Canadian Research in the Field of Helicopter Icing

By J R STALLABRASS
B SC , M C A I
(*National Research Council, Ottawa*)

A Paper presented to the Helicopter Association of Great Britain in the Library of The Royal Aeronautical Society, 4 Hamilton Place, London, W 1, on Friday, May 9th, 1958, at 6 p m

PROFESSOR J A J BENNETT (*Chairman, Lecture Committee*) *occupying the Chair*

The CHAIRMAN, in opening the meeting, said that the paper, which Mr Stallabrass had come over from Canada to present, dealt with a very important subject in the helicopter field, having as a practical objective the eventual achievement of all-weather helicopter operation The National Research Council of Canada had been studying the problem of aircraft icing long before it was necessary to devote attention to the special problems of helicopter de-icing, no doubt the climate in that part of the world having had something to do with this!

Mr Stallabrass had served in the Royal Air Force from 1941 to 1947 and had experience as a pilot with Coastal Command in anti-submarine operations Later, he took an honours degree at London University in electrical engineering and worked for a year on guided missiles with the General Electric Company In 1952 he went over to Canada, where he worked on various aspects of icing research at the low temperature laboratory of the National Research Council He was now Project Engineer on helicopter de-icing The Association was much indebted to him for undertaking to give members the benefit of his experience in this field of Canadian research and to the National Research Council for their kind co-operation

MR J R STALLABRASS

SUMMARY

This paper opens by discussing the background to the present work in helicopter icing research being carried out by Canada's National Research Council, and the unique flight test facility used to assess the effect of icing on helicopter performance and to evaluate icing protection systems The nature of these effects are described and the various considerations discussed, and in particular the application of electro-thermal de-icing to the main rotor blades

It is concluded that a solution to the helicopter icing problem is now within sight, thanks in some measure to the work of the National Research Council

INTRODUCTION

By reason of Canada's northern climate, with freezing temperatures prevailing at ground level during five months of the year, the problem of icing is of particular importance to air transport in Canada, and as such, has merited the attention of the Aeronautical Laboratories of the National Research Council since as early as 1935 From that time the National Research Council has kept well to the forefront in icing research and particularly in de-icing technology, first with the development of electro-thermal propeller de-icing and later in extending the principle of cyclic ice shedding by electro-thermal means to aircraft wings

More recently it had become abundantly clear that, with helicopters continually assuming more varied and diverse duties and with progress being made towards autostabilization and suitable blind flying instrumentation, the day was not far distant when all-weather capabilities would be as essential to helicopters as it is to fixed-wing aircraft Accordingly, about 5 years ago, the N R C commenced a programme to investigate the effects of icing on helicopter performance and to develop a suitable icing protection system for helicopters

For those not too familiar with the icing problem it may not go amiss if I say a few words about the phenomenon of ice formation on aircraft (Those to whom this is not new will have to bear with me for a few moments)

This phenomenon results from the impingement of super-cooled cloud droplets on all of the forward-facing surfaces The resulting impact upsets their unstable supercooled state and the liquid droplets return to a stable state at the freezing temperature of 0°C by forming a mixture of ice and water, the exact proportions depending upon the degree of supercooling Further heat transfer processes such as convective and evaporative cooling result in some or all of the water in the mixture freezing, depending on the ambient temperature, the speed and the mass of water droplets intercepted For a detailed mathematical treatment of this process see Ref 1

It is reasonable to suppose that this build-up of ice on the leading surfaces will result in adverse aerodynamic effects, the magnitude of which will vary inversely as the scale of the surfaces, a given thickness of ice representing a proportionately greater distortion to the geometry of the smaller scale surfaces Furthermore the rate of icing varies inversely with the scale since, owing to the smaller radius of curvature of the streamlines, the small scale surface has a greater " catch efficiency," i e , ratio of water intercepted to the total water present in the volume of air swept out by the surface

These considerations lead to the conclusion that the rotor blades of a helicopter will be far more critical than the wings of an aeroplane with respect to loss of efficiency due to the presence of ice It also follows that rotor blade icing on a helicopter will be of paramount importance relative to fuselage icing, since, in addition to scale effects, it sweeps out a much greater specific volume of air by reason of its added rotational speed

These conclusions have been borne out by actual flight tests of helicopters in icing conditions

EARLY FLIGHT TESTS

The first attempt to investigate the effect of icing on helicopter performance in Canada was in the winter of 1951-52 during cold weather trials of a Bristol Sycamore helicopter carried out at the R C A F C E P E Climatic Detachment at Edmonton on behalf of the British Ministry of Supply A fire hose equipped with a fog nozzle simulated icing conditions at a temperature of —30°C by spraying water from the top of the control tower The helicopter attempted to hover in the spray, but no ice formed on the rotor blades It was thought that the spray never reached the blades because of the turbulence created, although one observer recalled that the fog nozzle had proved unco-operative and that most of the time a hail shower was produced instead of an icing cloud

Nevertheless, in spite of failure, this crude test was the germ from which sprang the now familiar concept of actual helicopter flight in simulated icing conditions

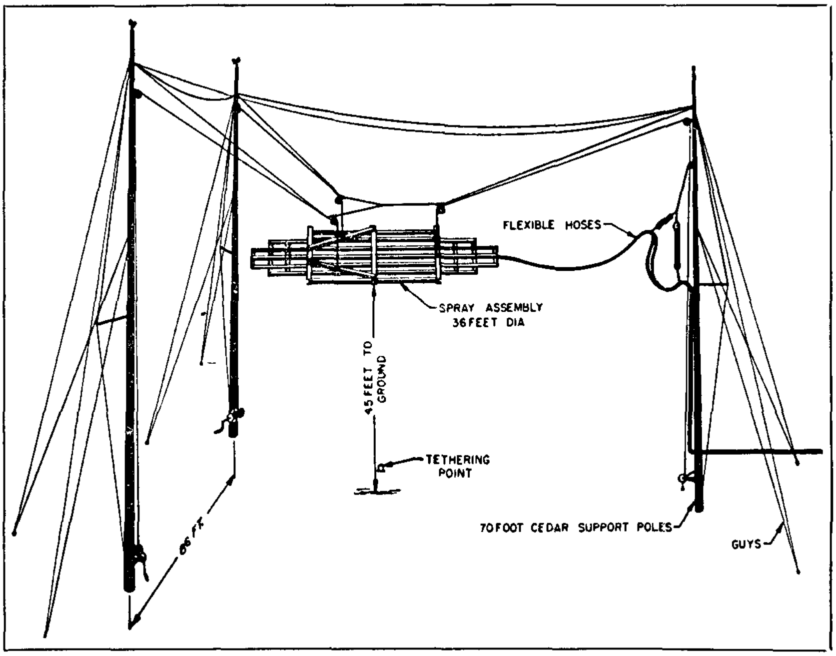


Fig 1 Spray Rig used in early Helicopter Icing Tests by N R C

In the early part of 1954, the National Research Council at Ottawa constructed a rather more refined rig than that used at Edmonton 2 years earlier This consisted of a circular framework supported horizontally in the open between three poles (Fig 1) On this framework were mounted 151 spray nozzles

This seems to be a convenient place to correct some obvious and apparently quite widespread misconceptions as to how a simulated icing cloud is produced I have seen it variously stated that we merely produce a cloud of steam or that we just spray warm water, and other explanations In actual fact we adopted and modified the method used in icing wind tunnels whereby water is atomized by compressed air in a suitable spray nozzle (Ref 2) The atomized water droplets are carried by the airstream and cool down to a temperature somewhat below the ambient If this is below freezing a supercooled cloud is obtained, simulating closely natural conditions Considerable research and development work has been done in England, Canada, Japan and elsewhere to produce suitable nozzles which give droplet size spectra similar to those experienced in natural atmospheric clouds

Because of the quantity of compressed air that would have been necessary to atomize the large mass of water to be sprayed by this rig, we found it necessary to use steam as the atomizing medium, since this was readily available in the quantities required Unfortunately this has the disadvantage of injecting into the cloud of atomized droplets a large number of very small condensed steam droplets which upsets to some extent the desired droplet size spectrum , more serious though, these very small droplets reduce visibility in the cloud to only a few feet On the other side of the balance sheet are the advantages of not having to pre-heat the water to prevent

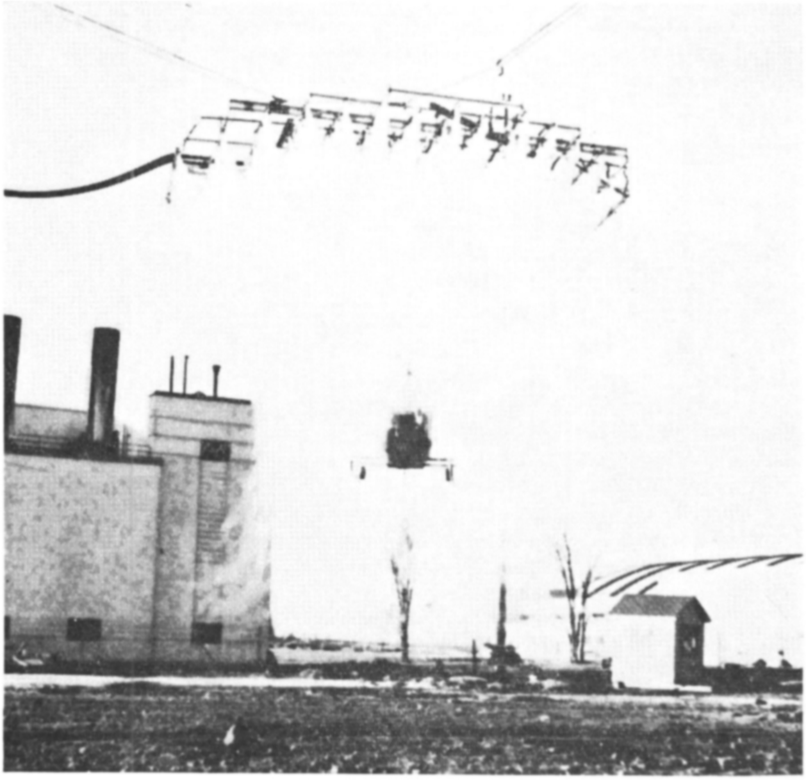


Fig 2 Bell HTL-4 Helicopter flying under early Spray Rig

premature freeze-out of the droplets and of using the heat of the steam to prevent the freezing up of the exterior plumbing of the rig

