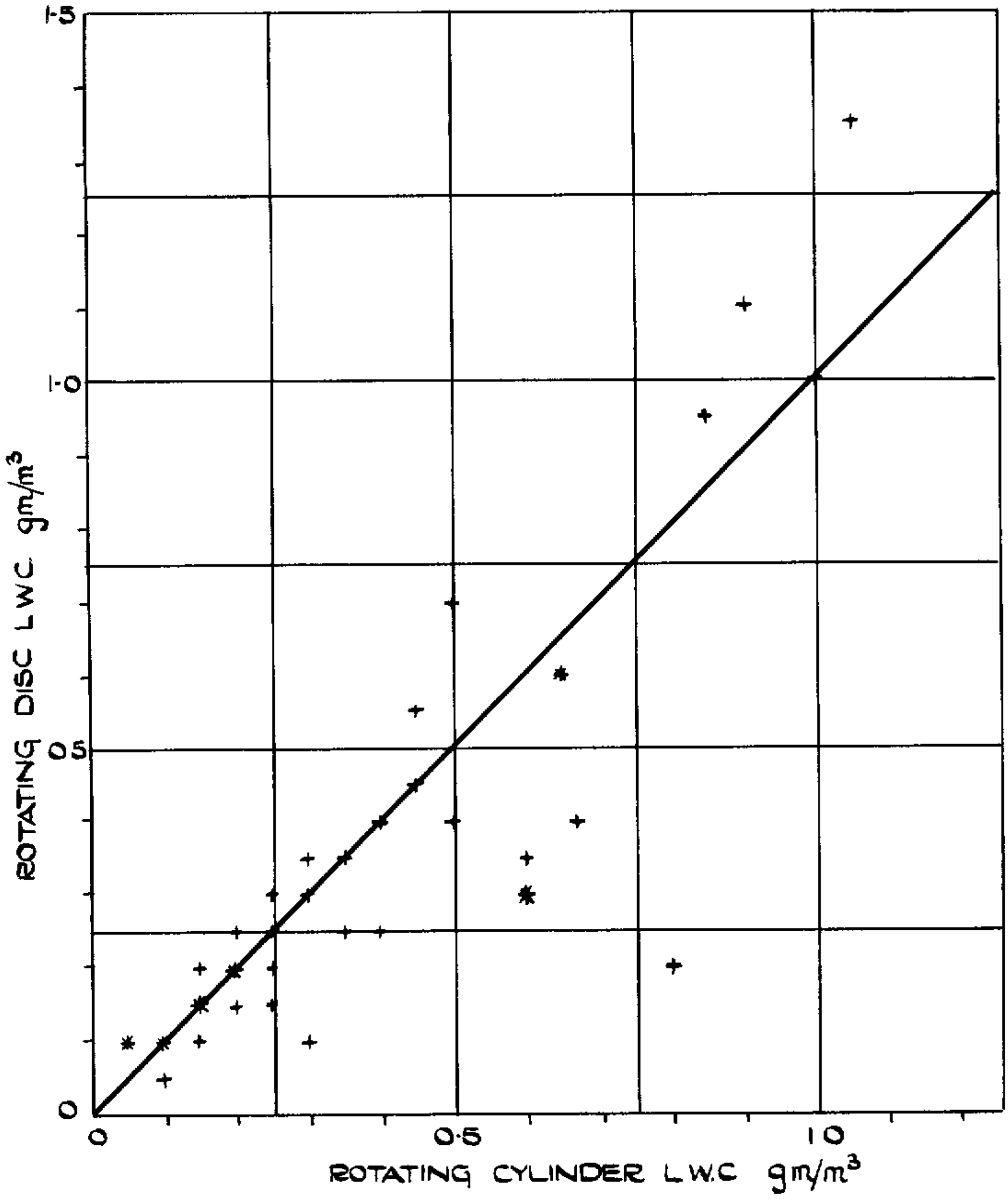
A study of the melting process of a number of ice crystals.

FIG.5.



