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AIRCRAFT ICING

OBJECTIVE MEASUREMENT AND CLASSIFICATION

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TABLE OF CONTENTS

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FOREWORD

During the third Session of the Meteorology Division of ICAO, held in 1950, proposals were formulated for a standard classification of types of aircraft icing and for a study of such problems as the development of an icing rate meter, the icing characteristics of turbine-type aircraft power plants, the development of a humidity measuring device capable of functioning at low temperatures and the feasibility of installing, on special aircraft, equipment for measuring the size and distribution of drops within clouds. Parts of these proposals failed to gain the approval of the ICAO Council, and in particular, a simpler classification for types of aircraft icing appeared to be desirable and was later proposed by the first Air Navigation Conference in 1953.

The fourth Session of the Meteorology Division, in 1954, reviewed the progress made by States since 1950 in research and development work on the difficult problems associated with aircraft icing. It was clear that States had shown great interest in this question and had made great efforts to obtain reliable and accurate information about the conditions which lead to ice accretion on aircraft. Instruments already in use had been thoroughly tested and new instruments had been devised to measure the significant atmospheric parameters. Moreover, a better understanding of the causes and effects of aircraft icing had resulted from advances made in thermodynamic studies of the problem. Attempts had also been made to correlate experimental results with synoptic conditions.

The Meteorology Division agreed that the most urgent need, and one on which early action might be practicable, concerned the adoption of a standard instrument, to be fitted to commercial aircraft as an indicator of ice accretion. The Meeting did not feel competent to offer advice on a particular instrument but felt that among those currently in use it might be possible to select a suitable one so that the important objective of standardization could be achieved. It was also considered that significant evidence had been found to indicate that ice formation might be classified into well defined groups based on the shapes assumed by the accretion. While more research on this aspect remained to be done, the Meeting agreed that attention should be given to the development of an instrument which would provide an accurate indication of both the rate and shape of icing. The following Recommendation (No. 38) was accordingly agreed upon:

"Standard aircraft icing indicator and aircraft icing classification

Recommendation No. 38

It is recommended that:

ICAO, in consultation with States

1) give urgent consideration to ways of meeting the need for a suitable aircraft icing indicator to be adopted as a standard instrument for all aircraft operating regularly in icing regions;

2) give attention, when considering the problem referred to in paragraph 1) above, to the possibility of classifying icing conditions on the basis of both rate of icing and shape of ice accretion.

Comment

1) When considering the feasibility of recommending the standard instrument referred to in part a) of Recommendation No. 38, States should take into account the practical limitations imposed by its utilization on board commercial aircraft. It is recognized that certain types of icing instruments which may give accurate information on ice accretion conditions are not suitable for use on commercial aircraft and should be kept for research purposes only. A certain compromise between the accuracy of the information and the simplicity of the design will be necessary.

2) Data collected during icing tests in various experiments carried out in the last few years show a very definite trend in the type of ice accretion on certain collectors under various conditions, indicating the possibility of classifying the ice formation into well defined groups based on the shapes of the accretion. Theoretical investigations point to the possibility of satisfactory explanations of the physical processes associated with each one of the characteristic types of ice accretion shapes. Although there is a continuous transition from one characteristic pattern to another, the variation of icing conditions being continuous, all shapes of ice formation could be classified into a few basic types. This new approach to the problem of icing classification was considered by the Meeting to offer promising prospects in connection with the adoption of a simple standard instrument as an icing indicator for commercial aircraft."

The Council of ICAO approved this recommendation and proposals for achieving the objects of the recommendation are now in course of preparation.

Secretariat Study

In order to provide States, prior to the fourth Session of the Meteorology Division, with a résumé of recent progress on the subject, the Secretariat surveyed research carried out by States, particularly in the years 1950 to 1954, and presented the Division with a working paper in which the results of the Secretariat's study were summarized. This working paper was considered by various delegations to warrant reproduction in a less ephemeral manner as it was found to form a convenient source of reference regarding the present stage in the development of aircraft icing detecting and measuring equipment. The Air Navigation Commission, when reviewing the results of the fourth Session of the Division, supported this view.

The present circular is therefore issued as a re-print of the Secretariat study, referred to above, with slight editorial changes only.

SUMMARY

Progress in the field of aircraft icing in the last few years has been most significant with regard to the development of objective icing detection, rendering observational data which can be applied to actual operations and, at the same time, enabling a satisfactory aircraft icing classification to be developed for reporting and forecasting purposes.

This circular records the results of recent theoretical and experimental research on the subject. It discusses the possibility of the adoption of a standard instrument for use by commercial aircraft; a new approach to the problem of aircraft icing classification and certain steps in support of further research.