This rig was ready for operation as the winter came to a close and only a few days of actual tests were possible before temperatures rose above freezing For these tests (Ref 3) a Bell HTL-4 (type 47D) was used (Fig 2) The helicopter's high degree of susceptibility to icing was clearly illustrated, for it was found that less than $\frac{1}{8}$-inch thickness of ice on the main rotor blades was sufficient to force the helicopter to the ground This amount of ice was picked up in about one to two minutes The main rotor blades were equipped with stick-on type electro-thermal de-icer pads The maximum power density obtainable was 13 4 Watts per square inch, and this was found insufficient to overcome irregularities in the heating intensity of the conducing rubber element used in these pads These tests therefore were rather a failure so far as the de-icing aspect was concerned

PRESENT FACILITIES

This spray rig had several serious disadvantages, not least being that of flying within such a birdcage in zero visibility Even though a tethering rope was attached to the helicopter to prevent it climbing into the sprays, it was, to say the least, rather a hazardous operation !

As a result a new structure was built (Ref 4) which overcame the objections to the earlier rig, but which permitted the helicopter or, if so equipped, it's icing protection system to be tested in free flight

This rig is illustrated in Fig 3 It consists of a frame 75 feet wide and 15 feet high on which are mounted 161 spray nozzles In operation this frame is hoisted to the top of a 70-foot steel mast and can be rotated through 360° to position it normal to the wind direction Water and steam are supplied through flexible rubber hoses, and all controls and instruments are housed in a hut at the foot of the mast

Unlike the earlier device, this rig relies on the wind to carry the cloud it produces downwind and clear of the rig The helicopter thus hovers in the cloud about 100 feet from the mast and does not require to be tethered in any way By hovering just in the base of the cloud reasonable downward visibility is assured, although the rotor blades and most of the fuselage are enveloped in cloud Occasional gusts do completely obscure visibility, but usually not for more than a few seconds at a time

Since this rig came into service at the end of January 1955, tests to determine the effect of icing on performance and handling, and the extent to which icing protection might be necessary were carried out on a Bell HTL-4 and a Sikorsky H04S (civil designation S55) De-icing tests have been done on protective systems on a Bristol Sycamore on behalf of the Ministry of Supply, a Bell H13-H in co-operation with Bell Helicopter Corp on behalf of the U S Navy and, on our own behalf, a Bell 47G-2

Whilst on the subject of test facilities, it might be worth while comparing the N R C facility with other helicopter icing test facilities To my knowledge there are only two others, both in the United States One is situated at the top of Mount Washington, a 6,000 foot peak in the State of New Hampshire, and is part of the icing test facility operated by Aeronautical

Icing Research Laboratories, Inc on behalf of the U S Air Force The other is the Climatic Hangar at the Eglin Air Force Base in Florida

At both of these facilities the helicopter is secured firmly to the ground, but whereas at Eglin Field icing conditions are simulated by an overhead spray rig in an artificially refrigerated hangar, on Mount Washington natural cloud icing conditions are used whenever they prevail—which is not infrequent during the winter months

I will list, as I see them, the advantages and disadvantages of these facilities

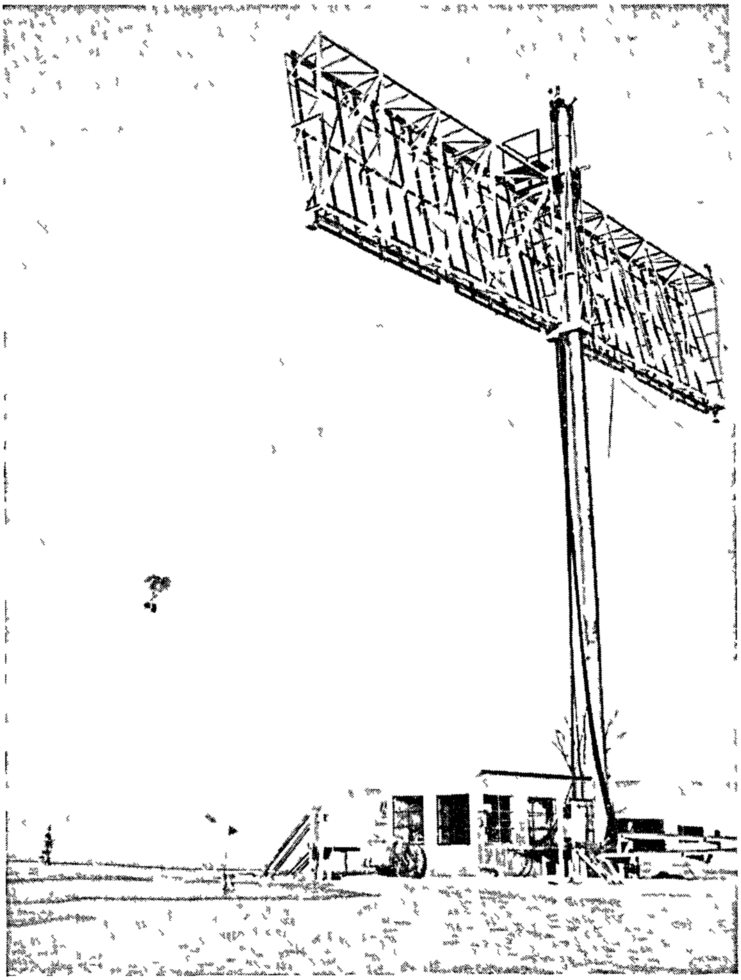


Fig 3 Present Spray Rig in operation

The Mount Washington Facility

Advantages The only real advantages seem to be those of natural icing conditions and the ability, given the right conditions of wind, of testing under higher flight speed conditions At higher windspeeds it is also possible to measure with reasonable accuracy the icing conditions (i e the liquid water content and droplet size)

Disadvantages The greatest disadvantage of this facility are those of getting equipment to the top of this mountain in winter time and of the rigourous and most difficult working conditions, often equipment has to be dug out of several feet of snow before a day's tests can commence Windspeeds of 120 m p h are not uncommon up there and then work is brought to a standstill As for the tests themselves, there is the disadvantage that the helicopter is tied down, and therefore flight conditions have to be simulated by arbitrary control settings In the past, I think, the results have been rather unrepresentative of those for actual flight, and for the most part abnormally large accretions have been allowed to build up on the blades which could not have been tolerated in flight Due to their large mass, these accretions are shed more easily and tend to present the de-icing system under test in a rather optimistic light

Eglin Field Climatic Hangar

Advantages The great advantage of this facility is that it is not dependent upon the vagaries of weather, since both temperature and water droplets are produced and controlled artificially It has the advantage as far as the test personnel are concerned that they can soak up the Florida sunshine in leisure moments

Disadvantages It has the disadvantages, due to the helicopter being tied down, already ascribed to Mt Washington, but is less versatile as only hovering conditions can be simulated I feel sure that the icing conditions are modified by recirculation within the hangar of ice crystals, thus causing some premature freeze-out in the sprays , this would be of greater consequence in the testing of anti-icing rather than de-icing systems Apart from this, it should be relatively easy to determine and control both liquid water content and droplet size

The N R C Flight Test Facility

Advantages The over-riding advantage of this facility over the other two is that of testing under actual flight conditions , when there are as many variables involved as in the case of helicopter flight I consider there is no real substitute, except perhaps at disproportionate cost and effort The conditions under which test personnel work is infinitely better than on top of the mountain, in fact on a nice sunny winter's day it can be quite pleasant and if the wind chill begins to make itself felt we have a warm test hut into which to retreat I won't deny that the weather can be quite miserable at times too The helicopter itself is stored and serviced in a heated hangar, and this is in itself an enormous advantage, as anyone who has operated aircraft in northern winter conditions knows

Disadvantages I have to admit to some disadvantages ! The list seems rather long, but this is because of my first hand knowledge, whereas the other two facilities undoubtedly have disadvantages of which I am unaware In the first place of course we are subject to the whims of nature since we rely on her to provide the refrigeration and airspeed We normally expect suitable sub-freezing temperatures from December until about the end of March, however we were dealt a dirty blow this past winter and were only provided with four suitable days throughout the whole of March and a warm spell in late January also helped to curtail testing The air-speed range is limited to 5 to 30 m p h , the lower limit because the cloud is not carried sufficiently clear of the rig and the upper limit being dictated by wind load limitations on the spray rig A gusty wind can make it difficult to keep the helicopter in the cloud Evaporation and diffusion from the edges of the cloud tend to create lack of uniformity of water concentration across it, and this together with some necking of the cloud through the rotor disc tends to reduce the icing intensity towards the blade tips This perhaps results in slightly optimistic results so far as performance in icing is concerned, but is not considered a serious disadvantage I have already made mention of the poor visibility in the cloud resulting from using steam for atomization, and the modification to the droplet size spectrum so produced Another disadvantage is the difficulty in measuring liquid water content and droplet size whilst tests are in progress, and we have had to resort to prior calibration , we are fairly confident about the droplet size calibration, but the liquid water content at the point at which the helicopter is flying is determined not only by the water and steam flow settings, but also by the rate of evaporation and diffusion of the cloud which in turn depends on a number of factors including wind speed, gustiness, temperature, relative humidity, distance of helicopter from the nozzles and also the ability of the pilot in maintaining

