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HELICOPTER ROTOR ICE ACCRETION AND PROTECTION RESEARCH

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Abstract

Recent research by RAE on helicopter rotor ice accretion and protection systems is summarised.

Results are presented of calculations of droplet trajectories around aerofoils in compressible flow, showing the effect on droplet impingement of aerofoil section, chord and droplet size. A computer model of the thermodynamic process of ice accretion in compressible flow has been used to predict the shape and position of rotor ice; results are compared with flight and tunnel observations.

Work on protection systems has involved tests of a non-rotating section of blade fitted with electrothermal deicing, tested in front of an open jet nozzle in Cell 3 West, NGTE. After initial demonstration of the feasibility of deicing in the absence of centrifugal force, a wide range of conditions was explored, with results which correlate well with flight trials.

Plans are outlined for future experimental and theoretical work on accretion and electrothermal deicing systems.

1. INTRODUCTION

During helicopter flight in clouds containing supercooled water droplets, ice will accrete on the rotor blades and will progressively change the shape and hence the characteristics of the aerofoils, to the detriment of the aircraft performance. The main effects of rotor icing are an increase in the rotor torque required to maintain a given flight condition, an increase in vibration levels and control loads and a general contraction of the overall flight envelope. The rate at which this degradation takes place depends not only on the severity of the atmospheric icing conditions but also on the particular aircraft; it has been found by experience that some helicopters are more tolerant of icing than others. In the worst cases, both rotor torque and control load limits can be reached within one minute of entering icing, with loss of control occurring soon after unless very prompt evasive action is taken. Even in less severe cases, asymetric self shedding of ice can cause rotor imbalance with unacceptably high vibration and control loads. Despite these potentially hazardous effects, it has been found possible to issue limited releases for certain helicopters with unprotected rotors, such as the S-61, for a restricted range of icing conditions[1]. It is considered essential for helicopters requiring a wider or unrestricted icing clearance to have protected rotors.

The work described in the present paper forms part of the overall UK helicopter icing research programme. It has been aimed at investigating the physical process of ice accretion on rotors and the problems of the design and optimisation of rotor protection systems. An understanding of the accretion process is important for both unprotected and protected helicopters; without such knowledge it will not be possible to explain the differences in sensitivity to icing of different rotor designs, nor to increase the confidence in limited clearances for unprotected rotors. The range of icing severity encountered and the hours of icing experience on which such clearances are based are often limited and at present there is little basis for extrapolation. For the protected rotor, the accretion process is significant because the protection will almost inevitably be by a deicing system, that is, one which permits ice to grow and then sheds it in a controlled fashion. To optimise such a system, the rate and type of growth must be understood, as must the heat transfer modes on the blades which are fundamental to the whole icing/deicing process.

The particular areas on which research is being done at RAE include:

a) Ice accretion

- theoretical study of the trajectories of droplets around aerofoils in compressible flow;
- computer modelling of the thermodynamic process of ice accretion on an aerofoil in compressible flow;
- experimental investigations in icing tunnels of accretion on aerofoils, including surface temperature measurements;
- in-flight measurement of blade surface temperatures;
- studies of the effects of icing on aerofoil characteristics.

b) Rotor protection

- tunnel tests on non-rotating sections of blade with electrothermal deicing systems;
- theoretical studies of heat transients in multilayer electrothermally deiced structures;
- experimental validation of the thermal transients theory.

2. ICE ACCRETION

The study of ice accretion on rotors is considered in three stages. Firstly, where and at what rate do droplets impinge on the blades; secondly, how do the impinging droplets freeze to form the ice accretion; and thirdly, what is the effect of the ice on the rotor aerodynamics. The aim is to develop a method for predicting the position, shape and rate of growth of ice at any spanwise position on the blade, and further, to assess the effect of the ice on aircraft performance.

2.1 Droplet trajectories

Because of its inertia, the trajectory of a cloud droplet in the airflow adjacent to an aerofoil will not follow the streamlines; near the leading edge the trajectories will be less curved than the streamlines and will impinge on the surface. The trajectory is a function of both the flow field (ie velocity, temperature and pressure) and the cloud particle (ie droplet diameter or ice crystal size and shape).

Fig 1 shows a typical family of droplet trajectories. The top and bottom trajectories, tangential to the aerofoil, define the limits of catch beyond which no droplets will impinge on the surface. At any point between these limits a catch efficiency can be defined, such that

$$\beta = \frac{dy}{ds}$$

where y is the initial free stream particle position as shown and s is the surface distance round the aerofoil. This catch efficiency, in combination with the air velocity (V) and the cloud liquid water concentration (LWC) give the local rate of water catch (Rw) on the surface. Thus

$$Rw = \beta . V . LWC.$$

To calculate the trajectory, one must solve the differential equations of motion of the particle. These equations are well known and have been presented in, for instance, Ref 2 and more recently, Ref 3. The calculation requires a knowledge of the flow field and of the drag coefficient characteristic of the particle; the latter is well known for spherical droplets but more difficult for irregular shaped ice particles.

In the present work, a program has been written to investigate the effect of droplet size and aerofoil section and chord on catch efficiency. The flow field is calculated by a viscous Garabedian-Korn program [4] and is assumed to be two dimensional. The droplet motion equations are integrated by a Runge-Kutta method. Full allowance is made for the variation of air properties (density and viscosity) due to compressibility. Inputs to the program are the aerofoil coordinates, Mach number, incidence, chord, droplet size and atmospheric temperature and pressure. Outputs are the trajectories and local values of catch efficiency.

Table 1 shows the aerofoils and droplet sizes considered to date, all being at a Mach number of 0.4.

Section	Chord, c	Incidence, α	Droplet Diam. d_d
NACA 0012	.415 m	0°	10, 20, 40 µm
"	"	8°	"
NPL 9615	"	0°	"
"	"	8°	"
RAE 9645	"	0°	"
"	"	8°	"
"	.75 m	0°	20 µm
"	"	8°	"

TABLE 1

Trajectories for d_d = 10, 20 and 40 µm on NACA 0012 at $\alpha = 0^\circ$ and C = 0.415 m are shown in Figs 2; the chordwise limits of catch are indicated. In Fig 3, the catch efficiency β is plotted against chordwise position x/c for the three aerofoils with $\alpha = 0$, c = 0.415 m and d_d = 20 µm. Fig 4 is a similar plot for $\alpha = 8^\circ$. In Fig 5, results for RAE 9645 with c = 0.415 m and 0.75 m are compared.

The catch characteristics shown in Figs 3 and 4 show only slight differences for the three aerofoils at one chord (0.415 m), all having the same peak β value of 88%. Fig 5 shows a generally reduced catch efficiency on the larger, 0.75 m chord aerofoil, with a marked shift of the upper surface catch limit. Such differences in catch behaviour may be significant in the positioning of deicing heater mats. Study of the trajectories of droplets just outside the primary catch range may be useful in assessing the likelihood that runback ice, which has formed on a heated blade aft of the primary catch zone, will grow by direct catch of droplets from the airstream.