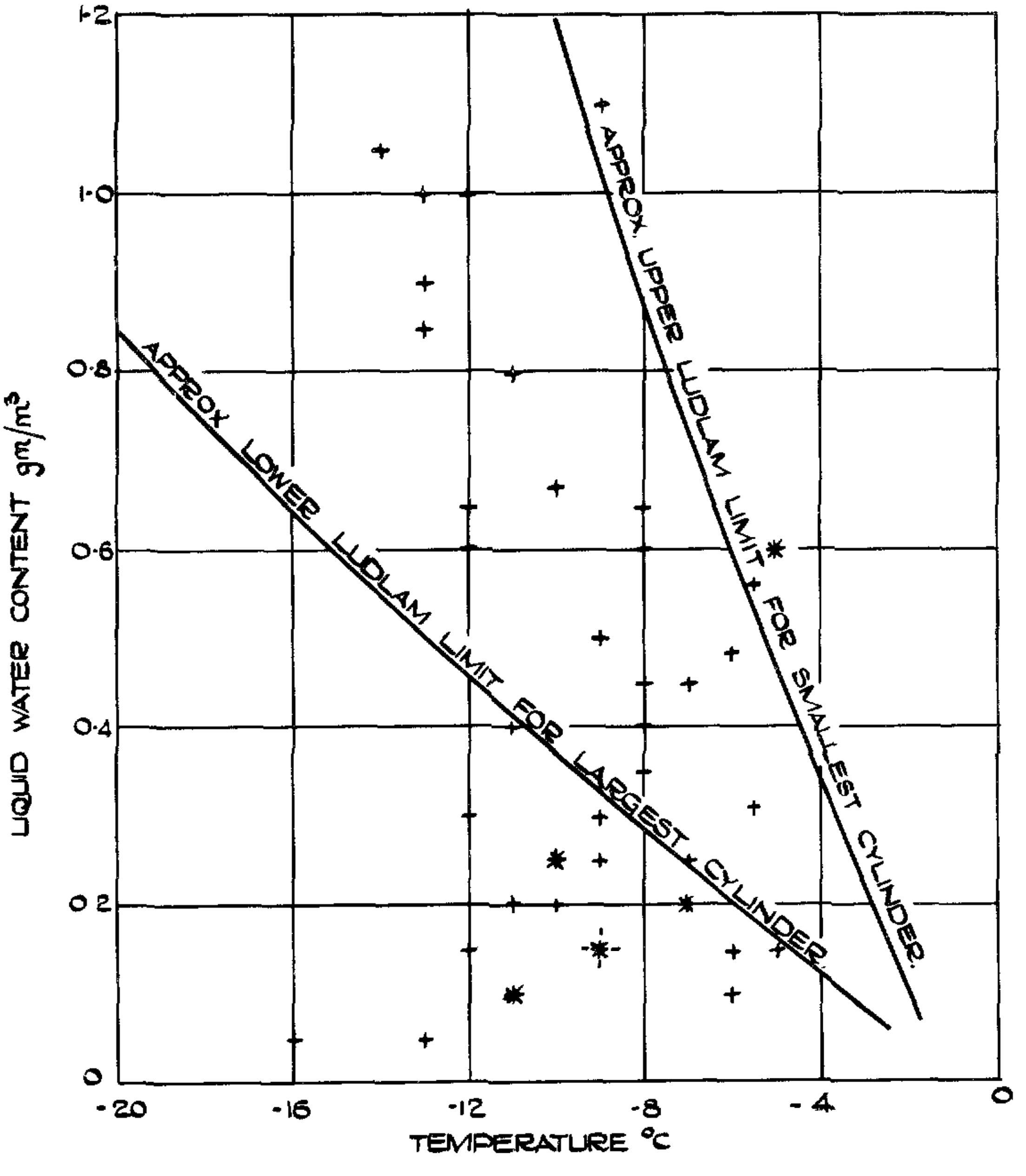
The melting process of ice crystals when mixed with supercooled water droplets.

FIG. 6.