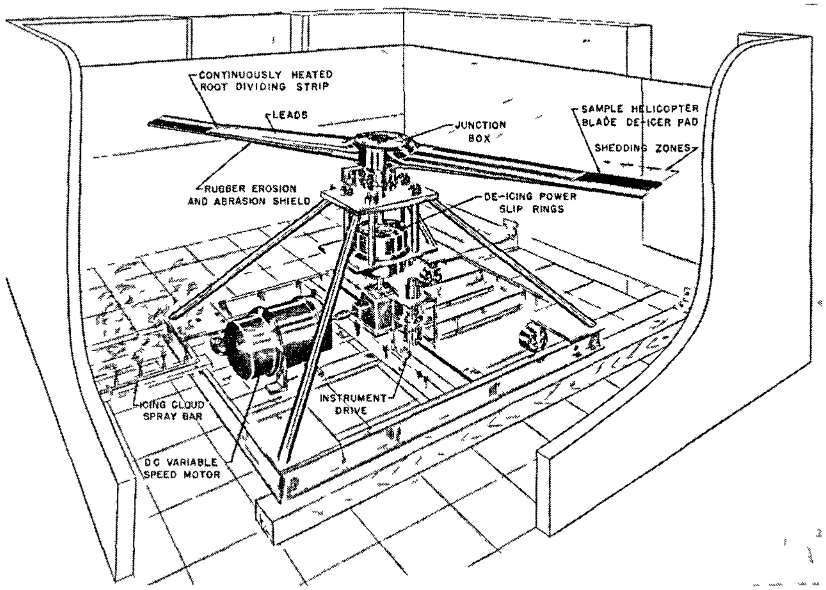


Fig 4 Whirling arm for testing samples of Helicopter Rotor Blade de-icer pads installed in 10 ft × 10 ft cold chamber

a steady position in the cloud We try to take some of these factors into account when setting up the water and steam flows to give a certain liquid water content, but wherever possible we like to cross check this after the flight by working backwards from the thickness of ice accreted on the stagnation line of the main rotor blade An example of this type of analysis is presented in the appendix

Before I leave the subject of test facilities altogether, I will mention briefly a whirling arm rig (Fig 4) which is installed in one of the cold chambers of the Low Temperature Laboratory This apparatus was designed to compare and evaluate suitable materials and techniques used in the construction of helicopter electro-thermal de-icer pads Sample pads are mounted at the outer ends of the 9-foot diameter rotor, and icing conditions are simulated by spray nozzles positioned beneath the rotor disc In this way the electrical energy required for de-icing can be controlled closely, and the ice shedding process can be observed visually by means of stroboscopic lighting

THE EFFECTS OF ICING ON HELICOPTER PERFORMANCE AND HANDLING

I will not deal with the form, extent or occurrence of ice accretion on the blades or other parts of the helicopter, except in as far as it may be necessary to introduce them when dealing with their effects or with the requirements of a protective system For a discussion of them I would refer you to Ref 4 or Ref 5

Attention has been focussed primarily on icing as it affects the aerodynamics of the main rotor blades, but let me interpolate here for emphasis that icing on the tail anti-torque rotor may have equally serious adverse effects I will return to this later and deal first with the main rotor

It goes almost without saying that the primary effect of an ice accretion on the main rotor blades is an increase in profile drag The pilot discerns this by having to open the throttle to maintain the r p m at a fixed value This opening progressively increases as the ice accretion builds In fact we have found under quite moderate icing conditions that a rate of increase of manifold pressure of 2 inches per minute is by no means abnormal Quite obviously at such rates it is not long until maximum boost is reached and the helicopter is forced to land

The ice accretion, contrary to a fairly widely held misconception, has negligible effect on the lift coefficient at normal angles of incidence We have demonstrated this by installing a collective pitch indicator in both a Bell 47 and a Sikorsky H04S (S55) , no significant increase in pitch was required to maintain height even as such diverse types of ice accretion built up as illustrated in Fig 5 The misconception of decreased C_L may have arisen because the lift-drag ratio is reduced owing to the increased drag The maximum lift coefficient is however reduced and increases the possibility of blade stall, so that the pilot should exercise a little more care in executing manoeuvres when in icing conditions

The pilots involved in our tests were unable to detect any control force changes ascribable to ice on the blades, and so we assume that changes in moment coefficient are negligible

Besides aerodynamic effects caused by ice on the rotor blades, there are

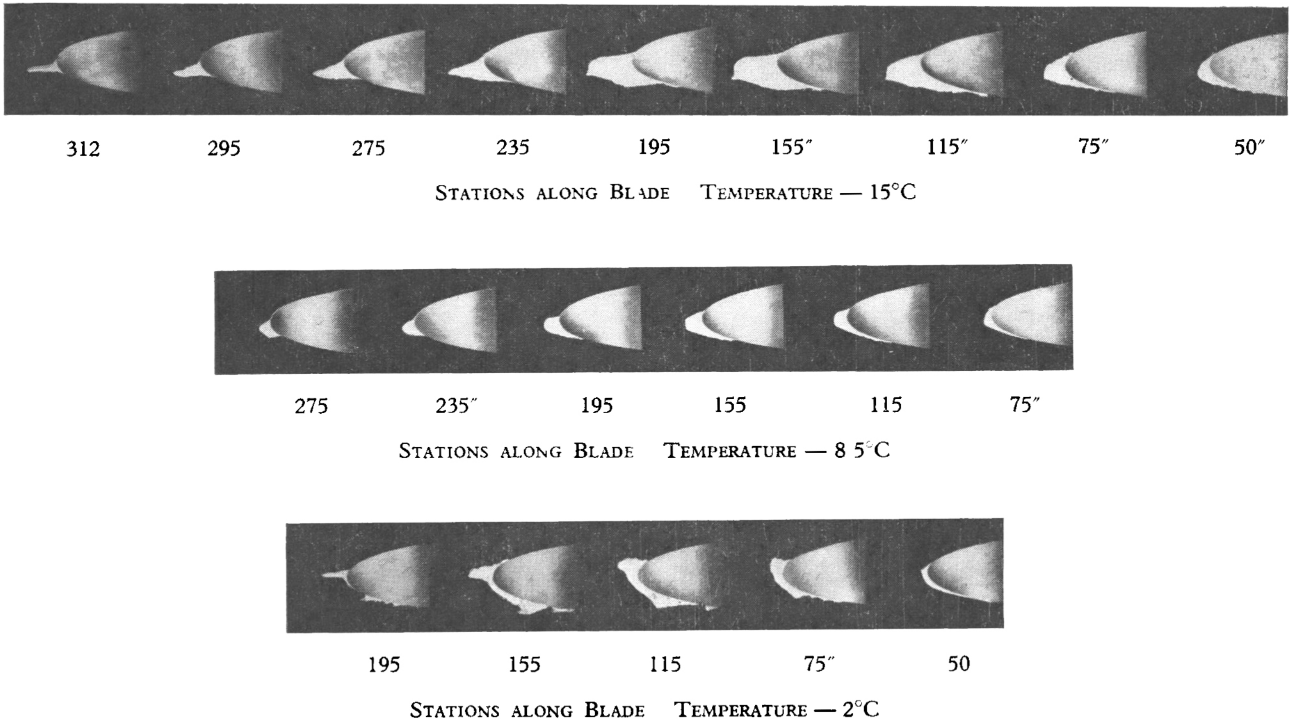


Fig 5 Rotor Blade Ice Formation at various Temperatures

two purely mechanical effects which occur when sufficient ice has accreted on the blades to cause self-shedding, i e, when the centrifugal "g" forces on the ice exceed its adhesive and cohesive forces and some of the ice is thrown off The first of these secondary effects is the damage that may be caused by large pieces of flying ice

The second effect, due to uneven self-shedding of ice from the blades, is that of vibration It seems that self-shedding seldom takes place entirely symmetrically, possibly due to variations in surface texture or in cleanliness The result is vibration of rotor frequency which may on occasions be rather unpleasant, but seldom, in our experience, severe enough to be termed unacceptable

I drew attention earlier to icing on the tail rotor This, due to its smaller scale although having about the same tip speed, is a more efficient ice collector than the main rotor However, its contribution to the total drag effect is probably relatively small, but owing to centrifugal "g" forces roughly five times greater the tail rotor is considerably more susceptible to self-shedding than the main rotor For some obscure reason too, the tail rotor has proved itself more prone to asymmetrical self-shedding, as illustrated in Fig 6

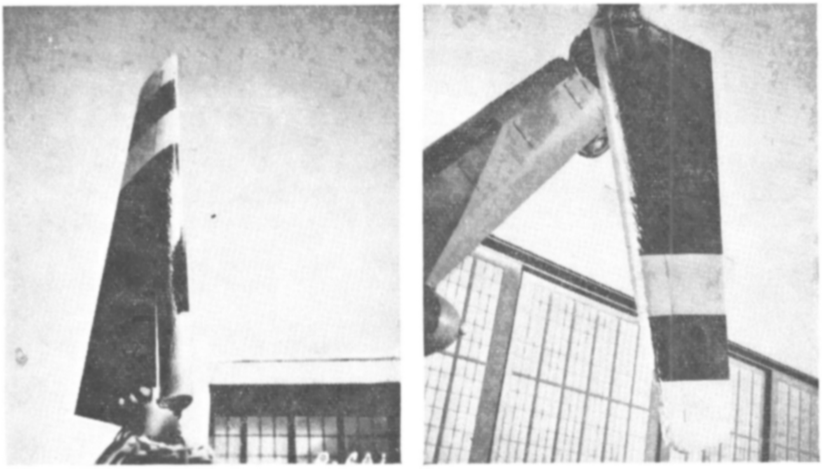


Fig 6 Asymmetrical self-shedding from the Tail Rotor

This results in rather serious vibrations due to the unbalance and the danger of damage to the main rotor blades and stabilizers by the ice which is thrown off with considerable force For these reasons tail rotor icing may be as great a hazard to the safety of the helicopter as icing on the main rotor