Recent progress in the research on the relationship of aircraft icing and cloud characteristics,such as water and ice content and particle size distribution has been summarized by the WMO in its Technical Note No. 3: "Meteorological Aspects of Aircraft Icing" (WMO - No. 30. TP. 9)

1. - INTRODUCTION

The MET Division, at its third Session, considered the subject of "Development of a standard classification for types of aircraft icing and means for determining types and rates of accumulation of icing". The outcome of the discussion is contained in a recommendation which includes a general classification of aircraft icing and calls for a study of the following problems:

a) Development of an icing rate meter to be installed on aircraft.

b) Compilation of information regarding the icing of turbine-type aircraft power plants.

c) Development of a standard accurate humitity measuring device which will operate at low temperature.

d) Feasibility of installation, in all meteorological reconnaissance aircraft and possibly in aircraft flying on international air routes, of equipment for measuring drop size and distribution within clouds.

The classification of types of aircraft icing incorporated in the above-mentioned recommendation, to meet meteorological and operational requirements, was intended to provide not only the background for an observational code, but also the basis for an understanding of the physical processes which were responsible for each particular type of ice accretion. Four primary types and five sub-types of aircraft icing were developed, indicating its appearance and the nature of its formation. Subsequent correspondence with the Contracting States of ICAO has shown that the proposed classification was considered unsatisfactory. Two main difficulties appeared to be connected with its adoption:

a) There was no general agreement on the terminology applied in the classification.

b) The new classification was considered too detailed to be suitable for reports made on board commercial aircraft and, therefore, of no practical value.

In the light of this discussion, the Council of ICAO disapproved the proposed classification.

The recommendations connected with sub-paragraphs c) and d) above, were also disapproved by the Council. The comments from States indicated that humidity was not regarded as an important parameter in connection with icing. On the other hand, although droplet size was at one time considered as a primary factor in determining the form of ice accretion (see, for instance, Reference 1), it appears now well established that it is in fact a secondary factor affecting only the collection efficiency of ice collectors. The instruments now in use for measuring droplet size and distribution are of limited application (see paragraph 4) and their operation is rather delicate, the subject being, therefore, still confined within the limits of research projects.

Information received from States, and literature published on the subject since the third meeting of the MET Division, show that great efforts have been made to obtain reliable and accurate information on the conditions of ice accretion on aircraft. New instruments have been devised and tested to measure the significant atmospheric parameters, whereas the instruments already in use have been investigated in greater detail, both theoretically and experimentally, in order to determine their value and limitations. At the same time, advances in the thermodynamic theory of ice formation have led to a better understanding of the cause and effect of the various types of icing on aircraft frames and on turbine-type aircraft power plants, and have opened a road which may lead towards the prediction of rates and physical characteristics of ice accretion.

Furthermore, attempts have been made to correlate the experimental results with the actual types and distribution of cloud formations within which the measurements were made, so as to get a better description of the processes from the synoptic viewpoint. The experience gained in recent years, and the amount of information accumulated, point to the need for a fresh start on the subject.

2. - GENERAL CONSIDERATIONS RELATING TO THE METEOROLOGICAL ASPECTS OF ICING PROBLEMS

The ultimate goal of weather forecasting, in connection with the problem of aircraft icing, is the description of the type of ice formation and the rate of accretion which a given aircraft, flying at a known speed, will undergo under certain synoptic conditions. The overwhelming difficulties of this task are immediately clear if it is realized that it embraces several problems which are still unsolved.

The goal, if it could be attained, would involve the following steps:

a) The prediction, in a given synoptic situation, of the type and space distribution of clouds and precipitation and the field of atmospheric temperature.

b) The prediction, for the forecast cloud systems, of the number, size and temperature of water droplets.

c) The determination of the rate and type of ice accretion on objects of various shapes and sizes traversing, at a certain speed, an atmosphere where the foregoing characteristics are known.

The difficulties connected with each of the preceding problems are of different degree and nature.

Any specific consideration of a) will be omitted since it is only one aspect of the general problem of weather forecasting. It should be emphasized, however, that its final goal c) requires a more detailed knowledge than is usually the case with other types of forecasting. The fulfillment of this task is far from the stage which would allow for the provision of some procedural rules which could be incorporated into the routine forecast.

The knowledge of the distribution of significant atmospheric parameters inside clouds could be considered as being in its early stages. However, extensive research, both theoretical and experimental, has given, in recent years, a clearer idea about the distribution of water vapour content and droplet size in various types of clouds (see, for instance References 2 and 22). Investigations of the type reported by Zaitser (Reference 22) point to a certain regularity in the distribution of water content and droplet sizes within clouds.

Four well defined zones were found within cumulus clouds, which appear to be related to the pulsation of updrafts. The results are very promising and seem to indicate that extensive research within this field, applying the most advanced observational techniques, could lead to a considerable improvement in the understanding of cloud structure as a preliminary step towards the solution of the forecasting problem.