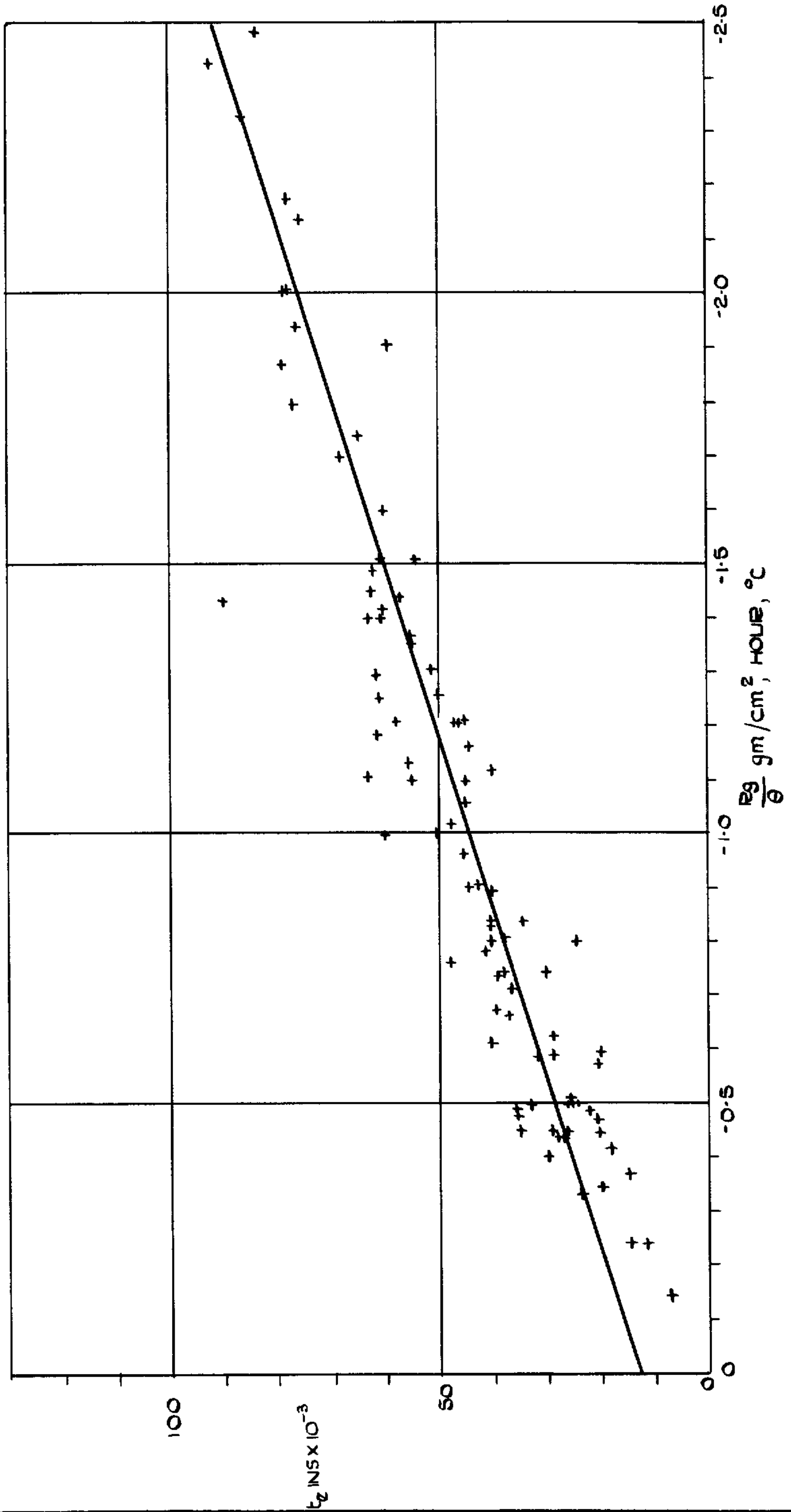
COMPARISON OF THE VALUES OF LIQUID WATER CONTENT MEASURED BY THE ROTATING CYLINDERS & THE ROTATING DISC.

FIG. 7.