As evidence of this, on several occasions during the tests with the Sikorsky helicopter, the pilot landed the machine in a hurry fearing structural failure of the tail cone due to the vibration set up This was the pilot's own assessment of the situation, but whether he tended to be overcautious or not, it serves to illustrate its seriousness

I won't dwell long on the effects of icing on other parts of the helicopter, since they are, in general, of less importance or present little that is different from icing on fixed wing aircraft An exception is the rotor blade pitch control and droop restraining mechanisms These, being located close to the rotor axis, are in an area of low water catch and present little problem in icing encounters of short duration, but serious consequences may result from extended encounters at higher flight speeds For instance, ice on the sloppy link of the main servos of the S-55 may cause serious control difficulties, and we ourselves have experienced difficulty at the completion of icing flights with ice on the droop stop mechanism

METHODS OF ICING PROTECTION

The foregoing remarks indicate a definite need for icing protection of the main and tail rotors and the rotor hub mechanism if all-weather capabilities are to become a reality To ensure the pilot has good visibility at all times, windscreen anti-icing is also necessary

How is the desired protection to be applied ? There are two different principles available, one being anti-icing, the aim of which is to prevent any ice from forming, and the other de-icing, which allows ice to form but sheds it at intervals before it can have any serious effect

These principles may be put into effect in a variety of ways Table I summarizes some of the possible methods that may be employed and a brief discussion of them follows

TABLE I

Item to be Protected	*Reasons for Protection*	*Methods of Protection*
Main rotor blades	1 To prevent excessive increase in blade drag 2 To prevent rotor unbalance due to asymmetrical self-shedding of ice 3 To eliminate the danger inherent in self-shedding large pieces of ice	1 Thermal anti-icing 2 Chemical anti-icing or de-icing 3 Mechanical de-icing 4 Thermal de-icing (*a*) Hot gas (*b*) Electrical
Tail rotor blades	1 To prevent damage due to thrown ice 2 To eliminate serious vibrations due to unbalance	1 Chemical anti-icing 2 Electro-thermal de-icing
Windshields	To provide visibility, particularly during landing	1 Alcohol spray with windscreen wipers 2 Electrical anti-icing
Stub wings and stabilizers	To prevent drag increase	Fixed wing practice
Rotor hub mechanism, droop stops	To prevent control difficulties	1 Cleaner design 2 Covers and baffles to prevent direct impingement on vital moving parts

Main Rotor Blades

(1) Thermal anti-icing This in many cases appears attractive owing to rotor blade spar construction and the availability of quantities of hot air from turbine power plants The greatest deterrent to its use appears to be the very high root end temperature required to ensure adequate surface temperature at the tip for satisfactory anti-icing

(2) Chemical anti-icing or de-icing I regret that my knowledge of these systems as they might be applied to rotor blades is limited , I am therefore unqualified to pass any comment on this method I hope to rectify this deficiency before I return to Canada

(3) Mechanical de-icing The pneumatic pulsating boot is the only method worthy of consideration, and even this is not too promising by reason of the installation drag, the small scale involved, and the distortional effect of centrifugal force on the non-rigid boot

(4) Thermal de-icing Economies in thermal energy are afforded by using a de-icing instead of an anti-icing method, and this makes such a method particularly attractive in the case of the helicopter where engine power is, in general, at a premium A hot gas system has much the same advantages and disadvantages as the hot air anti-icing system, but in addition thermal lags and the complications of fast-acting hot air valves make it unattractive By far the most attractive method is that of electrical de-icing, since heat may be applied efficiently and uniformly and with precise regulation, while the control and distribution of power to the various shedding areas is also comparatively simple The heating element does not interfere with the basic blade structure, and since the heating takes place close to the blade surface, thermal lag is much less and permits the necessary rapid heating and cooling of the surface for shedding without runback

Tail Rotor Blades

Owing to the location and scale of the anti-torque rotor, only two methods appear at all practical

(1) Chemical anti-icing appears somewhat more attractive on this rotor than the main rotor, especially since an anti-icing method is more desirable in this aplication

(2) Electro-thermal de-icing This is the most readily implemented method since a wealth of knowledge already exists in regard to propeller de-icing which is directly applicable to the tail rotor

Windshields

Two well tried methods from fixed wing practice are available for anti-icing, these are an alcohol spray in conjunction with wipers and an electrically heated glass panel The latter method is the more elegant

Stub Wings and Stabilizers

Icing on these components is likely only to be a problem on configurations such as the Rotodyne rather than on more conventional helicopters Here the designer may resort to fixed wing practice about which plenty has been written, so I'll only comment here that the area of droplet impingement is likely to be very much greater than in the fixed wing case owing to the wide range of speed and incidence possible

Rotor Hub Mechanism

This includes pitch control linkages, servos, and blade droop stops The only practical means of protection for these items is to prevent any droplet impingement on them This may be achieved by cleaner design to eliminate protruding parts as far as possible, and where this is not possible to protect them from direct impingement by baffles, flexible rubber covers and the like

REQUIREMENTS FOR A MAIN ROTOR DE-ICING SYSTEM

Not only for the practical reasons mentioned above, but also for experimental convenience, the National Research Council adopted the principle of electro-thermal de-icing as the means of investigating the requirements of a main rotor icing protection system

Coverage

To determine the coverage required the area of droplet impingement was calculated for various flight conditions It was decided that the basis for design should be determined by the advancing blade since, although the incidence is higher on the retreating blade, the relative velocity and the rate of icing is greater on the former It was also concluded that, although the extent of impingement on the lower surface is considerably greater, the upper surface should be favoured because of the more serious aerodynamic effects of ice on the upper surface

With regard to spanwise extent, the rotor tips were considered of greatest concern because of their higher velocity (giving greater rates of icing) and the greater distance from the hub (giving correspondingly larger power losses and unbalance effects) Although kinetic heating will prevent ice formation at the tip at higher ambient temperatures, it will not do so at lower temperatures (below about —8°C, but varying with tip speed and icing severity), and so protection to the extreme blade tips is necessary At the inboard end it seemed unnecessary to protect the blades inboard of the point of flow reversal at cruising conditions, because the low relative speed results in low rates of icing

The rubber de-icer pads used in the early test 4 years ago therefore were designed with a coverage of about 30 per cent chord on the upper surface and about 40 per cent on the lower surface and extended from 15 per cent radius to the tip

Subsequent studies of the ice accretions on Bell and Sikorsky helicopters showed that the chordwise extent of ice accretion was less than had been expected, particularly on the upper surface I don't wish to imply that the original calculations were wrong, but rather that, since ice accretion is a continually changing process, the initial area of impingement does not necessarily represent the final area of ice accretion, in addition kinetic heating and blow-off effects have a modifying influence, particularly towards the blade tips

The actual ice extent was found to be less than 10 per cent chord on the upper surface and, on the lower surface, to be less than 30 per cent chord outboard of about 50 per cent radius Inboard of this radius frost-like formations occasionally extended to the trailing edge on the lower surface, but these were considered to have negligible adverse effects at these radii

The effects of kinetic heating on spanwise extent were confirmed, but the rate of accretion was found to be less than expected towards the tips probably due to water blow-off Nevertheless protection to the extreme blade tips is still considered necessary to cope with the lower temperature conditions, but need extend no further inboard than about $\frac{1}{3}$ radius

Spanwise vs Chordwise Shedding

Because of the relatively large area of coverage and to take advantage of the principle of cyclic de-icing, it is desirable to divide the de-icing mat up into a number of shedding areas The N R C decided on dividing up the span to provide a number of chordwise shedding areas (Fig 7) It will be easier and possibly save confusion if I refer to this as the N R C method Another way is to divide the pad into a number of span-wise strips, and this I believe is sometimes referred to as the American method

In both methods, since centrifugal force is to be used to remove the ice once sufficient heat has been applied to reduce its adhesion sufficiently, no leading edge parting or breaker strip is necessary