A comprehensive survey of the effects of section, incidence, Mach number, chord and droplet diameter is planned. At present, this work is limited to study of trajectories around clean aerofoils and takes no account of the change of shape and hence flow field that occurs as the ice grows.

2.2 Thermodynamics of ice accretion

2.2.1 Basic theory

Having established local rates of water impingement on the surface, the thermodynamics of the accretion process must be considered. Icing in supercooled water droplet clouds has been studied for many years both experimentally and theoretically, particularly for fixed wing aircraft, and the work of Hardy [5], Messinger [6] and others in the 1940's and 50's is still valid. Basically it is proposed that the icing of a surface is governed by the balance of a number of heat flows, as follows:

a) Kinetic heating/convective cooling;

b) Evaporative/sublimative cooling;

c) Sensible heat loss in warming impinging droplets to $0^{\circ}C$;

d) Sensible heat gain in cooling accreted ice to **ts** (the surface equilibrium temperature);

e) Latent heat of freezing of the water;

f) Kinetic energy of the impacting droplets.

For simplicity, the structure of the blade itself is assumed to be non-conducting. The balance of the heat flows (a) to (f) determines whether the surface is wet or dry and also its equilibrium temperature, ts.

For the surface to grow dry ice, the cooling terms must be sufficient to dissipate all the latent heat of freezing, so that all droplets freeze on impact (freezing fraction n = 1) and the surface temperature is below zero. The ice so formed is known as rime and is white and opaque. In this case, the rate and shape of accretion are calculated simply from the local rates of water impingement.

If the cooling is insufficient, as a result of either a relatively high temperature, high velocity or a high LWC, then the surface will run wet at $0^{\circ}C$, with only part of the water freezing ($0<n<1$) and the rest running back as liquid, possibly freezing elsewhere. The accretion will be clear, transparent 'glaze' ice, and will in general be much rougher, bluffer and aerodynamicly damaging than rime ice.

At still higher temperatures/speeds, the surface will run wet with $ts>0^{\circ}C$ and no ice formation (n = 0).

2.2.2 Computer model

A computer model of this process has been developed in which the heat balance is calculated, first at the stagnation line and then, step by step, at points round the top and bottom of the aerofoil. If the stagnation line is wet, with a freezing fraction of less than unity, the excess water is allowed to run back on to the next region and is included as an extra term in the heat balance. At each point the surface temperature and local rate of ice accretion are calculated, giving an overall accretion shape. At present, only steady 2-D flow is considered. Also, no allowance is made for the time varying change of aerofoil shape and hence characteristic parameters as the ice grows.

In order to perform the calculation, the chordwise distribution of the following parameters must be known:

$P/_{Ho}$ – local pressure – controls kinetic heating and evaporative cooling – available as normal aerodynamic data;

β – catch efficiency – controls sensible heats and latent heat of freezing – obtained from trajectory calculations;

h – convective heat transfer coefficient – controls kinetic heating, convective and evaporative cooling – can be calculated for clean blade via Reynolds analogy from skin friction coefficient – difficult to calculate for surface roughened/deformed by ice.

The present model allows fully for the effects of compressible flow on the kinetic heating and evaporative cooling terms. This is essential for rotor aerofoils on which a very high suction peak occurs on the upper surface very close to the leading edge, particularly at high incidence. In this region, kinetic heating is much reduced and evaporative cooling is enhanced by the local reduction in water vapour concentration at the edge of the boundary layer.

2.2.3 Model results and correlation with experiments

Applications of the model include prediction of the spanwise limit of ice as a function of outside air temperature (OAT), prediction of the variation of growth rate and shape with blade span and detailed prediction of the chordwise variation of surface temperature in clear air and icing conditions.

Fig 6 shows for a low LWC (approximately 0.1 g/m^3) the predicted spanwise extent of ice on the stagnation line as a function of OAT. It is seen that with reducing OAT, the kinetic heating becomes less effective in keeping the outboard end of the blade clear. Also shown are experimental observations from trials of a Wessex aircraft fitted with a camera to photograph the leading edge and underside of the blades in icing. Several hundred photographs were analysed and the maximum spanwise extent of ice determined at various OAT's. For the prediction, the mean blade speed was used, with no allowance for the cyclic variation present in forward flight.

Fig 7 shows a typical spanwise distribution of surface temperature on the stagnation line in clear air and at LWC's of 0.1 g/m^3 and 0.3 g/m^3, with an OAT of -10^oC. Below are shown the ice shapes predicted at points along the blade. A notable feature is that although ice will not grow on the stagnation line and underside of the blade once ts exceeds 0^oC (at about 85% span), the reduced kinetic heating and enhanced evaporation in the suction region make it possible to form ice in this area to a greater spanwise extent. This has been confirmed in tunnel tests and in flight, where, for example, ice has been photographed on the upper surface at 90% span with an OAT of -4^oC, way beyond the leading edge limit shown in Fig 6. The form of this suction region ice is a ridge or in worst cases a beak, and it is liable to be particularly damaging aerodynamically.

Fig 8 shows typical chordwise surface temperature distributions in clear air and at LWC's of 0.2 g/m^3 and 0.4 g/m^3, with both computed curves and measurements made on a model aerofoil in an icing tunnel. The results are for a Mach number of 0.4, incidence of 8^o and OAT of -14.6^oC. In clear air, the effect of the pressure distribution is seen, and the correlation with theory is good. In light (rime) icing, again the correlation is good. In more severe icing, giving a glaze accretion, the correlation on the upper surface and leading edge is still reasonable, but on the underside is poor. This is thought to arise from a large (and unpredictable) increase in the convective heat transfer coefficient on the underside due to roughness of the ice.

It is believed that the complex and irregular form of glaze ice will impose a practical limit on the purely theoretical model. Development will have to involve a major input of experimental data from flight and tunnel tests.

2.3 Aerodynamic Characteristics

A programme of work is just starting to study the sensitivity of the aerodynamic characteristics of aerofoils to ice accretion. The work will be done on both static and oscillated model aerofoils, with measurements of pressure distribution (hence lift and pitching moment) for all cases, plus drag for the static cases. Because it is impractical to investigate the vast range of ice shapes occurring in natural icing, the work will use small stylised protuberances. Points of particular interest are the effect of the height and chordwise position of a protuberance in the suction region on $C_{L\,max}$ and stall characteristics and of simulated runback ice (see Section 3) on drag. The data produced will be used for theoretical investigations of the performance of helicopters in icing, similar to that previously reported by Young [7].