The problem stated in c) has received special attention in the last three years, and it is within this field that progress has been most noticeable. Both theoretical and experimental results would indicate that the methods of observing and reporting ice accretion on board aircraft and the systems of ice classification can be established on solid grounds which are physically and operationally significant.

3. - PROBLEMS CONNECTED WITH ICE ACCRETION ON AIRCRAFT

The impossibility of solving, with the present meteorological knowledge, the general forecasting problem as it was formulated above indicates the necessity of breaking it down into less inclusive component problems. As a preliminary step, it appears natural to collect observational data under every possible icing condition, and to systematize the results in an attempt to obtain a reliable basis for the comparison of observations taken from different aircraft under different circumstances. In this manner it would be possible to carry out a double process a) to ascertain the value of the significant meteorological parameters from the observational data obtained on board a given aircraft, and b) to assess the effect of known meteorological conditions, evaluated by the process indicated in a), on another aircraft of different characteristics. The feasibility of this process will be shown below. This paragraph will only be concerned with the applications of the observational material.

The collection of meteorological data indicating the distribution of the relevant atmospheric parameters in a given synoptic situation, as well as the geographical and seasonal variation of icing occurrences, has two main aeronautical purposes. Firstly, they are used to establish design requirements for icing protection systems; secondly, they are of operational interest in connection with the assessment of the amount of ice accretion likely to be undergone by an aircraft on a particular flight.

The evaluation of the heat requirements of an icing protection system is based on the rate at which the heat must be supplied and the extent of the aircraft surfaces over which it must be applied. This requires a knowledge of the statistical distribution of the above-mentioned atmospheric parameters, in space and time, which will permit the assessment of the probable maximum duration and the frequency of occurrence of various icing conditions. Therefore, for design purposes (icing protection systems) the main task is to collect meteorological data which would enable an estimate to be made of the worst cases which could be encountered by an aircraft at any time or place, and the frequency of the various degrees of severity.

A great amount of statistical data has been collected in the United States by the National Advisory Committee for Aeronautics (NACA) in an effort to establish methods of selecting design criteria for icing protection systems (References 11, 14 and 19). The applicability of these results is, however, restricted by the limited representativeness of the data themselves. Two main limitations should be mentioned in this connection: the limitation imposed by the instruments used to determine ice accretion rate (see paragraphs 4 and 5), and the restricted geographical area over which the experimental flights have been made.

To obtain a more realistic picture of actual conditions likely to be encountered in icing situations, theoretical studies made in Canada by the National Aeronautical Establishment (NAE) have incorporated values of atmospheric parameters which are consistent with measurements performed with more refined techniques (see References 6 and 7). These results, although having a fairly sound basis, should be considered as tentative in character and call for further investigations of cloud properties based on reliable measurements of the relevant atmospheric parameters.

The information about the average distribution of the atmospheric parameters under extreme conditions is usually presented in graphical form as correlations of the following pairs of parameters:

a) water content -temperature

b) droplet size - temperature

c) droplet size - water content

d) water content - altitude

Isolines are drawn for different average water contents of encountered icing and additional diagrams are given of maximum average water content for a given extent of icing. As indicated above, the diagrams so far available in the literature need confirmation with data obtained with more reliable instruments and over more extended areas of the world.

The meteorological problems connected with the provision of information on ice formation for operational purposes are far more complicated, due to the great variability of the parameters in space and time. Advances in this direction have not so far been very significant. The main factor affecting progress has been the lack of accurate observations giving significant information. Present methods of reporting ice formation on commercial aircraft are very subjective and largely dependent on aircraft parameters which are difficult to compare. Standardization of observing instruments and a simple and physically significant method of reporting the observation are, therefore, essential if any improvement of present practices is to be expected. The 6th Annual Technical Conference of IATA (Puerto Rico, April 1953) has already recognized "the urgent need for a satisfactory icing rate meter". There is evidence that observations obtained with a standard instrument may be used for operational purposes. In a survey of icing conditions measured during routine transcontinental airline operations (Reference 19) a comparison was made of the total ice accretion values, given by measurements on a NACA pressure-type icing rate meter, with the pilot's estimates of the icing intensity based on his observations of the accumulations on the aircraft frame and the corresponding effects on the aircraft performance. All measurements and visual estimates were made on board four-engine DC-4-type aircraft, and the ice thickness values were calculated by multiplying the average icing rate, measured by the instrument, by the time in measurable icing. It was found that the correlations were, in general, very consistent, and that the pilot's reports of icing conditions as "trace", "light", "moderate", "heavy" or "severe" correspond approximately to measured ice accumulations of less than 1 inch, 1-2 inches, 2-4 inches, 4-6 inches and more than 6 inches, respectively. Obviously, the results would be different with different types of aircraft. They would indicate, however, that it should be possible to gain enough experience by experimenting with various types of aircraft so as to be able to infer what effect a known amount of ice accretion, as measured with a standard icing rate meter, would have on a particular type of aircraft.