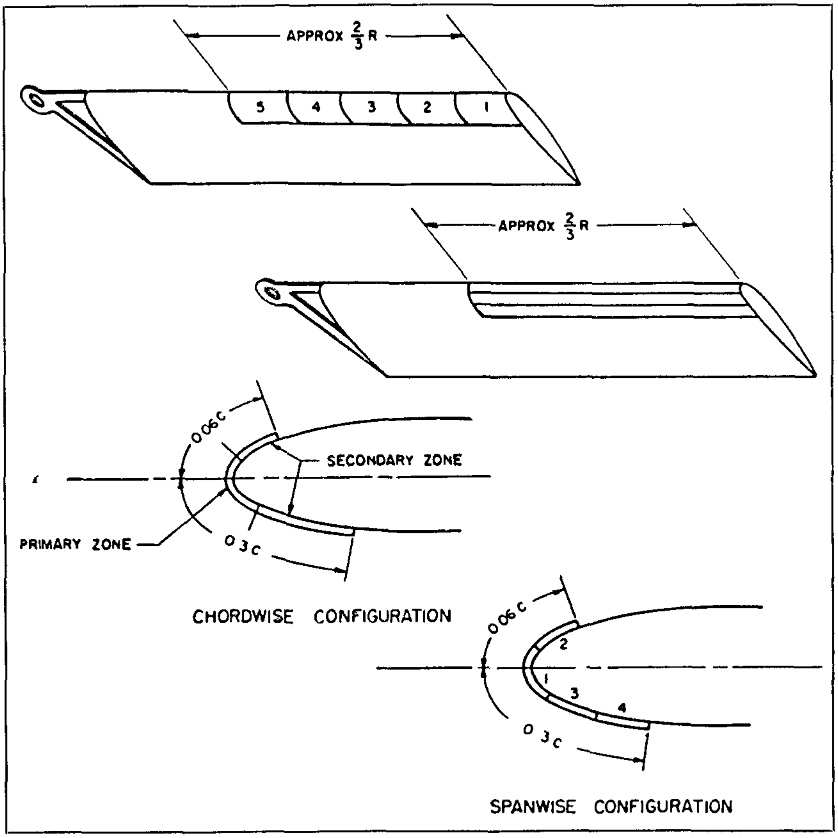


Fig 7 Main Rotor Blade de-icing pad arrangement

In the N R C method it is obvious that to avoid obstructing ice removal from adjacent segments, the sequence of shedding must be from tip to root, whereas in the American method the leading edge strip must be energized first to remove in one piece the solid bulk of the accretion, followed by the other strips in an aft progression to remove the more discontinuous secondary formations

It is convenient here to compare critically the two methods From the practical aspects of manufacturing and system installation the American method has it over the N R C method Each strip may be subdivided into three strips for 3-phase operation, all supply connections being made at the root end and a floating star connection at the blade tip By comparison, heater elements for the N R C method are more complex, especially if 3-phase operation is desired, and supply leads have to extend along the blade as far as the outermost segment resulting in additional weight We claim that the N R C method results in more efficient shedding with less chance of rotor unbalance, since the complete chordwise extent of the accretion is shed as one unit, the only restraining force being the tensile cohesive force between segments The strip method on the other hand requires the whole spanwise length of the ice accretion to be sheared when the first strip is energized unless this strip is wide enough to shed the solid leading edge ice cap as a unit In either event more energy is required and more runback is likely to be produced (rather than less as claimed in Reference 6) since in the first case the additional energy required before the ice sheds produces an excess of water at the interface which successively flows back over the remaining strips to the unheated area, and in the second case if the leading edge ice cap is shed as one piece, there is insufficient bulk remaining in the secondary feathery type of accretion for efficient shedding and it tends to melt and run back

Although in general shedding effectiveness is improved if wider and therefore fewer spanwise strips are used, less advantage is being taken of the cyclic principle, larger installed generating capacity is required and the available time between energization cycles is utilized less efficiently

Uneven shedding produced by mismatching of the heating rate of each blade or by cold spots results in unbalance At low temperatures, requiring long heat on times, the ice may not shed from one blade until several seconds after it has shed from the others, the resulting vibration is most severe and certainly unacceptable as far as passenger-carrying helicopters are concerned With the N R C method the maximum asymmetry that can occur is the length of one segment (about 3 feet), and the resulting unbalance is considerably less severe

The choice lies therefore between simpler (and cheaper) heater elements and more efficient operation

Heater Pad Design Considerations

Whichever method the user decides upon, there are certain requirements and principles in the design of the heater elements common to both

The ideal heating element is one which has zero heat capacity and in which 100 per cent of the energy flows outwards and none inwards into the blade structure on which it is mounted This is of course impossible, but the aim should always be to come as close to this ideal condition with the aid of technological progress as practical considerations permit It would be possible to get reasonably close to the ideal but for a nigger in the wood pile His name is sand and grit abrasion and he has a cousin named rain erosion If the protected blade is to be used universally from desert to arctic conditions, then a stainless steel cover of at least 0 012 inch is desirable

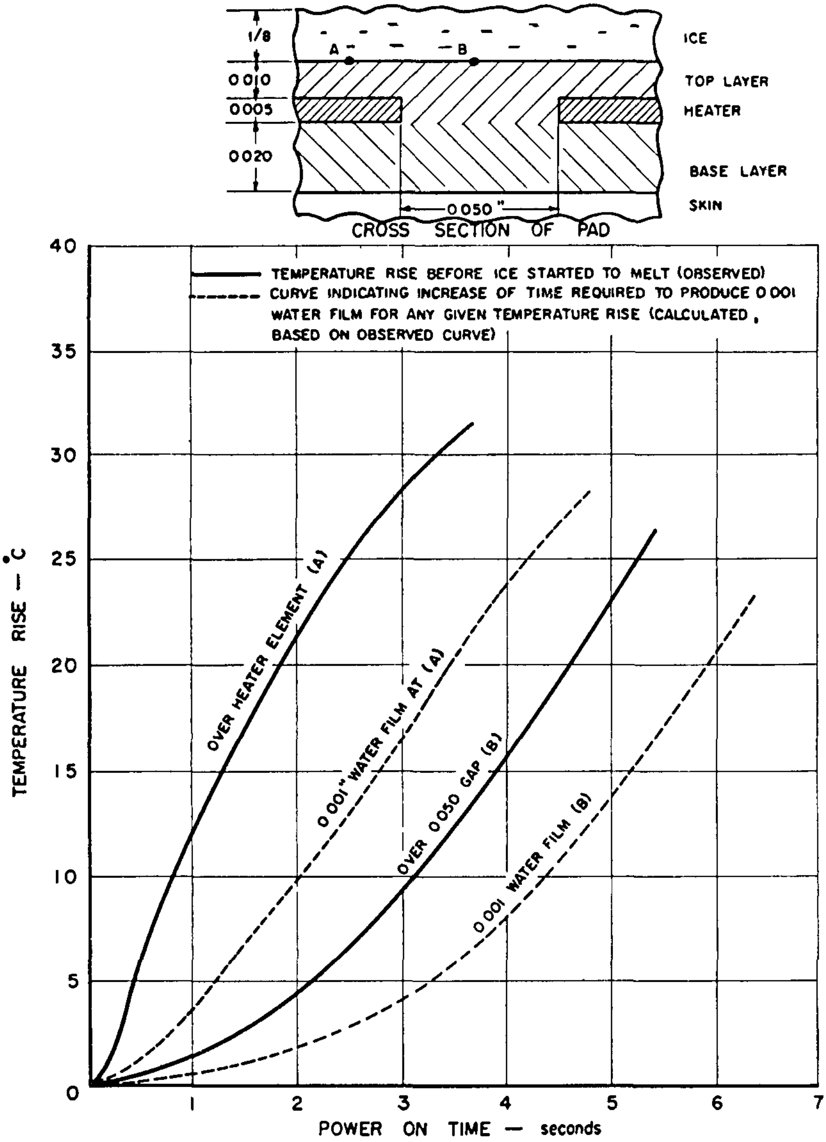


Fig 8 Transient temperature rise observed at 40 watts/sq in with ⅛ ice layer

to protect against these scoundrels, but if two types of blade are logistically acceptable, a standard blade for normal operations and a protected blade for when the icing hazard may be encountered, then a cover of about 0 005 inch may be adequate

Before we realized that we had no choice but to accept this thermal barrier, considerable effort had been put into trying to perfect as near an ideal heater as possible This effort was not wasted though, because the lessons we learnt are still applicable Briefly, the main principles are

(1) The outer electrical insulation layer (between electrical element and abrasion cover) should be as thin as possible which means that it must have a high dielectric strength , if possible it should also have a high thermal diffusivity (thermal conductivity/specific heat × density) Thicknesses of as little as 0 005 inch are possible with modern materials

(2) The electrical resistance element should be thin and of low thermal capacity It is preferably a uniform film, but if it is not and consists of strips or wires, then the gaps between the conductors should be no greater than twice the thickness of the outer insulation layer, otherwise a decided cold line will occur It is paramount to avoid such cold areas since the de-icing

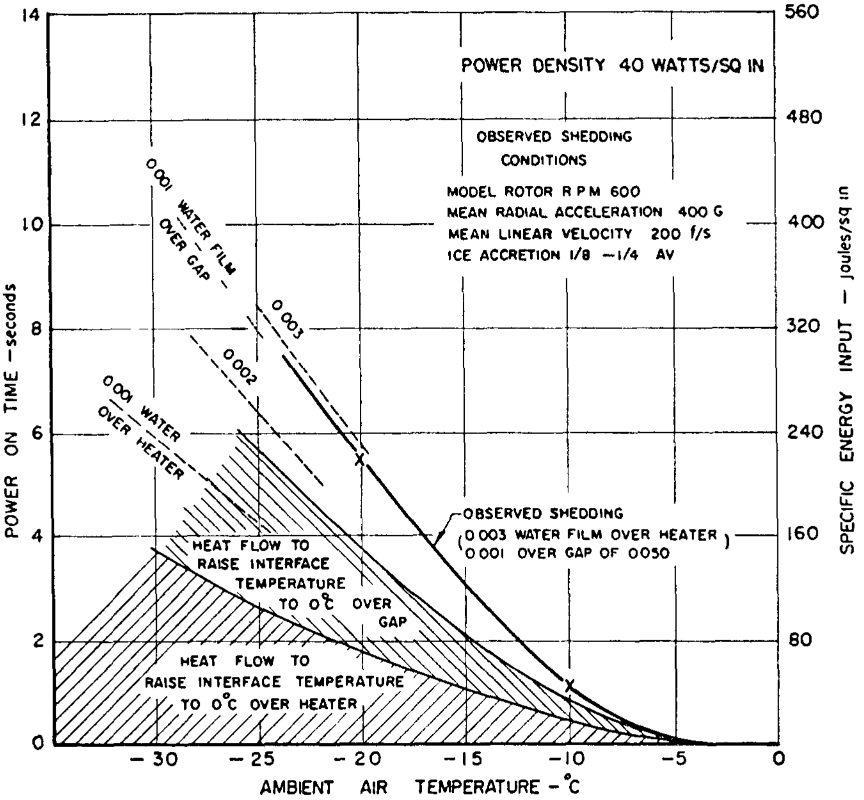


Fig 9 Specific energy and power—on time required for shedding ice from pad having gaps of 0050" between heater elements

performance of the pad as a whole is only as good as the performance over the coldest spot due to ice anchorage at this point, and the excess heat in the rest of the pad (over and above that which would be required in the absence of cold spots) only goes to produce runback Fig 8 illustrates the difference in heating rates over the element and over the gap, and Fig 9 shows the additional energy required for shedding