2.4 Future work

Further validation of the compressible flow icing model will be sought from results of blade temperature measurements currently being made in flight on a Puma helicopter. The chordwise distribution at 50, 70 and 90% span will be measured in clear air and cloud above 0°C over the full flight envelope. These tests will also indicate the magnitude of the transient effects due to cyclic pitch and velocity.

It is hoped to develop the model further to include such transient effects. In order to do this, transient conduction into and out of the ice/blade surface will be included in the heat balance calculation. It is suspected that these transients may be important in the formation of the suction region "beak" ice, which in practice seems to grow to a limiting size and may be a determining factor in the observed difference in icing sensitivity of different unprotected aircraft.

3. PROTECTION SYSTEMS

3.1 A large number of systems have been proposed for ice protection of rotors, including electrothermal, paste, flexible substrate, fluid, microwave, pneumatic boot and vibratory systems. RAE work has been confined mainly to the first three of these, and the work on pastes and flexible substrates has been described in a previous Forum paper [8]. The present paper therefore deals only with development and testing of the electrothermal system.

3.2 Icing tunnel tests

For many years, flight trials have been conducted on helicopters fitted with electrothermal deicing systems, leading to the recent series of UK trials with the heated rotor blade Wessex [9]. However it has always been clear that system development via flight trials is a time consuming, expensive and often frustrating process, relying on the ability to find suitable natural icing conditions, and it has often been questioned whether useful development work could be done in ground facilities. The only rig large enough for full size rotors is the NRC Spray Rig in Ottawa, which has limitations and is not altogether convenient for basic development work. Scaling of protected rotors cannot be done satisfactorily. The use of non-rotating specimens of full size blade has therefore been investigated. The primary doubt was whether successful ice shedding could be achieved in the absence of centrifugal force; and even if shedding did occur, a further doubt was whether the deicing system parameters such as optimum heat intensity and on-time and runback formation would be the same as those found in flight.

Two series of tests have now been carried out in Cell 3 West, NGTE[10], using a 0.91 m span section of Wessex blade fitted with spanwise electrothermal deicing elements. Two heater mat constructions have been studied, using a control system which enabled a wide range of heater cycles, on-times and heat intensities to be tried. The test rig configuration is shown diagrammatically in Fig 9 and in the photograph, Fig 10. The blade specimen was mounted in front of the 0.76 m diameter blowing nozzle and was pivotted on its 1/4 chord line. The blade was oscillated in pitch at 250 rpm to simulate the cyclic pitch variation of forward flight and also to assist ice shedding. The tests covered a range of Mach numbers from 0.25 to 0.5 at static air temperatures down to −20°C and LWC values up to the specification continuous maximum.

Figure 11 shows typical photographs of the blade during an icing run. In (a), a leading edge accretion has formed prior to energisation of the deicing mats. Photographs (b) show the blade after several heater cycles; the leading edge is clear, but runback ice has formed behind the primary heated zone. In (c), the mats further aft have been used to clear this runback ice.

The conclusion drawn from the two test series was that useful testing could be done over a wide range of conditions, with the deicing performance apparently similar to that seen in flight trials. One major problem with the rig testing is the definition of the criteria by which to judge the system performance. In flight, the torque, control loads, vibration etc can be measured and the best system is the one which minimises the effects of icing. In the rig, only visual evidence is available. As an example, at low static temperature, below $-16^{\circ}C$, the ice was difficult to shed, tending to come off part of the blade on one heater cycle and elsewhere on the next cycle, so that the whole span of the blade was rarely clear. In the long term, this irregular shedding contained the ice growth, so that the accretion was no larger after 50 minutes than after 10 minutes. It was not possible to judge however what effect this would have on the aircraft. Despite this, it did appear possible to make valid comparisons of different cycling systems, power intensities and on-times. At warmer temperatures where good shedding was regularly achieved, other phenomena, such as the formation of runback ice behind the primary heated zone, looked similar to flight.

3.3 Heat transients in electrothermal deicing mats

At a more basic level than these large tunnel tests, theoretical and experimental studies have been made on thermal transients in deicing mats.

A one-dimensional transient heat conduction program has been written to calculate temperature-time histories in a multilayer deicing mat. The program uses a finite difference method, similar to that of Stallabrass [11], to solve the differential equations for the temperatures at nodes throughout the mat and ice layers. The temperature of primary interest is that at the interface between the ice and the blade surface, since, in principle at least, when this reaches $0^{\circ}C$ the ice should shed. The program includes an icing heat balance calculation for the external heat transfer to the boundary layer and also allows ice to grow during the cool down periods between deicing pulses.

To validate this one dimensional theory, a set of three flat plate specimens, each 100 mm square, has been tested, having constructions representative of three different heater mat/blade configurations. Each was fitted with 50 μm diameter thermocouples at various points in its lay-up to give temperature-time data for direct comparison. Tests to date have been done in still air (natural convection) in a cold chamber, and results show good correlation with theory.

3.4 Future work

Further tests are planned on oscillating sections of full size deiced blade, with test specimens to include cambered composite blades of approximately 0.45 m and 0.75 m chord. All will incorporate an array of temperature sensors fitted as close to the surface as possible, at positions corresponding to the centre lines of elements and the insulation gaps between elements. Observations during previous trials showed that the ice did not necessarily shed when a particular area reached $0^{\circ}C$. The ice was often retained by attachment on an adjacent unheated area. Also it has been seen in flight that attachment on the insulation gaps between elements, where rates of temperature rise are slower, is a major problem. It is hoped that data from the proposed temperature sensors will provide a much better understanding of these effects.

The theoretical studies will be extended to a two-dimensional program to enable these element edge effects to be studied. Initially a flat plate model will be used, with the external heat transfer distribution being varied to simulate the distribution around the blade chord. Later, the conduction calculation in the mat structure may be extended to more realistic shapes.

4 CONCLUSIONS

Considerable progress has been made in understanding the process of ice accretion on rotor blades and developing models with which to predict the icing characteristics of new aerofoils. The droplet trajectory model enables catch efficiencies to be calculated as a function of aerofoil shape, size and angle of attack and droplet size, and although limited to two dimensional steady flow, is believed to be adequate for comparative purposes.

The accretion model enables accretion position, shape and growth rate to be predicted, again for steady two-dimensional flow. Extension to cyclically varying two dimensional flow is thought necessary in order to model properly the accretion in forward flight when cyclic variations of pitch and speed become significant.

On the protection aspects, the use of a non-rotating section of blade for testing electrothermal deicing systems has been shown to give useful results, comparable with those obtained in flight. Further tests are planned to study blades of different construction, aerofoil section and size. Supporting theoretical work on thermal transients in deicing mats will be extended to two-dimensions.