From the knowledge which is now available, it appears that the problem of gas turbine aircraft engine icing does not require special consideration from a meteorological point of view. The atmospheric conditions under which icing occurs in jet engines do not differ from those leading to airframe icing, nor do the types of ice accretion present any special characteristics.

4. - ICING RATE METERS

The determination of liquid water concentration, droplet size distribution and mean effective droplet diameter, in supercooled clouds, is usually made by means of instruments acting as ice collectors.

Rotating cylinders were the first and have been the most widely used of these rate meters. The method of calculation depends on measuring the rate of accretion of ice on the collectors and comparing it with the results obtained from evaluation of droplet impingement based on theoretical water droplet trajectories (<u>see</u> Reference 13).

The theoretical rate of ice accretion is considered to be a function of:

a) size and shape of the instrument;

b) liquid water concentration in the air;

c) drop size;

d) airspeed.

The "collection efficiency" or "efficiency of catch" is defined as the ratio of the amount of water caught to the amount of water in the swept path. The variables determining the collection efficiency are the size of the collector, the droplet size and the airspeed past the instrument. To obtain the liquid water concentration, with a particular instrument, under given conditions, it is enough to compare the weight of the ice collected, with the collection efficiency calculated for the same instrument and same conditions. The main assumption which is made to allow that comparison is that all those supercooled droplets that strike the instrument freeze completely on the surface.

Droplet size distribution and mean-effective droplet diameter can be obtained when instruments of different size are exposed simultaneously so that all the other variables are known.

The method suffers from various shortcomings. In the first place, it involves a certain amount of subjectivity, since the actual data should be matched with theoretical values, based upon hypothetical droplet-size distributions, which do not necessarily exist in an icing situation. On the other hand, the method shows a very high insensitivity to changing conditions within a cloud. Measurements reported by the NACA (Reference 3) show that, with an allowed error in measurement of ice accretion of $\pm 5\%$ in a cloud in which the droplet size was actually 30 microns, the following errors could be expected in the determination of mean-effective droplet diameter:

for an airspeed of 200 miles per hour - up to 35%;

for an airspeed of 300 miles per hour - up to 50%;

for an airspeed of 400 miles per hour - up to 70%.

In recent investigations it has been proved that the failure of the method is mainly due to the assumption that all water droplets freeze upon impact (*see* paragraph 5).

Rotating disc

The rotating disc type of instrument is essentially a rotating disc presenting its edge to the airstream. A feeler measures the thickness of the ice collected (Fig. 1). This instrument was first developed by the Massachusetts Institute of Technology and there have been various versions of it, developed by the NACA and by the NAE, differing in the thickness of the disc, the speed of rotation and the reading mechanism.

The instrument is highly accurate and gives reliable information within a large range of water content.

The measuring and removing devices make the construction of the instrument rather delicate. Ice is likely to be formed on the mechanism and supporting structure, and the calibration should be made with great care. These difficulties make the instrument of limited value for operational use on normal commercial aircraft, and, therefore, it must be primarily considered as a research instrument.

The "NAE Hot-Rod"

The NAE has devised a very simple instrument known as the "NAE hot-rod" (References 8 and 9). It is essentially a tube, 9 inches long 1/4 inch in diameter, with an internal electrical heater. At the outer end a tip is placed, with a small scale which allows for a visual observation of the time taken for a certain thickness of ice to accrete (Fig. 2). The heater (200-watt) can be operated by a manual switch and permits quick de-icing of the rod. The instrument is suitable for mounting in a position where both the scale of the tip and the configuration of the ice-accretion can be easily seen from the cockpit. This instrument seems to offer the most inexpensive and practical way of collecting information on board normal commercial aircraft.

The limitations of the "hot-rod" and the type of information which can be obtained from it will be discussed below (paragraph 6).

Orifice Type Icing Detector

This type of instrument has been developed in Canada, the United Kingdom and the United States. The method depends essentially on the blockage of pressure orifices by icing. The following description of the Canadian type is taken from Reference 8.

"The exposed probe consists of a tube with a number of pressure holes facing into the airstream and a smaller number of suction holes at the rear. Under normal conditions the pressure and suction holes combined give a positive pressure in the tube. When the pressure holes are iced up, however, this pressure becomes negative.