(3) The lower insulation layer between the electrical element and the blade structure should have a low thermal conductivity and low thermal capacity In practice it is often convenient for the upper and lower insulation layers to be of the same material, and if this is the case the lower layer should be at least twice the thickness of the upper layer to minimise the flow of heat into the blade structure

(4) The addition of a metal abrasion cover imposes a further requirement on the materials used for the insulating layers It is essential that these be rigid materials such as phenolic or polyester resins and not elastomers such as neoprene or silicone rubber, since stones, hail and shed ice can peen or dent the metal cover when it has a resilient backing and so promote electrical breakdown of the insulation or mechanical damage to the element itself Further, the use of a non-rigid backing can result in buckling and cracking of the metal cover due to blade flexing

Energy Requirements

Wind tunnel tests have shown that the use of high specific powers (greater than about 25 watts/sq in) applied for short periods of time result in fast, clean shedding with little opportunity for runback and after-freezing—essential requirements for rotor blade de-icing for the sake of maintaining dynamic and aerodynamic balance

It was shown also that the minimum energy required for shedding occurs at a specific power input which is a function of the ambient temperature , the lower the temperature the higher the optimum power density This has also been shown by an approximating analytical method used in the Low Temperature Laboratory (Fig 10) If the power is switched off prior to shedding so that the interface temperature just overshoots to 0°C, the energy required for shedding always becomes less as the specific power is increased, as shown by the broken curves Paradoxically, this reduction in energy, produced as it is by higher specific powers, actually implies reduced power requirements, and a study carried out shows that on going from 15 to 40 watts/sq in the saving in shedding power could be about 30 per cent on a helicopter rotor blade de-icer This advantage is achieved only by increasing the number of shedding zones, but it appears possible to achieve this without a resulting weight penalty, so that a real gain is achieved These results are illustrated in Fig 11 which uses the actual power-on time *vs* power density relationship obtained during the de-icing tests conducted by the Bell Helicopter Corporation at Ottawa earlier this year

Typical power-on time *vs* temperature curves obtained in the N R C de-icing tests this year are shown in Fig 12, but more test data will be required before curves can be drawn with complete confidence, these will be obtained next winter It is considered that these curves represent fairly well typical shedding times that may be expected in an electro-thermal rotor blade de-icing system, but do not necessarily indicate the best that could be achieved

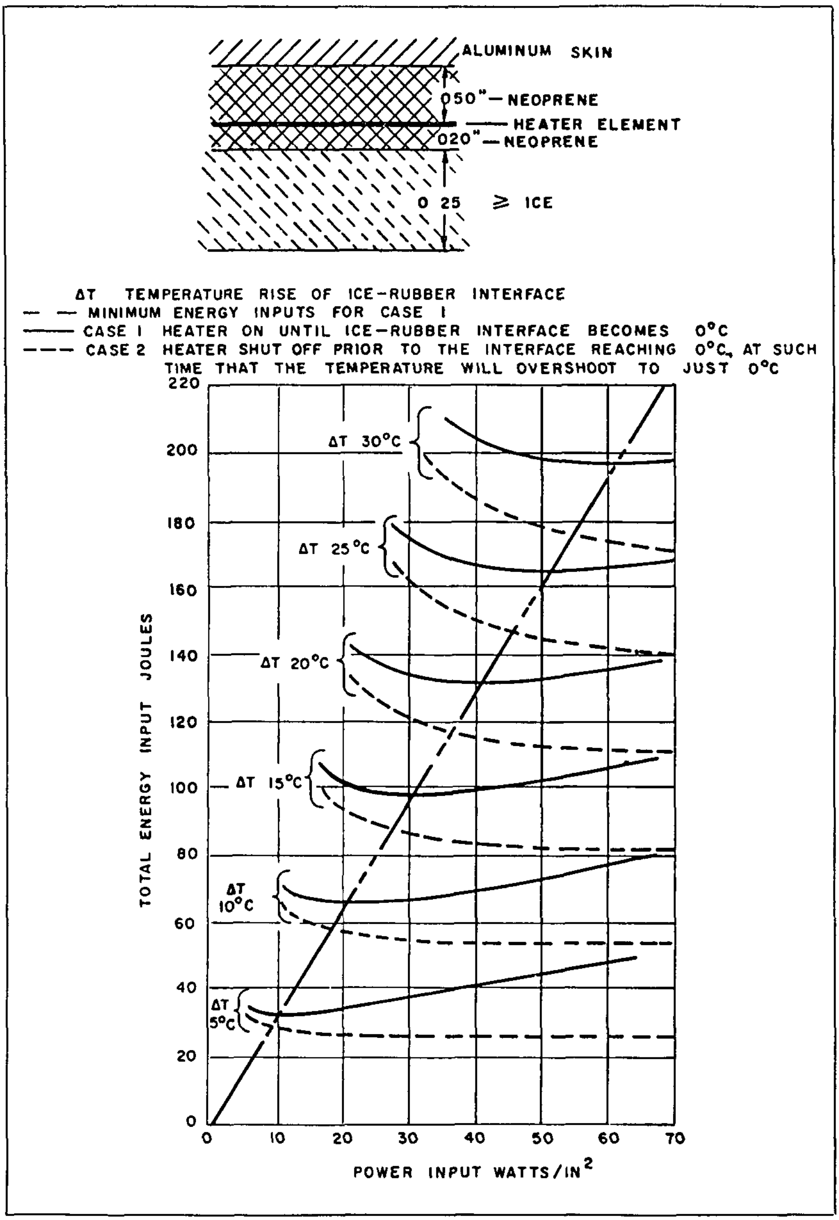


Fig 10 Minimum energies required for ice shedding (derived by approximating analytical method)

Accretion Time

The icing period is determined not only by considerations of drag increase, permissible unbalance and the possibility of structural damage which demand a minimum of ice build up, but also by the necessity of accreting sufficient mass of ice to effect clean and efficient shedding If there is insufficient ice, aerodynamic pressure and surface tension prevent its removal and all it does is melt away at the expense of large amounts of energy and the formation of runback On this basis, an ice thickness of about $\frac{1}{8}$ inch or slightly more appears to be a satisfactory compromise The frequence of shedding is thus a function of the rate of accretion which, due to the varying heat balance along the span of the blade, is not only a function of liquid water content, but also of ambient temperature This is demonstrated in Fig 13

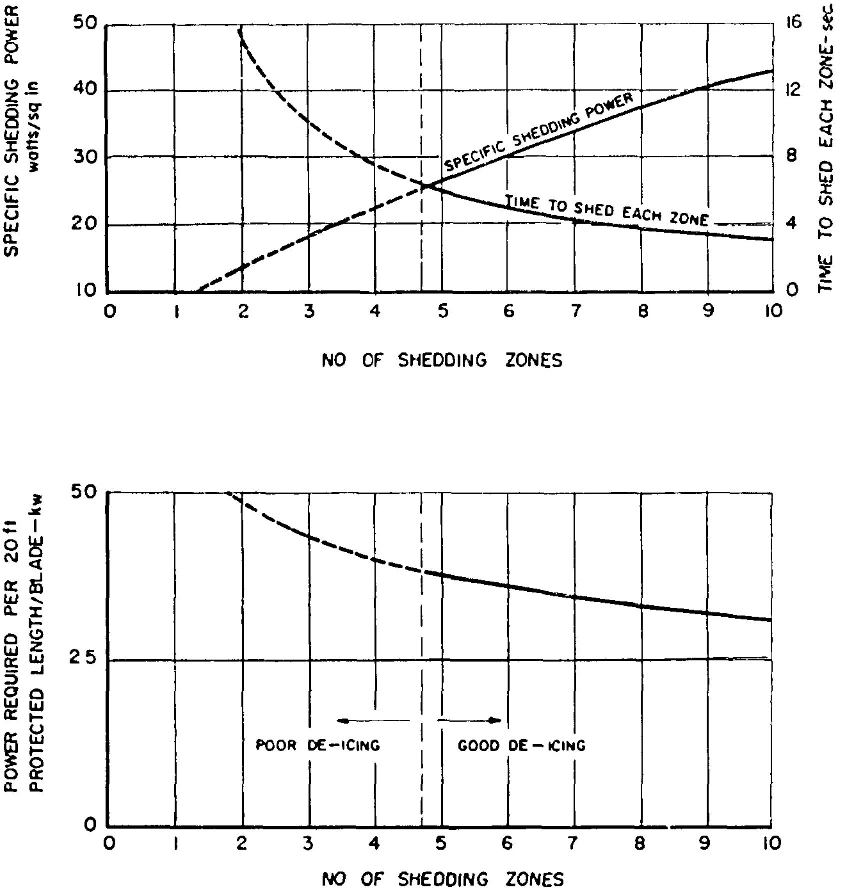


Fig 11 Total power requirements for typical Helicopter Rotor Blade de-icer pad (For air temperature—18°C and maximum allowable total shedding time of 30 seconds)