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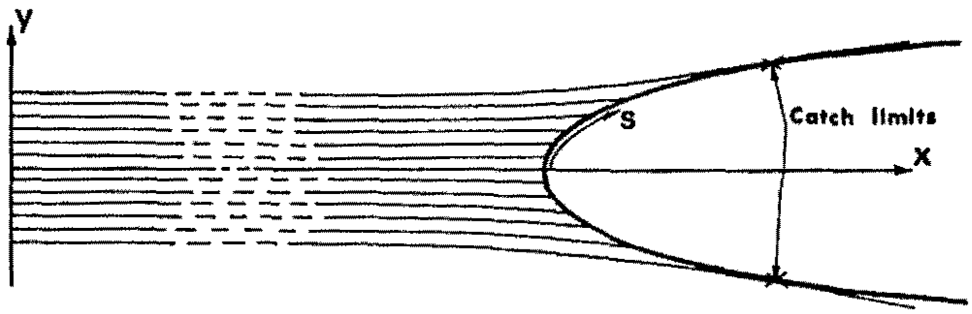


Fig 1 Typical droplet trajectories

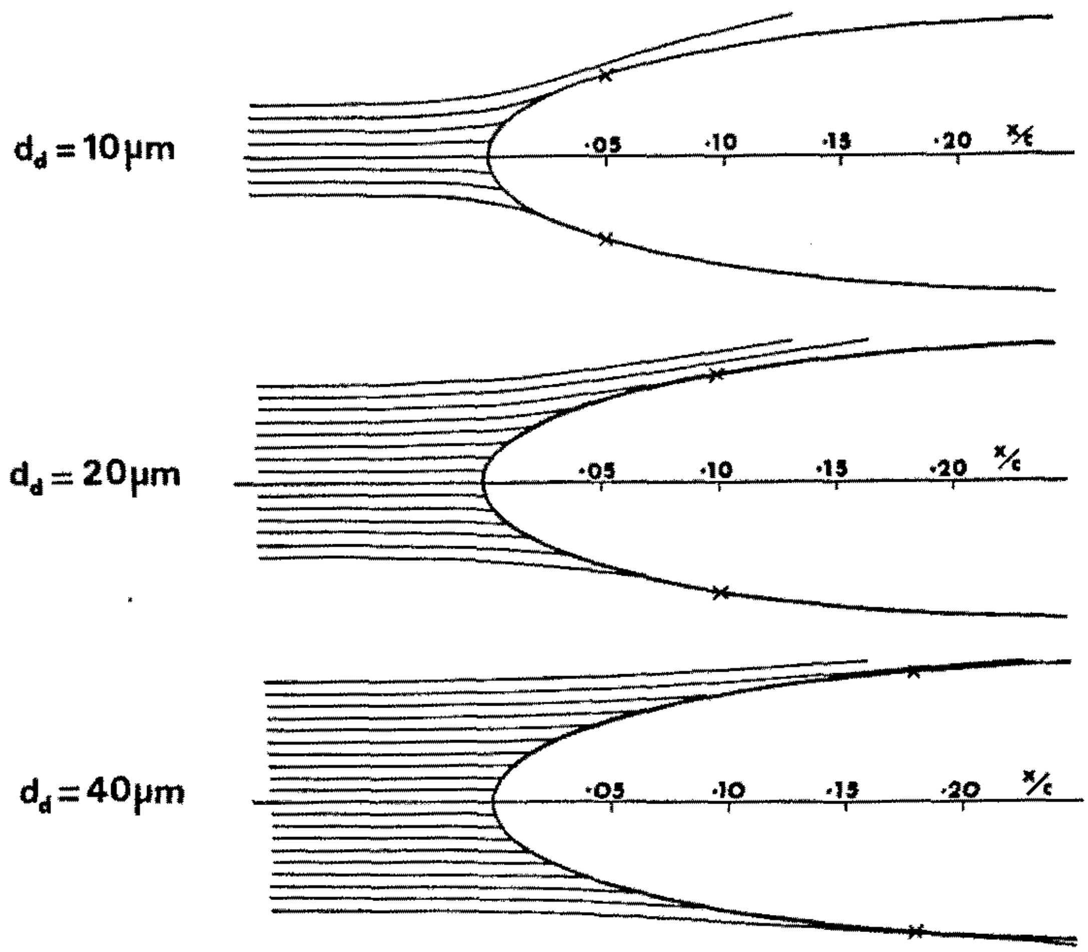


Fig 2 Effect of droplet diameter on trajectories
NACA 0012; M=0·4; $\alpha=0^{o}$; C=0·415m.