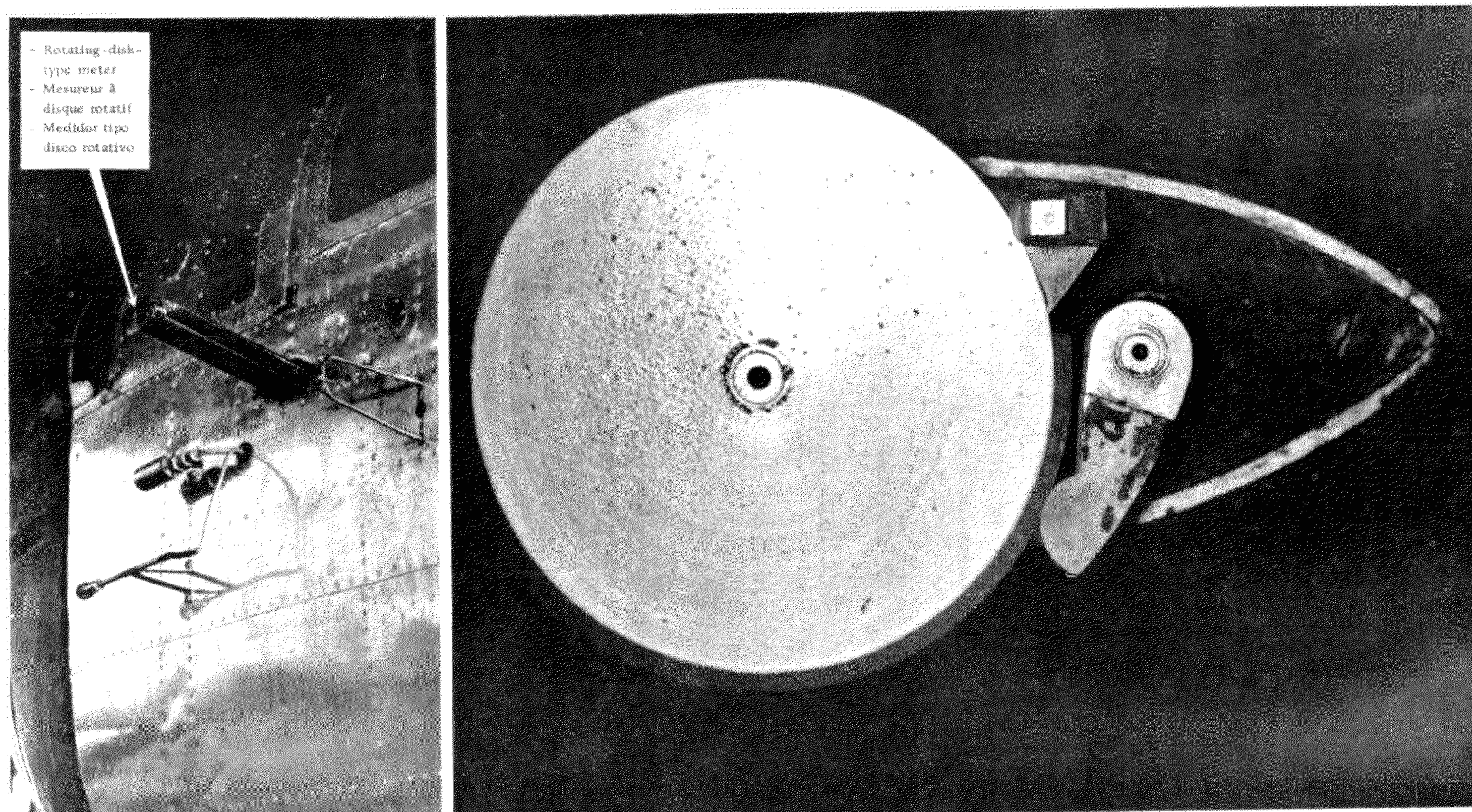


Fig. 1 Rotating disc type of icing rate meter mounted on left side of fuselage of research aircraft (from Ref. 20).

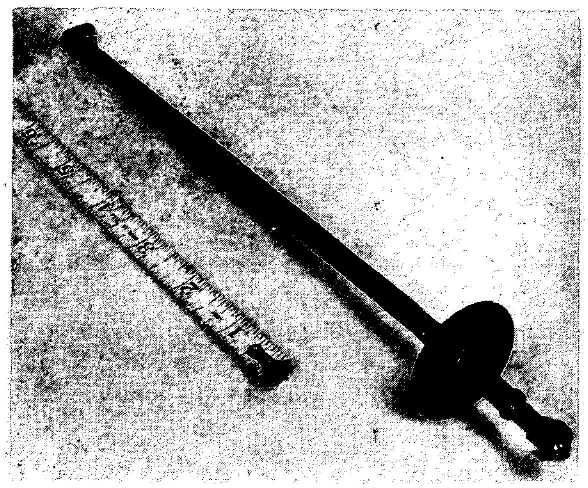


Fig. 2 NAE hot rod rate-of-icing indicator (from Ref. 8).

The probe pressure is transmitted to a pressure switch, which closes at a negative value of the pressure, and opens again just before the pressure becomes positive. Thus each time the pressure holes are iced up the probe is de-iced and a signal is given; and as soon as the probe has de-iced it becomes cold again and ready to collect a further ice accretion.