Controls

The foregoing remarks point out clearly that the use of fully-automatic controls are essential to ensure good, clean shedding and to minimise run-back Other desirable functions are to conserve energy and relieve the already overworked pilot of further decision-making responsibilities

The function of the de-icing control is to allow a sufficient, but not excessive, amount of ice to accumulate on the rotor blades, and then, to ensure that sufficient heat is applied to each shedding zone in turn to cause removal of the ice without excessive runback

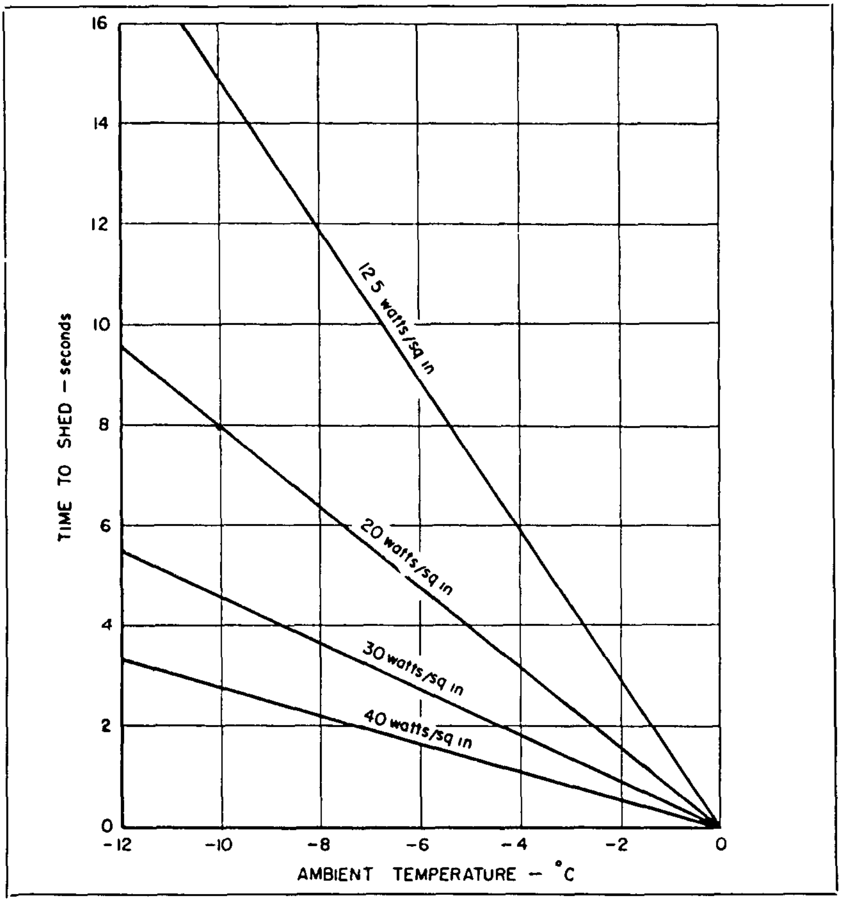
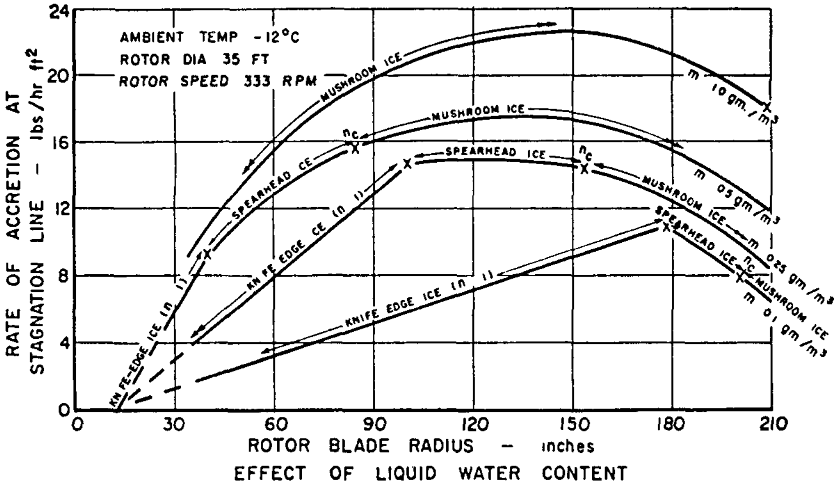


Fig 12 Time to shed vs ambient temperature N R C de-icing tests on Bell 47 G-2

In fixed wing practice the appropriate thickness of ice for shedding can be conveniently determined by counting the number of signals from an orifice-type icing detector, since each signal represents approximately the same thickness of ice accretion on the detector probe It is happily fortuitous that both the sensitivity of the orifice-type detector (Ref 8) and the maximum rate of icing on the rotor blades (Fig 13) vary inversely as the ambient temperature Unfortunately, in its standard form, this detector relies for its operation on a relative air flow over it in excess of about 100 ft /sec It is therefore of little use on a helicopter, but work is under way, both at the National Research Council and elsewhere, on the development of icing detectors, based on the orifice principle, which will operate down to zero airspeed



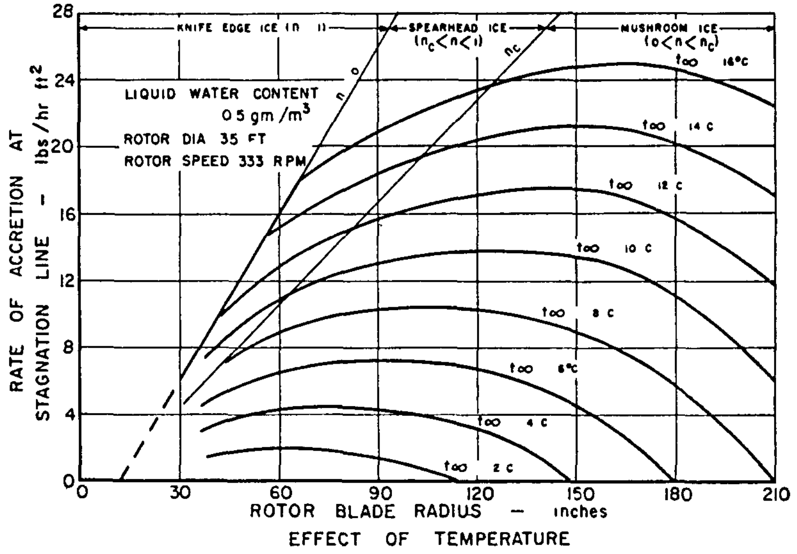


Fig 13 Effect of Liquid Water content and temperature on rate of accretion and ice type

It is to be hoped then, that before long an icing detector will be available that will suit the needs of a helicopter de-icing control In the meantime a simple temperature controlled timer may possibly be used to give accretion times ranging from, say, 2 minutes at —20°C to about 5 minutes at 0°C, the actual times required being determined during icing flight trials

Once the shedding cycle is initiated, heat is applied to the various shedding zones in turn by ordinary sequence switching, but in order to ensure clean, efficient shedding, the heating time must be varied to suit the icing conditions This can be done by using a temperature controlled timer, the calibration of which is based on the experimental relationship between shedding time and ambient temperature (see for example Fig 12) Alternatively, heat may be applied to each shedding zone only until the surface temperature reaches a predetermined value at which it is known de-icing is assured The former is the easier to apply in the case of the helicopter, although as far as I am aware only the latter is presently employed in fixed-wing application

It will be appreciated from the foregoing that the use of either fixed time cycles or constant cycle ratios for a shedding system are quite unrealistic, since they may either detract from shedding performance or encourage run-back

CONCLUSIONS

The work done in Canada in the field of helicopter icing has done much, by virtue of actual flight tests, to point out the true nature of this problem and its serious effects, both aerodynamic and mechanical It has shown that practical icing protection systems for helicopters are possible and that, in particular, the electro-thermal method holds out the most promise for success It may be concluded that one serious barrier to all-weather helicopter operations is well on the way to being removed, and I fully expect by the end of 1960 that we shall see helicopters entering service fully protected from the effects of icing

Acknowledgements I wish to thank the National Research Council for permission to present this paper Any opinions expressed are my own and do not necessarily reflect those of the Council I would like to thank also the Royal Canadian Navy who have given us so much help and encouragement in the flight trials

REFERENCES

1 Messinger, B L Equilibrium Temperature of an Unheated Icing Surface as a Function of Airspeed *Journal of Aeronautical Sciences*, Vol 20, p 29, January, 1953

2 Rush, C K, and Wardlaw, R L Wind Tunnel Simulation of Atmospheric Icing Conditions National Aeronautical Establishment paper presented to AGARD 5th General Assembly, Ottawa, June, 1955

3 Robertson, E O Preliminary Helicopter Icing Flight Trials National Aeronautical Establishment Lab Rept LR-106 July, 1954

4 Bailey, D L Description of the Spray Rig Used to Study Icing on Helicopters in Flight National Aeronautical Establishment Lab Rept LR-186 January, 1957

5 Stallabrass, J R Helicopter Icing Research *National Research Council Quarterly Bulletin*, April-June, 1957

6 Stallabrass, J R Some Aspects of Helicopter Icing *Canadian Aeronautical Journal*, Vol 3, No 8, October, 1957

7 Richardson, D A , Wahl, H A , and Clifford, J M Solutions for Helicopter Rotor Blade Icing Presented to 26th annual meeting of Institute of Aeronautical Sciences, January 27—30, 1958 (Preprint 810)