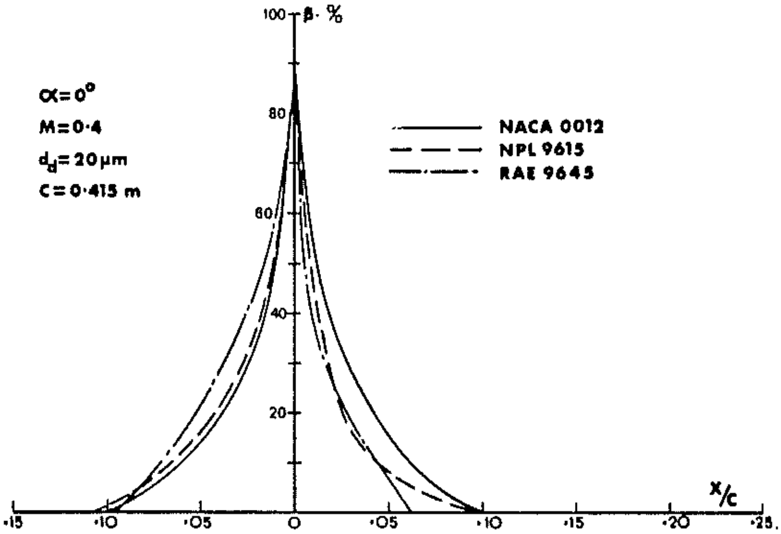


Fig 3 Effect of section on catch efficiency

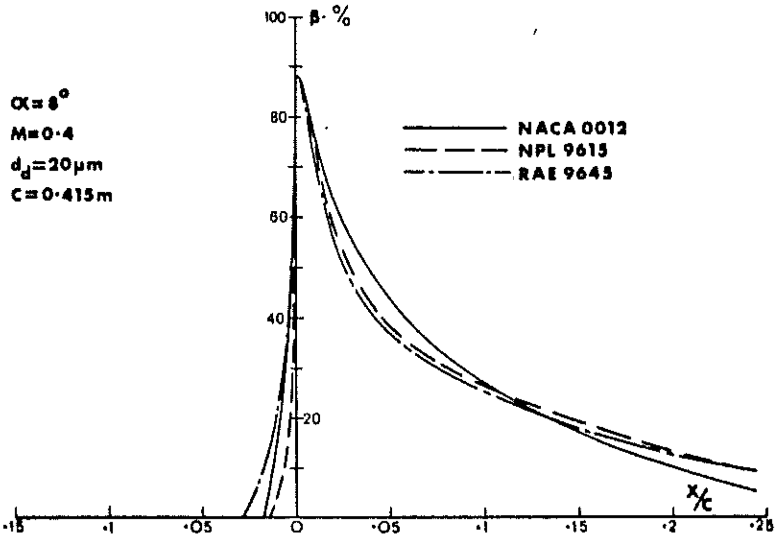


Fig 4 Effect of section on catch efficiency

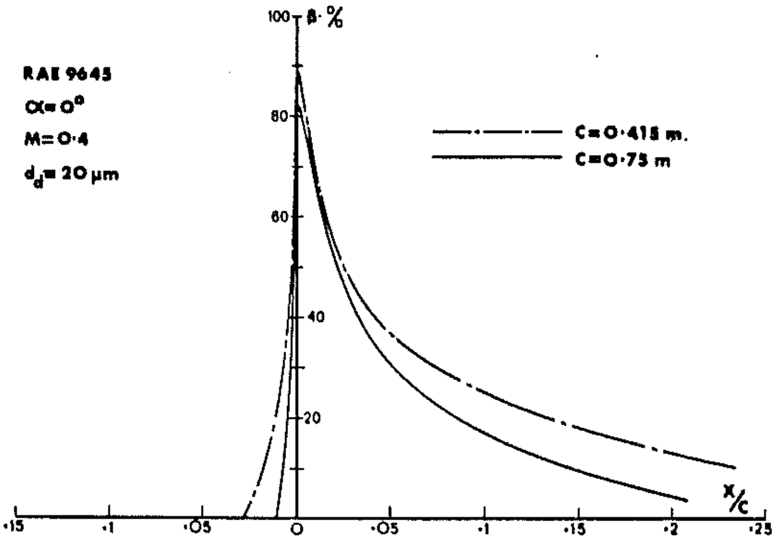


Fig 5 Effect of chord on catch efficiency

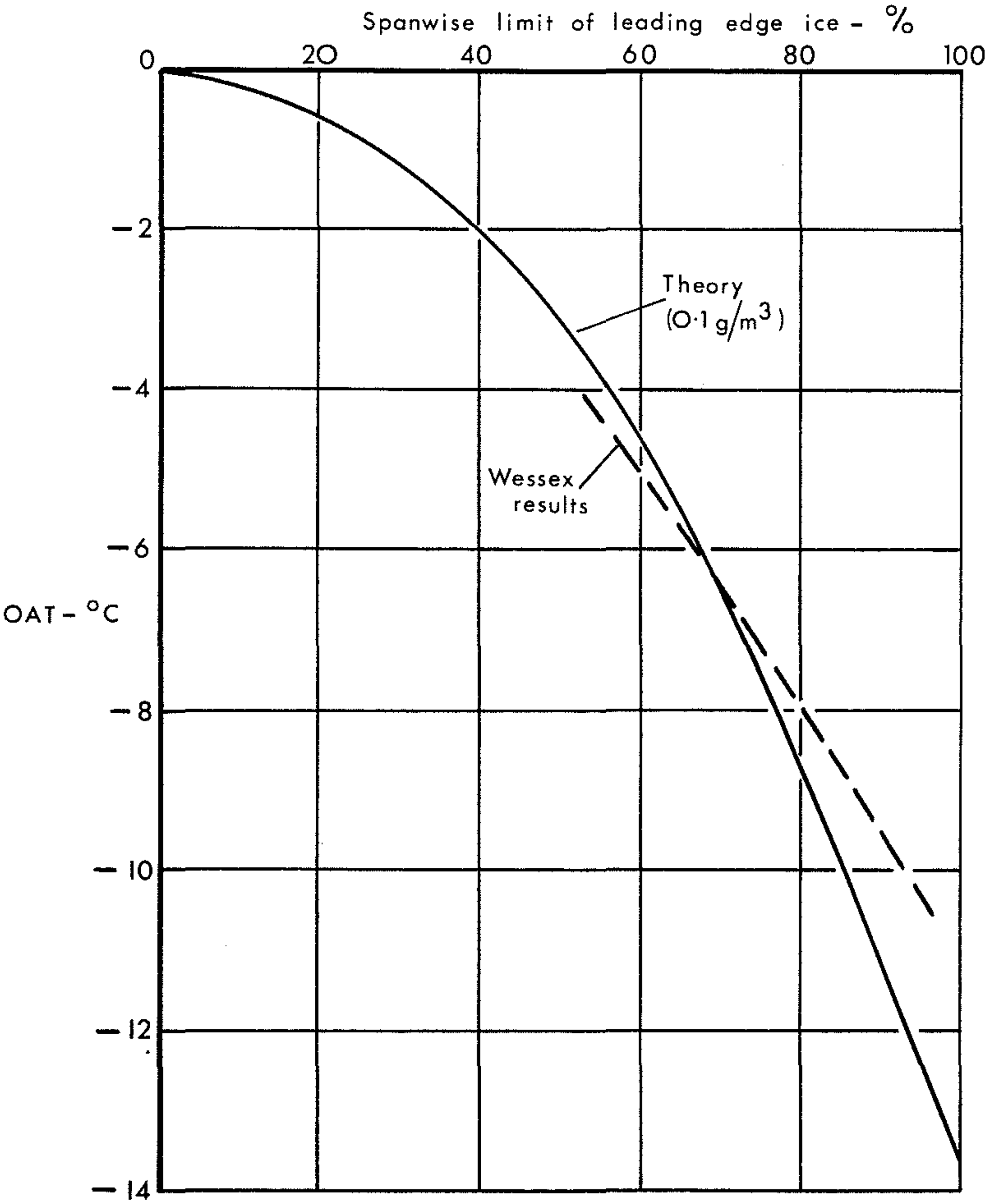