It has been found that the interval between signals can be calibrated in terms of a rate-of-icing. The amount of ice required to block the orifices depends on the shape of the ice which is largely a function of the rate-of-catch and the air temperature, and this must be taken into account in the calibration. If this is done it is estimated that the accuracy of the instrument is about ±10%, but otherwise an error up to 150% may occur. In addition to having saturation limits of about the same order as a 1/8 inch diameter rotating cylinder, this instrument also has a lower limit of accuracy, at low rates of icing and low temperatures, when an extreme form of 'knife' ice occurs.

However, the instrument is very simple and reliable, and numbers of them have been prepared for collecting statistical data on Canadian airlines, giving both visual indications and photographic records."

Heated-Wire Water Content Meter

The Ames Aeronautical Laboratory (NACA) has devised an instrument (Reference 18) the sensing element of which is a loop of electrical resistance wire which is heated by passing current through it (Fig. 3). The resistance of the wire is a function of the temperature, and it decreases with decreasing temperature. Therefore, if the voltage across the wire terminals is kept constant, the electric current flow through the wire can be used to measure its temperature. When water droplets impinge on the instrument, the wire is cooled due to heat losses by convection and evaporation of the water on the cylinder surface (radiation effects being negligible). For a given instrument, and a given ambient-air temperature and free-stream velocity, the total heat loss (measured by the drop in temperature and, hence, by the rise in the electrical current) gives the liquid water concentration of the air stream passing the instrument.

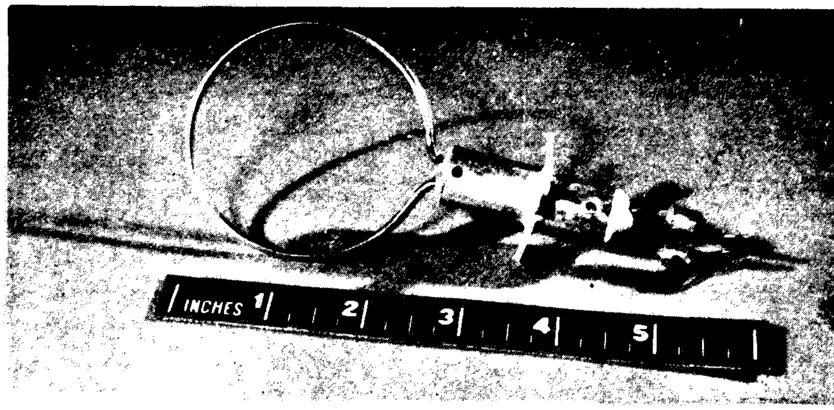


Fig. 3 Heated wire rate-of-icing indicator (from Ref. 18).

The instrument has high sensitivity to rapid variations in water content, is easy to operate and has a simple and durable construction. Furthermore, it is suitable for measuring higher water contents than the instruments described before.

The limitations of the instrument are briefly as follows (References 10, 18 and 25):

> It suffers from a "saturation" effect at high water contents. This is due to the fact that aerodynamic forces on the drops tend to remove part of the water from the wire surface before it is entirely evaporated, whenever the amount of impinging water exceeds a certain rate for a given temperature. To avoid this effect the operating temperature of the wire should be kept high enough.
>
> There appears to be a limit to the size of droplets which can be entirely evaporated. Experiments reported by the NACA (Reference 18) indicate a maximum water droplet size of 25 microns for the particular size of wire that was used. It seems, however, that this difficulty could be overcome by increasing the diameter of the wire.

The operating voltage should be selected for fixed conditions of airspeed, pressure-altitude and air temperature. For large variations in these parameters adjustments are required. No self-compensating mechanism has yet been devised.

The instrument operates also at temperatures above freezing and in the presence of ice crystals, without distinguishing between water droplets above freezing, supercooled water droplets and ice crystals. Since the calibration of the instrument varies from liquid to solid state of the water, due to the latent heat of fusion of the ice crystals, there is no way to ascertain the actual water content, in the case of mixed conditions, unless there is an independent method of determining the ratio of liquid water to ice crystals.

In spite of the above-mentioned limitations it appears possible that the instrument could be developed to such a stage that it could become the most useful tool for determining high water content within clouds.