8 Fraser, D The Characteristics of an Orifice-type Icing-detector Probe National Aeronautical Establishment Lab Rept LR-71 June, 1953

9 Dickey, T A An Analysis of the Effects of Certain Variables in Determining the Form of an Ice Accretion U S Navy, Naval Air Material Center, AEL-1206, 1952

10 Langmuir, I , and Blodgett, K B A Mathematical Investigation of Water Droplet Trajectories U S AAF Tech Rept 5418, February, 1946

APPENDIX A

SAMPLE CALCULATION, ILLUSTRATING RELATIONSHIP BETWEEN LIQUID WATER CONTENT AND ICE THICKNESS ON ROTOR BLADES

List of Symbols

a	Droplet radius	
B	Ambient atmospheric pressure	in Hg
b	Relative heat factor, $R_w c_w / h_c$	
C	Cylinder radius	
c_p	Unit heat capacity of air	B t u /lb °F
c_w	Unit heat capacity of water	B t u /lb °F
D	Cylinder diameter	inches
d	Droplet diameter	microns
E_m	Water droplet catch efficiency	
g	Gravitational constant, 32 2 ft /sec ^{2}	
h_c	Coefficient of thermal conductance	B t u /hr ft ^{2}°F
J	Mechanical equivalent of heat, 778 ft lb /B t u	
K	Droplet deposition parameter	
L_e	Latent heat of vaporization of H_2O	B t u /lb
m	Liquid water content	gm /m ^{3}
n	Freezing fraction	
n_c	Critical freezing fraction	
P_∞	Vapour pressure of atmospheric moisture	in Hg
P_{sw}	Vapour pressure over water t_{se}	in Hg
r	Recovery factor applying to kinetic heating	
R_o	Rate of ice accretion at stagnation line	lb /hr ft ^{2}
R_w	Rate of water catch at stagnation line	lb /hr ft ^{2}
s	Ice thickness at stagnation line	inches
t_∞	Ambient free-stream temperature	°F
t_f	Average boundary layer temperature	°F
t_{se}	Equilibrium surface temperature	°F
T	Time	
V_∞	Free-stream velocity	ft /sec
β_o	Local droplet catch efficiency at stagnation line	
θ_m	Maximum angle of impingement	degrees
θ_1', θ_2, θ_3'	Heat balance parameters	°F
μ	Air viscosity	lb /ft sec
ρ_a	Air density	slugs/ft ^{3}
ρ_w	Water density	lb /ft ^{3}
φ	Droplet deposition parameter	

Basis of Analysis

When the equilibrium surface temperature is less than 0°C , all the impinging water is considered to have solidified in its impingement area (*i e* , n = 1) and the ice accretion rate will be simply the water catch rate

Since this analysis considers only the accretion rate at the stagnation line, we have for n = 1

$$R_o = R_w = \beta_o m V_\infty \qquad \text{(A 1)}$$

For a surface having an equilibrium temperature equal to 0°C , there exists a range of conditions dependent on the fraction of the impinging water that freezes on impact This freezing fraction, n, having a value ranging from 0 to 1, must be introduced into the equation for accretion rate at the stagnation line

$$R_o = nR_w = n\beta_o m V_\infty \qquad \text{(A 1a)}$$

If conditions remain constant, then in time, T, the ice thickness at the stagnation line will be

$$s = R_o T/\rho_i \qquad \text{(A 2)}$$

Whether it is desired either to compute the rate of accretion knowing the liquid water content, or to determine the liquid water content from a known rate of accretion, it is necessary to determine the values of β_o and n It is the evaluation of these two parameters that constitutes the body of the analysis

Determination of β_o

Since droplet deposition data on aerofoils is available only for a limited number of aerofoil profiles at a few angles of incidence, it was decided to base the analysis on an equivalent cylinder, for which extensive droplet deposition data have been produced by Langmuir and Blodgett (Ref 9) by the use of a differential analyser

Reference 9 presents values of E_m, β_o, and θ_m in the form of curves plotted as a function of parameter K, for a series of values of parameter φ

These dimensionless parameters are defined as follows

$$K = \frac{2}{9}\,\frac{\rho_w A^2 V_\infty}{\mu C} \qquad \text{(A 3)}$$

$$\varphi = 18\,\frac{\rho_a{}^3 C V_\infty}{\rho_w \mu} \qquad \text{(A 4)}$$

using self-consistent units

If we evaluate ρ_w as 62 4 lb /ft ^{3}, we can write these equations as

$$K = 8\ 95 \times 10^{-10}\,\frac{d^2 V_\infty}{\mu D} \qquad \text{(A 3a)}$$

$$\varphi = 12\ 47\,\frac{\rho_a{}^2 D V_\infty}{\mu} \qquad \text{(A 4a)}$$

using the units given in the list of symbols for the various quantities

Determination of n

The value of the freezing fraction may be determined by solving the heat balance equation Messinger in Reference 1 has reduced this to a convenient form, and since we are only concerned with the case when t_{se} = 32°F , we may write (using Messinger's symbols)

$$\theta_1' = \theta_2' + \theta_3 \qquad \text{(A 5)}$$

$$\theta_1 = 32\,(1 + b) + 2\ 9\ L_eP_{sw}/B \qquad \text{(A 6)}$$

$$\theta_2' = t_\infty\,(1 + b) + 2\ 9\ L_eP_\infty/B + 144\ nb \qquad \text{(A 7)}$$

$$\theta_3' = (r/c_p + b)\ V_\infty{}^2/2gJ \qquad \text{(A 8)}$$

where throughout, $b = R_wc_w/h_c$ (A 9)

If we insert the values L_e = 1075 B t u /lb and P_{sw} = 0 180 in Hg

$$\theta_1 = 32\,(1 + b) + 560/B \qquad \text{(A 6a)}$$

$$\theta_2' = t_\infty\,(1 + b) + 3120\ P_\infty/B + 144\ nb \qquad \text{(A 7a)}$$

Should the equilibrium surface temperature not in fact be 32°F this will be readily apparent by the solution of equation (A 5) resulting in an impossible value of n, in which case its value should be taken as either 1 or 0 as appropriate

Numerical Example

The rate of icing is to be determined at the stagnation line of a Bell HTL-4 blade at a radius of 100 inches (0 476 R) under the following icing conditions

Ambient temperature, t_∞ = —9 0°C (15 8°F)

Liquid water content, m = 0 5 gm /m ^{3}

Median volume droplet diameter, d = 30 (microns)

Barometric pressure, B = 29 92 in Hg

The helicopter will be assumed to be in pure hovering flight (no translational velocity) with a rotor speed of 333 r p m (engine speed 3,000 r p m)

At the 100-inch blade station, an equivalent cylinder diameter, D, of 1 0 inch has been assumed

Under the above conditions,

$$V_\infty = 292\ \text{ft /sec}$$

$$\mu = 1\ 12 \times 10^{-5}\ \text{lb /ft sec}$$

$$\rho_a = 2\ 60 \times 10^{-3}\ \text{slugs/ft}^3$$

$$K = 21\ 0 \qquad \text{(eq A 3a)}$$

$$\varphi = 2{,}200 \qquad \text{(eq A 4a)}$$

$$\text{Hence } \beta_0 = 0\ 90 \qquad \text{(Fig 4 of Ref 9)}$$

From equation (A 1) and using the units denoted in the list of symbols

$$R_w = 0\ 225\ \beta_0 m V_\infty \qquad \text{(A 1b)}$$

$$= 29\ 6\ \text{lb /hr ft}$$

In equation (A 9)

$$c_w = 1\ 0 \text{ B t u /lb °F}$$

$$h_c = 0\ 194\ t_f^{\,0\ 49} \left(\frac{V_\infty \rho_a}{D}\right)^{0\ 5}$$

$$= 67\ 0 \text{ B t u /hr ft}^2 \text{ °F}$$

$$b = 0\ 442$$

$$\text{Thus } \theta_1 = 64\ 9 \text{ °F} \qquad \text{(A 6a)}$$

$$\text{and } \theta_3 = 6\ 93 \text{ °F} \qquad \text{(A 8)}$$

$$\text{for } r = 0\ 875$$

$$c_p = 0\ 241 \text{ B t u /lb °F}$$

$$\text{And } \theta_2 = 58\ 0 \text{ °F}$$

Substituting this value in equation (A 7a), together with $t_\infty = 15\ 8$ °F and $P_\infty = 0\ 084$ in Hg , we arrive at

$$n = 0\ 415$$

$$\text{Thus } R_o = nR_w = 12\ 3 \text{ lb /ht ft}^2$$

Assuming an icing time, T, of 3 minutes and an ice density, ρ_1, of 45 8 lb /ft ^{3}, the total thickness at the stagnation line will be

$$s = 0\ 161 \text{ inch}$$

$$= \text{approx } \tfrac{3}{32} \text{ inch}$$

Further, the type of icing to be expected may be determined by evaluating the critical freezing fraction, n_c, for Dickey has shown in Reference 10 that the following correlation exists between the freezing fraction and the ice shape

$0 < n < n_c$ mushroom ice

$n_c < n > 1$ spearhead ice

$n = 1$ knife-edge ice

$$\text{where } n_c = \frac{180\ E_m}{\pi \theta_m \beta_o} \qquad \text{(A 10)}$$

Values of E_m and θ_m in addition to β_o are provided in Reference 9, and in the case of the numerical example above these are

$$E_m = 0\ 825$$

$$\theta_m = 81 \text{ degrees}$$

And thus $n_c = 0\ 66$, and the accretion under consideration is of a mushroom formation