Fig 6 Variation of spanwise extent of leading edge ice with OAT

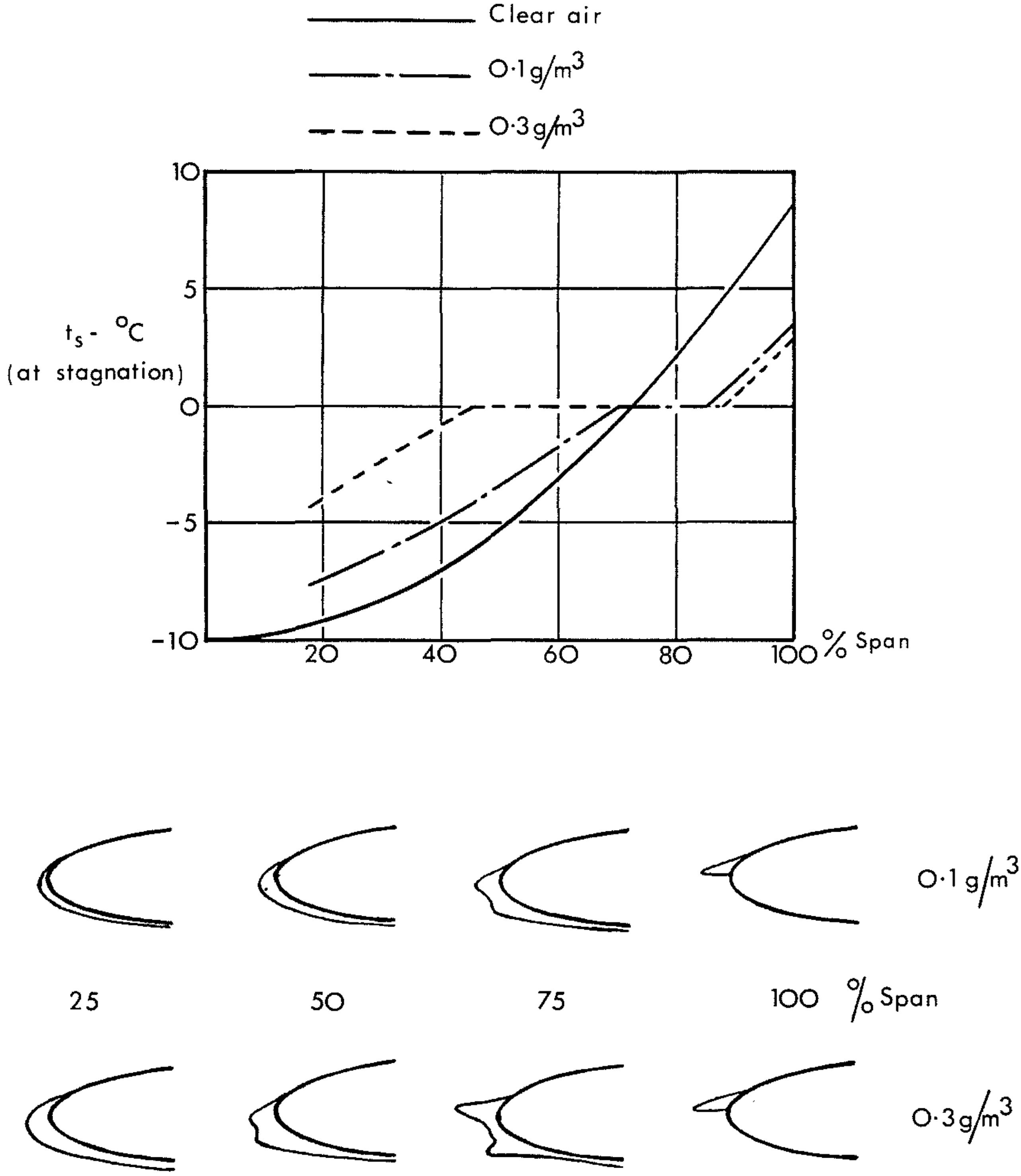


Fig 7 Spanwise variation of temperature and ice shape. OAT= −10°C

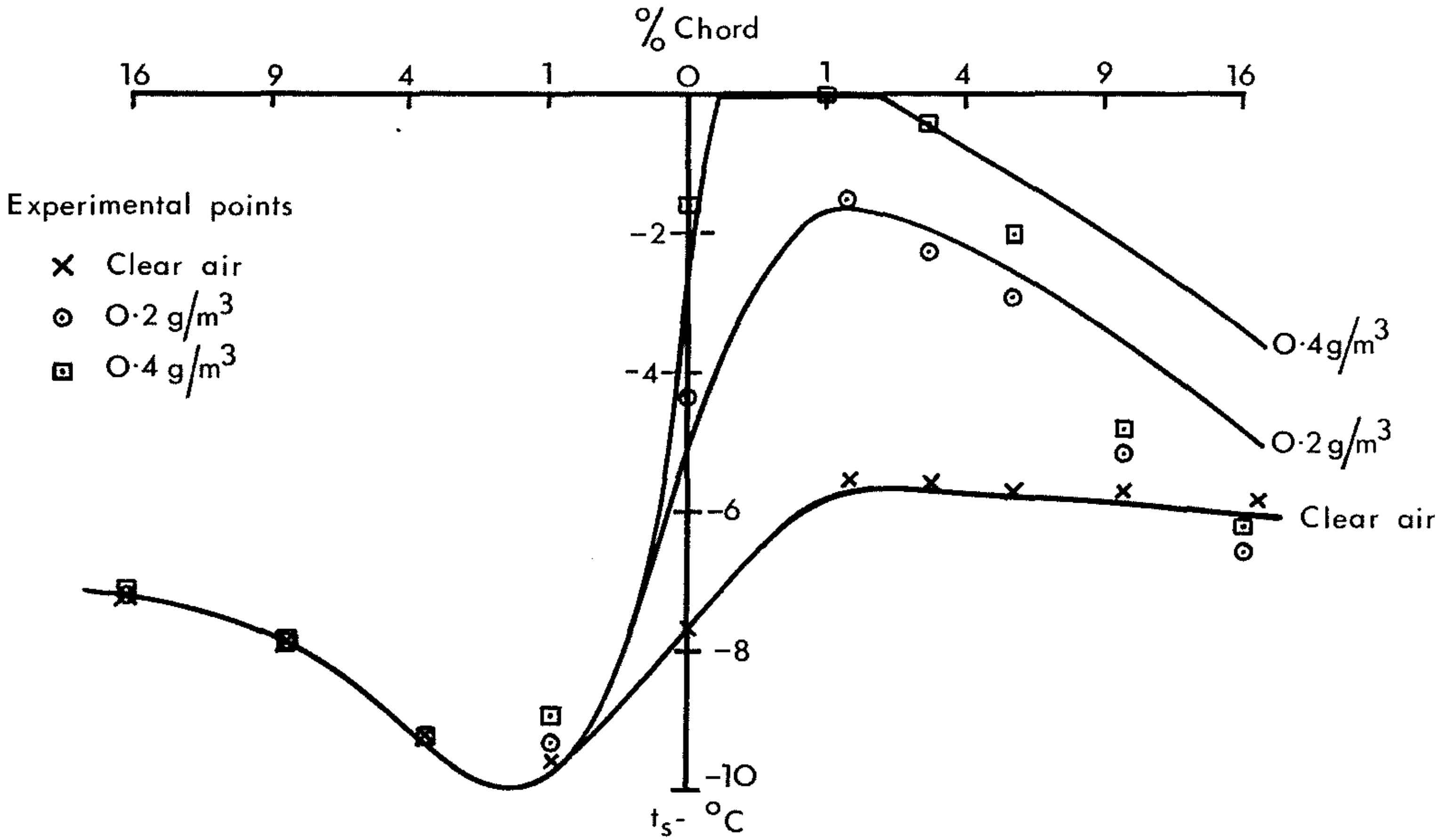


Fig 8 Computed and experimental chordwise temperature distributions

$OAT = -14{\cdot}6\,^{\circ}C$; $M_{\infty} = 0{\cdot}4$; $\alpha = 8^{\circ}$.