5. - THEORETICAL ASPECTS OF THE BEHAVIOUR OF ICE ACCRETION INSTRUMENTS

Thermodynamic analysis of icing rate meters based on measuring the rate of ice accretion on an unheated body (rotating cylinders, rotating disc, orifice-type ice detectors) shows that the usefulness of these instruments is restricted to certain ranges of supercooled water content (References 10 and 15). Furthermore, these theoretical considerations give a clear understanding of the transition from one to the other of the two fundamental types of ice accretion: rime and glaze. A brief summary follows:

When the ice collector instrument moves through the cloud, the supercooled water droplets intercepted by the instrument will begin to freeze on impact. Since the freezing is accompanied by the liberation of latent heat of fusion, the temperature of the instrument becomes higher than the surroundings. To re-establish the thermodynamic equilibrium, heat is lost by the instrument to the air. To a first approximation this is accomplished by processes of convection and evaporation (or sublimation). Two possibilities will then arise:

a) If the rate of impingement of water droplets on the instrument is such that convection and evaporation are capable of disposing of the heat of fusion, all droplets will be frozen and a deposit of rime will result.

b) If water is caught by the instrument at a high rate, the temperature of the instrument will rise until it reaches 0°C and thereafter not all the impinging water can be frozen. The surface of the instrument becomes "wet". Part of the water will freeze, forming clear ice (glaze), whereas the rest forms a film upon the instrument and it will be lost either through evaporation or by being shed into the wake.

The consideration of the preceding paragraph was first applied by Ludlam (Reference 15) to a rotating cylinder. The maximum heat lost by convection and evaporation at a given temperature occurs when the surface of the cylinder, moving through a supercooled cloud, reaches 0°C. This is therefore the temperature at which the water is frozen at the maximum possible rate. Knowing the total heat lost by convection and evaporation at 0°C, it is easy to calculate the amount of water which has a latent heat of fusion equal to the total heat lost. Hence the critical value of water concentration is obtained. When this value is exceeded not all the water caught by the instrument is frozen on its surface, but part of it will stream off the lee side of the cylinder.

Ludlam's calculations were further refined in the NAE (Reference 10) and subjected to experimental tests. The saturation limit, i.e., the limiting water content which can be revealed by the cylinder at a given temperature, was called the "Ludlam-limit", and the curve of limiting water content versus temperature in any given conditions was called the "Ludlam-line". Both theory and experiments were also applied, with analogous results, to rotating discs and orifice-type detectors. Two sets of experimental data gave satisfactory confirmation of the theory:

a) When the rotating cylinder flight data available in current literature are plotted in a diagram of water content versus temperature, very few readings lie above the theoretical Ludlam-line.

b) Icing-tunnel tests establish that the rate of icing measured from the instruments and the amount of water being sprayed in the tunnel depart sharply from each other when the liquid water content of the air in the tunnel reaches the value of the calculated Ludlam-limit.

Theory and experiments based on the preceding analysis allow the following conclusions to be drawn:

a) Unheated icing rate meters are incapable of measuring the maximum liquid water content which may occur within clouds.

b) The use of multiple cylinders to determine drop size distribution in clouds is of restricted application. When they operate within clouds of high liquid water content, cylinders of different diameters will reach the saturation limit at different stages.

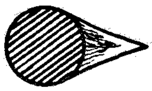
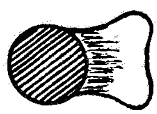
c) The physical appearance of ice accretion is directly connected with the saturation limit. The transition from a rime to a glaze formation takes place at about that limit. When a certain margin has been exceeded, the ice formation becomes knobby and irregular.

d) It appears that accurate measurement of high water content will require the development of refrigerated ice accretion instruments.

6. - EXPERIMENTAL AND THEORETICAL RESEARCH ON THE SHAPES OF ICE ACCRETION

Data collected during icing tests at Mount Washington (References 1 and 5) and in the NAE of Canada (unpublished), show a very definite trend in the type of ice accretion on certain collectors under various conditions, indicating the possibility of classifying the ice formation into well defined groups, based on the shapes of the accretion. Theoretical investigations on the energy balance of freezing water on cylinders exposed to airstreams containing supercooled water droplets, along the lines indicated in paragraph 5 (see, for instance, References 5 and 21) point to the possibility of satisfactory explanation of the physical processes associated with each one of the characteristic types of ice accretion shapes.

This new approach to the problem of ice classification was started by Bartlett and Dickey (Reference 1) who observed and classified ice formation on jet-engine guide vanes. They found that, when the ice deposited on a collector has reached a thickness sufficiently great as compared with the size of the collector, the ice accretion reaches a stable form which is independent of the shape of the collector. This stable form presents a definite shape which depends only on the given icing conditions. These facts have received further consideration in Reference 5 and have also been firmly established in experiments carried out in the NAE (unpublished). It can be concluded from these results that, although there is a continuous transition from one characteristic pattern to another, the variation of icing conditions being continuous all shapes of ice formation on small collectors could be classified into three basic types as indicated in the following table:

Shape	Designation			
	References 1 and 21	Reference 5	NAE (unpublished)	Tentative reporting term
 Greatest width at the base, diminishing to a sharp edge	C	"Knife" or "Stream-lined"	"Knife-edged"	Sharp
 Pointed, but with a maximum width at some intermediate point between the leading edge and the surface of the collector	B	"Inter-mediate"	"Spearhead"	Blunt
 Leading surface flat or concave	A	"Mushroom"	"Mushroom"	Mushroom

Each characteristic pattern corresponds to a definite type of heat balance which takes place within certain values of the air temperature and/or the rate of catch. The three steps could be schematized as follows:

If the temperature and/or the rate of catch is sufficiently low, all drops freeze upon impact. The deposition of successive layers will follow the shape of the trajectories of the water droplets, giving finally a sharp leading edge at the level of the stagnation point. The shape of the ice will be, therefore, of the type called "sharp" in the table, and its appearance will be opaque (rime) due to the entrainment of air between drops.