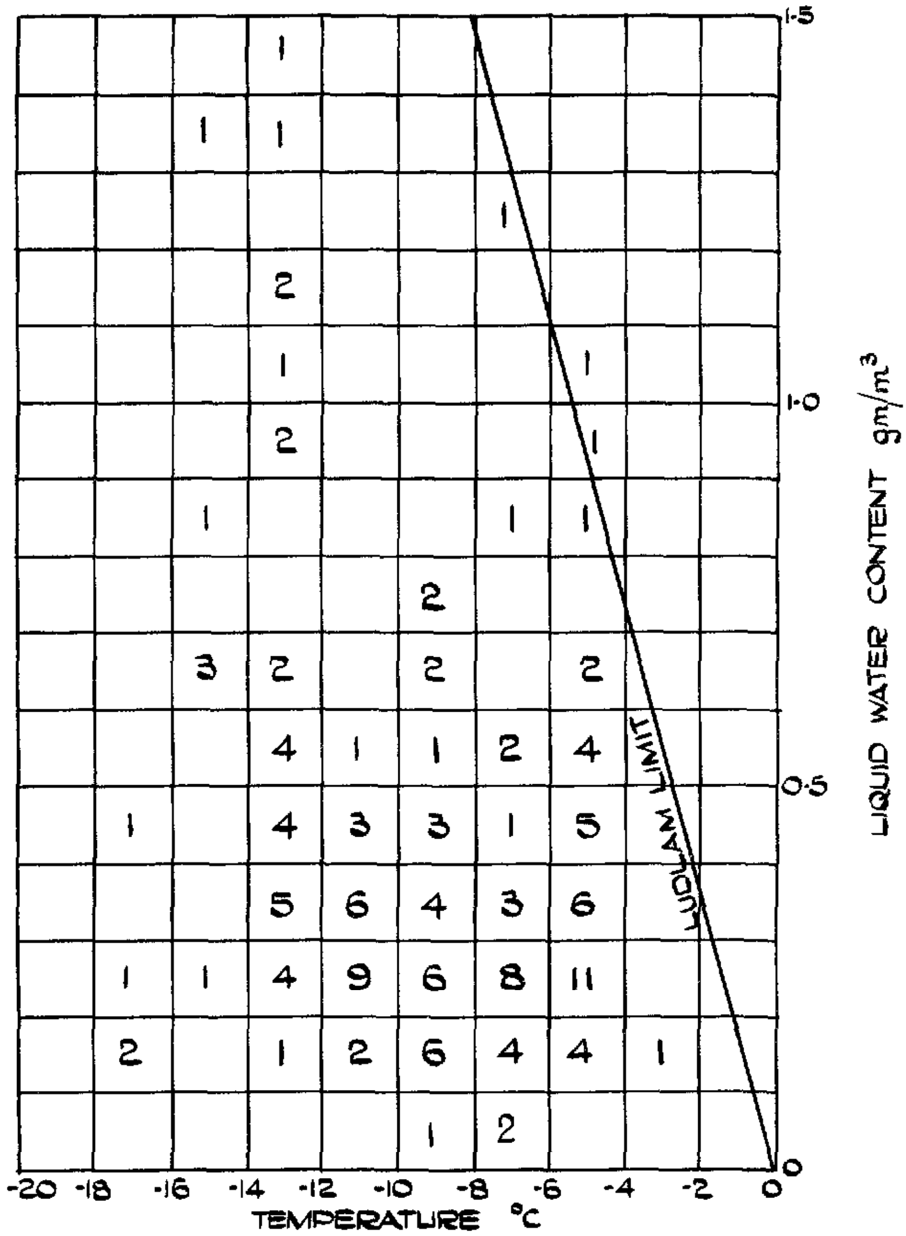
PLOT OF LIQUID WATER CONTENT MEASURED BY ROTATING CYLINDERS AGAINST STATIC AIR TEMPERATURE SHOWING APPROXIMATE LUDLAM LIMITS.

FIG. 8.



CALIBRATION OF SMITHS ICE DETECTOR AGAINST ROTATING DISC.

FIG. 9.



N.B. NUMBERS INDICATE NUMBER OF ENCOUNTERS IN EACH SQUARE.

PLOT OF AVERAGE LIQUID WATER CONTENTS MEASURED BY ROTATING DISC AGAINST STATIC AIR TEMPERATURE.

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