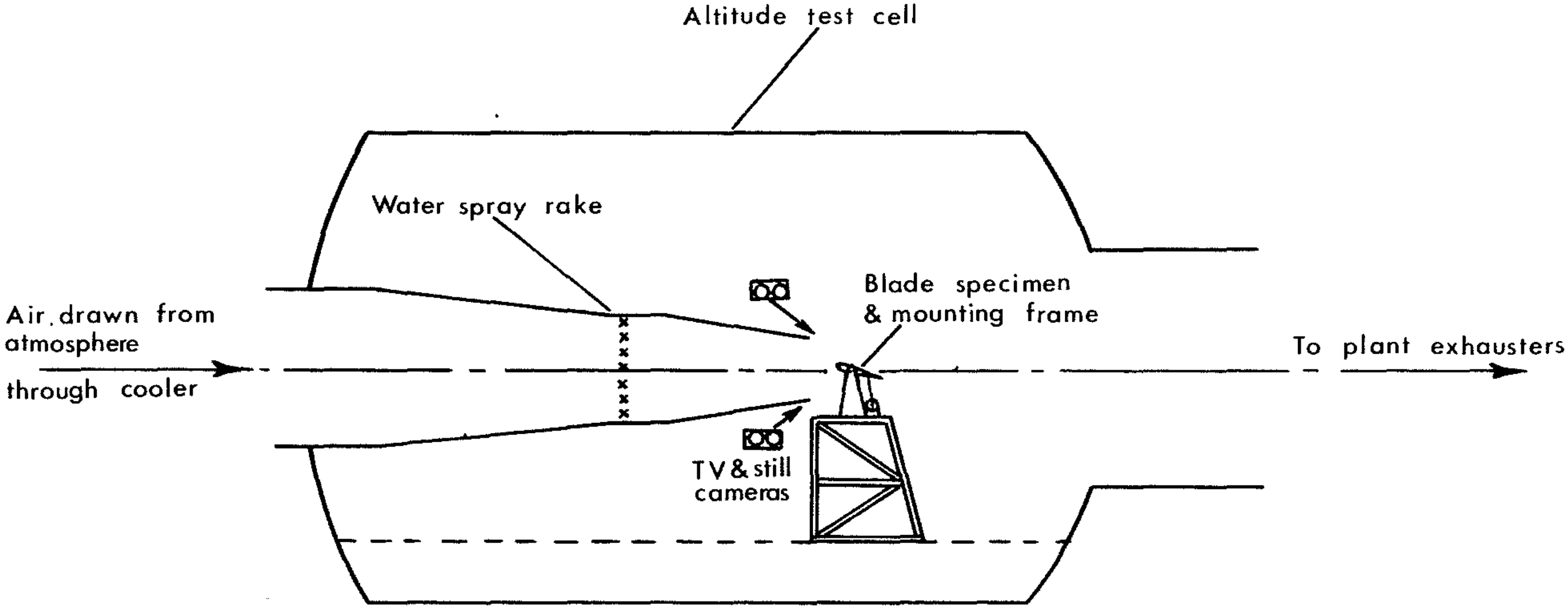


Fig 9 General layout of Cell 3 West installation for rotor deicing tests

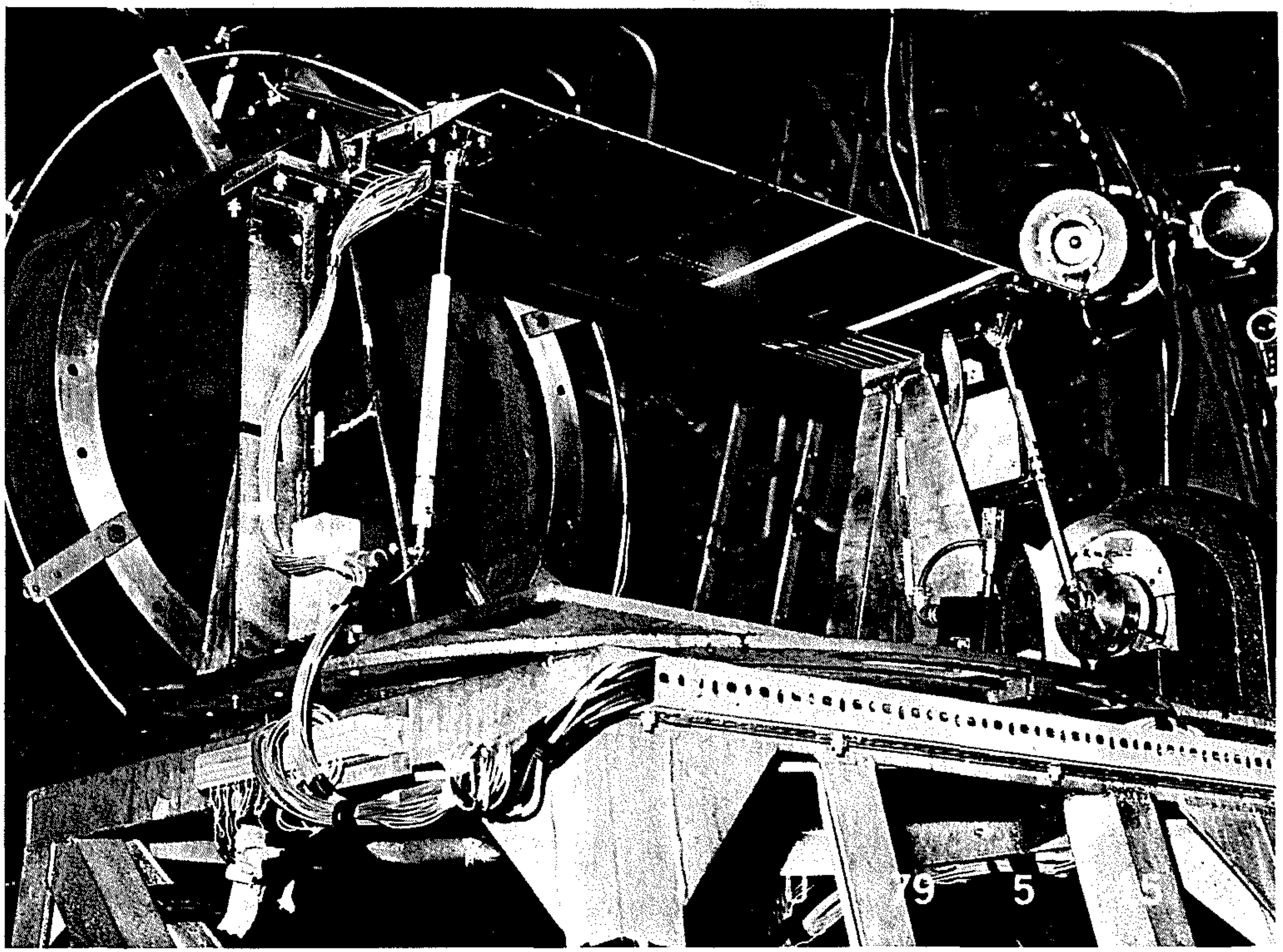
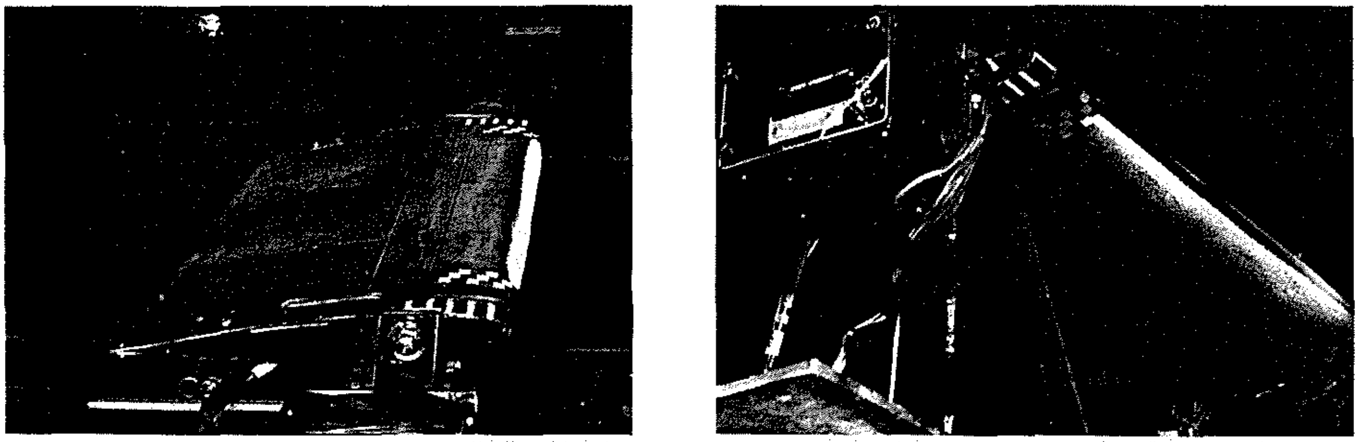
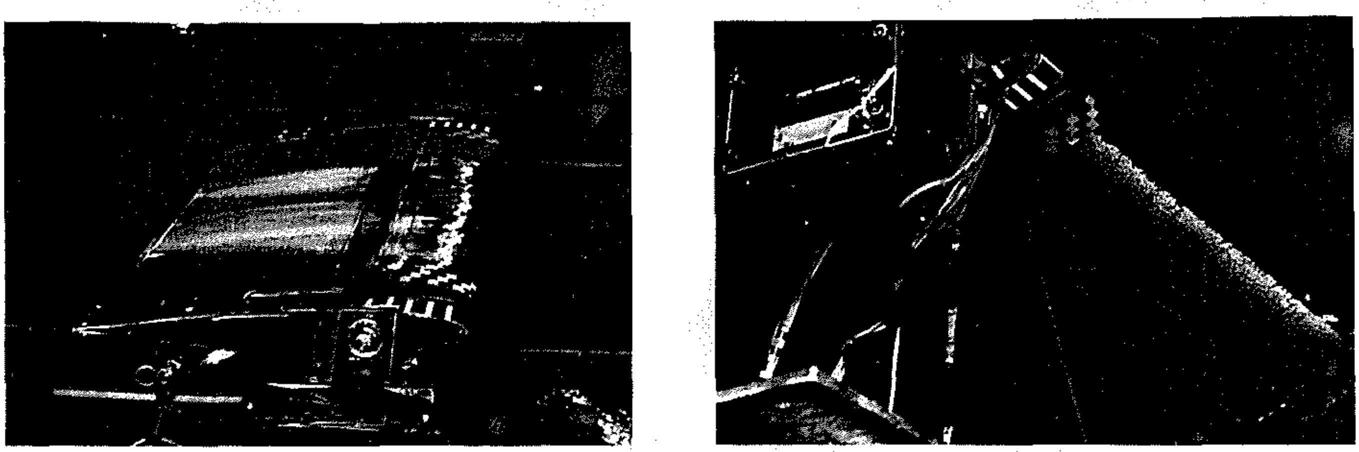