For higher temperature and/or rate of catch, not all the water freezes on the surface of the cylinder. If the part of the local catch which freezes in the region where it impinges (called "freezing fraction" after Reference 1) is high enough, a small amount of water will actually run on the surface of the cylinder and it will be frozen near either side of the stagnation point. The ice accretion will have the shape named "blunt".

If, under the latter conditions, the freezing fraction is sufficiently small, a major part of the water will move away from the stagnation point, increasing the deposition on either side and leaving a liquid film which will spread on the surface of the collector, and part of which will finally be shed into the wake. A mushroomed form of ice will result, and the appearance of the ice will be translucent (glaze) since the sheet of water prevents the entrainment of air.

Theoretical considerations based on the work of Messinger (Reference 16) and Tribus (Reference 21) permit the prediction of conditions under which each type of ice accretion will occur. In actual practice, there is, as should be expected, a great deal of variation in shape within each group, and the dividing line between one class and the next is difficult to establish. The classification seems, however, to be entirely satisfactory for practical purposes.

7.- CONCLUSIONS

The present status of theoretical and experimental work on the icing problem, briefly reviewed above, gives solid grounds for the following conclusions:

a) Ice classifications, based on physical appearance, however detailed and however sound from a physical viewpoint, will not solve the problem of collecting significant data for either operational or theoretical uses.

b) It appears that a classification based on the shape of ice formation on small collectors would simplify the task of the observer and provide information which has important bearings upon the physics of the process.

c) Standardization of an observing instrument, for observations on board commercial aircraft, is of paramount importance as a means of systematizing data collected on a comparable basis.

d) It appears to be possible to have a simple observational code, based on measured rate of accretion and geometrical configuration of the accretion on a standard instrument, which will be suitable for operational use.

e) Whereas the selection of the standard instrument for operational use has to be guided by simplicity of operation and maintenance, as well as low cost of installation, it will be still necessary to continue with special research projects which, using more advanced techniques of observation, will render more precise results for use in theoretical investigations within the field.

f) A critical revision of the data available on water content, drop sizes and drop distribution within clouds seems to be necessary. Conclusions drawn on the basis of observations taken with rotating cylinders, now appear, unwarranted, in the light of the discussion referred to in paragraphs 5 and 6.

g) The accumulation of new observational material obtained with new techniques will greatly help the understanding of the problem of cloud physics connected with ice formation.

8.- ACTION PROPOSED TO THE MET DIVISION, FOURTH SESSION

The adoption of a standard instrument to measure and report icing on board commercial aircraft. The NAE "hot-rod" is suggested as the most economical and practical for universal use.

The adoption, on an experimental basis, of a reporting code based on:

a) the shape of ice formation, and

b) the amount deposited over a certain period of time.

The following structure is suggested for figure code form (as I_C in the POMAR Code), corresponding abbreviations being necessary for reporting in the AIREP form:

0	None	
1	-)	
2	-)	
3	-)	Sharp
4	-)	
5	-)	
6	-)	
7	-)	Blunt
8	-)	
9	Mushroom	

(Dashes should be replaced by figures corresponding to either cm per minute or any other convenient unit).

The maintenance of the present system of reporting ice formation as "light", "moderate" and "severe", in accordance with the definitions adopted by the First Air Navigation Conference, in combination with the system suggested above, as a means of gaining experience regarding the effect on each particular type of aircraft of known conditions.

The use of a combination of "hot" and "cold" (unheated) types of ice accretion instruments, as suggested by NAE (references 8 and 10) for research purposes, in order to obtain reliable information on atmospheric parameters under conditions of high water content.

The re-evaluation of data available in the literature in the light of present knowledge on the limitations of the ice accretion instruments used in each.

The encouragement of theoretical studies in cloud physics, aiming to improve the present techniques used in forecasting ice conditions.

9. - ACKNOWLEDGMENTS

The kind co-operation of the National Advisory Committee for Aeronautics (United States of America) and the National Aeronautical Establishment (Canada) for providing information on most recent research, and that of the latter in providing an opportunity for further discussion, is gratefully acknowledged

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- END -

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