Fig 10 General view of deiced rotor blade specimen and blowing nozzle-

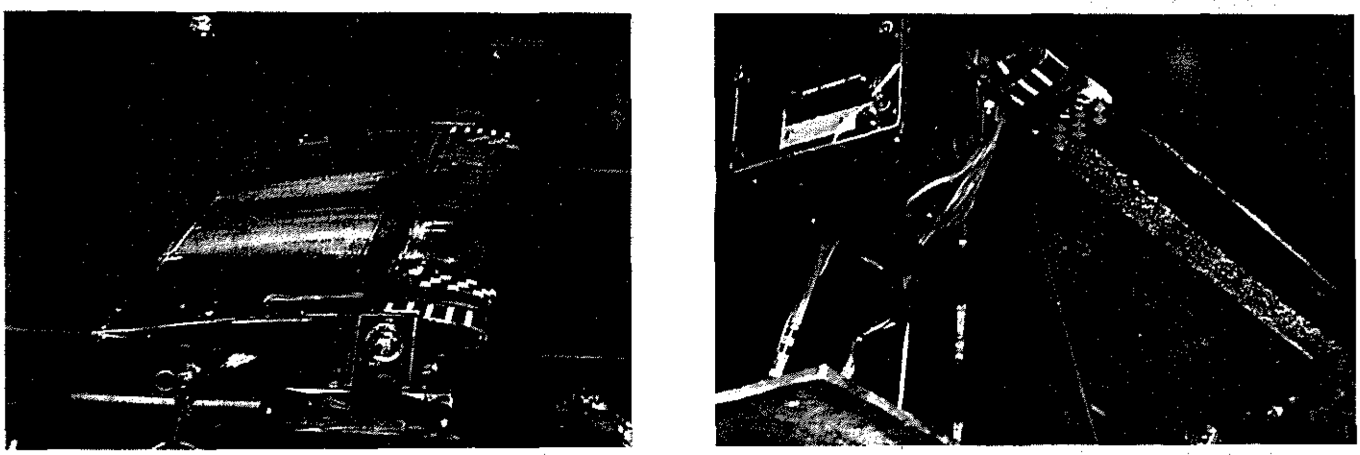
Cell 3 West, NGTE.



(a) Before deicing



(b) After several leading edge deicing cycles



(c) After runback clearance

Fig 11 Typical deicing sequences.